ABSTRACT

JOSHI, HARSHVARDHAN P. Distributed Robust Geocast: A Multicast Protocol for Inter-Vehicle Communication. (Under the direction of Assistant Professor Mihail L. Sichitiu.)

Inter-vehicle communication is expected to significantly improve transportation safety and mobility on road. Several applications of inter-vehicle communication have been identified, notably safety and warning applications, traffic control applications and driver assistance applications. A majority of these applications require multicast to a group of vehicles satisfying a geographic criterion. To reap the benefits of inter-vehicle communication in a short time with minimal investment, use of vehicular ad hoc networks (VANETs) is envisioned. It has been shown that VANETs, with very high node mobility, benefit from the use of location information for routing. The multicast of a message, using geographic routing, to nodes satisfying a geographical criterion is called *geocast*. Numerous protocols for geocast have been proposed in literature for general mobile ad hoc networks as well as VANETs. It has been shown that explicit route setup approaches perform poorly with VANETs due to limited route lifetime and frequent network fragmentation. The broadcast based approaches have considerable redundancy and add significantly to the overhead of the protocol. In this thesis, we propose a completely distributed and robust geocast protocol that is resilient to frequent topology changes and network fragmentation. We use a distance-based backoff algorithm to reduce the number of hops and introduce a novel mechanism to reduce redundant broadcasts. We also propose several approaches to overcome network fragmentation and to keep a message alive in the geocast region, ensuring that a node entering the region even after the spread of the message receives it. The performance of the proposed protocol is evaluated for various scenarios and compared with simple flooding and a protocol based on explicit route setup.

Distributed Robust Geocast: A Multicast Protocol for Inter-Vehicle Communication

by

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To my parents . . .

Biography

Harshvardhan P. Joshi was born on September 17, 1979 in Nadiad, Gujarat, India. He earned a Bachelor of Engineering (B.E.) degree in Instrumentation and Control Engineering from Dharmsinh Desai Institute of Technology, Nadiad in May 2000. After an internship at Masibus Instruments Pvt. Ltd., Gandhinagar, he was convinced of the need for broader education and joined B. K. School of Business Management at Gujarat University in Ahmedabad, India. After graduating in May 2002 with a Master of Business Administration (M.B.A.) degree, he worked in marketing departments of various companies. He also taught business and economics to engineering students and information technology to business majors. In Fall 2004, Harshvardhan joined North Carolina State University for graduate studies in Computer Networking, and became a member of the Wireless and Local Area Networks research group.

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Chapter 1

Introduction

1.1 Motivation

Automobiles are by far the most popular means of transportation in the United States with trips in personal vehicles accounting for more than 88 percent of all trips. An adult American spends nearly an hour (55 minutes) in a vehicle every day, driving 29 miles [1]. The quality of road transport can have a significant impact on quality of life as well as the economy. Motor vehicle accidents caused 42,643 deaths in the United States alone in 2003, from an estimated 6,328,000 crashes also resulting in injuries to estimated 2,889,000 persons [2]. This was keeping in trend with the past, with an average 41,857 deaths and 3,183,796 injured persons from 6,375,575 crashes during 1990 to 2003. In the year 2000, the total economic cost of motor vehicle crashes in the United States was $230.6 billion. This is equal to approximately $820 for every person living in the United States and 2.3 percent of the U.S. Gross Domestic Product [3]. In 2003 it took 37 percent longer, on average, to make a peak period trip in urban areas compared with the time it would take if traffic flowed freely [4]. The annual highway congestion cost per capita in these urban areas rose from $339 in 1998 to $422 in 2003. These costs can reasonably be expected to go higher with 6,263,453 more vehicles added to the roads in 2004 alone [2].

It is understandable that considerable research effort is concentrated on making road transport safer and more comfortable while cutting the travel time. A majority of the outcomes of this research falls into the domain of *Intelligent Transportation Systems* (ITS), which are designed to improve transportation safety and mobility through the use of advanced communications technologies. The U.S. Department of Transportation has identified at least 16 application areas for ITS [5]. *Inter-Vehicle Communication* (IVC) has the potential to increase the benefits of ITS manifold by allowing vehicles to share locally relevant information in a resource efficient manner. Applications of IVC include:

- *Safety Applications:* Collision warning system, Emergency vehicle notification
- *Traffic Control Applications:* Traffic monitoring, Traffic control, Route planning
- *Driver Assistance:* Platoon formation and maintenance, Merging assistance
- *Miscellaneous:* Localized advertisements, Instant messaging, Interactive gaming

The safety and traffic control applications have generated considerable interest in the research community because of their potential impact. A collision warning system can provide advance notification to drivers when visual cues are obstructed by other vehicles, curvature of the road or fog, and can prevent pile-ups on a highway. An emergency vehicle notification application can warn drivers to clear path for emergency vehicles and even control traffic lights to allow emergency vehicles to pass rapidly. The traffic control applications can help authorities and drivers monitor traffic in an area and divert the traffic to reduce congestion. They can also help a driver dynamically select a route to the destination based on the latest traffic information.

To serve the applications identified above, an IVC system should satisfy the following criteria:

- *Reliability:* the system should be reliable enough to serve the safety applications.
- *Low Delay:* safety applications can be intolerant to end-to-end delays.
- *High Throughput:* traffic control, driver assistance and some other applications can generate considerable packet traffic requiring high throughput.
- *Scalability:* the system should be able to scale for thousands of nodes and several square miles.
- *Robust Architecture:* the system should be robust enough to withstand high node mobility, frequent topology changes and temporary network fragmentation.

- *Infrastructure Independence:* the systems should not rely on an external infrastructure for its operation.

