SNGF

Selected Node Geographic Forwarding Routing Protocol for VANETs

by

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Abstract

This thesis presents a protocol for intervehicle communication for use in Vehicular Ad Hoc Networks (VANET). VANET is a natural extension of mobile ad hoc networks (MANET) in which the restrictions related to power and mobility are relaxed. The routing protocols used for MANETs are generally dependent on the state of the network. With changes in the network topology, routing messages are generated so that the states of the routers in the network are updated. In the case of VANETs, in which the level of node mobility is high, message-routing overhead has serious implications for the scalability and throughput of the routing protocol.

This thesis introduces criteria that are recommended for use when protocols are designed for VANET applications and presents the Selected Node Geographic Forwarding (SNGF) protocol. The SNGF protocol implements controlled flooding in an efficient manner in order to reduce unnecessary communication overhead. The protocol has a destination discovery mechanism that allows it to initiate correspondence between nodes without reliance on static location services. The protocol avoids formation of clusters by using the concept of selective forwarding, thus providing the advantages of cluster based approaches without actually forming one itself. It effectively deals with blind flooding by introducing a comprehensive retransmission time delay in the nodes. This retransmission delay favors the nodes in the direction of the destination and prevents other nodes from retransmitting the same message. The SNGF protocol does not use routing tables, which require frequent updates in mobile networks, instead it relies on directing the messages to geographic locations which are forwarded by any available intermediary nodes. The protocol also provides techniques for handling network fragmentation which can be a frequent problem in vehicular networks. It is capable of delayed message transmission and multiple route discovery in the case of the non-availability of the shortest path to the destination.

To evaluate the performance of the SNGF protocol, an extensive study of mobile networks was conducted using the NS2 simulator. The simulation results demonstrate the reachability of the protocol, its scalability advantages and its total independence from location services.

The SNGF protocol allows each participating node to operate independently of other nodes in the network. Nodes in the network are able to communicate with other nodes without ever becoming dependent on intermediary nodes. This feature opens new possibility for individual node based application development in ad hoc networks. The traffic profiling is described as it would be observed by an independent node participating in VANET using the SNGF protocol. The node communicates with other nodes and collects relevant data through the discourse capability of SNGF. The data collected by the node is viewed as a snapshot in time of the traffic conditions down the road based upon which future traffic condition is predicted. Traffic profiling is investigated for different levels of VANET deployment. The simulation results show that the proposed method of traffic profiling in a VANET environment using the SNGF protocol is viable for even lower levels of deployment.

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Chapter 1

Introduction

Intelligent Transportation Systems (ITS) encompass a broad range of wireless and wireline communications based information and electronics technologies. When integrated into the transportation system's infrastructure, these technologies are envisioned to relieve congestion, improve safety and enhance productivity. Intelligent transportation systems are characterized by information, dynamic feedback and automation. They include the full scope of information technologies used in transportation, including control, computation and communication, as well as the algorithms, databases, models and human interfaces. The emergence of these technologies as a pathway for transportation is a relatively new phenomenon.

The importance of ITS can be highlighted by the fact that, in North America alone, an average driver can experience an annual delay of approximately 40 hours, costing individual cities several billion dollars per year in lost productivity [51]. If relevant information is available to the drivers while they are on the road they can make better informed decisions before they encounter a problem, such as a traffic jam ahead. Real time information is therefore considered crucial for motorists.

Although this kind of information is readily available today through internet, radio networks etc., the accuracy, timeliness and coverage of current systems are considered to be only marginally acceptable (ITS America 2000). Another major drawback of current intelligent transportation systems is their requirement for fixed and often expensive infrastructure to enable their functioning. For instance, most traffic data is collected through embedded loop sensors and mounted video monitors. The data collected in this manner not only requires significant infrastructure but also relates to only a limited section of the highway.

One method of overcoming the lack of required infrastructure for ITS communication is to use ad hoc networks. An ad hoc network is characterized by the absence of any fixed infrastructure to support or regulate communication between nodes. In a mobile ad hoc network (MANET), the nodes are also non-stationary. An intelligent transportation system can be viewed as a MANET in which vehicles can be seen as mobile nodes that form the ad hoc network.

Recently, there has been significant interest in Mobile Ad Hoc Networks (MANET) of vehicles for Intelligent Transportation Systems (ITS). The U.S. FCC has approved 75 MHz of spectrum in the 5.9 GHz band for Dedicated Short Range Communications (DSRC). The DSRC system is expected to provide first wide-scale on-the-road communication in North America. Governments and major automotive manufacturers have launched important VANET projects for example, Advanced Driver Assistance Systems ADAS [24], Chauffeur [9], CarTALK2000 [3], California Partners for Advanced Transit and Highways California PATH [64] and CarNet [43].

In a MANET based ITS, the vehicles are able to communicate with one another and can share data regarding traffic flow conditions. The data communicated between the vehicles depends on the number of vehicles equipped with MANET capability. However, the most significant feature is the fact that an ad hoc network provides an effective means of communication between vehicles without utilizing any infrastructure. The ability to communicate without infrastructure is important because it means that communication is possible anywhere on the road so that drivers can become aware of the traffic conditions ahead of them. The number of equipped vehicles will perceivably be very low in the early stages of deployment and thus the performance of any traffic condition monitoring system has to be evaluated under low numbers of equipped vehicles.

In an intelligent transportation system vehicles with MANET capability will provide direct wireless communication between vehicle-to-vehicle and vehicle-to-roadside nodes. Application of MANET has been envisioned for both safety and navigational purposes. Some of the applications are traffic management, accident avoidance, event coverage and vehicle discourse.

The vehicular transportation network defines what is known today as Vehicular Ad Hoc Network (VANET) [4]. Vehicles acting as nodes in VANET are able to make queries and respond to queries from other participating nodes in the ad hoc network. Node or vehicle mobility may cause frequent topology changes, thereby rendering proactive routing techniques ineffective or severely constrained with respect to network congestion. For a VANET to function effectively the nodes or vehicle should be able to overcome network fragmentation and relay messages to other nearby networks.

The mobility of the nodes and lack of infrastructure also exacerbate the problem of locating the destination node for message delivery. Proactive protocols are unsuitable because of the continuous topology changes which causes excessive network traffic to continuously update the routing tables. Reactive protocols will suffer from the limited time availability of discovered routes and the need to discover new routes because of the continuously changing topology of the network.

If the location of every node in the network is known then source-destination pairwise location aided routing can be used [29, 19]. Many protocols have been suggested including Location Aided Routing (LAR) [29], Distance Routing Effect Algorithm for Mobility (DREAM) [8] and Grid Location Service (GLS) [35]. However, when the location of the destination node is unknown or not readily available, then the whole network must be explored to detect a route to the destination node [37]. In case of a vehicular network, this might be a very likely scenario for the discourse of nodes in the absence of any fixed infrastructure.

A significant amount of work has been reported in the area of MANETs, but it has been shown in [12, 11] that an inter vehicular communication (IVC) network behaves in a way fundamentally different from that of a MANETs. The differences arise because of the following notable considerations:

- The network topology of an IVC changes much more rapidly than that of the frequently studied MANET.
- The problem of network fragmentation is much more severe in IVC networks.
- The nodal connectivity diameter in an IVC is much smaller than in a MANET.
- Redundancy is very limited in an IVC compared to other MANETs.

The differences between MANET and VANET provided the motivation behind this research work as explained in the next section.

Although the concept of mobile nodes in MANET provides the basis for VANETs on a conceptual level, the operating conditions and functional requirements and limitations are quite different for VANETs in comparison to MANETs. Whereas MANETs are unsuitable for deployment in ITS because of their limitations, ITS can benefit by utilizing VANETs to achieve the envisioned target of relieving congestion, improved safety and enhanced productivity. VANETs can provide an effective and efficient way of sharing information between vehicles in the ITS.

1.1 Motivation

The latest developments in communication technology have provided the ability for vehicles to communicate with each other without any fixed infrastructure so that useful information can be provided to motorists in a timely fashion. The increasing availability and accuracy of communication systems has reinforced the need for an efficient protocol capable of handling vehicular communication. Another important development over the last few years is that the Global Positioning System (GPS) technology has become available inexpensively and the use of GPS technology is suitable for vehicular applications as the availability of power is not an issue.

Protocols developed for MANETs have proven unsatisfactory in a number of respects. Their performance deteriorates rapidly in the case of node mobility. Topology based protocols suffer from network traffic overhead generated by regular updates that are necessary for refreshing the routing table. They also do not scale well when topologies are constantly changing. Position based protocols require the location of the destination and hence depend on some locator service. This locator service is often in the form of a fixed infrastructure or a local proxy gateway node. Network fragmentation is considered an issue in both topology and position based protocols.

A need has hence been demonstrated for a smart protocol that can provide the following advantages:

- Minimize network traffic overhead by using efficient routing strategies that minimizes blind flooding.

- Locate destination nodes without relying on fixed infrastructure or the use of a location service.
- Provide a built-in recovery mechanism in the case of network fragmentation.
- Provide for ability for the vehicles to discourse. The sharing/gathering of information will allow the development of useful tools that vehicles can use locally in order to help drivers make better decisions regarding driving conditions on their travel path. They may, for example, gather information from other vehicles down the road in order to predict traffic conditions in their own pathway.

It is reported in [45] that the plain flooding protocol performs relatively well as compared to other multicast protocols. For this research controlled and efficient flooding was investigated as a basis for specialized protocols for vehicular ad hoc networks (VANET) in which node mobility is expected to be high.

1.2 Objectives

This research has developed a new protocol for use in Intelligent Transportation Systems based on Ad Hoc Network of Vehicles. This protocol is based on a generalized structure of communication for vehicular traffic application. The protocol provides for all possible types of communication in a VANET: emergency broadcast, normal broadcast, and discourse.

The problem of congestion in a communication channel is handled by a mechanism for decision making that is based on the need for message retransmission. The nodes in the ad hoc network use the concept of message priority and are also able to evaluate the need for the retransmission of the received message. For example, if the message being relayed is already being transmitted by a nearby neighbor then the current node may decide not to retransmit it at all. A message may also be used locally by a node for information gathering and may be retransmitted in its entirety if the specified action in the message is not satisfiable by the local node. If the network becomes fragmented, the nodes will also retransmit but with a delay so that the travel time includes possible contact with new nodes.

To demonstrate the viability of the developed protocol for VANETs, the traffic profiling problem was investigated by viewing it from the perspective of an individual node in the network. The new protocol allows the node that is performing the profiling to collect date from other nodes and to predict traffic conditions down the travel path. The data collected through discourse among the vehicles can be viewed as patterns of traffic conditions on the road. The node collecting the data for traffic profiling can then use appropriate pattern recognition techniques such as a classifier based on weight of evidence to help classify the traffic condition down the road.

The specific objectives of this research are as follows:

- Propose a new protocol for VANET communication that is suitable for intelligent vehicle systems.

- Exploit the flooding technique to promote scalability by selecting suitable nodes to forward messages.
- Eliminate reliance on a locator service by discovering the geographic location of destination nodes without blindly flooding the network.
- Provide a mechanism within the protocol to alleviate the problem of fragmentation in VANETs by buffering messages and delaying transmission when no direct connection is available for destination node.
- Study the performance of the developed protocol for VANET under different load conditions.
- Demonstrate the viability of the developed protocol for problems encountered in an ITS, such as traffic profiling.

1.3 Thesis Outline

The remainder of this document is organized as follows. Chapter 2 provides the background about the area of ad hoc networking and outlines the relevant related work in the literature. It also briefly describes some of the existing routing protocols for mobile ad hoc networks. Chapter 3 explains the existing routing protocols with respect to their suitability for VANETs. Multicast routing structures are reviewed and insights into the design of a purely VANET based routing protocol are provided. Chapter 4 presents the developed SNGF routing protocol in detail, alongwith a discussion of its salient features and a comparison with existing protocols. Chapter 5 outlines the simulation setup used to validate the effectiveness of SNGF. It also provides a comparison with existing protocols and an analysis of the results of the simulation experiments. Chapter 6 demonstrates the viability of the SNGF protocol through a description of its application for solving the traffic profiling problem in VANETs. Chapter 7 highlights the contributions of this research.

Chapter 2

Ad Hoc Network Protocols for ITS

This chapter is a review of the literature related to mobile ad hoc networks, specifically those areas relevant to intelligent transportation systems.

In a mobile ad hoc network (MANET), the nodes communicate with one another in the absence of any fixed infrastructure [61]. A mobile ad hoc network of vehicles is further characterized by the high mobility of its nodes. In addition to the inter nodal communication over wireless links, the mobility of the nodes creates constant changes in the network topology. These changes make the task of routing a message to its intended destination node very challenging.

Research work in the area of MANETs is dominated by routing issues [6, 34, 38, 49, 53, 56]. Routing in the network can be unicast or multicast. In unicast a specific route between the source and the destination nodes is predetermined whereas in multicast a message is received by all member nodes. Routing protocols can be classified as either topology based or position based [40], as explained in the following sections.

2.1 Topology Based Routing

Topology based routing uses the concept of a routing table in order to forward messages. The routing tables are maintained by individual nodes and must be updated in order to reflect changes in the network. The updating of the routing tables can be periodic, on demand or based on a scheme that is a combination of both.

Topology based routing protocols can be categorized as proactive, reactive and hybrid [40].

2.1.1 Proactive Protocols

Proactive routing protocols maintain routing information about all possible destinations by periodically sharing information among the nodes of the network. Network routing information depends on the topology of a mobile ad hoc network which may change for several reasons, including node mobility, the discovery of new nodes, node failure and node departures. Any change in the topology of the network is followed by an update of the routing information in the routing tables of all the nodes in the entire network. The nodes in the network maintain all routes even if a route is not currently being used by any communication channel. This proactive maintenance of the routes generates excessive communication overhead, thereby restricting the bandwidth available for packet communication.

Proactive protocols are better suited for static or slow changing topology networks but they do not scale well for constantly changing topologies such as those in mobile ad hoc networks [41]. Examples of proactive routing protocols include Destination Sequenced Distance Vector (DSDV) [46] and Optimized Link State Routing Protocol (OLSR) [25].

2.1.2 Reactive Protocols

Reactive protocols do not constantly maintain the routing information for the entire network. The routing information in a reactive protocol is updated according to the current needs of the communicating nodes. This method reduces bandwidth usage compared to proactive protocols but may result in an initial delay in packet delivery due to the route discovery process required in order to establish communication. Reactive protocols maintain only the routes that are currently in use of the network. The routes currently in use may be only a small subset of all the possible routes and thus save a considerable amount of overhead from the network. On the other hand, in the case of mobile nodes, the established routes may quickly become outdated and require frequent updates, which generates extra network traffic overhead.

In the case of VANETs, where the nodes are fast moving, route discovery may have to be initiated before each message transmission and may then have to be updated frequently according to network dynamics. Examples of the reactive protocols are Dynamic Source Routing (DSR) [26] and Ad hoc On Demand Distance vector (AODV) [47].

2.1.3 Hybrid Protocols

Some protocols use the concepts of both proactive and reactive protocols in an attempt to minimize network overhead and improve scalability. In hybrid protocols, a subset of nodes maintain routing information proactively whereas others respond reactively to network requirements. One possible combination is the use of local routing on a proactive basis and global routing on a reactive basis. However, hybrid combinations still must maintain the routes that are currently in use, which limits the changes in topology that can be tolerated by the protocol. Examples of hybrid protocols are Zone Routing Protocol (ZRP) [23] and Adaptive Distance Vector Routing ADV [13].

2.2 Position Based Routing

In topology based routing, the network topology plays a central role in determining available or possible paths for packet flow. In the case of mobile networks the network topology becomes critical for determining the scalability and bandwidth utilization of the network. In position based routing in a mobile ad hoc environment, the node uses additional information regarding the location of the destination node to help route the packet. The physical location of the sender node is available through a Global Positioning System (GPS) and a *location service* (e.g., a Grid location Service GLS [35]) is employed to track the location of the destination node. The node decides to forward the packet to its neighbor based on the available locations of both neighboring nodes and the destination node. The nodes therefore, do not have to maintain a routing table, thus saving network bandwidth.

Position based protocols rely on prior knowledge of the location of the source and destination nodes. Routing decisions are made based on the location of destination and one hop neighboring nodes. An important consideration is the availability or accessability of this information about the source and the destination nodes. To obtain self location information the nodes can use Global Positioning System [54, 55], which can also be used to acquire the physical position of the sending vehicle or node. Unlike ordinary nodes in a MANET the vehicular nodes in a VANET can easily use GPS because they are not subject to the power consumption limitations. The use of GPS simplifies the problem of obtaining source location information, but acquiring information about the location of the destination node is still a nontrivial problem.

Theoretically, there are several types of solutions for this problem. One is to obtain the destination location through flooding the entire network with destination location inquiry packet. However, flooding in a network creates challenges with respect to bandwidth and utilization of the network resources. One way to avoid flooding in a network is to use the concept of controlled flooding, in which not all nodes are required to forward the packets [63].

In another solution, the position of the destination is obtained with the help of an external position location service. The latter solution although suggested and conveniently used by many ad hoc network routing algorithms maybe contradictory to the definition of an ad hoc network, which is characterized by lack of infrastructure requirements.

Position based routing protocols can be described according to their three main features: location service, forwarding strategy and recovery strategy. Several position based routing algorithms have been presented in the literature including Distance routing effect algorithm for Mobility ($DREAM$) [8], Location Aided Routing (LAR) [30], Grid Location Service (GLS) [35] and Greedy Perimeter Stateless Routing ($GPSR$) [28]. The suitability of each for highly mobile ad hoc network of vehicles is discussed in the following subsection.

2.2.1 Distance Routing Effect Algorithm for Mobility

In the DREAM algorithm each node maintains a position database that contains the position information of all other nodes that are part of the network. Each node transmits packets regularly in order to update its own position information that is maintained by all other nodes. The transmitting node controls the frequency of its position updates (temporal resolution) and also how far a position update may travel (spatial resolution).

The temporal resolution, or frequency of the position updates depends directly on the mobility rate of the node, and the spatial resolution depends on the distance effect of the node [7]. The distance effect is the motion of nodes relative to one another which is dependent on the distance separating them. If the separating distance is large, the relative motion is small, as shown in Figure 2.1.

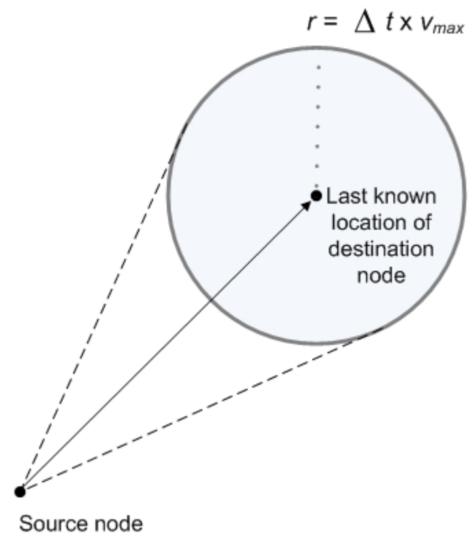


Figure 2.1: DREAM. The circle with radius r represents the expected region.

To send a packet to the destination, the sender node forwards the packet in the direction of the destination node. This direction is represented by a circle or expected region around the destination node. The radius of this circle is set to $(t_1 - t_0)v_{max}$, where t_1 is the current time, t_0 is the timestamp of the position information, and v_{max} is the maximum velocity of the nodes in the system. If a node does not have a one hop neighbor in the direction of the destination node then a recovery procedure has to be undertaken but this is not specified as a part of DREAM [40].

2.2.2 Location Aided Routing

Location aided routing uses position information to determine the route. In the route discovery phase, it uses controlled flooding in the direction of the destination location; if the direction is known, otherwise, it is reduced to simple flooding. If the destination information is available, e.g., from a previously established route, then a *request zone* is defined.

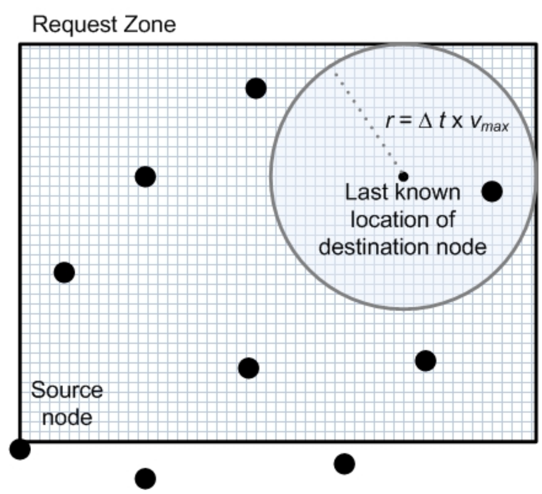


Figure 2.2: LAR. The rectangular region depicts the expected zone.