IVC can be single-hop or multi-hop. Multi-hop IVC is expected to be achieved using *Mobile Ad Hoc Networks* (MANETs). MANETs are wireless networks with autonomous mobile nodes that collaborate in order to transport information without relying on external infrastructure. The mobility of nodes can cause frequent topology changes, which makes routing in MANET a significant challenge. Several on-demand as well as proactive routing algorithms for MANETs have been proposed, e.g. [6, 7, 8], and [9] has an exhaustive survey of many of these algorithms. Use of location information has the potential to significantly improve the efficiency of routing in MANETs, especially when the nodes are highly mobile. Several algorithms that use location information for efficient route discovery have been proposed [10, 11, 12, 13].

In recent times, the term *Vehicular Ad Hoc Networks* (VANETs) is frequently used in place of MANETs in the context of IVC, highlighting its distinct characteristics such as: high node speeds, constrained mobility, availability of resources such as location information (GPS) and abundant energy. Given these characteristics, it is generally accepted that VANETs should use some form of geographical routing. For many of the applications of IVC listed above, especially safety and traffic control applications, it is desirable to send a message to a particular geographic region. The multi-cast of a message to nodes satisfying a geographical criterion is called *geocast*. Several algorithms for geocasting have been proposed based on location information [14, 15]. These algorithms, though distributed compared to other traditional routing protocols, require at least some state information, like the knowledge of neighbor nodes. Keeping state information adds overhead and consumes resources like bandwidth and memory.

It is possible to address nodes using either fixed addressing (e.g. IP addresses) or geographical addressing. If fixed addressing is used for geocast, the fixed addresses have to be mapped to geographic address and the message has to be unicast or multicast to each node within the geographical region. This can be done either centrally by a server updating each node's location or on-demand in a distributed manner by flooding a query. Due to highly dynamic nature of VANETs, mapping fixed addresses to geographical addresses has the following disadvantages:

- *Expensive in terms of bandwidth:* a query or an update will have to be repeated frequently to ensure accurate mapping.

- *Higher Delay:* querying either a server or a group of nodes adds delay, which may be unacceptable in some applications, e.g. safety applications.
- *Unreliable:* if flooding of query is done using broadcast, it is possible that some vehicles in the target area may not hear the query, their mapping remaining incomplete.
- *Short Route Lifetime:* requires setting up of routing tables that are bound to be obsolete soon after their setup.

In summary, IVC has potential to improve transportation safety and mobility, and has many other applications as well. VANETs are the preferable way of achieving IVC, and geocast can effectively and efficiently serve many of the applications envisioned using geographical addressing.

1.2 Contribution

This thesis proposes Distributed Robust Geocast (DRG), a geocast protocol designed for VANETs which is completely distributed, without control overhead and state information and is resilient to frequent topology changes. We use a distance-based backoff similar to [16, 17, 18] for directed and restricted flooding. However, unlike [16], we do not require neighbor information for forwarding decision and neither do we assume a one-dimensional road. We use a state-less forwarding algorithm which efficiently spreads the message through the target region and ensures delivery to all the relevant nodes. The forwarding algorithm can work for two-dimensional street network as well as one-dimensional highways and a target region of any shape. Furthermore, the algorithm is resilient to the underlying radio transmission range model and can work with non-circular transmission range model caused by fading and pathloss. The algorithm can overcome a temporary network partitioning or temporary lack of qualified relay nodes and has a mechanism to prevent loops. We also show a completely distributed method for keeping a message alive in the target region thereby ensuring that a node entering the region even after the spread of message receives the message. We evaluate the performance of DRG and compare it with pure flooding and with ROVER, an on-demand protocol based on AODV and modified for VANET. For performance evaluation we use SWANS/STRAW [19, 20], a network simulator on top of a microscopic simulator of vehicular traffic. We also modify STRAW, the vehicular traffic simulator, to include lane-changing model proposed in [21]. We carry out an exhaustive performance evaluation of the protocols for safety and traffic monitoring applications, on highways and city streets, for various node densities, transmission ranges, and target region area.

1.3 Thesis Outline

This thesis is organized as follows: Chapter 2 describes the related work. Chapter 3 considers the need for a completely distributed and robust geocast protocol and describes the proposed protocol including the backoff and forwarding algorithm. Chapter 4 describes the simulation model used and compares the performance of the proposed protocol with pure flooding and a modified AODV. Finally, Chapter 5 summarizes the results of our work and discusses future work.

Chapter 2

Related Work

The literature related to position-based unicast routing and geocast can be divided into general routing protocols for MANETs and routing protocols designed specifically for VANETs. The protocols falling into the later category address the special challenges posed by IVC such as high node speed, radio obstacles in cities and need for scalability. At the same time they try to exploit other characteristics like mobility limited to streets and availability of resources like global positioning system (GPS) to optimize routing. The position-based routing algorithms can be classified as either using restricted flooding of data packets or using explicit route setup approaches where control packets may be flooded but data packets are not.

Blum et al. [22] show the differences between VANETs and MANETs using very realistic vehicle movement traces. They find that network topology changes rapidly in VANETs, with average link life being less than a minute, and that the network is subjected to frequent fragmentation. However, the most significant finding is that route lifetime in VANETs is extremely small as the number of hops in a route increases. With around nine hops, the average path breaks even before the first packet can be acknowledged. Therefore, protocols that find routes before sending messages are likely to perform poorly in VANETs. It is suggested that position-based routing may be the best suited approach to routing in VANETs.

All position-based routing algorithms require each node to be aware of its own position and the position of the destination of a packet. In addition, for a majority of the algorithms a node has to also be aware of the position of its neighbors. Usually each node is assumed to know its position through GPS [23] or other positioning systems [24]. The position of the neighbors can be obtained through periodic hello messages, which include location information. The position of the destination can be obtained through a location service. Surveys of various location service approaches for MANETs are given in [25, 10]. A survey of position-based routing algorithms for MANETs is given in [10], while [14, 15] survey the geocast routing protocols. We present below some of the relevant geocast routing algorithms and outline their strengths and weaknesses in relation to inter-vehicle communication.