The request zone can be rectangular, as shown in Figure 2.2, or can vary depending on the estimated destination coordinates plus the distance to the destination [30]. In the latter case the node is allowed to forward the packet if it is some δ (a system parameter) farther away from the previous node, and the forwarding node then updates the distance field in the packet with its own current distance to the destination. This process is similar to that of the DREAM approach [40]. The rectangular zone limits the forwarding of the packet to one quadrant of the topology of the network, resulting in network resource savings because nothing is broadcast to or from the remaining three quadrants.

2.2.3 Grid Location Service

In GLS, a proactive distance vector routing protocol is used at the local level and position based routing is used for long distance message forwarding. This method basically requires one proactive position aware node in each area that can act as a proxy gateway. GLS also allows nodes without position awareness to be part of the ad hoc network and to use the position aware nodes as their proxies in the network.

If a forwarding node has no immediate neighbors that can make forward progress, it discards the packet and sends a notification to the sender of the packet. The sender then chooses a single intermediate position randomly within a circle around the midpoint of the line between the sender and the receiver. Packets must traverse that intermediate position. If the packet is discarded again, the same process is repeated but with a larger radius. This whole process is repeated for a predefined number of times, after which, if the packet is still undelivered, the sender assumes that the receiver is unreachable.

2.2.4 Greedy Perimeter Stateless Routing

In Greedy Perimeter Stateless Routing the packets are primarily forwarded based on a greedy approach but the forwarding algorithm switches to perimeter mode once the greedy forwarding is determined to be impossible.

GPSR assumes the position of the destination nodes to be known with one hop accuracy and depends completely on an external location service for this information. The packets are forwarded based on local information and the packet header. The nodes in GPSR are not required to store any additional information. A forwarding node makes decisions based on the node locations (neighborhood list) and on information from the packet header.

GPSR basically forwards the packet in greedy mode. If the greedy mode fails, then the GPSR switches to perimeter mode forwarding, as shown in Figure 2.3 . When a packet enters perimeter mode, the GPSR records the location in the packet header, which prevents the packet from being sent in loops if the destination is unreachable. In perimeter mode the packets are forwarded in a simple planar graph traversal with a node being selected based on the right hand rule. The algorithm can switch back to greedy mode at any time if it becomes possible to forward the packets using a greedy approach.

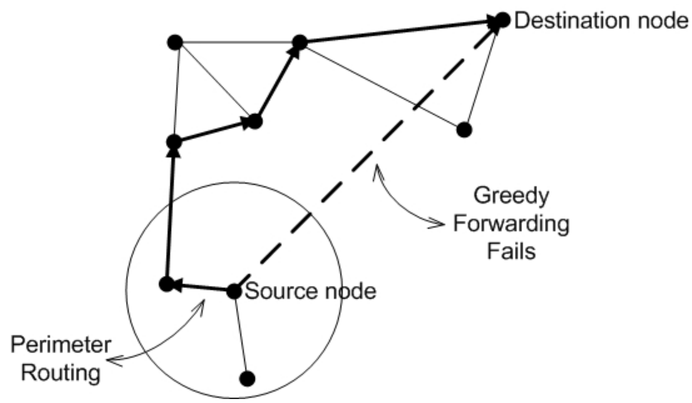


Figure 2.3: Greedy Perimeter Stateless Routing (GPSR)

2.3 Related Work

Mobile networks have long been used in telecommunication systems and ad hoc networking has been used for a variety of applications that a conventional network can not cover. This section highlights work in this area and relates that work to its suitability for use in VANETs.

Mase *et. al.*, [39] described a vision of a next generation ad hoc network, which is termed a universal ad hoc network. The paper presents several flooding based schemes such as gateway forwarding and selected gateway forwarding. These schemes rely heavily on a cluster formation of nodes. The control packets required for clustering consume bandwidth, and this overhead increases with node mobility because the clustering cycle must be kept small so that the clustering is properly reconfigured. The clustering technique is thus adequate for networks with relatively low mobility.

Niculescu and Nath [44] have presented an ad hoc positioning system (APS) based on a distributed hop by hop positioning algorithm. The algorithm extends the capabilities of GPS to non-GPS enabled nodes. The positioning is based on a hybrid method combining distance vector like propagation and GPS triangulation to estimate a location in the presence of errors in signal strength measurements. The algorithm is loop free because the packet is dropped if all the neighbors fail to satisfy the forwarding criteria. The mobility of the node is also not explicitly considered, and the APS is designed for networks with limited changes in topology.

Ko and Vaidya [31] use a variation of multicasting, called geocasting. Geocasting is useful for sending a message that is likely to be of interest to everyone in a specified area. The basis for the algorithm is derived from Location Aided Routing for unicasting. It also assumes that each node periodically broadcasts its position information in control packets throughout the network to maintain a location database that is utilized for the delivery of geographic messaging. The proactive updating and maintenance of position information in a high mobility ad hoc network may prove very costly and hence be unsuitable.

Kuhn *et. al.*, [33] developed a new geometric routing algorithm named $GOAFR+$ pronounced as 'gopher-plus'. The algorithm assumes that the destination position is known and proposes a method for routing around voids that is both asymptotically worst case optimal as well as average case efficient. Geographic routing is scalable because nodes keep state only for their neighbors, and it supports a fully general any-to-any communication pattern without explicit route establishment.

However, knowledge of the destination location node may be a natural assumption in some settings (e.g., sensornet nodes with GPS devices), there are many settings where such destination location information is unavailable.

Gerla and Kwon [63] produced a comparative study of efficient flooding based protocols. Efficient flooding is possible when the topology or neighborhood information is available thereby restricting the number of nodes to which the packet is forwarded as opposed to blind flooding in which all nodes forward the received packet. The study shows that the collection of accurate neighborhood information is very hard in ad hoc networks due to node mobility, unreliable packet delivery, and low bandwidth.

Santos *et. al.*, [50] have presented a location based routing algorithm with cluster based flooding for vehicle to vehicle communication. The nodes are clustered, and each cluster head maintains a cluster table. The cluster table contains the addresses and geographic locations of both member and gateway nodes.

Liu *et. al.*, [37] have proposed a protocol that dynamically creates a pre-routing region between each source-destination pair and limits the propagation of route request packets to this region. All qualified nodes inside the pre-routing region are required to relay route requests in order to ensure the discovery of the optimal route within the region. The other nodes do not retransmit the route requests.

Mir and Khan [42] have presented an algorithm that combines a zone based location service and restricted directional flooding for geocasting to a particular location. The initial geocasting region is assumed to be known and as such the purpose is simple geocasting. The algorithm does not seem well suited for VANETs that have discourse capability.

Lipman *et. al.*, [36] developed a reliable minimum spanning tree based flooding algorithm for packet delivery, however, their algorithm does not take into account mobility of the nodes and hence is unsuitable for application in VANETs.

Avramopoulos and Kobayashi [5] have presented flooding based protocols that guarantee packet delivery based on the assumption that the source router is connected to the destination router by at least one non-faulty path. This scheme basically tries to form a loose cluster of nodes and then attempts to find the optimal route between them.

Briesemeister and Hommel [15] explored the concept of waiting times in the retransmission of messages by the nodes in the vicinity of the source node. The delay in the retransmission time prevents peak load conditions in the network system because the nodes are forced to wait.

Feng and Lu [21] have presented a forwarding scheme based on the relative velocity between the intended forwarding node and the destination node. The scheme then uses motion predictive models to predict the location of the destination.

In this chapter a brief summary of the existing protocols in the area of VANETs have been reviewed. Besides listing the salient features of well known protocols such as LAR, GLS and GPSR, some of the other techniques available in the literature were also presented along with their shortcomings. In the the following chapter the guidelines for designing a VANET specific protocol are identified and discussed in detail.

Chapter 3

Design Criteria for VANET Protocols

Vehicular ad hoc networks (VANETs) consist of mobile nodes that are capable of establishing connectivity via multihop wireless communication that does not rely on any centralized control or infrastructure. This freedom from the requirement for any fixed infrastructure allows ad hoc networks to be instantly deployed and hence makes them very useful in cases when immediate communication facilities are required. Although VANETs may be considered a natural progression of wired networks they are inherently different from their wired counterparts . In wired networks, changes in topology are very rare, and thus if a change ever occurs, its propagation throughout the network is not considered expensive. Wired networks are also characterized by an abundance of link capacities. Both changes in topology and link capacity are very different in the case of VANET protocols. In

VANET constant motion of nodes produce a high rate of change in the topology. If a node is in the vicinity of the communicating node then the communication between nodes is accomplished by one radio hop direct communication. However, when the nodes are far apart it may be necessary for the packet to travel through two or more hops in order to establish indirect communication between nodes. In indirect communications, packets must be forwarded by intermediary nodes in the direction of the destination node. Moreover the bandwidth available to mobile nodes is an order of magnitude less than that of their wired counterparts.

Given these factors, VANET based routing protocols must be very adaptive in order to deal with the changes in topology and must also have low network overhead because of their limited link capacity. It is the opinion of the author that the extension of wired networks to mobile networks is negatively affected by this lack of crossover phenomenon.

One major perceived advantage of VANET lies in its role as an information provider for several nodes at the same time. This ability means that the VANET protocol should be able to multicast as and when required. Multicasting in wired networks is usually accomplished through an IP multicast structure, but this method requires that every router in the network must be multicast enabled. One means of avoiding this problem is to use a multicast tunnel in which multicast traffic is encapsulated and then sent toward the destination as a unicast message. Multicasting in a wired network requires the maintenance of some form of spanning trees for all nodes and in a network with high rate of change in topology, the performance of protocols based on an IP structure can deteriorate very rapidly. Continuous changes in the topology means that the spanning tree must also be continually updated. Multicast protocols developed for wired networks are therefore not suitable for VANETs.

Multicast routing protocols have recently been developed for mobile ad hoc networks (MANETs). A number of the differences between MANET and VANET have been highlighted in Chapter 1. The next section describes currently existing multicast routing protocols.

3.1 Multicast Routing Protocols

Multicast routing can be defined as a 'Sent by one, Received by many.' Multicasting is phenomenon inherent in the wireless routing protocols. All messages that are sent by one node are received by many surrounding nodes. The delivery structure of the routing protocol governs the behavior of the receiving nodes, so the mobile routing protocols can be classified according to their delivery structure. The method of packet forwarding defines the delivery structure which forms the path for the routing of the packet to its intended destination. Protocols can employ several options for packet forwarding, the most common of which are explained in the following subsections.

3.1.1 Flooding

Flooding is a non specific delivery structure whereby the packet is flooded globally to all nodes in the vicinity of the transmitting node. The receiving nodes may then repeat the process under the control of a selected mechanism. Although robust, a flooding protocol results in high bandwidth usage due to the duplication of data forwarding. Mechanisms are then required in order to limit bandwidth usage by controlling packet forwarding and preventing a broadcast storm.

3.1.2 Tree Based Forwarding

Tree based protocols maintain a tree structure between the multicast nodes. These protocols can be further classified as a Source Based multicast Tree (SBT) or a Core Based multicast Tree (CBT) depending on the type of tree structure that is maintained between the multicast nodes.

In the Source Based multicast Tree (SBT) protocol, for each multicast source node in each multicast group, a multicast tree is formed and maintained. This process results in efficient packet forwarding from the source node to the multicast nodes. Shortest path trees are more commonly used as multicast trees between the source nodes and the multicast nodes in each group due to their simplicity and efficiency. The use of an SBT results in challenges with respect to scalability when the number of source nodes and multicast groups increases. This protocol also requires topological knowledge and must recalculate or reformulate trees in the case of topological changes, which occur frequently in mobile ad hoc networks.

A Core Based Multicast Tree (CBT) uses a core node to establish a shared tree for each multicast group. Packets are forwarded to all the nodes in the multicast group through this shared tree. This method reduces the scalability problem of the SBT because only one common tree must be maintained rather than multiple trees for each multicast group, but the selection of a core node is required. A CBT entails difficulties related to congestion because the shared nodes retain the primary responsibility for traffic flow. This feature may also result in reduced efficiency because only shared links are considered for routing, and the single core node may also be subject to single point of failure. Reconfiguration of the trees may be required as a result of topological changes in the network.

3.1.3 Mesh Based Forwarding

With a mesh based forwarding protocol, a mesh is created for each multicast group, resulting in multiple paths between the nodes. This process improves robustness and is beneficial during topological changes in the network because frequent reconfigurations are not required as they are in tree based protocols. However, this protocol may result in increased bandwidth usage due to the forwarding of packets along redundant paths.

3.1.4 Group Based Forwarding

With a group based forwarding protocol, instead of maintaining a tree or a mesh, for each multicast group, a group of nodes are selected to be responsible for multicast packet forwarding. In this group based forwarding process multicast forwarding nodes are selected so that each group remains reachable. This method results in reduced processing at the node level because the nodes are not required to maintain links as in the tree or mesh based forwarding protocols. However, this protocol is restricted by the need to select nodes to act as forwarders, and because of frequent topology changes in mobile ad hoc networks, frequent selection may be necessary.

3.1.5 Existing Ad Hoc Multicast Routing Protocols

Table 3.1 lists multicast protocols classified according to their delivery structure. The table also indicates the most common or representative protocol in each category.

Table 3.1: Classification of Multicast Protocols According to Delivery Structure

Existing Routing Protocols for Mobile Ad Hoc Networks			
Source Based Tree	Core Based Tree	Group Based Forwarding	Location Based
Distance Vector Multicast Routing Protocol (DVMRP)	Ad Hoc On Demand Distance Vector (AODV)	On Demand Multicast Routing Protocol (ODMRP)	Location Based Multicast (LBM)

3.2 Developing a VANET Specific Protocol

The development and employment of VANETs have been highly motivated by their intended real life functionality. VANETs allow messages to be communicated between vehicles in an ad hoc network formation. The nature of messages in a vehicular environment dictates the priority that should be assigned to their handling. For example, a message concerning a safety issue that is being relayed by a vehicle that has been in an accident on a main highway should receive priority for broadcasting to all other vehicles in the region. On the other hand in discourse between the nodes the messages should be routed toward the destination node in order to overcome the problem of fragmentation of the ad hoc network.

The broadcast operation plays a fundamental role in a mobile ad hoc networks and has both a positive and a negative effect. The positive effect stems from the fact that whenever a message is transmitted by a node, it is received by all the nodes within broadcast range of the sender. The negative effect results from possible interference with other communications.

Flooding provides a method of disseminating messages to all the nodes in the network but it may also trigger a broadcast storm that can overload the network. A broadcast storm can be avoided through the use of efficient and controlled flooding schemes that have the goal of reducing the number of retransmitting nodes, which in turn reduces network traffic while ensuring that the intended nodes do receive the message.

Although position based protocols are relatively free from the problems that limit the use of topology based protocols for VANETs, in practice, the deployment of VANETs remains restricted subject to the resolution of several important challenges.

3.3 Challenges with Position Based Protocols

This section focusses on laying the foundation for a comprehensive framework for mobility based inter-vehicle communication. Three main design factors have been identified with respect to the development of protocols for VANETs.

The first problem is the determination of the (initially unknown) location of the destination node. The second challenge is the development of an efficient forwarding strategy which should minimize the possibility of broadcast storm. The final difficulty is to develop a robust recovery strategy in case the route to the destination node is not readily available.

3.3.1 Destination Discovery

To establish communication between two nodes in a mobile network the first requirement is knowledge of the location of the destination node. The transmitting or initiator node must know the destination location in geographic terms so that the packet can be directed toward it. Most routing protocols for ad hoc networks assume the availability of a location server or service from which such information can be readily obtained. This assumption limits the applicability of ad hoc networks and in fact renders them dependent on infrastructure. It is the opinion of the author that the protocol for communication in VANET should be free of this restriction. The protocol should be equipped to find out the destination location on its own without reliance on any location service.

When a source attempts to find a destination with an unknown position, it must explore the whole network in order to locate the destination. Conventional ad hoc routing protocols are inclined to combine destination discovery with optimal route discovery. As a result, every node in the network is involved in the rebroadcasting of the routing request messages. The destination location discovery should not cause excessive overhead network traffic and at the same time, should be able to obtain the required information about the location of the destination node from the network.

A location service is used to acquire the location of the destination node. The mobile nodes in a network register with the location service and update it periodically with their position. When a node wants to send a message to a particular node it contacts the locator service to request the destination node location. Designated servers with well known addresses are used in classical cellular networks to serve as position servers.

In the case of mobile ad hoc networks that have no fixed infrastructure, it would be difficult to obtain this information if the server itself were a part of the network. If the location service is static, it requires infrastructure to be in place and if it is mobile itself then it is difficult to guarantee the availability of at least one location server in the local ad hoc network. A centralized position locator service is thus viable only if it can be reached through non-ad hoc means [40]. To overcome this problem decentralized approaches to location services have been investigated, as reported in [8].

For VANET routing protocols, the nodes in the network should be able to locate their intended destination efficiently by using the provisions in the protocol and not by depending on any infrastructure based location servers.

3.3.2 Packet Routing Strategy

The nodes in an ad hoc network communicate with one another by sending and receiving data packets. In wired networks, this operation is very simple because the nodes have fixed IP addresses and the routing protocol relies heavily on routing tables to forward packets to nodes that are located in the direction of the right destination nodes. In mobile ad hoc networks, routing tables are not feasible because constant changes in network topology very frequently render them outdated. The cost of updating routing tables network wide is significantly high in terms of bandwidth utilization, therefore, a different method of packet forwarding must be adopted.

In the absence of routing tables, the forwarding strategy is guided by the position location of the destination node. The intermediary nodes are responsible for forwarding the packet toward the destination node. The author believes that in addition to using the destination location to act as a pull force on the message, it may also be worthwhile to employ the originating location to act as a push force. This combined effect may be viewed as a push and pull strategy on the message where the push factor is generated by the originating node and the pull factor is contributed by the destination node.

In a position based protocol, a forwarding strategy controls the overall broadcast traffic in the ad hoc network. The strategies reported in the literature can be classified as greedy forwarding, restricted directional flooding, and hierarchical approaches [37]. With greedy forwarding, the transmitting node forwards the packet to the one hop neighbor that is closest to the destination and with restricted directional flooding the packet is forwarded to one or more of the one hop neighbors that are closer to the destination node. In the latter case, the selection of the destination node is based on the optimization criteria of the forwarding algorithm. Excessive retransmission by competing nodes can be resolved through the use of waiting times for retransmission based on the distance from the origin node [15].

Hierarchical approaches are used to reduce the level of complexity associated with message forwarding that nodes in large scale network must handle. An example of this type of approach is to use a proactive routing strategy if the destination node is close and to switch to greedy forwarding if the destination node is farther away [10].

3.3.3 Recovery Mechanism

In vehicular ad hoc networks, communication routes between nodes may not always be maintained due to rapid changes in the topology. An effective built-in recovery strategy is therefore required so that communication can be maintained. A recovery strategy should be an inherent part of the protocol because fragmentation may be a significant problem when nodes are mobile. An effective recovery strategy limits network traffic and provides better packet delivery in the network.

A recovery strategy is needed when the forwarding strategy fails to deliver the packet to the intended destination. For example, with greedy forwarding, the forwarding strategy fails if it is unable to find a one hop neighbor closer to the destination than itself. Alternative forwarding approaches, such as a greedy perimeter search or face routing, can also be used.

In the case of highly mobile nodes operating in an ad hoc environment such as VANETs, a recovery strategy may also be needed because the network can become fragmented so that then there is no immediate connection or route available to the destination node. In this case, rather than dropping the transient packet, a recovery strategy can be employed to delay the transmission of the packet until such a time as new neighbors are detected.

3.3.4 Developing Applications Using VANETs

In addition to challenges with the protocol design the possibilities of using VANET routing protocols were also investigated with a view to developing applications that can be used by vehicles in realtime mode, such as those for detecting traffic jams on highways. The author believes that readily available applications running on ad hoc mobile networks will enhance the implementation of VANETs in real life.

One major use of VANETs is as applications running individually on nodes that can be used to help drivers on the road. These applications would extend beyond simple alarms or warning generating systems, such as, those for avoiding collisions. A communication protocol for VANETs should facilitate gathering of information by the nodes from their surroundings and then use the data gathered in order to predict, for example, traffic conditions further down the road.

3.4 Assumptions for Communication Environment

VANET is a peer-to-peer network that allows nodes to communicate directly with one another if they are within radio range. It also allows multihop communication for out-of-range nodes, using the appropriate protocol necessary for finding a route to the destination. Without loss of generality the following assumptions have been made with respect to the VANET communication environment:

- All participating vehicles are equipped with wireless communication equipment. This assumption means that all nodes are able to perform similar networking and communication functions, although not necessarily at the same time.
- All nodes are also equipped with a GPS system through which they are aware of their own physical location at all times.
- Each vehicle, or node, in the VANET is identified by a unique identification number.
- Each node can communicate with surrounding nodes within one hop and maintains a list of its neighbors and their geographic locations.
- The discourse vehicles are located in a specified geographic area in the same plane but not necessarily within a one-hop communication range.

In this chapter the essential components for a VANET specific protocol have been identified. Next, Chapter 4 presents a new protocol for VANET communication that is based on the previous discussion and considerations.

Chapter 4

Selected Node Geographic Forwarding Routing Protocol

This chapter presents a new routing protocol based on controlled flooding, called the Selected Node Geographic Forwarding (SNGF) routing protocol. As mentioned in Section 3.4, all participating nodes are aware of their surrounding neighbors identified by unique identity numbers and their respective geographic positions. This list of neighbors and the information carried in the packet header is all the data necessary for the node to make a packet forwarding decision under SNGF routing protocol.

4.1 SNGF: A New Protocol for VANETs

Because of the high rate of mobility of the nodes and the constant changes in the topology of the network, the proposed protocol does not rely on maintaining routing tables on the nodes. The proposed protocol is designed to use a message forwarding mechanism based on the geographic location of the destination node. The message is propagated in the direction of the destination node by any available intermediary nodes. If more than one node is capable of forwarding the message in its intended direction, then the only node that forwards the message is the one that is able to make the best contribution in terms of delivering the message to its intended destination [58].

The SNGF routing protocol is designed to meet the following criteria:

1. Minimize the use of flooding by selecting appropriate nodes to which it will forward packets.
2. Avoid generating extra control traffic in the case of link failure.
3. Make use of geographic positional information about destination nodes whenever possible.

The constituent structure of the proposed protocol is represented in Figure 4.1.

The proposed protocol is based on performance related to the type of message it forwards. It recognizes message types and routes packets according to the state

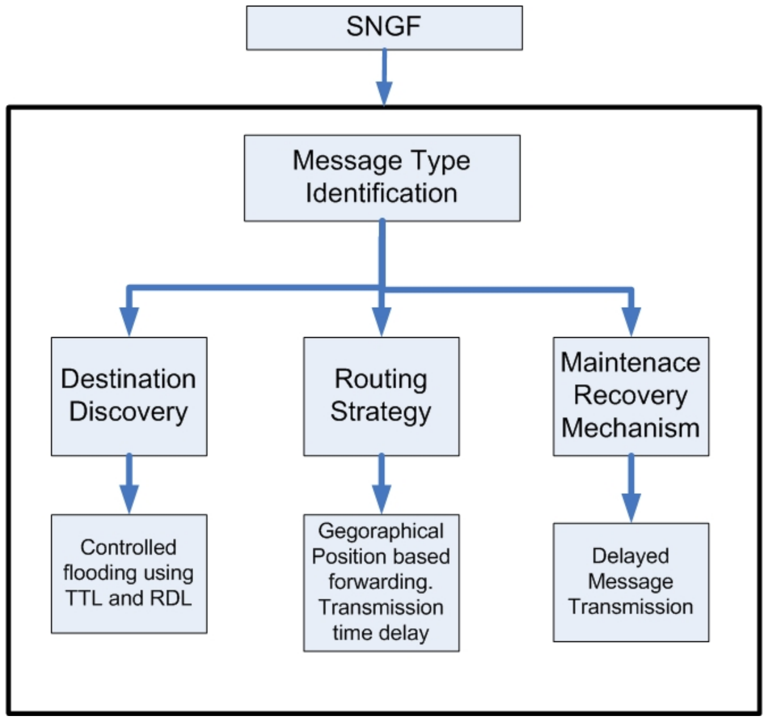


Figure 4.1: Main blocks of the proposed protocol

of its knowledge about the location of the destination node. When a direct route is unavailable the protocol enters into recovery mode and tries to route the packets after a specified time delay.

The following subsections present the constituent components of the proposed protocol in detail.

4.1.1 Message Types

The routing of the data packets depends on the kind of message and on the location of the source, the destination and the neighbors. In SNGF three kinds of messages are distinguished. The first is a beacon, or hello, message that is usually meant for one hop neighbors and is used both to update the location of the sender and also as a heartbeat mechanism. The second is an emergency message related to safety, as in the case of a requirement to avoid an accident because of the sudden stalling of a vehicle in a highway lane. The third type is regular messaging between two vehicles traveling on the road. These message types are summarized in Table 4.1.

Table 4.1: Types of Messages Recognized by the Routing Protocol

No.	**Type**	**Message description**
1	Beacon or Hello	Heartbeat Neighbor
2	Emergency Broadcast	Limited Geographical Area
3	Unicast Communication	Discourse

For communication purposes, the messages in a VANET are sent in the form of packets. The packet header field used by the SNGF routing protocol is shown in Table 4.2. The table lists all the information required by the SNGF protocol in order to facilitate the routing decisions of the packet as it moves through the network.

Table 4.2: SNGF Packet Header Description

Name	**Function**
Packet Type	Type of Message
Packet Time	Time of Origin
Packet Sequence Number	Packet ID Number
Source ID	Source Node ID
Source Location	Source Node Location
Destination ID	Destination Node ID
Destination Location	Destination Location
Previous Hop ID	ID of Last Forwarding Node
Previous Hop Location	Location of Last Forwarding Node
Packet HTL	Hops/Time Allowed for Packet to Live
Packet RDL	Radial Distance or Hops Allowed

The packet header is initialized by the source node which sets up all the required fields. The source node specifies the hops to live (HTL) and radial distance limit (RDL) for the particular packet, which enable downstream nodes to make appropriate decisions. Each forwarding node then updates the previous hop ID, location, HTL, and RDL accordingly. The rest of the packet header remains unchanged after initialization by the source node.

The message type dictates what will be proper handling by the transmitting node. The type of message also determines the intended audience and the destination location. The developed protocol provides for all possible kinds of communication scenarios for vehicles on the road.

4.1.2 Destination Location

As previously mentioned, all vehicles are equipped with GPS and know their own location coordinates. The intended destination of the message depends on the type of message being transmitted. Depending upon the type of the message the protocols starts the destination location sequence. If the message is type 1 or a beacon, it is intended only for the nearby neighbors and the destination location is a one hop neighbor only. The originating node for this kind of packet sets the packet type to type 1 and broadcasts the packet. The nodes within a one-hop vicinity of the sender receive the hello packet and update the corresponding neighbor entry in their list.

If the message is type 2, i.e., an emergency broadcast, then geographic information is used to efficiently disseminate the message within the network but only in the limited area of interest. The destination location can be established either by using a hop counter to limit the broadcast range or by using a source location based radial distance. The originating node sets up the packet type as 2 in the packet header and broadcasts the packet. All the receiving nodes extract the information, and if the RDL and HTL are still in the limits, they become possible forwarders for the packet. The forwarding decision is based on the routing strategy described in Section 4.1.3.

Finally, if the message is type 3 and the destination location is unknown, the protocol must locate the intended destination using controlled flooding throughout the network. Controlled flooding is used in order to avoid excessive network traffic by allowing only a subset of nodes to retransmit the query message. Each node that receives the query message evaluates its own position in order to determine its contribution to the overall process of determining the destination location. This step means that the intermediate nodes wait and allow the nodes on the farthest side of the sender node to propagate the message more effectively.

Each query message has a HTL and a RDL. The query process is continued until the HTL or the RDL expires, at which point the query packet is dropped. The source node can rebroadcast the query message with an extended HTL or RDL after a specified timeout. This process is similar to the time to live (TTL)in AODV protocol but has the added feature of limiting the search to a geographic boundary. The TTL in AODV limits the search distance by means of specifying the number of hops but in the case of fragmented networks, this method might call for repeated transmissions of the query message. By using the RDL factor the number of retransmission can be reduced by allowing a large HTL, and the peripheral nodes can then wait to overcome the fragmentation in the network through the possibility of coming in contact with other nodes.

Once the destination location is discovered, the routing strategy makes use of this information to limit the flow of messages to the intended physical location only, thus effectively controlling the overall network traffic.

4.1.3 Routing Strategy

The main component of any routing protocol is its packet forwarding strategy. For VANETs the forwarding strategy must be based on the fact that the nodal topology is constantly changing. This characteristic of rapid change means that the routing tables are in need of constant updates and hence a large overhead with respect to the network bandwidth.

The SNGF forwards packets based on geographical expansion through controlled flooding. Each time a packet is received at a node that has not yet reached the destination it goes through a process of evaluation in order to assess the contribution of the node towards the intended destination. Prior to transmission each node transmission evaluates its contribution to the dissemination of the message and then decides whether to retransmit or discard the packet. In [15], the concept of waiting times for retransmission was introduced. SNGF uses a similar idea but model the retransmission time in a more comprehensive manner suitable for location based routing protocols.

As shown in Figure 4.2, the packet transmitted by sender node S is received by all the nodes in its vicinity, i.e., A, B and C. Although all nodes are candidates for retransmitting the packet toward the destination, only the best suited is favored by the SNGF protocol to actually perform the act of retransmission.

The retransmission decision is based on three factors. The first is the retransmission time, which is calculated based on the locations of the sender and the receiver node. The greater the distance, the shorter the time period. In this

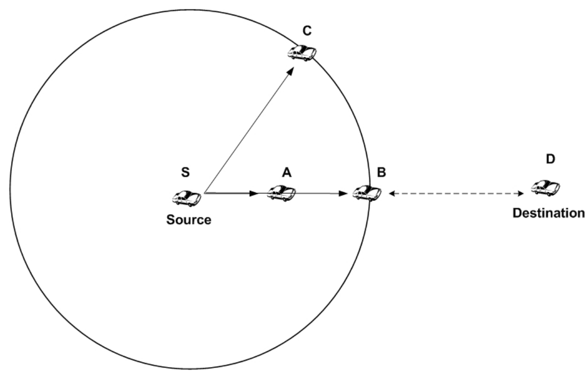


Figure 4.2: Controlled flooding. Although all nodes receive the packet only node B is qualified to retransmit.

way problems related to the hidden nodes and unnecessary retransmission can be avoided. The second factor is the Euclidean distance from the current position of the node to the intended destination. The third factor is the number of times the message is received by the node, which indicates whether too many nodes are competing to retransmit the packet.

To avoid collisions and restrict the retransmission of the same message by all the receiving nodes, the concept of a waiting time for message retransmission was formulated as the weighted sum of the above three factors, according to the following equations:

$$T_R = \Sigma_{i=1}^{3} W_i F_i \tag{4.1}$$

$$F_1 = 1 - \frac{\min(d_{is}, r)}{r} \tag{4.2}$$

$$F_2 = \frac{\min(d_{id}, d_{sd})}{d_{sd}} \tag{4.3}$$

$$F_3 = \frac{N_r}{M_r} \tag{4.4}$$

where,

T_R = Retransmission time delay

W_i = Normalized weight of each factor

F_1 = Factor based on the locations of the sender and intermediate receiver node

F_2 = Factor based on the Euclidian distance from the current position of the node and the intended destination

F_3 = Factor that is the number of times the message is received by the node

d_{sd} = Distance from the source node to the destination node

d_{is} = Distance from the source node to the intermediate node

r = Range of transmission of the node

d_{id} = Distance from the intermediate node to the destination node

N_r = Count of times the current node receives the same message

M_r = Maximum count the node is allowed to receive the message

The advantage of using the given T_R is that, when the location of the destination is available, it recognizes the nodes that are near the destination. Selecting an appropriate weight and the maximum number of times the node is allowed to receive the message curtails network traffic and provides an efficient way of forwarding the message toward its destination. The proposed method is effective even if the destination location is not available due to factor F_2 as it serves only to reduce the retransmission delay in a weighted manner [58].

The weighted sum provides a means of controlling the contribution of each of the three factors namely F_1, F_2 and F_3 in equation 4.1. Under different operating conditions the normalized weights of the individual factors may be manipulated in order to minimize collision in the network by limiting retransmission by the node. Although it remains a possibility but in this thesis the factors are assigned equal weights to demonstrate the viability of the SNGF protocol. (In the authors opinion finding the optimal weights would require conducting significant amount of simulation work and may help in fine tuning the working of the protocol but this exercise is beyond the logistics and time constraints of this thesis.)

Once a node receives a packet, the decision to retransmit is guided by an evaluation of the contribution of the current node to the packet delivery process with a minimum flooding effect. The current node makes an informed decision based on its knowledge of the surrounding nodes and of the destination location of the packet. If the destination location is known, the decision is based on proximity to the destination node. If the destination location is not known, the decision is based on the greatest distance from the last forwarding node.

When it is making a decision, the current node calculates a number of quantities (distances) between itself and the other nodes: the last forwarding node, the neighboring nodes and the destination node. The following equations give all the distances calculated by a node in order to make the forwarding decision:

$$d1 = \Delta(CN, FN) \quad (4.5)$$

$$d2_i = \Delta(FN, NC_i) \quad (4.6)$$

$$d3 = \Delta(CN, DN) \quad (4.7)$$

$$d4_i = \Delta(DN, NC_i) \quad (4.8)$$

$$d5 = \Delta(FN, DN) \quad (4.9)$$

where,

i	=	$1..k$ (number of neighbors)
$d1$	=	Distance between current node and forwarding node
CN	=	Current node
FN	=	Forwarding node
$d2_i$	=	Distance between forwarding node and the ith neighbor node
NC_i	=	ith neighboring node in the contact list
$d3$	=	Distance between current node and destination node
DN	=	Destination node
$d4_i$	=	Distance between destination node and the ith neighbor node
$d5$	=	Distance between forwarding node and destination node
Δ	=	Euclidian distance

It should be recalled that all nodes maintain a list of their one hop neighbors and their respective geographic locations. Based on these calculated distances, the node must evaluate its position with respect to its contribution toward forwarding the packet in the direction of its destination. The node may determine that it is in one of the following four possible states:

1. State 1: The current node determines that it is the best forwarder and that it also has possible next hops for the packet in its list.
2. State 2: The current node is not the best forwarder, but it has possible next hops if it has an opportunity to retransmit the packet.
3. State 3: The current node is not the best forwarder, and it also can not determine any next hops for packet retransmission.
4. State 4: The current node determines that it is the best forwarder but does not have any next hops available for forwarding the packet.

The decision of the node based on the above mentioned cases is represented as as FD. This function calculates the time delay for retransmission, as shown in Algorithm 1.

The SNGF component of the decision to retransmit a received packet is shown in the form of a flow chart in Figure 4.3. The input to the algorithm is the arrival of packet to be forwarded. The packet forwarding algorithm distinguishes between two conditions: whether the location of the destination node is known or unknown.

```
input  : List of Neighbors, Packet Header
output: Decision to Transmit Packet with Calculated Delay
switch FD do
    case 0
        Node State=1;
        T_R = 0;
    case 1
        Node State=2;
        Calculate T_R;
    case 2
        Node State=3;
        Drop packet;
        break;
    otherwise
        Node State=4;
        Recovery mode;
        Long delay;
    end
end
```

Algorithm 1: Retransmission Decision

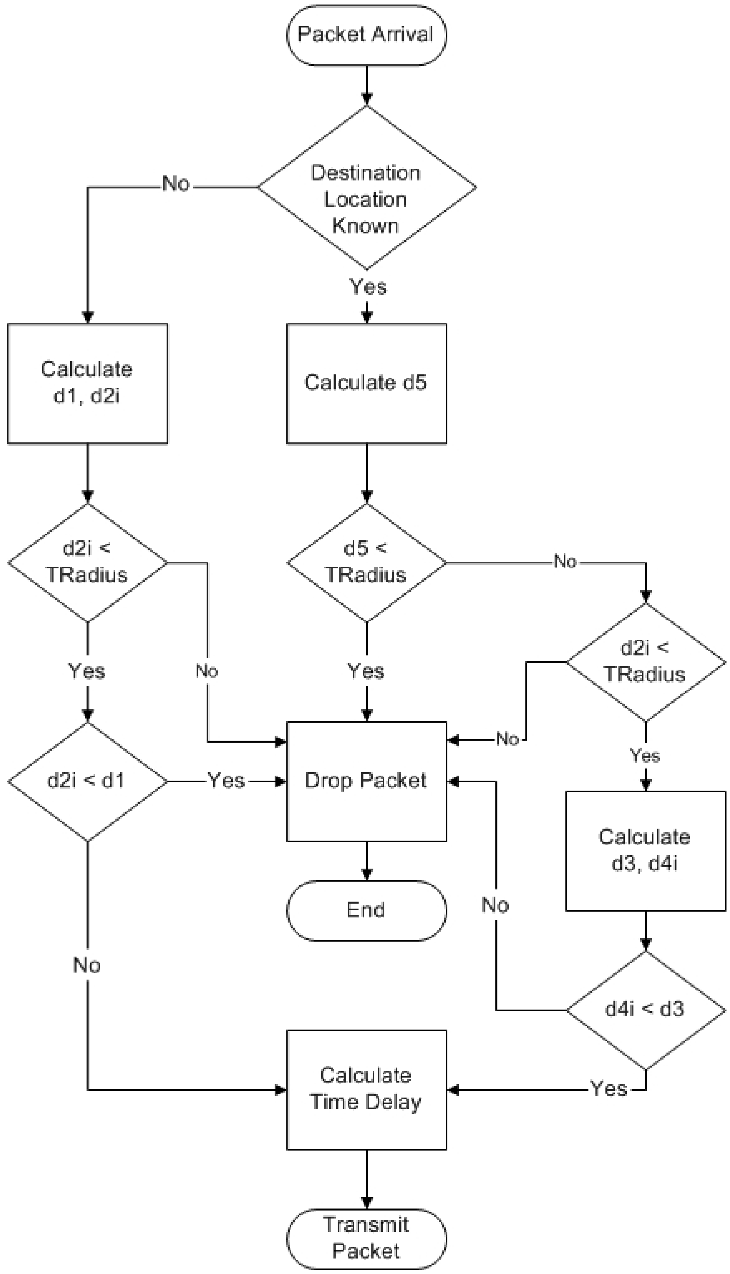


Figure 4.3: Directed flow of a message toward the destination node. Δ = distance, CN = Current node, FN = Forwarding node, NC = Neighboring nodes in the contact list and DN = Destination node: $d1 = \Delta(CN, FN)$, $d2_i = \Delta(FN, NC_i)$, $d3 = \Delta(CN, DN)$, $d4_i = \Delta(DN, NC_i)$, and $d5 = \Delta(FN, DN)$.

4.1.4 Maintenance and Recovery Strategy

In SNGF, only the source node maintains the geographic location of the destination node with a time stamp. This information is updated during the communication session and once the communication is finished the location information is also discarded within a specified time frame.

Figure 4.4 is a representation of the flow of the message towards the destination node once the location of the destination node is known. The new protocol does not rely on the routing tables of the intermediate nodes: instead it forwards the message toward the destination node based on the available information about the destination location. Any available node can take part in the forwarding process once it satisfies the parameters of routing strategy as explained in the previous section.

The nodes, or vehicles, shown in figure 4.4 are the ones that have the least time for retransmission T_R and hence, are the ones which form an active route for delivery of the message. Any change in topology or movement of the intermediate vehicles does not affect the routing process because it is not dependent on the routing table. Any new node that moves into the vicinity of the qualifying nodes simply processes the message with the routing criteria, and it may then replace the current node if its T_R is less than that of the others. In this way, the network overhead previously needed because of maintenance of cluster formation is reduced.