Flooding the network is a tempting solution for IVC because of its simplicity. However, Ni, Tseng et al. [26] show that simple flooding has significant redundancy, and can cause considerable contention and collisions. They propose that to alleviate the contention and collision the redundancy in broadcasts should be reduced, and present five schemes for this purpose. The distance-based and location-based schemes assume equal transmission range for all nodes, and are founded on the concept that a node should not rebroadcast unless the broadcast can significantly add to the coverage of previous broadcasts. If two nodes are quite close, the coverage of one node will significantly overlap the coverage of the other node. In the distance-based scheme, a node does not rebroadcast unless its distance from the previous sender is above a certain threshold. For location-based scheme a convex polygon test is proposed to determine if a rebroadcast will add significantly to the coverage. If the node is within a convex polygon formed by other transmitters, its transmission will not cover a significantly new area and hence it should not transmit. However, this test works only if the node has received the same packet from at least three other nodes. The location-based approach is similar to the one used in this thesis for implicit acknowledgement decision, though we propose a simple angle based test instead of the convex polygon test which works with two nodes.

Williams and Camp [27] present a comparison of broadcasting techniques for MANETs. They classify the broadcasting techniques as simple flooding, probability based methods, area based methods and neighbor knowledge methods.

- *Probability based methods* assign some probability to a node to rebroadcast. Since in dense networks multiple nodes have similar transmission coverage, by not having some node rebroadcast network resources can be saved without adversely affecting delivery effectiveness. While assigning low probability for rebroadcast reduces redundant transmissions, it also reduces the reliability of packet delivery for a given node density.

- *Area based methods* allow a node to rebroadcast only if the rebroadcast will reach sufficient additional coverage area. These schemes are the distance-based and location-based schemes of Ni et al. and they are discussed earlier in greater detail.

- *Neighbor knowledge methods* maintain state on their neighborhood, through hello packets, which is used in the decision to rebroadcast. These methods may keep state on 1-hop or 2-hop neighbors. While some of the methods specify through data or control packet on which nodes are supposed to rebroadcast the packet, other methods allow a node to make re-broadcast decision locally. These methods trade-off the overhead of larger data packets for the overhead of smaller control packets. This trade-off is profitable only if there is significant difference between the size of control and data packets.

It is shown through simulations that in a static network probability based and area based techniques of broadcasting, such as location based scheme of [26], are less effective in reducing redundant broadcasts compared to neighbor knowledge based methods.

2.1 Geocast for MANETs

In a seminal work [28], Ko and Vaidya outline two schemes for location-based multicast to a geographical region called multicast region. A forwarding zone is defined to include the multicast region as well as other areas around it such that delivery of packet to the multicast region is improved. The membership to the forwarding zone is defined using one of the two proposed algorithms. Scheme 1 defines forwarding zone as the smallest rectangle that includes current location of the sender and the multicast region. In scheme 2, a node belongs to the forwarding zone if it is closer to the center of multicast region than the sender by a certain threshold. Both these schemes are based on restricted flooding and does not require topology information. However, they do not include any mechanism for overcoming empty forwarding zone or network partitioning. The algorithms proposed here are similar to the algorithms proposed in [11] for unicast routing.

Ko and Vaidya propose another geocasting protocol, called GeoTORA in [29], which combines a unicast routing protocol, TORA [30], with flooding. The packet is delivered to one of the nodes in the geocast region using a route created by a slightly modified TORA, and then flooded within the geocast region. GeoTORA is shown to be better than flooding and location-based multicast [28] in terms of overhead, although the end-to-end delay caused by route creation has not been evaluated.

In [13], Stojmenovic and Lin show that memory-less routing algorithm based on direction of destination, such as scheme 1 in [11] or [31], do not guarantee loop-free paths. They, however, show that routing algorithms which forward to nodes closest to the destination or with the most forward progress [1] are inherently loop-free. Stojmenovic, Ruhil and Lobiyal, in [12], propose the use of Voronoi diagram or convex hull for finding a neighbor closest to the destination or having the most forward progress. These algorithms require at least one-hop neighbor location information, and hence introduce additional overhead of location updates or query.

2.2 Geocast for VANETs

The geocast algorithms and protocols discussed in this section are optimized for specific characteristics of VANETs, identified earlier.

Lochert, Hartenstein et al. [32] address the problem of radio obstacles in city affecting the performance of routing algorithms. They propose a routing approach, based on Greedy Perimeter Stateless Routing (GPSR) [33], that forwards a packet along the streets and junctions. Each node is assumed to know the map of the city streets and can compute the path, in terms of junctions, a packet has to traverse to reach the destination. The path can be included in the packet header, as in source routing, or it can be calculated by each forwarding node. Forwarding between junctions is done by greedy forwarding. A repair strategy to overcome network partitioning or obstacles based on perimeter-mode of GPSR is suggested, though it may cause routing loops. The performance of the proposed approach is shown to be better than non-position based routing protocols such as AODV and DSR.

In [34], Lochert, Mauve et al. present a routing approach that does not assume

[1] Refer [13] for more details

map information. Each node is assumed to know whether it is located in the area of a junction or not, and maintains a table of its neighbors. A packet is forwarded along a street towards the next junction using greedy routing. However, if there is a node among the neighbors which is located at a junction, called a coordinator, the packet is forwarded to that node. The coordinator then decides the street the packet should follow subsequently, by selecting a neighbor with largest progress towards the destination. To detect whether a node is at a junction, special beacon messages with information about all the neighbors are required. Alternatively, the correlation in the position of a node's neighbors can be used to detect presence of a junction. Both these approach require frequent updates of neighbor table since a vehicle may pass a junction very rapidly, and hence introduce considerable overhead.