The destination node may change its position over time. The source node can

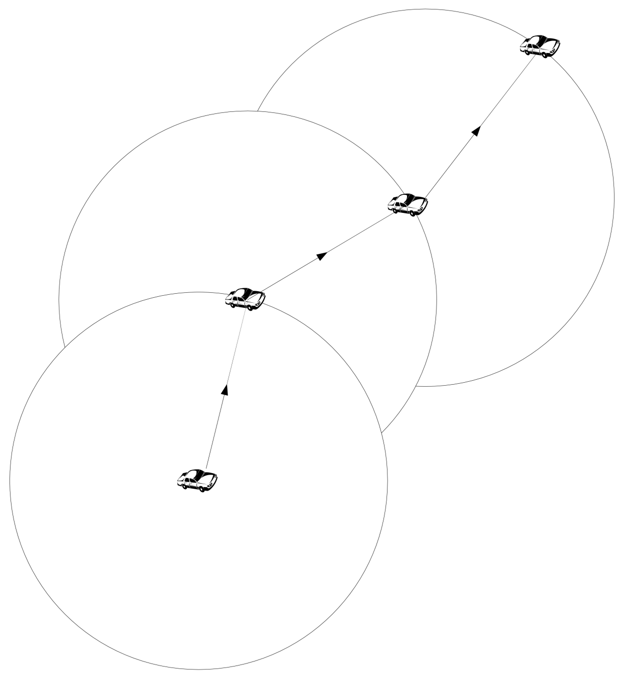


Figure 4.4: Directed flow of message toward the destination node.

keep track of the destination node location and its movement and may adjust the destination location to expected location based on its prediction of the movement of the destination node. In Figure 4.5, the location of the destination node is depicted as it would be perceived by the source node in continuous time.

Depending on the distance from the source and the direction and speed of the movement of the destination node, the location information may no longer be valid. The destination may have moved out of the effective range of reception of the message. The source node must then make an adjustment to the location of the destination before transmitting the message in its direction. It must be

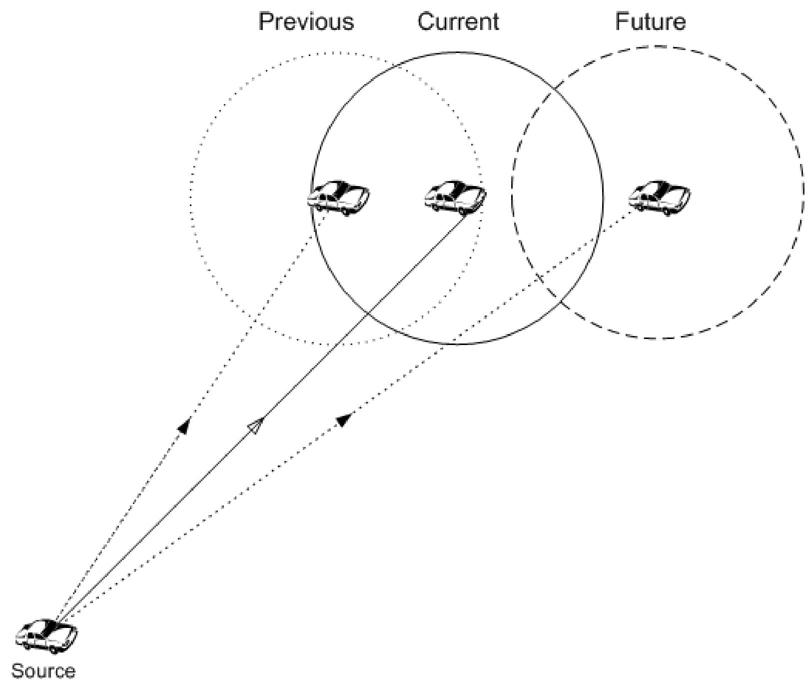


Figure 4.5: Predicted location of the destination node.

pointed out that the adjustment will only be needed when the destination node has moved farther than the radio range of the last forwarding node. If the destination moves within the radio range then it will keep on receiving the packets destined to it. Since the communication packets between nodes contain their latest geographic locations therefore frequent location updates are not required and the source node can update the location of the destination node with the new information available from the destination node through the discourse messages.

If, during the routing sequence, the node fails to find a successor neighbor then a recovery strategy will be adopted. The recovery strategy could be that the node that fails to find a successor node can introduce a delay that will allow the node to carry the packet for some time until it comes into contact with new nodes that can assist with the message delivery. This is similar to the action of nodes in the delay tolerant networks (DTN). In DTN the nodes have long term storage and network topology is assumed to be disconnected over very long intervals of time [1, 2]. In VANETs the storage capacity may not compare to the size of storage available in the DTN nodes and also the topology is assumed to be generally connected or disconnected over relatively short intervals of time. Since SNGF is a VANET protocol so it is assumed that the topology is disconnected for short periods of time and nodes store the packets for that short duration.

In the worst case of not finding the destination node the current packet is dropped and when the sender does not receive an acknowledgment, it can resend the packet with relaxed forwarding zone requirements as discussed further in the next section.

4.2 Properties of the Developed Protocol

The SNGF protocol has been designed to operate in a vehicular ad hoc network environment and therefore should exhibit properties that are essential for the smooth operation of protocols for ad hoc communication. This section presents a detailed discussion of two basic properties of the SNGF protocol: it provides measures to ensure loop freedom and it offers multiple path handling.

4.2.1 Loop Freedom

A routing loop is defined as a path specified in the routing tables of nodes at a particular point in time, such that the path visits the same node more than once before reaching the intended destination [22].

Loop freedom is a fundamental requirement in routing protocols. The AODV protocol avoids looping by use of sequence numbers, a concept borrowed from the DSDV protocol specifications. GPSR avoids looping by keeping track of the distance traveled toward the destination node, but it is not equipped with a destination discovery mode.

The SNGF protocol is inherently free of the looping problem because of two main reasons. First, it does not store a routing table so there is no problem with stale routes, and second it allows only those nodes that are capable of decreasing the distance to the destination to participate in the forwarding process. If the destination is not known, as in the discovery phase, SNGF forces packet propagation outward from the source node, thus effectively disallowing looping. SNGF further has the provision of message count which ensures that a message is not transmitted repeatedly by the same node.

4.2.2 Multiple Path Handling

In mobile ad hoc networks, multiple transmission of messages can be a source of communication overhead but can also provide an alternate route in the case of primary route failure. In the SNGF protocol, multiple transmission is possible only in the case of messages being propagated through disjoint paths. This concept has been exploited in the recovery process for determining alternate routes. Multiple path transmissions are restricted when the destination is known in order to avoid overhead but are allowed only as as a means of determining alternate routes.

In the developed protocol, the message can be forwarded only in the direction of the destination and each node that participates in the process makes sure that the Euclidean distance to the destination location is minimized. This criterion restricts the physical area in which the nodes are allowed to transmit messages. However, as shown in Figure 4.6, it remains possible for the message to be propagated through multiple disjoint paths towards the destination.

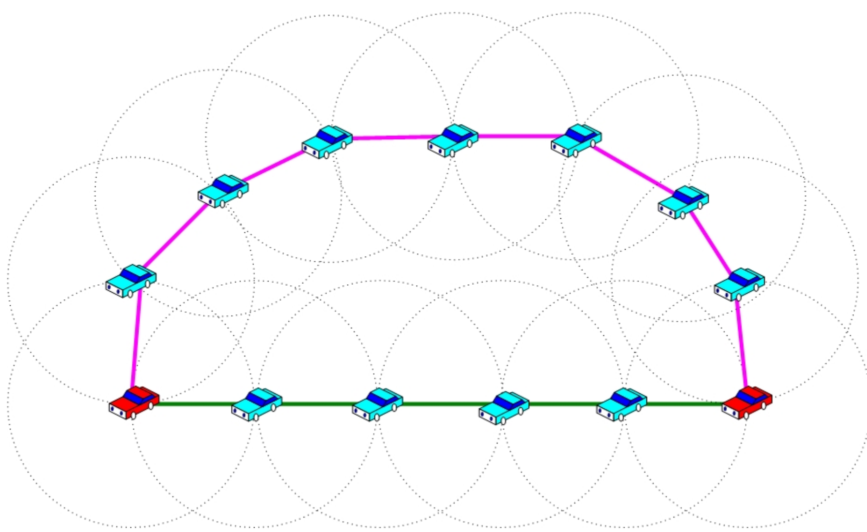


Figure 4.6: Possibility of multiple path message propagation in VANETs.

The developed protocol avoids multiple retransmissions by using the concept of different ranges for the transmission and forwarding of messages [62]. In particular two ranges are defined: R_t and R_f. R_t is the transmission range of a node, and all other nodes inside this range receive a copy of the message transmitted by the node. R_f is the forwarding range, and only the nodes in the forwarding range are allowed to retransmit the received message. As shown in Figure 4.7, the forwarding range allows nodes within communication range of the source node to compete for message transmission, and only the node with the minimum retransmission time retransmits the message toward the destination direction. Upon receiving multiple copies of the message, the other nodes are prevented from retransmitting the message. This restriction keeps the message from being propagated through disjoint paths, as previously shown in Figure 4.6.

The transmission and forwarding ranges are designed so that the nodes in the forwarding range of the source node in the direction of the destination are within transmission range of one another. This provision ensures that each node receives a copy of the message that is retransmitted by the node with the shortest retransmission delay. Thus, only one node is able to forward the message, and all other nodes refrain from retransmission.

Figure 4.7 depicts the transmission and forwarding ranges of the nodes. When a source node S propagates a message, the nodes within its transmission range R_t receive the message. However, only the two nodes A and B are within the forwarding range R_f of the source node S; therefore, only these two will compete for retransmission. Because node C is outside the forwarding range, it is not

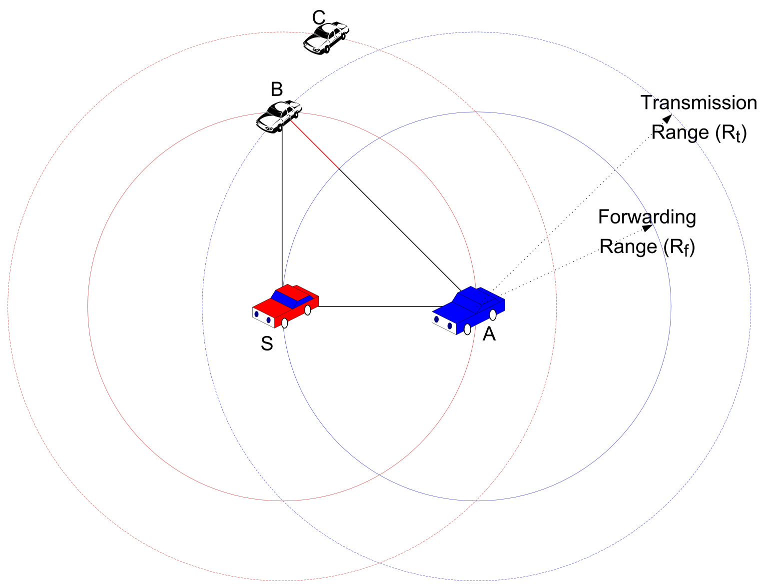


Figure 4.7: Restricting multiple path propagation through the use of transmission and forwarding ranges.

allowed to retransmit. Nodes A and B are within transmission range of each other, and only one will be permitted to retransmit the message toward the destination node.

If the retransmission fails to contact the destination node, the transmission and reception range can be relaxed and a disjoint multiple path can be determined as previously explained. Although this option is possible, this thesis is based on the more restricted approach and does not evaluate the performance under relaxed conditions.

4.3 Comparison With Existing Protocols

This section provides a comparison of the salient features of the SNGF protocol with those of AODV and GPSR (location based protocols). AODV is included in the comparison because it is the most widely cited ad hoc routing protocol. Although GPSR relies on a location service in order to identify the location of its destination, it does not represent a complete ad hoc routing protocol, but it is included in the comparison in order to explain the salient features of SNGF. The comparison is based on the following parameters: routing scheme, routing metric, flooding, multiple routes, network fragmentation, and repair procedure.

4.3.1 Routing Scheme

As previously stated, mobile routing protocols can be classified according to their delivery structure. The delivery structure defines the structure that ultimately forms the path for the routing of the packet to its intended destination. The SNGF protocol belongs to the family of location based protocols. Because proactive protocols are not suitable for scenarios that involve rapid topology changes, a reactive structure is, by design, more suited for ad hoc protocols.

SNGF is designed as a geographical location based, reactive, on-demand protocol. The nodes in the network do not send network wide updates. SNGF uses the geographic location information about the nodes to forward packets toward destination nodes. Except for destination discovery mode, in which inquiry packets may traverse the network, all other communication between nodes is on demand only, and no network updates are sent.

4.3.2 Routing Metric

A routing metric is defined as any value used by routing algorithms to determine the performance of available routes. Since AODV maintains a routing table, it uses the shortest path to another member on the shared routing tree as the routing metric. In general, location based routing protocols including GPSR, assume knowledge of the destination node and therefore use the shortest distance to the destination node as the routing metric. The SNGF protocol does not assume knowledge of the destination location. When the destination location is not known, it uses the farthest distance from the source node as the routing metric. If the destination location is known, the protocol uses a combination of farthest-from-source and closest-to-destination as the routing metric.

4.3.3 Flooding

Although flooding is not a favored method of communication, it is a necessary part of ad hoc networks. AODV uses periodic flooding to synchronize the sequence numbers in its routing structure. Location based protocols that assume knowledge of the destination node are able to avoid the use of flooding. In SNGF protocol, controlled flooding is used for the discovery of destination location. Except when a node's location must be discovered, all beacons and messaging is restricted to one hop neighbors.

4.3.4 Multiple Routes

In wireless ad hoc networks, multiple paths are possible from a source to a destination. AODV simply does not use this knowledge, and location based protocols also do not allow multiple path handling. GPSR follows the right hand rule of perimeter search and in some cases may fail to find an existing route. The SNGF protocol utilizes the knowledge available and then decides on as-needed basis to allow message propagation through alternate routes.

4.3.5 Network Fragmentation

Network fragmentation is a real issue in VANET. AODV, GPSR and location based protocols in general have no built-in structure for handling network fragmentation. The SNGF protocol allows buffered and delayed message retransmission in the hope that the mobile node may come into contact with new nodes.

4.3.6 Repair Procedure

A repair mechanism is usually not available with AODV or location based protocols. The SNGF protocol provides two different approaches to overcome this problem. It employs multiple paths when needed and allows delayed transmission, and it uses a prediction mechanism in order to search for the destination node in the vicinity of its last known location.

The comparison is summarized in table 4.3.

Table 4.3: Comparison of the SNGF (Proposed Protocol) with AODV and Position Based Protocols

Parameter	AODV	Location Based Protocols	SNGF (Proposed Protocol)
Routing Scheme	On-demand	On-demand	On-demand
Routing Metric	Shortest path to another member on the shared tree	Shortest Path to the destination	Shortest path to the destination and farthest from the source
Flooding	Yes. Periodic (Sequence number)	No. But requires location of destination	Only to get location of destination
Multiple Routes	No	Yes	Controlled. On need Basis.
Network Fragmentation	No Routing	Perimeter routing	Delayed/buffered retransmission
Repair Procedure	Broken link to rejoin when possible	None	Multiple path and delayed transmission

4.4 Potential Application for VANETs Based on SNGF

The SNGF protocol allows nodes to communicate with one another on the basis of one-to-one communication within geographic proximity and also allows nodes to contact other nodes that are beyond the proximity of one hop radio contact. The nodes that contact each other are not dependent on any particular intermediary nodes for their contact session. SNGF allows one to one node contact based on node ID, and it also allows any node to contact any other available node within a particular geographic locality. This feature makes it possible for nodes to inquire about and obtain data for specific conditions.

An example is the case of detecting traffic conditions (jams) down the road. The node that is interested in knowing the traffic conditions in its path can contact other available nodes within geographic proximity and collect relative information such as their current heading and velocity and their perspective of the traffic condition around them. The node can contact its neighbors or even distant nodes to gather the required information, which can then be used in a locally residing application. The node can process this information in order to predict traffic conditions down the road. The results obtained can be shared with other nodes if they are interested [57].

This kind of an application will be stand alone residing on the node itself and can operate in the VANET environment without requiring expensive data-collection infrastructure to be in place.

The SNGF protocol facilitates the development of such independent applications. Only one sample scenario has been presented but it is by no means the only possible one. Other examples are warning dissemination, four way stop management, travel path planning, alternate route discovery, and many others.

This chapter outlined the SNGF protocol and its components in detail. The following chapter presents the simulation model used to validate the workings of the SNGF protocol. It also discusses the simulation results in detail.

Chapter 5

Simulation Model and Results

This chapter describes the simulation model used to carry out the validation of the SNGF protocol. The underlying assumptions and main features of the simulation model are explained, and detailed simulation results are presented. The chapter concludes with in-depth discussion of the performance of SNGF and a comparison with other existing protocols.

5.1 Simulation Environment

To validate the developed protocol, a comprehensive simulation environment was designed and implemented. This section presents the experimental setup used to simulate and evaluate the performance of the SNGF protocol. The simulation environment consists of three logical components, as shown in Figure 5.1.

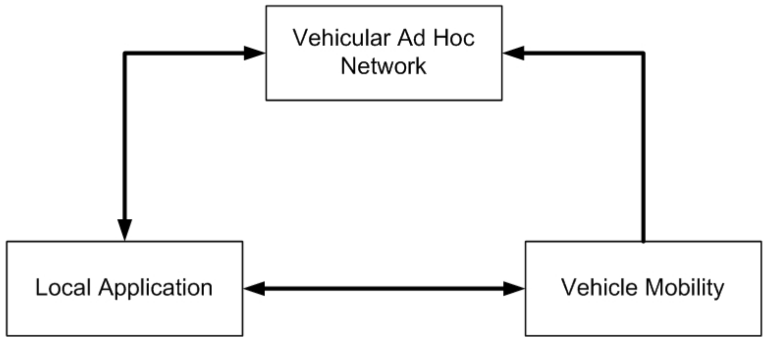


Figure 5.1: Simulation system overview.

The vehicle mobility component depicts the periodic computation of new position within a confined geographic space in which the mobile vehicles are contained. This component may be implemented by a traffic simulator. The vehicular ad hoc network constitutes the second component, which is dedicated to imitating the full functionality of a real wireless network with all of the complex effects related to mobile communications. Only a portion of the vehicles defined by the traffic simulator participate in the ad hoc network, which mimics the partial deployment stage of VANETs on the road. The other vehicles play a specific role in traffic considerations but are considered to be unequipped and hence do not participate in the ad hoc network communication. The third component is the local application, which is accountable for the control of the whole simulation environment. The local application operates in the same manner for all vehicles, it evaluates received messages, and it is able to generate new messages and broadcast them via the network. The application relies on up to date information about current vehicle positions, which are provided by the vehicle mobility module. The local

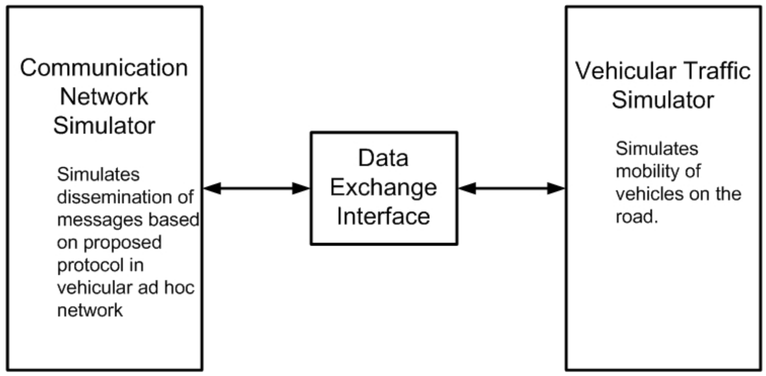


Figure 5.2: Interaction between the network and traffic simulators.

application was integrated into the network simulator as an additional module, which simplified the implementation because communication links are necessary only between two simulators, as depicted in Figure 5.2.

The simulation environment consisted of both a network simulator and a traffic simulator. The network simulator acts as a client requesting information from the traffic simulator. For example, it needs to know both the exact number of cars that are part of the network and their geographic positions within the scenario. The traffic simulator, on the other hand, acts as a server and sends all requested information to the network simulator.

In summary, the simulation environment required a high level of accuracy for the communication network and a lower level of accuracy was sufficient for simulating vehicle movement.

5.2 Network Simulation

As previously mentioned the network simulator is responsible for imitating the functionality of a wireless ad hoc network that connects vehicles. The network simulator chosen provided a comprehensive model of mobile wireless networks. It implemented the widely accepted communication standard IEEE 802.11, in a Wireless Local Area Network also known as WLAN, which specifies both the physical and the Medium Access Control (MAC) layers of the Open System Interconnect (OSI) model of the network architecture. WLAN has become the prevailing wireless transmission technology in the field of VANETs due to its low sensitivity to high velocities, its adequate transmission ranges, and its fast connection times [52]. Another important factor in selecting an appropriate network simulator was the possibility of including extensions, such as the implementation of a completely new network node behavior within the existing framework of the simulator.

Two widely used network simulators were considered: Global Mobile Information System Simulator 2 (GloMoSim2) and Network Simulator 2 (NS2). Although GloMoSim2 is a comprehensive simulator, it was found that it is available only for educational purposes and has not been updated since 2000. Finding technical support for GloMoSim2 is becoming increasingly difficult. The second simulator, NS2 is a renowned network simulator for IP-based wired and wireless networks. It is written in C++ and OTcl, a Tcl script language with object oriented extensions developed at MIT. Because it is also open for commercial use, its software architecture is well structured and enables the integration of software modules for data exchange with other programs, and is thus ideal for setting up a coupled simulation environment.

NS2 features a comprehensive model for simulating multihop wireless networks. NS2 supports the MAC-protocol IEEE 802.11 and also the routing protocol AODV is readily available. In contrast to GloMoSim, NS2 also features a simple model that provides for an adequate representation of reflections and the shadowing effects caused by buildings. A simple black and white bitmap-file containing a picture of the scenario (black: streets, white: buildings) can be read and interpreted. During simulation, NS2 ensures that nodes cannot communicate if there is no line-of-sight connection in between them.

In summary, NS2 is a comprehensive platform that can easily be modified and extended and therefore was an appropriate selection for this research. A comprehensive model of the new protocol was implemented into an NS2 environment within the framework of this thesis.

5.3 Data Exchange Mechanism

The developed protocol can be evaluated under several scenarios such as traffic profiling and traffic warning dissemination. The data exchange between the traffic simulator and the network simulator depends on the nature of the application being tested. For example, if the application requires warning message dissemination and action to be taken by the receiving nodes based on the disseminated messages, the traffic simulator and the network simulator must be either synchronized in time or coupled [20]. However, if the application requires only collection of data from other nodes without requiring action to be taken, then the traffic simulator can be used to feed data to the network simulator. For simplicity, the application development and protocol evaluation were restricted to the latter scenario, although the developed protocol may be used in either case.

5.4 Effect of the Hello Interval

The hello interval acts as the heartbeat of the system and therefore must be chosen carefully. Every node in the network periodically transmits a hello beacon message. Intended receivers of this hello message are the immediate one hop neighbors of the transmitting node. The packet itself is a very short derivative of the complete header, containing only the information about the transmitting node. On receiving the hello packet the neighboring nodes simply update their neighbor list and then discard the message. Under no circumstances is this hello packet ever forwarded.

The hello packet plays an important role in the performance of the routing protocol. The hello packet provides the receiving node with the most recent correct geographic location. All forwarding decisions are then based on this collected information. The choice of hello interval governs the timed accuracy of the location information for the corresponding node. A shorter hello interval provides more frequent updates but also results in higher network traffic in the

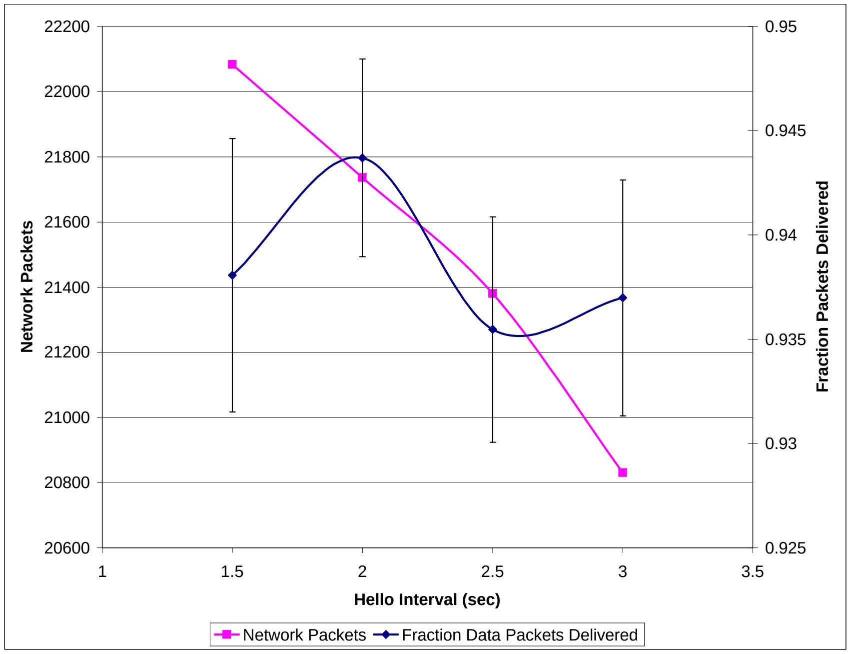


Figure 5.3: Effect of Hello interval on SNGF performance.

local proximity of the nodes. A range of scenarios were simulated with varying hello intervals; the average results are shown in Figure 5.3 and all data points are bracketed with 97.7% confidence interval. (The choice of 97.7% is purely customary to allow use of 2 in the quantile of the unit normal distribution in the confidence interval calculations.)

As depicted in Figure 5.3, increasing the hello interval results in a decrease in the number of network packets in the proximity of the nodes. The relationship of the hello interval to the number of packets successfully delivered is a bit more complex. The ratio of successful packet delivery reaches a maximum when the hello interval is two seconds. A two second hello interval was therefore chosen for this research.

5.5 Simulation Results

The SNGF protocol was implemented in an NS2 environment [18]. NS2 is a discrete event simulator developed by the University of California at Berkeley and the Virtual InterNetwork Testbed (VINT) project. NS2 supports C++ for detailed implementation and the scripting language TCL for configuring and experimenting with changing parameters.

The SNGF protocol was simulated in NS-2 using the wireless extension package developed at Carnegie Mellon University. This setup provides for full functionality of the IEEE 802.11 physical and MAC layers. NS2 simulates nodes mobility using several available mobility models including the random way point model within a plane of specified dimensions. In the random way point model, the nodes move by choosing a destination uniformly at random and then moving toward it at a chosen velocity. On reaching the destination the node stays at rest for a configurable period of pause time and then repeats the process. The pause time represents the degree of mobility for the simulation period, with shorter pause times indicating a higher degree of mobility and longer pause times, more stationary nodes.

The choice of simulation parameters such as the number of nodes, the size of the plane for movement, the number of packets etc. can be made over a wide spectrum, depending on the resources available. For this research, the selection of parameters was based on other reported work in the literature in order to ensure direct compatibility with published results.

The antenna gain, transmit power, and receiver sensitivity were set to approximate the Lucent WaveLAN direct sequence spread spectrum radio. The network simulated had 50, 112, and 200 nodes, with 802.11 bidirectional radios with a 250 meter range. The pause times in the mobility model were selected to be 0, 30, 60, 80, 100, and 120 seconds. A pause time of 0 represents the highest mobility where the nodes are continuously in motion. The simulation was run with 30 CBR traffic flows generated by a total of 22 transmitting nodes. This 30 CBR traffic flow with 22 nodes was selected partly because it makes greatest demands on the protocol and partly because it is the highest value available for comparison of data traffic and packet destinations. The CBR flow rate selected for the simulation runs was 2Kbps. This low bitrate was selected in order to avoid problems of congestion in 802.11 MAC because the simulations were run to demonstrate the performance of the routing protocol and not the packet capacity limitations of the MAC layer. As with the other values 2Kbps is in conformance with the results reported in the literature.

The first case selected was related to traffic flow in order to highlight the functionality of the developed forwarding scheme. This case scenario was designed to produce the maximum amount of network topology change in line with typical urban traffic flows. The traffic flow in shown in Figure 5.4.

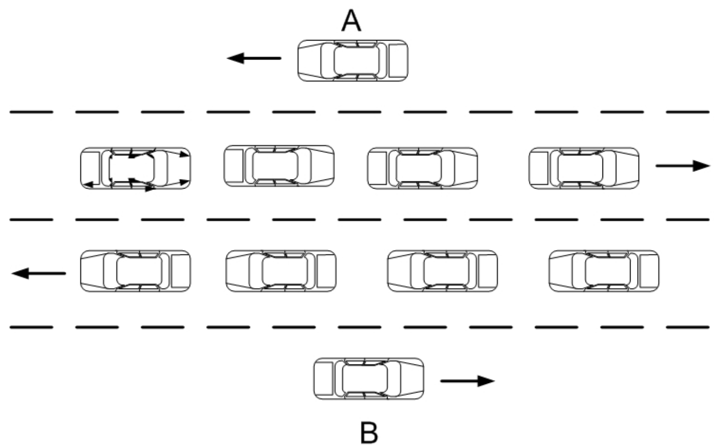


Figure 5.4: Node A communication with node B under continuous network topology change.

In this case node A is the transmitter, and node B is the receiver node. The same model was run using AODV, DSR, and the SNGF forwarding scheme. The performance of both AODV and DSR is affected by the readjustment of the routes, and the results show lower packet throughput with a higher network traffic load. In terms of packet throughput, SNGF performs at very nearly the same level as AODV, but it outperforms both AODV and DSR with respect to network traffic overhead load, producing a much lower load. The results are summarized in Table 5.1.

The following sections present the network simulation results for the 50 node topology under the same conditions reported in [28] and [16], so that the results can be compared with the published results. The simulations run length was chosen to be 900 seconds, and each pause time was simulated with 10 randomly

	AODV	DSR	SNGF
% of packets delivered	79.4	54.4	79.36
Average number of Network Packets	3296	1174	129

Table 5.1: Throughput and Network overhead.

generated node motion patterns. The mean of these 10 runs are presented for each metric. It should be noted that the number of runs and the duration of the simulation setup were highly limited by the cost of computation in cpu time and the amount of storage available for the simulation output data. The simulation time required for the 802.11 MAC layer rises quadratically with the number of nodes in the network because it measures signal strength for every packet at each node in order to determine which node should receive the packet [28].

Simulations using 112 and 200 nodes are presented in subsequent sections in order to demonstrate the scalability properties of the SNGF protocol.

To be consistent with results already published the SNGF protocol was evaluated based on the following four metrics:

1. Rate of packet delivery: This metric measures the rate of successful delivery of the packets by the routing protocol.

2. Routing protocol overhead: This metric measures the amount of control or routing protocol packets sent network wide by the routing protocol.

3. Optimality of path lengths: This metric measures the number of hops fol-

lowed by a delivered packet against the optimal number of hops possible.

4. State per node: This metric measures the storage required by the routing protocol in order to successfully deliver the transmitted packets in the network.

5.5.1 Rate of Packet Delivery

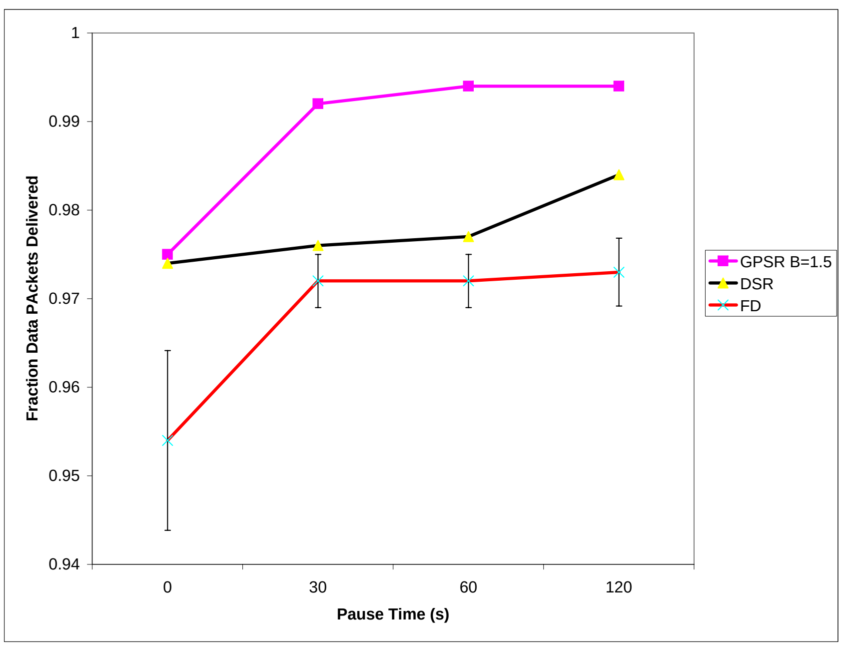


Figure 5.5: Fraction of successful packets delivered.

The first evaluation metric measures the rate of successful delivery of packets by the routing protocol. Figure 5.5 shows the number of packets successfully delivered by SNGF along with the number delivered by GPSR and DSR. All data points for SNGF are bracketed by their 97.7% confidence interval. On average all algorithms deliver above 95% of user packets. SNGF has a slightly lower throughput than GPSR because the GPSR algorithm assumes that the location of the destination is known to the originating node whereas no such assumption is applied in the SNGF.

5.5.2 Routing Protocol Overhead

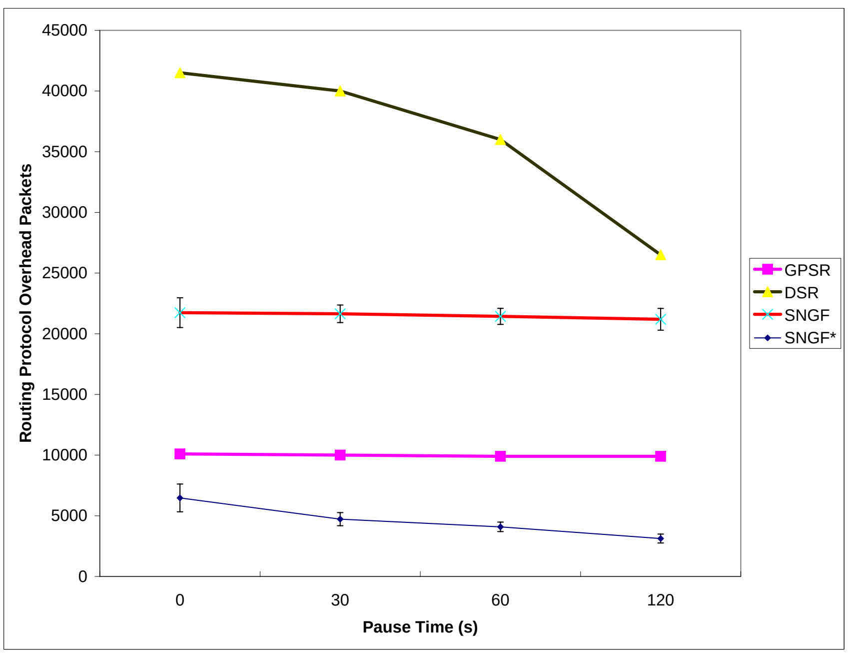


Figure 5.6: Routing protocol overhead.

The routing protocol overhead metric measures the amount of control, or number of routing protocol packets, sent network wide by the routing protocol. Figure 5.6 shows the total number of routing control packets that were sent network wide during the entire period of the simulation run. The algorithms depicted are GPSR, DSR, SNGF, and SNGF*. SNGF* is the same routing protocol as SFGF except that the initiating node is provided with the destination node location in order to compare the results with those of GPSR because GPSR assumes the availability of destination location through location service providers. Again all data points for SNGF and SNGF* are bracketed by their 97.7% confidence interval.

As depicted in the Figure 5.6 and reported in [28], GPSR offers a threefold to fourfold overhead reduction in comparison to DSR. Since GPSR assumes knowledge of the destination location, in the authors opinion, it is reasonable to compare it with SNGF*, which also assumes preliminary knowledge of the destination location. On average, SNGF* shows a twofold reduction in overhead compared to GPSR.

With respect to the contour of the SNGF* curve, it should be noted that with a decrease in node mobility depicted by larger pause times in the system, SNGF* also shows a slight reduction in overhead. This result is to be expected since less change in the topology means that nodes are at a specific location for a longer period of time, and hence fewer overhead packets are generated.

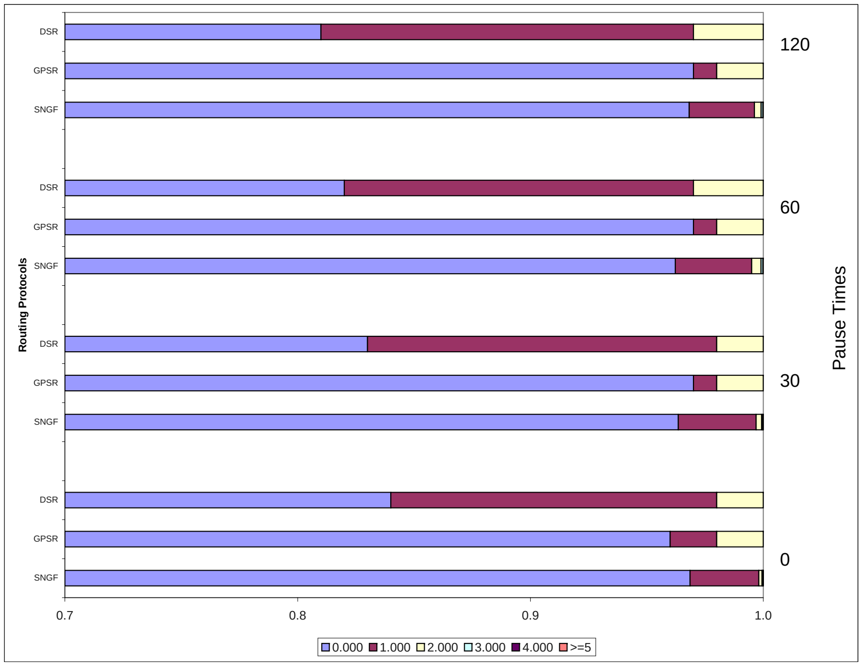


Figure 5.7: Path length beyond the optimal for successfully delivered packets.

5.5.3 Optimality of Path Lengths

The network simulator NS2 uses the Warshall all-pairs shortest path algorithm to compute the optimal path lengths between all nodes. The mobility of the nodes causes topology change and consequently, the optimal path lengths are also changed. For practical purposes, a time instant must be chosen in order to select the optimal path length, and in NS2 it is chosen as the time of the packet origin. This choice provides a good approximation because the usual time of travel for a packet from its origin to the destination is typically measured in milliseconds, which is not long enough for any significant topology change.

Figure 5.7 shows the number of hops beyond the optimal path length for all successfully delivered packets for the DSR, GPSR and SNGF routing algorithm. SNGF delivered about 97% of all successfully delivered packets in the optimal number of hops which is about the same percentage as GPSR. DSR delivered about 85%. DSR turns out to be the least optimal because of caching the routes, which may become suboptimal with time.

GPSR forwards the packets using a greedy forwarding approach and intuitively, on a densely connected radio network, greedy forwarding approximates the shortest path routing. SNGF makes up the difference by taking just one hop more than the optimal. The difference can be attributed to two factors. First, the SNGF operates in a purely broadcast fashion, and each node decides individually whether to contribute to the forwarding process. The greedy approach may thus not be followed in all instances. Secondly, the data reported for GPSR is based on the condition that only those packets for which a direct route is available are considered whereas SNGF reports all packets, including those that go through the recovery process of delayed transmission and alternate path availability. The performances of SNGF and GPSR are nonetheless comparable.