Briesemeister, Schäfers and Hommel present, in [17], a completely distributed forwarding algorithm tailored for inter-vehicle communication. The forwarding algorithm achieves a restricted flooding by introducing a distance based backoff such that the backoff time is shorter for the more distant receivers. Thus, nodes at the border of the reception area participate in forwarding, reducing the number of hops and redundant transmissions. In [16], Briesemeister and Hommel modify this simple algorithm so that a node relays a packet only if it has a neighbor other than previous senders. With this modification the algorithm can potentially overcome temporary network fragmentation caused by sparse nodes. However, this requires maintenance of a neighbor table, an ability to detect new neighbor, and considerable state information like the list of all senders for each packet.

In a work close to ours, Bachir and Benslimane [18] propose a geocast for inter-vehicle communication based on [17, 16]. This approach does not require maintenance of neighbor tables, and instead of detection of new neighbors, it uses periodic broadcasts to overcome network fragmentation. The re-broadcast period is calculated based on the maximum vehicle speed such that a node upon entering the current relay's reception area should be able to get at least one broadcast before it crosses safe braking distance from the relay. It might be noted that this is necessary only in the case when the current relay is the origin of a safety message, and that a much larger delay can be tolerated when the current relay is far from the incident location. Nevertheless, it is shown through simulations that the re-broadcast period can be as much as 1.5 seconds without loss of reliability. Though we also use periodic broadcasts to overcome network fragmentation, we recognize two different reasons for broadcasts and accordingly introduce use of two different re-broadcast periods.

The algorithm proposed in this work is designed for a one-dimensional highway scenario and does not adapt well to a two-dimensional city street scenario.

Geocast region of upto a few kilometers may be covered by a message in less than a second [17], however the message reaches only those nodes that are currently in the geocast region. It may be useful, or even essential, for a message to be available to vehicles that enter the geocast region later. Maihöfer, Cseh, Franz and Eberhardt [35] propose three different approaches to a time stable geocast - a geocast that enables a message to persist for a certain period of time. In all of these approaches the message delivery is done either periodically or on notification of a new node entering the geocast region. In the server approach, the geocast message is unicasted to a fixed or mobile server which subsequently geocasts it to the destination region. This approach requires a dedicated infrastructure and a unicast protocol in addition to geocast. In the election approach, a node in the destination region is elected to store the messages. This approach does not require an infrastructure, but has the added overhead of electing a node to store geocast messages. In neighbor approach, each node stores the geocast messages and delivers to a new neighbor either by periodic broadcasts or on notification. In [36], Maihöfer, Leinmüller and Schoch present a numerical and analytical evaluation of these approaches for a random waypoint mobility model, and show that approaches with local message storage cause less network load. We propose two mechanisms using neighbor approach to achieve time-persistence in our work. One of the mechanism is similar to the simplistic broadcast be each node proposed in this work. The other mechanism is a more efficient one designed to reduce redundancy and is based on the inherent characteristics of our forwarding algorithm.

2.3 Summary

The simulation models used for performance evaluation of the routing algorithms, discussed above, differ considerably in their detail, complexity and scope. While majority of the general geocast protocols for MANETs are evaluated using a random waypoint mobility model, most of the protocols designed for IVC attempt to model vehicle traffic with varying degree of detail. The vehicle traffic simulators used range from unspecified, as in [18], to realistic and popular simulator CORSIM [2] in conjunction with real traffic data,

[2]Details of the vehicle traffic simulators mentioned here can be found in the Appendix

as used in [22]. Whereas [16] evaluates performance on a straight highway using simulation model based on SHIFT, [34, 32] evaluate performance using a traffic simulator developed by DaimlerChrysler AG on real city topology of Berlin streets.

In summary, we have outlined here works showing that flooding is an expensive technique for routing, that restricted flooding may be a better alternative to explicitly setup routes for high mobility as in VANETs. Then we summarized some of the early work on geocast and position-based unicast routing which can be easily adapted to geocast. Following this, we have discussed the works that specifically addressed the problem of geocast for IVC, including the geocast designed for cities, geocast designed for safety messages on highways, and approaches to make geocast persist in time.

Chapter 3

Distributed Robust Geocasting Protocol

In this chapter we present our algorithm for a completely distributed and robust geocasting protocol. We first identify some of the desired characteristics of a geocast protocol for VANETs. Then we define our design space and outline the assumptions about the underlying system on which our protocol is based. We then present the core algorithms of our protocol.

3.1 Desired Characteristics of Geocast Protocols for VANET

We have identified some of the applications of inter-vehicle communication in Section 1.1, and the characteristics that an IVC system should have to serve those applications. The routing protocol that forms part of the IVC system, and thus support the functionalities of the system, should have the following characteristics:

- *Reliability:* the routing protocol should reliably deliver the packet to the *expected recipients*, i.e., all the nodes that satisfy the specified geographic criteria, called the *zone of relevance* and defined in Section 3.2.

- *Low Delay:* the packet should be delivered to the expected recipients within the quality of service (QoS) specifications of the relevant application. For safety applications, an explicit route setup approach may result in unacceptable delays.

- *High Throughput:* the protocol should minimize blocking of the shared wireless medium by reducing the amount of transmissions. Frequent transmissions of control packets, as in explicit route setup approaches or maintenance of neighbor tables such as [12, 16, 34], should be avoided - as should be unrestricted flooding of entire network.