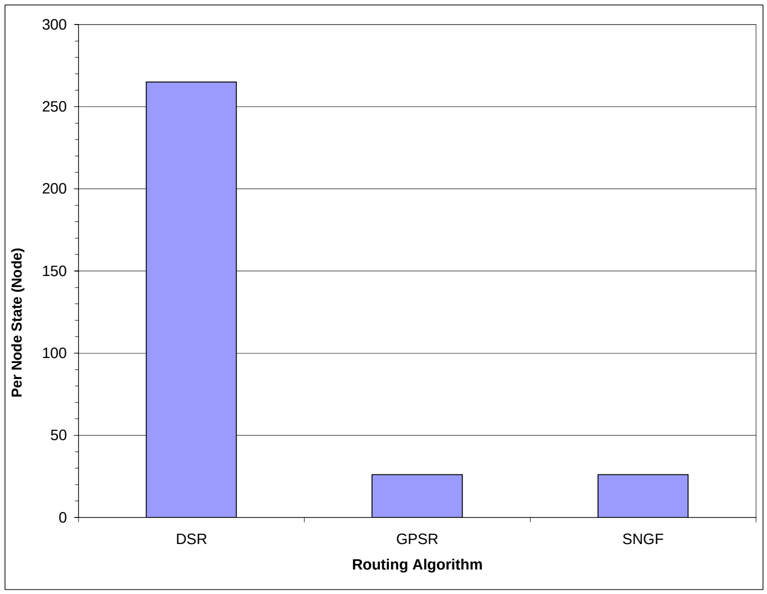
5.5.4 State Per Node

The state per node metric measures the storage required by the routing protocol to successfully deliver the transmitted packets in the network. The storage is measured according to the number of nodes stored in a router table and not the number of routes. Since DSR stores source routes, each route stored requires storage for each node along the route. Figure 5.8 depicts the state per node on average stored by DSR, GPSR, and SNGF.

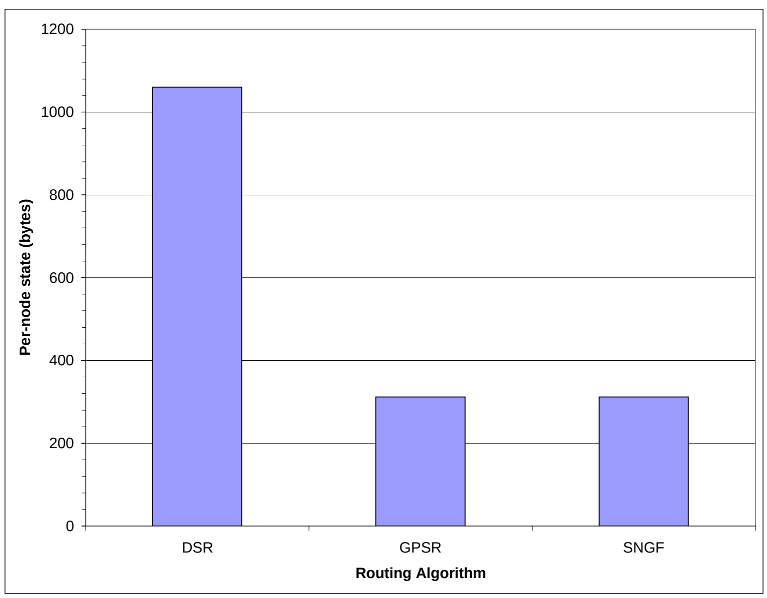
The state of a node varies continuously for the duration of the simulation run, so a snapshot in time was required at a particular instant in order to measure the states of the nodes. It was observed that both SNGF and GPSR store, on average, the same number of nodes whereas DSR stores states for all destinations for which packets arrive.

Both GPSR and SNGF stored on average, 26 nodes for the 200 node simulation. This result shows that both SNGF and GPSR store only the states of their one hop neighbors and this number depends on the node density of the network and not on the size of the network. With DSR, the average number of states stored is even greater than the number of nodes in the network because DSR stores all routes and may thus store stale routes for a period of time. The storage required by DSR increases with an increase in the number of nodes in the network.

It should be noted that for position coordinates and nodal address, DSR uses 4 bytes per address and that GPSR and SNGF both use 12 bytes. Arguably SNGF requires more storage space per node than DSR but this is fairly compensated by the smaller number of nodes stored per router.



(a) Number of nodes stored.



(b) Number of bytes stored.

Figure 5.8: State per node.

5.6 Effect of Network Diameter

The next measurement was of the scaling effect with SNGF, compared to that with DSR and GPSR. The values used were the packet delivery ratio and number of overhead packets propagated network-wide for a 112 and a 200 node network.

For 112 nodes the region of motion was 2250 by 450 meters and for the 200 node network, the dimensions were 3000 by 600 meters. These values were selected so that the number of square meters per node remained the same as in the previous simulations. The intent here was to evaluate scaling of SNGF compared to that of DSR and GPSR. The packet transmission source was also kept the same as in the previous simulations in order to ensure that the scalability was evaluated under constant workload conditions.

Figures 5.9, 5.10, 5.11, and 5.12 show the packet delivery success rates and routing protocol overheads for the 112 and 200 node networks. All data points for SNGF are bracketed by their 97.7% confidence interval.

The success of packet delivery for both 112 and 200 nodes follows the same pattern as in the previous experiments and SNGF shows a performance level very near to that of the GPSR.

With respect to network protocol overhead, the SNGF outperforms GPSR by a magnitude of nearly 2 because SNGF does not send any routing packets and instead relies fully on the broadcast pattern and nodal decisions about participating in the packet forwarding mechanism. GPSR sends routing packets proactively

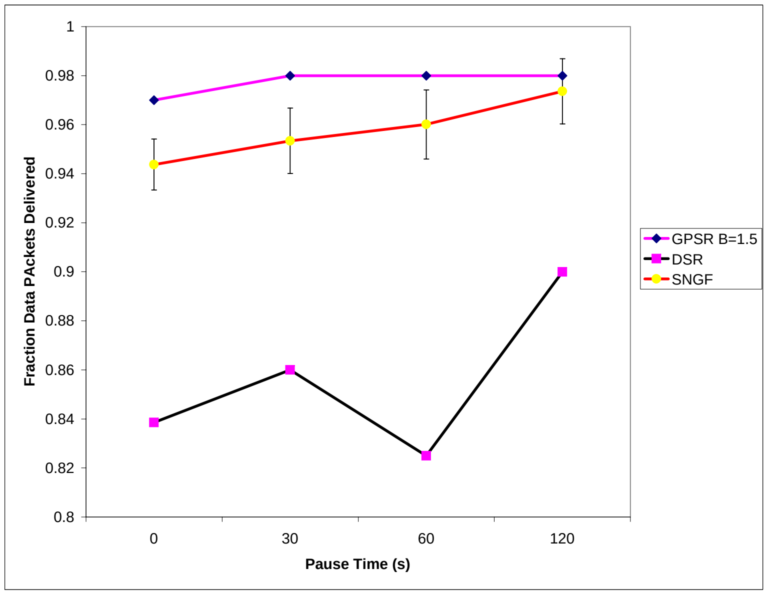


Figure 5.9: Packet delivery success rate for 112 nodes.

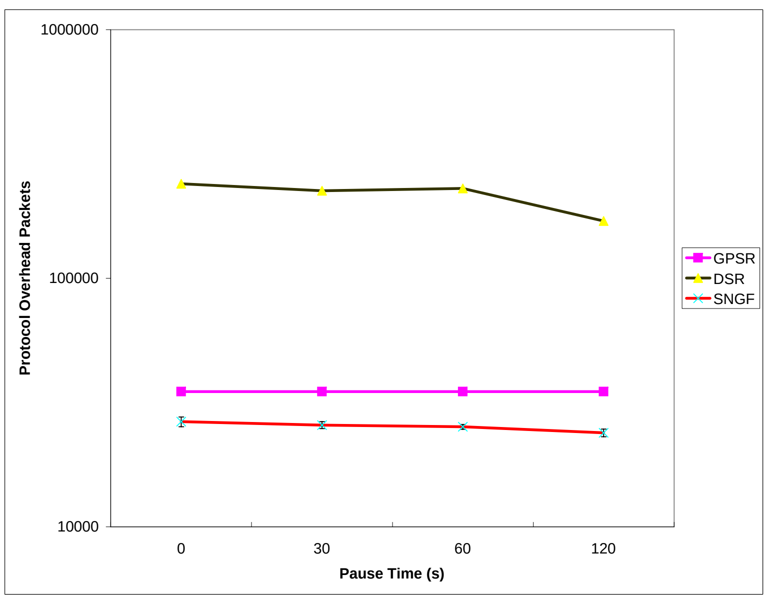


Figure 5.10: Routing protocol overhead for 112 nodes.

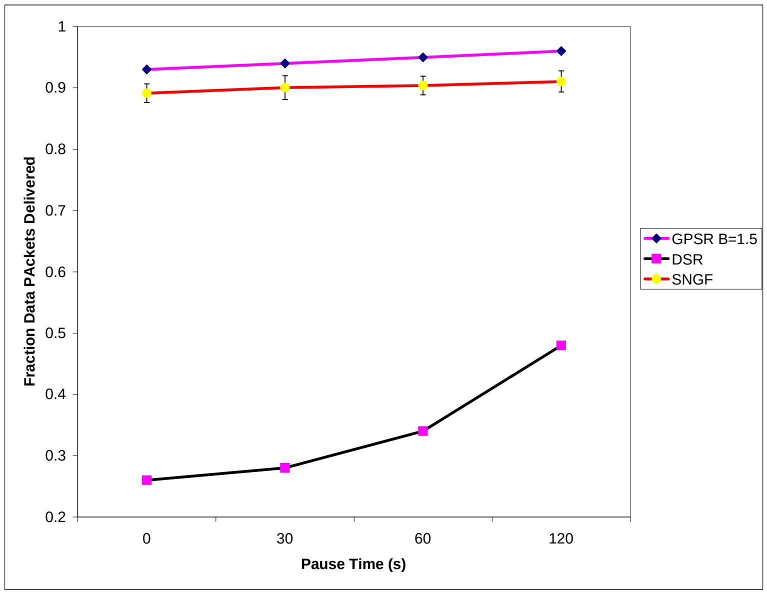


Figure 5.11: Packet delivery success rate for 200 nodes.

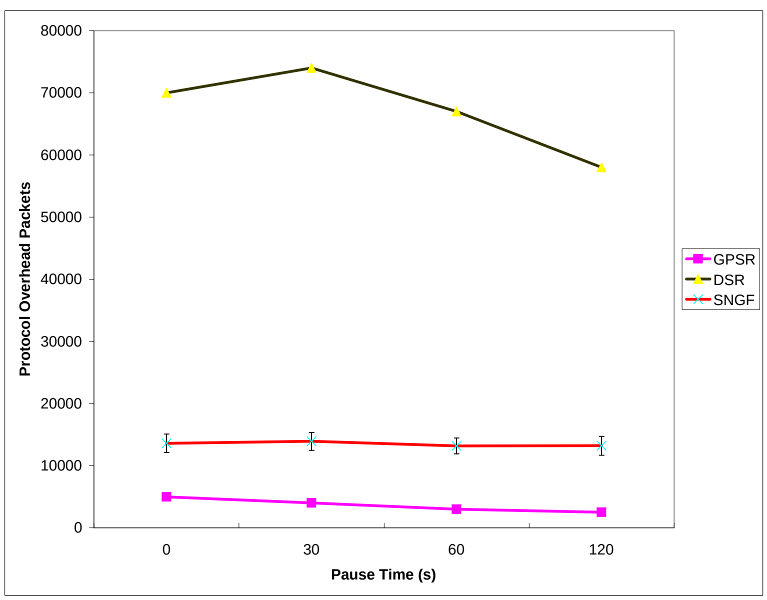


Figure 5.12: Routing protocol overhead for 200 nodes.

to its immediate neighbors, which accounts for the overhead increasing with an increased number of nodes in the network. However, it must be stated that those beacons are not propagated network wide and GPSR assumes the ready availability of the location of the destination, and that network overhead can therefore not be calculated. SNGF sends inquiries and receives replies network wide and hence the result is accurate in the sense that network overhead represents, the overhead packets used for communications that are sent network wide. SNGF shows remarkable scalability and no significant rise in network overhead when the number of nodes is increased.

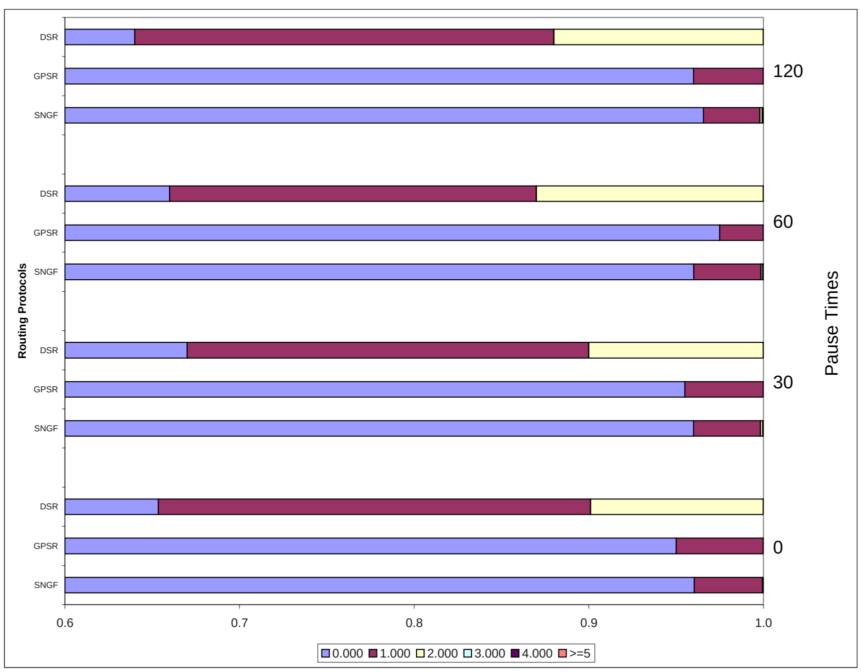


Figure 5.13: Path length beyond the optimal for successfully delivered packets for 112 Nodes.

Figure 5.13 shows the number of hops beyond the optimal for 112 node network. It can be observed that the performances of SNGF and GPSR show no significant difference from those with the 50 node run shown in Figure 5.7. The exception is DSR, which tends to learn new shorter paths available only when longer paths become stale or disconnected. SNGF has no memory of earlier connections and therefore chooses the best available shortest path at every node.

5.7 Effect of Node Density

Previous sections have presented the simulation results for 50, 112, and 200 nodes. Although the number of nodes was different but in all the scenarios the node density was kept constant. This section presents results for simulations for 50 nodes over an area of 1340 by 1340 meters thus reducing the node density in the network by a factor of 4. This change resulted in longer distances between nodes, requiring more hops for communication and a greater chance of fragmentation or voids occurring in the network.

Figures 5.14 and 5.15 present the fractions of successful packets delivered and the routing protocol overheads for DSR, GPSR and SNGF. To evaluate SNGF, a 1 Kbps CBR source was also used. Again all data points for SNGF are bracketed by their 97.7% confidence interval.

Increase in the number of voids, or disconnected nodes, affects all routing protocols. In DSR, a disconnected node causes the generation of queries that

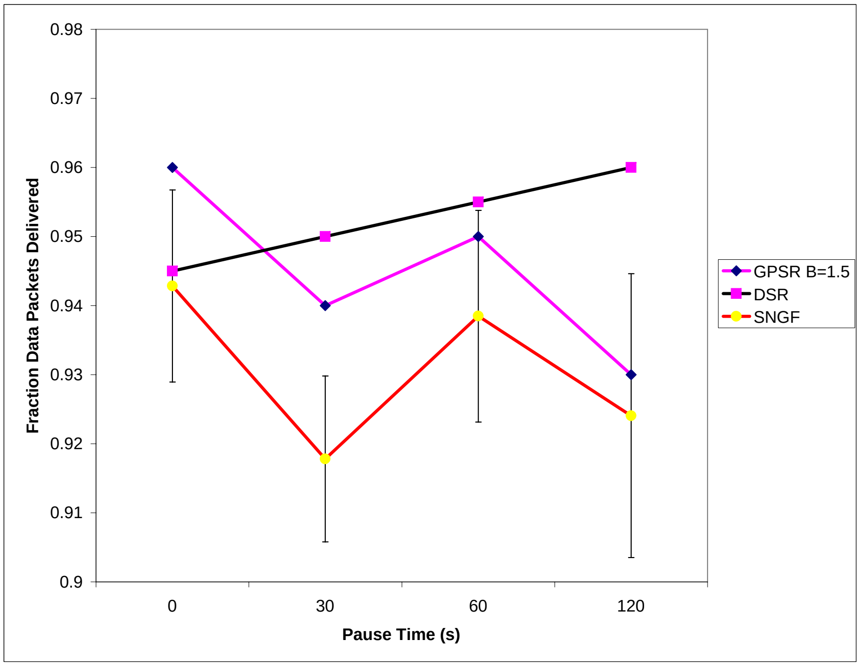


Figure 5.14: Fraction of successful packet delivery in sparse network.

are flooded in the network. These queries may result in the discovery of stale routes, which then cause query to be resent until stale routes are eliminated from the system. In GPSR, voids cause the perimeter mode to be followed. In a disconnected node, the packet traverses the entire face of the connected perimeter and will be dropped only when the first edge is reached for the second time.

In SNGF, voids force the nodes into delayed retransmission, or recovery mode, which may result in a packet taking a suboptimal path to the destination. A source node losing track of the destination also causes a destination query to be generated, which is apparent because of the increase in the routing protocol

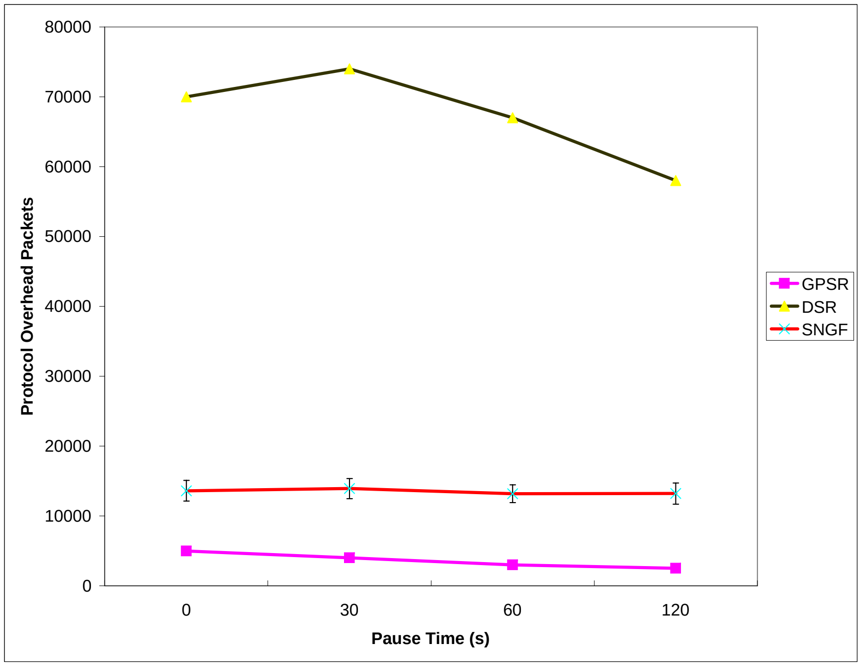


Figure 5.15: Routing protocol overhead in sparse network.

overhead. A direct comparison of routing protocol overhead with GPSR is thus not possible because GPSR makes no attempt to reestablish the communication session between the nodes. A comparison with the routing protocol overhead for 50 nodes with a four times greater node density (Figure 5.6), reveals that the overhead increases a little. This increase occurs because the voids cause more nodes to be disconnected thus forcing the SNGF protocol to generate more destination discovery packets.