- *Robust Architecture:* the protocol should be robust enough to work in a highly mobile environment with frequent topology changes. The explicit route setup approaches may fail in this environment, as pointed out in [22]. The protocol should have a mechanism to overcome temporary fragmentation of the network frequently occurring in a VANET.

3.2 Architecture

The architecture for Distributed Robust Geocast (DRG) protocol designed for VANET with the characteristics identified in Section 3.1 is presented here. We have shown earlier that an explicit route setup approach may not be the best approach for extremely dynamic network like VANET. Hence, we propose to use a restricted, directed flooding approach for the design of our geocast protocol. Before proceeding further, we define certain terms that are used in subsequent discussions.

The *zone of relevance (ZOR)* is defined as the set of geographic criteria that a node must satisfy in order for the geocast message to be relevant to that node. This is similar to the "geocast region" or "multicast region" of [28], except that additional criteria, e.g., the direction of node movement, can be used to select among the nodes that are within a geographic area.

The *zone of forwarding (ZOF)* is defined as the set of geographic criteria that a node must satisfy in order to forward a geocast message. This is similar to the "forwarding region" of [28] and others, except that additional criteria, e.g., the direction of node movement, can be used to select among the nodes that are within a geographic area.

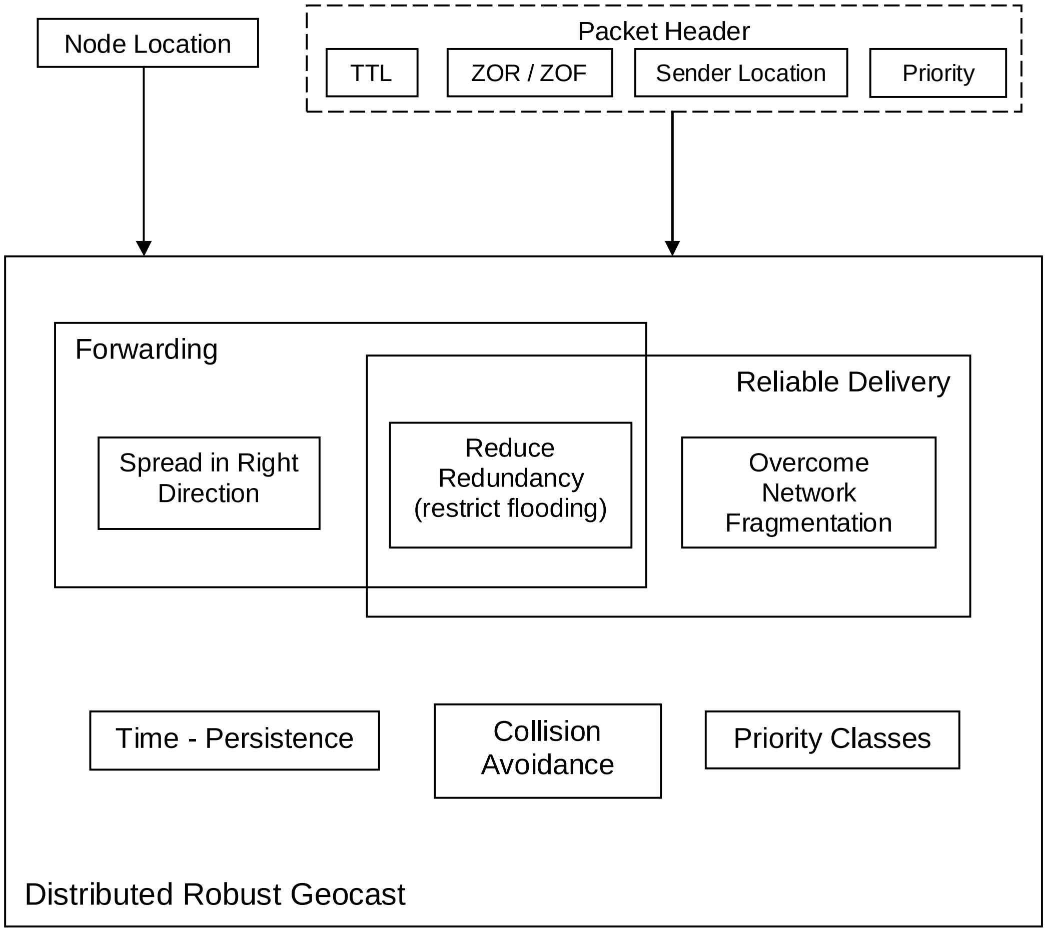


Figure 3.1: Architecture for Distributed Robust Geocast

We recognize that the geocast protocol has two main functions:

- *Forwarding* the message through zone of forwarding towards zone of relevance, and through zone of relevance such that the message travels towards the edges of zone of relevance, i.e., *spreading* the message in right directions.
- *Delivering* the message reliably to all the nodes within the zone of relevance.

These functions must be performed with the least amount of *redundancy*, by restricting flooding. The architecture of DRG is shown in Fig. 3.1

The information contained in geocast packet header regarding the sender location and the zone of relevance or zone of forwarding is used in conjunction with the node's current position to restrict flooding and reduce redundancy. A forwarding algorithm to restrict flooding with backoffs based on a node's distance from the last transmitter is discussed in Section 3.4. A mechanism to overcome network fragmentation frequently found in VANETs is outlined in Section 3.5. A criterion for reducing redundancy and at the same time ensuring spread of the geocast message in right directions is developed in Section 3.6. All of these algorithms are developed so that a node does not need to know its one-hop neighbors or to build multi-hop routes. The collision avoidance scheme and the support for priority classes are described in Sections 3.7 and 3.8, respectively.

3.3 Design Space

As we design the Distributed Robust Geocast protocol, certain underlying system and services are assumed to be available for support. These support services and systems are discussed below.

Like any other position based routing protocol, DRG requires a fairly accurate position information. The position information is assumed to be accurate enough as not to critically affect the performance of underlying position based routing algorithm. This is a reasonable assumption, since GPS receivers with accuracy within few meters are widely available and even deployed in many vehicles.

The application is assumed to be able to determine the location of the destination region or geocast region either independently or through the use of one of the location service described in [25]. For many of the applications it is reasonable to assume that the geocast region location can be determined independently. For example, a collision warning safety application may independently determine the geocast region as a rectangle extending 2 km behind the source node and 500 m on the sides.

Since we propose to use geographic addressing, the destination is identified by geographic criteria. However, this can be augmented by use of a unique node identifier. We propose to use a vehicle identification number (VIN) instead of an IP address as the node identifier. The VIN can also be used to identify a geocast message with the help of sequence number. The allocation of VIN is assumed to be done by some external agency.

We assume a medium access control (MAC) with a carrier sense multiple access (CSMA) mechanism, but without a collision detect (CD) capability. Such a MAC is in line with the expected use of either 802.11 or dedicated short range communications (DSRC) [37] standards for inter-vehicle communications. Since we propose to use only broadcasts at the data link layer (DLL), we do not need a mechanism to map MAC addresses to the network layer addresses. However, when we use an explicit route setup approach for performance comparison, we assume that the mapping of MAC address to network layer address is known to every node. In other words, we do not use a mechanism like address resolution protocol (ARP) in our simulations for performance evaluation. The hidden nodes problem is assumed to be handled by a request-to-send/clear-to-send (RTS/CTS) mechanism when link layer unicasts are used. However, for link layer broadcasts the system suffers both hidden and exposed nodes problem.

Before we discuss the physical model we need to define certain terms:

A *coverage disk* is the disk with the transmitting node at the center and the transmission range as the radius. Coverage disk is associated with the disk model of radio transmission.

The *coverage area* or *reception area* is the area around the transmitting node within which all the nodes are supposed to receive fraction of transmitted packets above a threshold value. The coverage area need not be circular. Coverage area assumes a more realistic model of radio transmission with fading, pathloss and radio obstacles. If the coverage area is circular and the threshold is 1, it is equivalent to the coverage disk.

We assume a physical model that allows for a symmetrical radio reception, i.e., if node A can receive a transmission from node B with probability x, the reverse is also true. This does not mean that we assume a disk model of radio transmission. The assumption only means that if node A is within node B's coverage area, then node B is also within node A's coverage area. The symmetrical radio model can work even in city environment, where the coverage area is not circular but can be approximated to be elongated along the streets.

We use real time as the time-to-live (TTL) value, instead of using a count hop. We assume that all the nodes in the network have accurate timing information available, and that all the nodes are synchronized. Since GPS are expected to be used, the timing information and synchronization are readily available.

3.4 Forwarding Algorithm

It has been shown that simple flooding causes redundant transmissions [26] resulting in significant contention and collisions. However, the redundancy can be reduced by selecting as relay only those nodes with the most forward progress towards the destination. An algorithm to select a node with the most forward progress has been proposed by Stojmenovic et al. [12], although the algorithm requires maintenance of neighbor table with position of each neighbor. However, a completely distributed algorithm can be used to select the relay node using a backoff scheme that favors the nodes at the edge of the transmission range. On receiving a message, each node schedules a transmission of the message after a distance-based backoff time. Any node that loses the backoff contention to a node closer to the destination cancels the transmission. If each node waits for a time inversely proportional to its distance from the last sender before retransmitting, the farthest node will be the first to transmit winning the contention. We propose the following distance-based backoff time:

$$BO_d(R_{tx}, d) = MaxBO_d \cdot S_d \left(\frac{R_{tx} - d}{R_{tx}} \right), \tag{3.1}$$

where BO_d is the backoff time depending on the distance from the previous transmitter, $MaxBO_d$ is the maximum backoff time allowed, S_d is the distance sensitivity factor used to fine tune the backoff time, R_{tx} is the nominal transmission range, and d is the distance of the current node from the last transmitter. Details on selecting a value for $MaxBO_d$ are given in Section 3.5.2. The proposed formula for backoff time is similar to that of [17], except that we introduce the distance sensitivity factor S_d to adjust the backoff time.

Consider the simple straight road scenario shown in Fig. 3.2. Assume that node B generates a message to be delivered to vehicles 2 km behind it. The shaded region on the road shows the zone of relevance. The dotted circles with a radius of nominal transmission range R_{tx}, is an approximation of the edge of the *coverage area* of respective nodes. The transmission from B is received by nodes A, C and D. Since node A is not in the zone of relevance, the message is ignored. Among nodes C and D, since node D has the most forward progress it should relay the message. With the backoff time proposed in (3.1), the node closest to the edge of coverage area (i.e., node D) indeed transmits the message first. Node C cancels its scheduled transmission on receiving a transmission from node D. The message spreads towards the destination in this fashion when node G wins the contention and becomes the relay as the node at the edge of coverage area. Now, if due to