Figure 5.16 shows the number of hop counts for successfully delivered packets in a sparse network. The sparse node density forces the routing protocols to

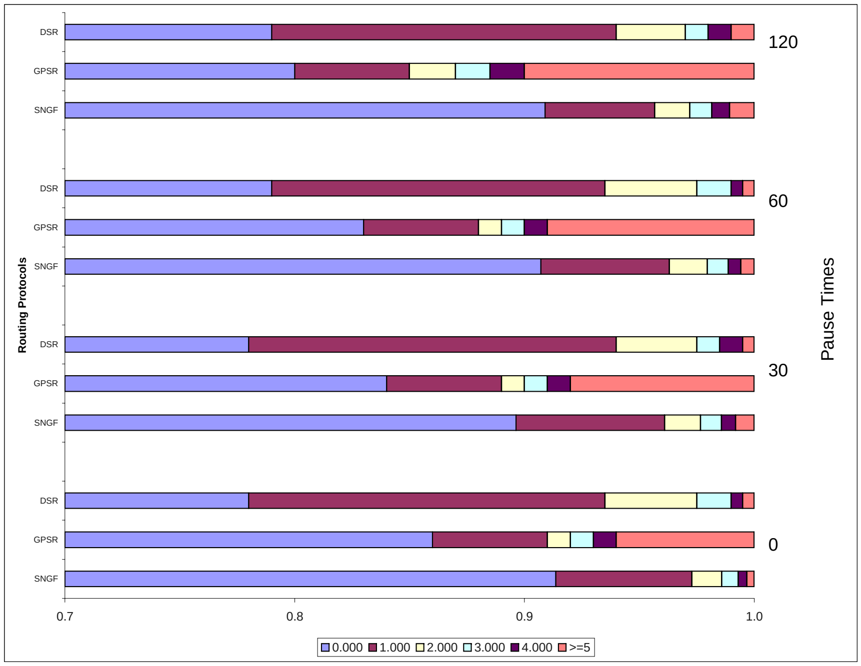


Figure 5.16: Hop count beyond the optimal for sparse network

incur more cost in terms of increased hop counts for the successful delivery of the packets. This effect of lower than optimal routing is more significant in the cases of DSR and GPSR with increasing pause times. In the case of SNGF, lower than optimal routing is observed but the effect seems to be free from changes in pause times. This is because the SNGF routing criterion remains constant even when the optimal routing path is not available. The only effect of voids in the path is an increased hop count, i.e, less optimal routing due to the failure of the best forwarding node and the job being taken by a less-than-optimal forwarder node.

5.8 Discussion and Future Work

This section describes the salient properties of the SNGF routing protocol alongwith scenarios for its best and worst performance and suggests future directions for improving the performance of SNGF.

5.8.1 Properties of SNGF

The simulation results from a wide range of scenarios presented in previous sections show that SNGF is a very robust and scalable routing protocol. The ratio of the successful delivery of packets by SNGF is comparable to that of other routing protocols, and SNGF outperforms both GPSR and DSR with respect to routing protocol overhead. SNGF overhead increases only with an increase in the number of communicating nodes and is not dependent on the size of the network diameter.

SNGF is a looping free protocol by design because it refrains from forwarding a packet if the packet is deemed to be not moving toward the destination in an incremental manner. It does not utilize any route sequence numbers, and decisions are based on the current topology of the surrounding network.

SNGF has a slight tendency to route packets for one or two hops more than the optimal route available, but this extra hop in no way hinders its packet delivery. It is expected that, on larger networks, where the routes are longer and more fragmentation is observed, the SNGF will use more hops to attempt to deliver the packet as long as it satisfies the anti looping criterion. In a sense, it will follow perimeter routing, but in a more subtle manner and each node individually decides whether to forward the packet.

In SNGF the decision to forward a packet or not depends entirely on the current one hop neighbor states and is in no way governed by the size or diameter of the network. On average, the SNGF forwarding strategy should work as effectively in larger networks as it does in the simulation networks. It is expected that the performance will be dependent only on the neighboring node density and not on the total number of nodes in the network.

In denser networks, when the best forwarder is able to forward the packet, the SNGF operates in a greedy manner, but as soon as the best forwarder is unable to forward a packet, the node which was not first classified as the best forwarder will forward the packet. This process may result in more hop counts but will also make it possible for the routing to be performed through an alternate available path because the new forwarding node will have a different set of neighbors. In this respect an effect that is observed in extreme cases is that the packet may be forwarded to the destination node from two entirely disjointed paths. However, observation has shown that this occurrence is a rare: usually in longer routes, the paths merge at some point where the packet can then be forwarded only once by that node. This possibility is a shortcoming, and although it was beyond the scope of this work, the right hand rule might be employed to eliminate this problem.

For this thesis, SNGF is considered to be a pure ad hoc routing protocol.

However, it should be pointed out that there is no restriction that would prevent SNGF from being able to communicate with the roadside hot spots for communication. A hot spot ID structure could be provided, and applications running on the SNGF routing protocol could easily take advantage of this facility where available.

The extensive supporting simulations have shown SNGF to be a viable VANET routing protocol. SNGF scales well for dense large scale mobile networks as well as for large sparse networks.

5.8.2 Future Work

Based on the preceding sections SNGF has been shown to be a very robust and scalable routing network protocol. Extensive simulation results have been presented in order to support the viability of SNGF. However, it is also apparent that SNGF may benefit from future work in several areas.

The first recommended future task would be to explore the performance of the SNGF protocol in terms of the latency of the packets delivered. SNGF is equipped with the ability to delay message transmission in packet forwarding but this feature was not explored further because of the goal of comparing this protocol with the ones reported in the literature.

With respect to message communication, if limitations allow an acceptable delay of, for example a range of 5-10 seconds, then it is expected that this time period can play a crucial role in network topology changes in VANETs. Topology changes can help SNGF forward packets in cases when it initially was unable to find any successful forwarders. A detailed analysis of this feature could lead to better packet delivery and a reduced number of voids in the network in terms of routing.

SNGF relies on beaconing or hello messages to keep track of one hop neighbors. This hello beacon provides location updates to a node about its neighbors and is sent to one hop neighbors only. The effect of allowing this beacon to travel two hops needs to be studied. Especially in the case of SNGF where forwarding decisions are being made by individual nodes based on information available about their neighbors, this extra information about next door neighbors may help SNGF make better decisions. It is expected that in that case SNGF will be able to make better decisions particularly for longer routes. The effect on network traffic and routing protocol overhead should be studied in detail.

In this thesis SNGF is considered to be a pure ad hoc routing protocol. However as previously pointed out, it can incorporate communication with any available roadside hot spots. This scenario should be tested because it might represent the future real-life scenarios.

All the simulations were conducted using 2-dimensional space and random way point movement. It would be interesting to investigate the performance of SNGF on a 3-D real life highway and urban traffic scenarios.

SNGF protocol is a viable protocol for VANET applications. This chapter presented in detail the simulation results under various conditions to highlight the salient properties of SNGF. In the next chapter SNGF protocol is used to demonstrate a unique approach in developing applications for VANETs.

Chapter 6

Traffic Profiling in SNGF Based VANETs

SNGF is a viable communication protocol for VANETs. SNGF allows nodes to communicate with one another without becoming a part of a group or cluster. A salient feature of SNGF is that it permits the nodes in the network to discourse with other nodes and collect relevant data which makes SNGF-based messaging very useful in a number of scenarios. Nodes can use SNGF based messaging in accident prevention, discovering alternate routes, resolving four-way stops and traffic profiling to name just a few.

This chapter presents traffic profiling in VANETs using the SNGF routing protocol. The node of interest collects information through SNGF based discourse with other nodes. For traffic profiling, the information gathered by a node is viewed as a snapshot of the current traffic conditions on a road segment. This approach of using snapshots of traffic for profiling is unique. A weight of evidence based algorithm is presented as a means of identifying different traffic conditions.

6.1 Introduction

Highway traffic congestion is a common problem faced by motorists around the world. It causes unwanted delays and results in production losses in the amount of several billion dollars per year [51]. The availability of real time traffic information is therefore crucial. Although this kind of information is readily available through the internet, radio networks etc., the accuracy, timeliness, and coverage of current systems are considered only marginal. Currently, most traffic data is collected by embedded loop sensors and mounted video monitors. The data collected in this manner is restricted to a limited section of the highway and requires significant infrastructure to be in place. Another method of collecting data is to use equipment mounted on vehicles. Although the equipment itself can be sophisticated and therefore expensive, it has the advantage of requiring no fixed roadside infrastructure to enable it to function. Using such equipped vehicles as mobile traffic probes is subject to difficulties created by factors such as the number of probe vehicles on the road, the type of data transmitted and the communication mechanism.

In SNGF-based ITS, vehicles are able to communicate with one another and can share data that can be used to identify traffic flow conditions. The data communicated between the vehicles depends on the number of vehicles equipped with MANET capability. However, SNGF provides an effective means of communication between the vehicles without utilizing any infrastructure. The ability to communicate without infrastructure is important in providing communication capability anywhere on the road and thus possibly helping drivers become aware of traffic conditions in their pathway. The number of equipped vehicles will conceivably be very low in the early stages of deployment, and thus the performance of any traffic condition monitoring system must be evaluated with respect to low numbers of equipped vehicles.

The problem of identifying highway traffic conditions such as jams or accidents, based on collected data can be viewed as a pattern recognition problem. The literature reports several attempts to analyze the traffic problem as a pattern recognition problem according to a variety of assumptions. In [48], the problem of network level traffic detection has been addressed as a two-class problem for simulated data collected on a freeway. The data is collected from fixed sensors at specific collection points on the freeway and therefore suffers from the limitation of required infrastructure. In [27], a similar problem is presented using a wavelet energy approach applied to data collected from FSP I-880 project. In [14], MANET based traffic condition detection is presented but the solution methodology is based on group formation which goes through the process of resolving selection of the leader and follower before any traffic conditions are considered. The literature describes many additional attempts to address the problem of traffic condition detection [11, 17], but the solutions presented are for a specific network communication protocol.

This research presents the problem of identifying road traffic conditions in the context of a SNGF-based mobile ad hoc network of vehicles. The vehicles acting as nodes in the ad hoc network communicate with one another using the SNGF protocol and gather information of interest from other nodes in the network. The collected information is then analyzed locally by each node. With this approach, each node or vehicle on the road can predict or detect the traffic conditions in its direction of travel. The information gathered by each node can be viewed as a snapshot in time of the traffic conditions. This snapshot of traffic flow is then analyzed using pattern recognition techniques in order to classify it into different classes such as free flow, pre-jam, or jammed condition. The formulation allows each vehicle equipped with MANET capability to view the current traffic conditions in front of it and to recognize the condition as a pattern recognition problem [58].

In pattern recognition problems weight of evidence has been used as a measure for classification because it has the capability of taking into account partial information [60]. When only limited data is available, this quality can be used in conjunction with a conflict resolution algorithm in order to predict classes. This chapter presents classification algorithm based on weight of evidence. The algorithm takes into account the fact that the available data may contain only partial or incomplete information. It provides a systematic method of evaluating the ability of each feature to correctly predict a specific class. For a particular observation, only the features that satisfy a specific criterion are allowed to participate in predicting the class of the data set. This mechanism is particularly useful in the case of limited data availability because it prevents features with low weight of evidence from the voting mechanism for determining the classification.

One such case of limited data availability is represented by the early stages of deployment of MANET-capable vehicles on the road where the snapshot of traffic will only represent a partial pattern for identification purposes. The developed classification scheme based on weight of evidence utilizes this ability to handle partial information and to provide an effective method of detecting traffic conditions when only limited data is available [59].

The new algorithm was tested using a simulation model for the microscopic modeling of traffic flow [32][14]. This model closely resembles other well-known models and is based on the fact that, in general, on any freeway, vehicles move without colliding, and their movement is characterized mainly by parameters that describe the typical acceleration and deceleration capabilities of vehicles. The model focuses primarily on traffic jam situations and hence is a natural choice for this work. The feature vectors of the data are very high dimensionally because the data collected from mobile nodes, or vehicles, is time and space dependent. Weight of evidence between features and classes was calculated based on sample data and tested using different testing data sets.

In an ideal setting, all vehicles on the road would be equipped and the node or vehicle of interest could view the current traffic condition with all data points being available. This assumption may not be true in the early stages of deployment of MANETs. Therefore, several data sets that reflect the different levels of MANET deployment on freeways were generated, including the particular cases of full, partial, and scarce deployment.

6.2 SNGF-Based Discourse of Vehicles

The basic requirement for traffic profiling performed by a node is the timely availability of data regarding traffic flow on the road. SNGF provides the means for the node to request and obtain the most recent data from all the available nodes in the area of interest. Figure 6.1 represents the steps involved in requesting and obtaining data from other nodes in the network.

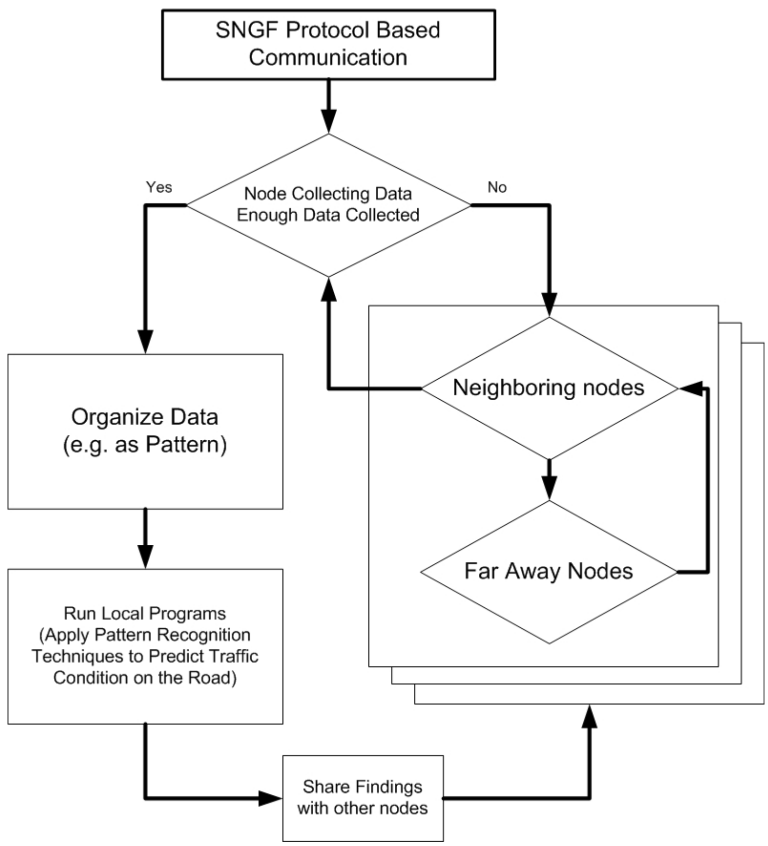


Figure 6.1: Sample setup for developing applications based on the SNGF Protocol

The user application resides on the node, and the node starts by gathering the data required from its neighbors. The communication is carried out using the SNGF protocol, which allows node-to-node communication. If the data collected initially from the immediate neighbors is not sufficient then the originating node may request other neighbors from more distant locations to supply the required data. The close proximity nodes act as facilitators for forwarding the inquiry messages and the reply-data packets in the appropriate directions.

Once sufficient data is available the originating node may process it locally and then deduce traffic conditions down the road. The node may also share this information with other participating nodes in the VANET, if requested.

6.3 Pattern Recognition Formulation

The problem of traffic condition monitoring is one basis for the application of MANETs in vehicular transportation systems. The discourse capability of the SNGF protocol for an ad hoc network of vehicles enables this problem to be considered as a pattern recognition problem.

In an ad hoc network of vehicles the vehicles communicate with one another and can gather information regarding the traffic conditions experienced by the individual nodes that participate in the ad hoc network. The traffic information, as gathered by any individual node, can be arranged as a pattern of traffic flow conditions around the node in real time. From the point of view of that particular node, the pattern can then be classified into classes of traffic conditions such as free flow or jam condition, by utilizing appropriate pattern recognition techniques .

To demonstrate this concept in the simulations, traffic flow was restricted to a single direction on a freeway. The node of interest was considered to be the node that most recently joined the group. Since the SNGF protocol allows nodes in MANETs to communicate with other nodes within a specific range by using the discourse option type of message, the node of interest can communicate with other nodes in order to gather relevant data from them.

Two different scenarios representing snapshots of the traffic flow as seen by the node of interest are shown in Figure 6.2. Figure 6.2a represents a free flow condition and Figure 6.2b represents a jam condition on the highway. Figure 6.2 thus represents two different patterns in time of the traffic flow on the highway.

For the sake of demonstration it was assumed that a node has a range of interest of two kilometers. The problem was analyzed from the point of view of the node most recently joining the snapshot. This node of interest can collect data over time from each participating node. The data collected from each node consists of the identification of the vehicle, speed of the vehicle, its current position with respect to the node of interest and its own state. The state of every participating node can be classified into one of the three possible conditions: free flow, pre-jam connected, and jammed.

The data is collected by MANET equipped vehicles and it is possible that

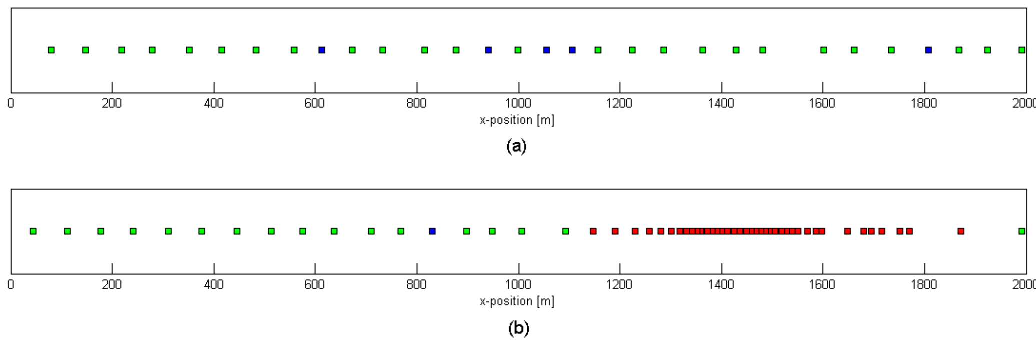


Figure 6.2: Snapshots of traffic on a single lane highway: a) Free flow and b)Traffic jam.

not all vehicles are equipped. Therefore, the data generated for different levels of MANET equipped vehicles will reflect the real life situation of sparsely equipped vehicles in the early stages of deployment.

In presence of patterns with incomplete or sparse data, the classification of patterns becomes a difficult task. The weight of evidence method has the capability of dealing with partial information and was therefore chosen as the preferred technique for the pattern classification of traffic conditions.

6.3.1 Weight of Evidence

Let $(\bar{X}, Y)$ be jointly distributed random variables with a q-dimensional vector $\bar{X}$ denoting a feature vector and Y denoting the attribute whose value is to be determined. The missing-value problem here is to find a decision rule $d(.)$ that maps R^q into the domain of Y such that certain properties of the data set are preserved. The feature vector $\bar{X}$ denotes a new observation and Y denotes its class label, or predicting attribute.

Given x_j, the weight of evidence in favor of $Y = y_i$ as opposed to $Y \neq y_i$ can be calculated as the difference of mutual information between the two possibilities [60]. If the weight of evidence is represented by W and mutual information by I then the following may be written:

$$W(Y = y_i/Y \neq y_i \mid \bar{X}) \\ = I(Y = y_i : \bar{X}) - I(Y \neq y_i : \bar{X}) \tag{6.1}$$

One can consider the process of estimating the value of $Y = y_i$ to be experiment E_1 and that of estimating the value of $\bar{X}$ to be E_2. The quantitative estimation of mutual information of these two experiments E_1 and E_2 can now be given as:

$$I(E_1, E_2) = I(Y = y_i, \bar{X}) \tag{6.2}$$

$$= log\frac{P_r(Y = y_i, \bar{X})}{P_r(Y = y_i).P_r(\bar{X})} \tag{6.3}$$

$$= log\frac{P_r(Y = y_i \mid \bar{X}).P_r(\bar{X})}{P_r(Y = y_i).P_r(\bar{X})} \tag{6.4}$$

$$= log\frac{P_r(Y = y_i \mid \bar{X})}{P_r(Y = y_i)} \tag{6.5}$$

The weight of evidence can now be rewritten as

$$W(Y = y_i/Y \neq y_i \mid \bar{X}) \\ = log\frac{P_r(\bar{X}, Y = y_i).(1 - P_r(Y = y_i))}{P_r(Y = y_i).(P_r(\bar{X}) - P_r(\bar{X}, Y = y_i))} \tag{6.6}$$

The numeric value of the weight of evidence can be positive, zero, or negative. A positive value indicates that $\bar{X}$ provides positive evidence for Y belonging to y_i whereas a zero value shows no information provided with respect to selecting a class. A negative value, on the other hand, indicates that there is evidence against Y taking on the class y_i, it might as well belong to some other subset of Y.

6.3.2 Classification Algorithm

The weights of evidence as provided by the features for the possible classes can take on either a positive, zero, or negative values. Depending on the weights of evidence provided by the features for all classes, a decision must be made in favor of a particular class. A classification algorithm was developed based on a voting strategy for comparing the weights of evidence as given by each feature for every class.