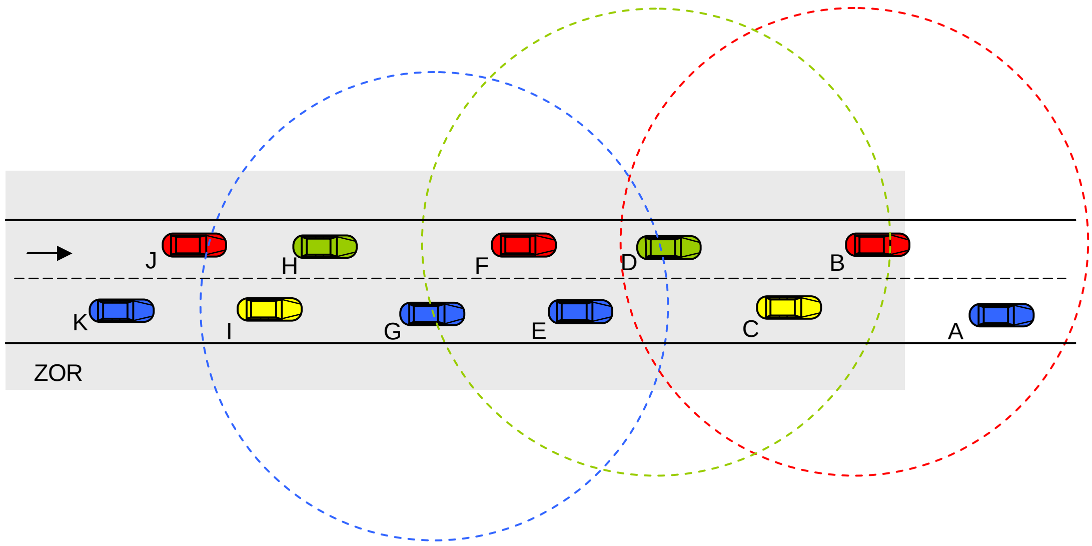


Figure 3.2: A straight road scenario with distance-based backoff

uncertainties inherent in wireless communication the node at the edge of the coverage area does not receive a packet, the node with next most progress will win the contention and become the relay. In Fig. 3.2, if node J does not receive the message from G, then node I will turnout to have the lowest backoff and will relay the message.

We have shown that the algorithm does not depend on a disk model of radio propagation to ensure selection of a node with most progress as the relay. However, a fairly accurate estimation of nominal transmission range is required if (3.1) is used for backoff calculation. If the nominal transmission range R_{tx} value is chosen too small, nodes with distance more than R_{tx} will calculate a negative backoff. If the negative backoff is substituted with a zero backoff, the transmissions from nodes with $d \geq R_{tx}$ will collide. If the chosen value for R_{tx} is too large, even the nodes at the edge of coverage area will have to wait for a long time before retransmitting, causing inefficiencies.

Note that the backoff algorithm favors nodes with distance close to R_{tx}, and that the value of R_{tx} is closely related to average hop distance and number of hops. We show in Section 3.6.1 that when two nodes are close they cover more of the each other's coverage area increasing the probability of other nodes within that area receiving the packet. Thus, the value of R_{tx} also affects the reliability of the network layer. Hence, we modify (3.1)

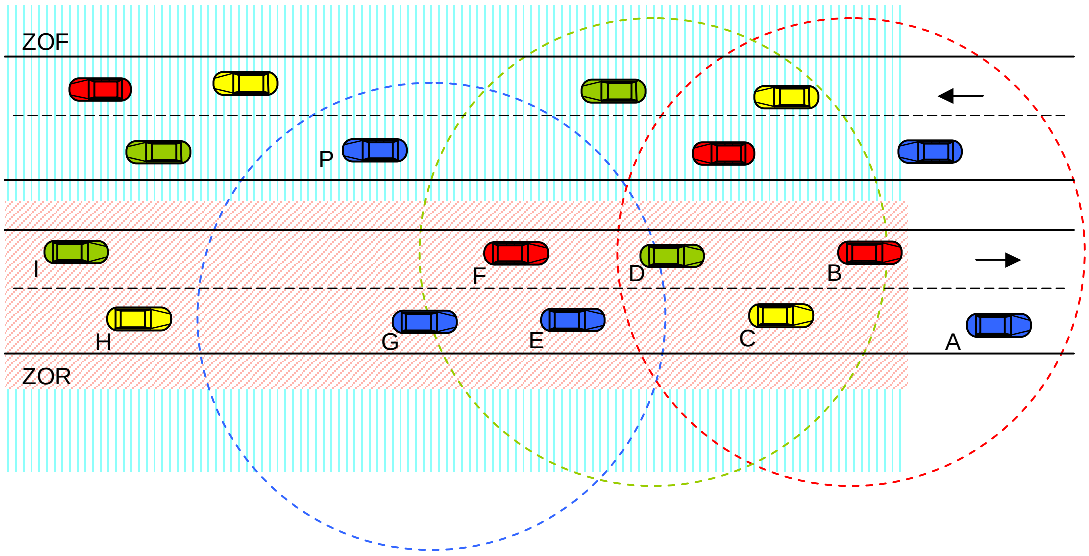


Figure 3.3: A temporarily fragmented vehicular network

such that the nodes closer to the desired retransmission distance (or average hop distance) R_D will be preferred:

$$BO_d(R_D, d) = MaxBO_d \cdot S_d \left| \frac{R_D - d}{R_D} \right| \tag{3.2}$$

The value of R_D selected would be a tradeoff between the efficiency of protocol and the reliability. It might be more useful to use this backoff time formula only in the zone of relevance, as in the zone of forwarding it is sufficient to forward the message with least number of transmissions regardless of delivery to all nodes.

The distance-based backoff can not completely prevent collisions caused by nodes located at similar distances (e.g., on a multi-lane road). A collision avoidance mechanism is described in Section 3.7.

3.5 Overcoming Network Fragmentation

It has been shown by Blum, et al. [22] that a VANET is prone to frequent network fragmentation, even though it may be temporary. Hence, the geocast protocol must have a mechanism to overcome network fragmentation in order to have a robust performance in an environment of sparse vehicle distribution. We identify three approaches to overcome network fragmentation: (a) periodic retransmissions (b) new neighbor approach, and (c) the vehicle as message ferry. Each of these approaches are discussed below.