Algorithm

- Step 1: Given Vector X with m features. $x_i \in X, i = 1 \cdots m$ represents m features collected from the participating nodes.
- Step 2: Calculate weight of evidence $w_{ij} \in W_{m \times n}$ from m features for n classes. (Here $n = 3$ representing the three classes of traffic conditions.)
- Step 3: Find $\bar{W}_{m \times 1}$, where $\bar{w}_i$ is a vote by a feature for a particular class:

$\bar{w}_i = \max(w_{ij}) \; \forall \; j = 1 \cdots n$ and $\bar{w}_i \geq w_{cutoff}$

- Step 4: If $\exists \; j, k \mid w_{ij} = w_{ik} = \bar{w}_i \in \bar{W}$, the feature i is not allowed to vote.
- Step 5: If $\bar{w}_i \leqslant 0$, feature i is not allowed to vote.
- Step 6: Count the number of votes for each class: $\forall \; i = 1 \cdots n$, $vote_i = \sum_{j=1}^{m} \bar{w}_j \mid \bar{w}_j = y_i$, where $y_i = i$. $Y = y_k$, where $k = \texttt{index}(\max(vote_i))$, represents the winning class.

Where w_{cutoff} is a minimal value chosen to prevent features with small numeric value of weight of evidence from taking part in the voting process.

6.4 Simulation Setup

The set up to simulate the problem of identifying traffic conditions in MANET equipped vehicles required the following steps:

1. Through simulation generate and classify microscopic traffic data for training and testing sets. The training sets were labeled into number of classes namely free flow, connected (towards jam) and jammed.
2. Use the training data set to generate the probabilities required for calculating weights of evidence.
3. Classify the test data set using a weight of evidence classifier.

To solve this problem required the generation of realistic traffic flow data. There are two kinds of traffic flow models available in the literature, namely Macroscopic and Microscopic. Macroscopic models consider the dynamics of vehicle density and average velocity. This research required a simple model capable of exhibiting enough features that a traffic jam condition would be recognizable that the vehicle could be simulated as a single entity. One such microscopic model is described by Krauss in [32]. The main features of the model are given briefly in the following subsection.

6.4.1 Krauss Model

The Krauss model defines a vehicle at any time step as consisting of four parameters and four update rules. The parameters are the maximum velocity v_{max}, the maximum acceleration a, the maximum deceleration b, and the amount of noise ε that introduces stochastic behavior to the model. The time is discrete and ticks with an interval $t = 1$ second. However, the spatial values of the positions are continuous. Figure 6.3 shows the model parameters.

The rules of the model describe how the vehicle chooses a velocity and applies it to reach a new position in the next time step. The rules mirror three observations of human driving behavior:

1. Drivers want to reach their goal as fast as possible.
2. They do not want to collide with other vehicles.

3. The human perception of speed and distance is inaccurate.

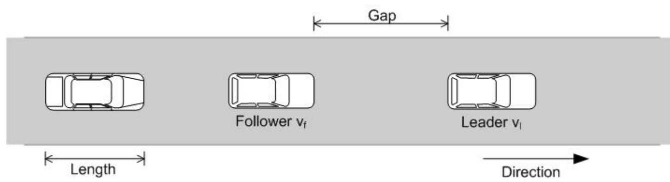


Figure 6.3: Traffic model parameters.

A noise term captures the latter observation and reduces the optimal velocity by a random value. The reaction time of the driver is set to $\tau = 1$ second. The update rules for the vehicle are as follows:

$$v_{safe} = v_l + \frac{gap - v_l.\tau}{\tau_b + \tau} \qquad with \qquad \tau_b = \frac{v_l + v_f}{2.b} \tag{6.7}$$

$$v_{desired} = min[v_{max}, v_f + a.\Delta t, v_{safe}] \tag{6.8}$$

$$v(t + \Delta t) = max[0, v_{desired} - \varepsilon.a.\Delta t.random()] \tag{6.9}$$

$$x(t + \Delta t) = x(t) + v(t + \Delta t).\Delta t \tag{6.10}$$

where x is the distance, v_l is the velocity of the leader, v_f is the velocity of the follower, gap is the gap between the leader and the follower, a is the maximum acceleration, b is the maximum deceleration, and ε is the influence of noise.

In this model a stopped vehicle is seen as a jammed vehicle. A vehicle connected to a jammed vehicle and traveling at a velocity below a lower threshold v_{JIn}, is also seen as jammed. A previously jammed vehicle escapes the jam only if it is not connected to the preceding vehicle and if it travels at a velocity above an upper threshold v_{JOut}. A vehicle is called connected to its leader if it must adjust its velocity because of the small gap between them. In terms of the model, the vehicle is connected if the minimum in rule 2 is v_{safe}. Accordingly, for this research, the lower threshold was set to 50% of the maximum speed. The upper threshold for escaping the jam was set to 70% of the maximum speed.

The microscopic traffic model was then applied to a highway scenario. Figure 6.2 provides an overview of the road model. For more than one lane, the model requires lane changes in order to capture influence of the traffic on neighboring lane. For this research, the implementation was restricted to a unidirectional flow with no lane changes in order to keep the model at a simple level because the main scope of this work is to focus on traffic pattern detection rather than on the traffic model itself. Other parameters of the road model are the total length, the width of a lane and the number of lanes per driving direction. Again, the number of lanes per driving direction was set to one because the extension of the traffic model for multi-lane traffic is not trivial.

The next subsection describes in detail the data set generated for this problem and provides preliminary analysis of the data in order to highlight the underlying complexity of the problem.

6.4.2 Data Generation and Analysis

The node mobility data for this problem was generated by implementing the Krauss model in MATLAB. The data was generated in steps of 30 second periods and was divided in training and testing set in a ratio of 4:1. The training data was labeled to represent one of the three possible classes namely free flow, towards jam, and jammed traffic scenarios. This mobility data was then used in NS-2 based simulator with the SNGF protocol for communication in order to collect data from the participating nodes. The rest of the simulation environment setup was similar to that previously explained in Chapter 5 and shown in Figures 5.1 and 5.2.

Each row of the data set collected represents all the vehicles present within a two kilometer range. Since the number of nodes available in this stretch of the highway is not known, the number of nodes was limited to 50, which is the approximate maximum number of vehicles possible in a 2 km stretch of highway according to the vehicle density assumption used in the Krauss model.

The data collected from each node includes the vehicle id, its current speed, and its distance from the node of interest. For every simulation run, a period of 30 seconds for collecting the data was selected. This time limit was chosen based on the assumption that a node traveling at the maximum allowed speed traverses the distance of 2 km during this time frame.

To simulate a situation that would represent a sparse distribution of MANET equipped vehicles, the data set was modified by including the effect of missing nodes, or unequipped vehicles. The data was generated through the Krauss model and then for every snapshot the allowed number of equipped cars was selected at random from the complete set. In this way, different levels of MANET deployment could be represented such as 60%, 40% and 20%.

Each data point in the data set generated by the simulation runs of the Krauss model had a dimension of 150 and belonged to one of the three classes. Principal Component Analysis (PCA) was used to provide insight about the separability of the three classes. One of the advantages of PCA is that reducing the dimension can help with the visualization of the data. Since more than 2-d data is difficult to visualize, the first two most significant components obtained by PCA were taken in order to graphically represent the data set.

PCA, also known as the Hotelling transform, is a technique commonly used in statistics, and signal processing. The main concept behind PCA is to find components $s_1, s_2, ..., s_n$ so that they explain the maximum amount of variance possible by n linearly transformed components. PCA can be defined in an intuitive way using a recursive formulation.

Define the direction of the first principal component, say w_1 ,

$$w_1 = arg \frac{max}{\parallel w \parallel = 1} E\{(w^T x)^2\} \tag{6.11}$$

where w_1 is of the same dimension m as the random data vector x. Thus, the first principal component is the projection on the direction in which the variance of the projection is maximized. Having determined the first $k-1$ principal components, the $k-th$ principal component is determined as the principal component of the residual:

$$w_k = arg \frac{max}{\parallel w \parallel = 1} E\{[w^T(x - \sum_{i=1}^{k-1} w_i w_i^T x)]^2\} \tag{6.12}$$

The principal components are then given by $s_i = w^T x$. In practice, the computation of w_i can be accomplished simply using the sample covariance matrix $E\{xx^T\} = C$. w_i are the eigenvectors of C that correspond to the n largest eigenvalues of C.

The basic goal in PCA is to reduce the dimension of the data. Thus $n << m$ is usually chosen. Such a reduction in dimension has important benefits.

Figure 6.4 shows the class separability of data. Figure 6.4(a) shows the class separability of data under the assumption that 100% of the vehicles are MANET equipped. Figure 6.4(b) shows the class separability of data under the assumption that just 40% vehicles are MANET equipped. As the comparison shows the problem of pattern identification becomes more complex as the sparse data set makes classification more difficult. This trend becomes more apparent as proportion of equipped vehicles is further reduced to 20%.

6.5 Results and Discussion

The results of the simulation are presented in Figure 6.5. The developed algorithm was used to predict traffic conditions under different scenarios. Specifically, levels of 20%, 40%, 60% and 100% of MANET equipped vehicle deployment on highways were tested. The probabilities required in order to calculate the weights

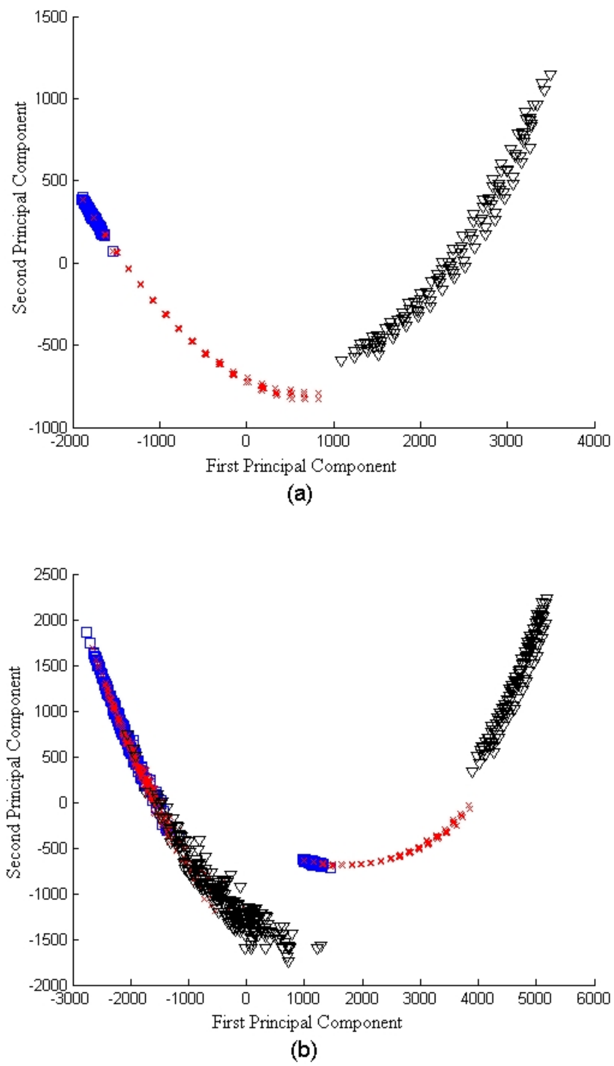


Figure 6.4: 2-D data representation of three classes of traffic condition in (a) 100% and (b) 40% MANET equipped scenario. □=Free Flow, ×=Connected, ∇=Jam.

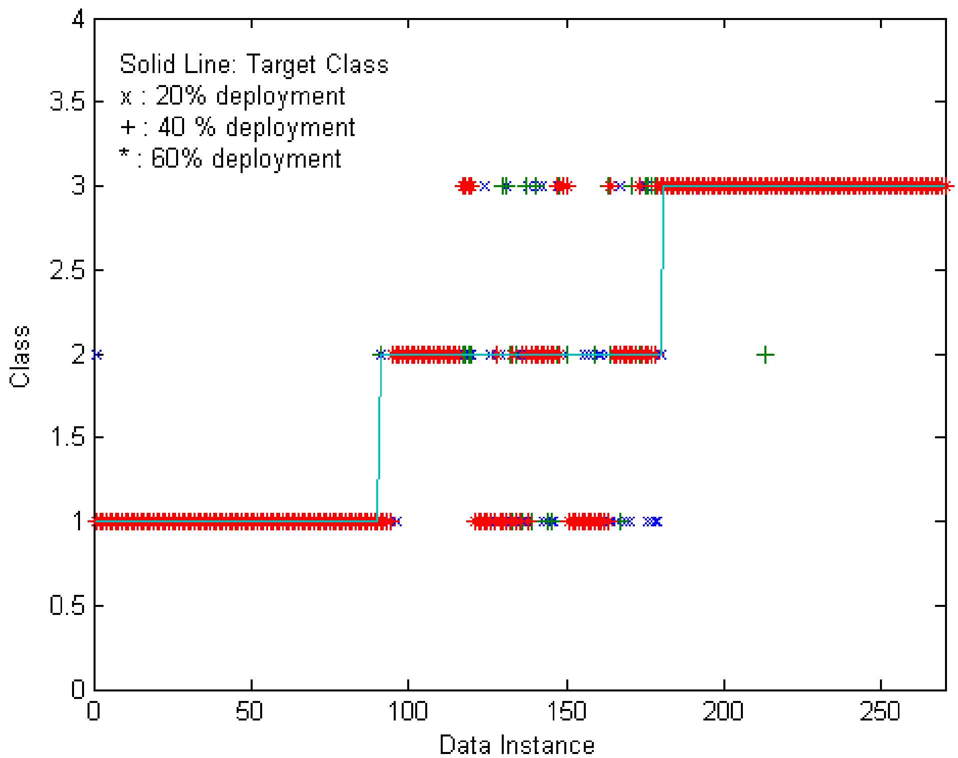


Figure 6.5: Classifier outputs

of evidence were derived from the training data set. The training data was composed of 270 events with 150 features and 3 classes. The probability of each class was assumed to be equally likely.

The testing data set was used to classify traffic jam conditions based on the weight of evidence based classifier. Each testing set was composed of 30 instances of each class.

Table 6.1: Training and Actual Errors for Various MANET Deployment Levels.

MANET Level	Training Error	Class1 Error	Class2 Error	Class3 Error
100%	5.5%	0	5.6%	0
60%	8.9%	0	15.5%	0
40%	9.8%	0	16.2%	0.3%
20%	14.3%	0.3%	17.0%	0

Table 6.1 summarizes the results obtained by the voting algorithm for the traffic condition detection problem using different levels of MANET deployment.

An examination of the results shown in Table 6.1 lead to a number of conclusions. The training error and testing error all show a consistent increase with the decrease in the percentage level of MANET equipped vehicles. This result was expected based on the PCA data analysis. A visual inspection of the first two principal components reveals that, as the level of equipped vehicles decreases, the classes become more and more overlapping. More specifically, as shown in Figure 6.5, the class 2 errors increase with the decrease in the number of MANET equipped vehicles. Class 2 is the pre-jam condition and is more difficult to predict than either the free flow or jammed conditions.

6.6 Conclusion

The problem of traffic flow condition detection has been presented as a pattern recognition problem for an SNGF-based ad hoc network of vehicles. The traffic pattern is analyzed by an individual node or vehicle and is independent of any infrastructure requirement. The nodes can communicate using SNGF protocol to collect the required information for pattern formation. The traffic flow condition is then detected locally by each node using the developed classification algorithm based on weight of evidence. Information theory based weight of evidence is used to classify the test data sets. It was shown that the vehicles in a mobile ad hoc network can indeed view traffic conditions as a pattern recognition problem. The proposed algorithm also works when only scarce data is available, such as in the case of the initial deployment of VANETs on the roads. The probability of errors in detecting traffic jams will decrease with a rise in the percentage of equipped vehicles.

The deployment of VANETs in the transportation industry is only a matter of time. Much work must be done before they can be used effectively in vehicle traffic prediction scenarios. Only one possible approach to solving this problem has been demonstrated, but several simplifying assumptions have been made. Future work on traffic pattern detection can continue in two possible directions. Firstly the algorithm should be tested using a more realistic multi lane traffic simulator. Secondly, the effects of network communication limitations, such as congestion and network fragmentation scenarios should be examined. Another possible direction for future research is to investigate the voting mechanism so that a relative confidence measure among competing features can be included.

Chapter 7

Conclusion

This chapter provides a summary of the contributions of this thesis to the field of Vehicular ad hoc networks. Some areas for future research in the direction of this thesis are also given.

7.1 Contributions

First this thesis has presented a Selected Node Geographic Forwarding (SNGF) protocol for the routing of packets in vehicular ad hoc networks. SNGF is a true ad hoc routing protocol and operates based on the absence of infrastructure requirements. SNGF uses the geographic information about neighboring nodes and forwards packets based on internal selection criterion that minimizes the flooding in the network. SNGF is free from routing tables and all decisions with respect to forwarding are made in a competitive manner. SNGF is highly robust and scalable because participating nodes are not required to update any routing tables. When a direct route is not available, SNGF selected node goes into recovery mode and attempts to find a better positioned forwarder through delayed message retransmission. The results of extensive simulation based on parameters well recognized in literature have been presented. The simulation results show that compared to DSR, SNGF has a high rate of packet delivery rate and is scalable. In comparison to GPSR, SNGF performs comparably with respect to successful packet delivery ratio, and it generates a much lower amount of network overhead. Unlike GPSR, SNGF is also equipped with a destination discovery and network fragmentation recovery procedure.

Second, this thesis has presented a new approach to application development that works with SNGF-based VANETs. This application development technique provides the basis for developing stand-alone applications for nodes that participate in VANETs. The traffic profiling has been presented as seen by a node on the road as a part of an SNGF based VANET. Using the SNGF-based discourse the node collects data from its peers and uses an algorithm based on information theory to treat the collected data as a snapshot of traffics condition in time. This approach to traffic jam detection is unique and is being reported for the first time in this thesis. Extensive simulation results have also been presented in order to show the viability of this approach for different levels of VANET deployment on the road. The author believes that VANETs will become a reality in the near future for the average driver on the road and that simple and effective stand-alone applications will foster their advent. SNGF can play a vital role in collecting data from nodes on the road needed by user applications running on VANETs.

In summary, this thesis has contributed in the following areas related to vehicular ad hoc networks:

- A new generic protocol for VANET communication has been developed. The design structure of this protocol is based on the special characteristics of VANETs, such as high speeds and constant changes in topology.
- The controlled flooding technique has been modified and used effectively in the design of the SNGF protocol, which is scalable and robust.
- Reliance on a locator service has been eliminated because of the ability of nodes to discover the geographic location of destination nodes without blindly flooding the network.
- A mechanism has been incorporated to alleviate the problem of fragmentation in VANETs through the buffering of messages and delayed transmission when no direct connection is available to the destination node.
- Extensive simulations have been conducted in order to evaluate the performance of the developed protocol for VANET under different load conditions.
- SNGF has been demonstrated to be a viable protocol for VANETs. A standalone application based on the SNGF protocol has been developed. The application demonstrates a novel approach based on pattern recognition that will help with traffic profiling in VANETs.

7.2 Future Work

This thesis has presented a new routing protocol which is shown to be robust and scalable. A new method of solving traffic profiling problem on the road has also been presented. Future direction of research for both SNGF and the traffic profiling problem has been given in the last sections of Chapters 5 and 6, respectively. The recommendations are summarized in the following points:

- Investigate the performance of the SNGF protocol in terms of the latency of the packets delivered. SNGF is equipped with the ability to delay message transmission with respect to packet forwarding but was not explored in this research. Due to the design structure of SNGF investigation of this feature can lead to better packet delivery and a reduced number of voids in the network with respect to routing.

- Explore the effect of the hello beacon if it is allowed to go beyond one hop neighbors. The extra information propagated beyond one hop neighbors may help SNGF make better decisions. The effect on the network traffic and routing protocol overhead must be studied in detail.

- It is desirable to test SNGF in the presence of fixed roadside hot spots. Although SNGF is considered to be a purely ad hoc based routing protocol for this research, it can also incorporate communication with available roadside hot spots.

- Although all testing and simulation for this research was limited to 2-D models, it would be interesting to investigate the performance of SNGF for a 3-D real-life highway and urban traffic scenarios.

- Future work on traffic pattern detection should include testing the algorithm using a more realistic multi-lane traffic simulator.

- Investigating the effects of network communication limitations such as congestion and network fragmentation scenarios would also help to improve the performance of SNGF.

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