3.5.1 New Neighbor Approach

This approach was proposed by Briesemeister et al. [16]. Each node maintains a list of neighboring nodes, and another list of senders for each geocast message. Whenever a node receives a geocast message, it notes the sender's identity against the sender list. If there are neighbors in the neighbor list that are not present in the sender list, the node sends the message to those neighbors. In case of a temporary network fragmentation, as shown in Fig. 3.3, when node H enters within the transmission range of node G, it is detected. On detecting the new neighbor H, node G sends the geocast message to H.

This approach requires maintenance of state information like the neighbor list and the sender list. It also requires a mechanism to detect a new neighbor. This can be done using "hello" messages, which cause additional overhead. The approach as described in [16] is also prone to redundant transmissions when the new neighbors already have the geocast message. For example, suppose the nodes G and C in Fig. 3.3 come within each other's transmission range some time after both of them having received the geocast message separately. They will detect their new neighbors and send the geocast message again. This can be avoided by including a list of geocast message received in the hello message header. However, it will further add to the overhead and reduce the advantage of difference in size between hello packet and data packet. A permanent or long term fragmentation can not be bridged using this approach.

3.5.2 Periodic Retransmissions

Periodic retransmissions can be used to overcome a temporary network fragmentation. The last node on the edge of network fragmentation periodically retransmits the message. When the network gets repaired, the message is delivered to the other part of the network and again the backoff based forwarding algorithm selects the next relay. This approach, proposed in [18], does not require maintenance of state information and is completely distributed. The details of the modification to the forwarding algorithm to implement this approach is described below.

After transmitting the geocast message, the relay node schedules a retransmission of the message with the maximum backoff time $MaxBO_d$. In terms of Fig. 3.3, after node B transmits the message at time t, it also schedules the message for retransmission at time $t + MaxBO_d$. Thus, node B also enters the contention for the next transmission of the message, with the least preference for getting selected. When the node near the edge of coverage area, i.e., node D, wins the contention and transmits the message, both node C and node B cancel their transmissions treating the transmission from D as an *implicit acknowledgement* of the message being forwarded. However, near a network fragmentation when a node, e.g., node G, does not get an implicit acknowledgement it goes ahead with the retransmission and again schedules another retransmission after $MaxBO_d$. This sequence of retransmission continues until a node, e.g., node H, enters the coverage area of node G and wins the contention providing implicit acknowledgement to G. The network fragmentation may turn out to be a long term or permanent division, in which case the retransmissions stop when the time-to-live (TTL) expires for the message. The periodic retransmissions also increase the reliability of the protocol since wireless communication is notoriously error prone, and the original transmission or the acknowledgement can be lost.

Since the maximum backoff time $MaxBO_d$ is used for scheduling retransmissions, its minimum value should be at least the round trip time for the packet to the farthest node in the coverage area.

$$
\begin{aligned}
MaxBO_d &\geq 2 \times (\text{maximum end-to-end delay}) && (3.3)\\
&\geq 2 \times (\text{max (transmission + propagation + processing) time}) && (3.4)
\end{aligned}
$$

Thus, for given maximum packet length, bit rate and maximum distance between neighbors, we can calculate the minimum bound for $MaxBO_d$. Selecting a value higher than this bound will result in unnecessarily longer delays. Hence, the equality in (3.4) gives the value for maximum backoff time $MaxBO_d$.

We show later in Chapter 4 that typical values for $MaxBO_d$ are of the order of milliseconds. However, it takes much longer for vehicles to cover significant distances. Hence, in case of a temporary network fragmentation, quite a large number of redundant retransmissions may be made before the network is actually repaired. Hence we propose a modification to this periodic retransmission mechanism by introducing a *long backoff* ($LongBO_d$) time after a certain number of retransmissions, denoted *maximum retransmis-*

sions ($MaxReTx$). A few retransmissions at short duration are needed to make sure that the absence of implicit acknowledgement is not due to transmission losses. However, after a few retransmissions it can be safely assumed that an implicit acknowledgement is not received due to network fragmentation. Hence, the next retransmission can be scheduled after a comparatively longer period $LongBO_d$, which allows time for the network to get repaired. However, the value of $LongBO_d$ can not be too large if the end-to-end delay in packet delivery is to be minimized. The selection of value for $LongBO_d$ is a trade-off between redundant transmissions and end-to-end delays. The maximum value of long backoff, $MaxLongBO_d$, should be the time it takes a vehicle to reach the relay node after it enters the coverage area. This limit is necessary in case the relay node is the node that is involved in an accident. Thus,

$$MaxLongBO_d = \frac{R_{tx}}{V_{max}}, \tag{3.5}$$

where, R_{tx} is the nominal transmission range, and V_{max} is the maximum velocity of the vehicles.

3.5.3 Vehicle as Message Ferry

The characteristic node mobility in VANET can be used to overcome network fragmentation by using vehicles moving in the opposite direction to bridge the gap in the network. For example, in Fig. 3.3 the direction of vehicle movement, zone of relevance and zone of forwarding for the geocast message are shown. The geocast message is relevant only for the vehicles moving from left to right. However, the zone of forwarding is defined to also include vehicles moving in the other direction. In Fig. 3.3, since node P is moving towards node H, it is likely to come within the coverage area of node P sooner. Thus, P can deliver the message to node H even when the mobility characteristics cause the network of cars moving in same direction to be fragmented for a long time. For actual delivery of the message, either the new neighbor approach or the periodic retransmission approach can be used.

By using vehicle as a message ferry, even a fairly long term or permanent fragmentation in network of vehicles moving in the same direction can be bridged. However, this approach requires the use of one of the two approaches outlined earlier for actual delivery of the message to the next network fragment. Hence, it suffers from most of the disadvantages the earlier approaches had. If it is used with new neighbor approach, faster

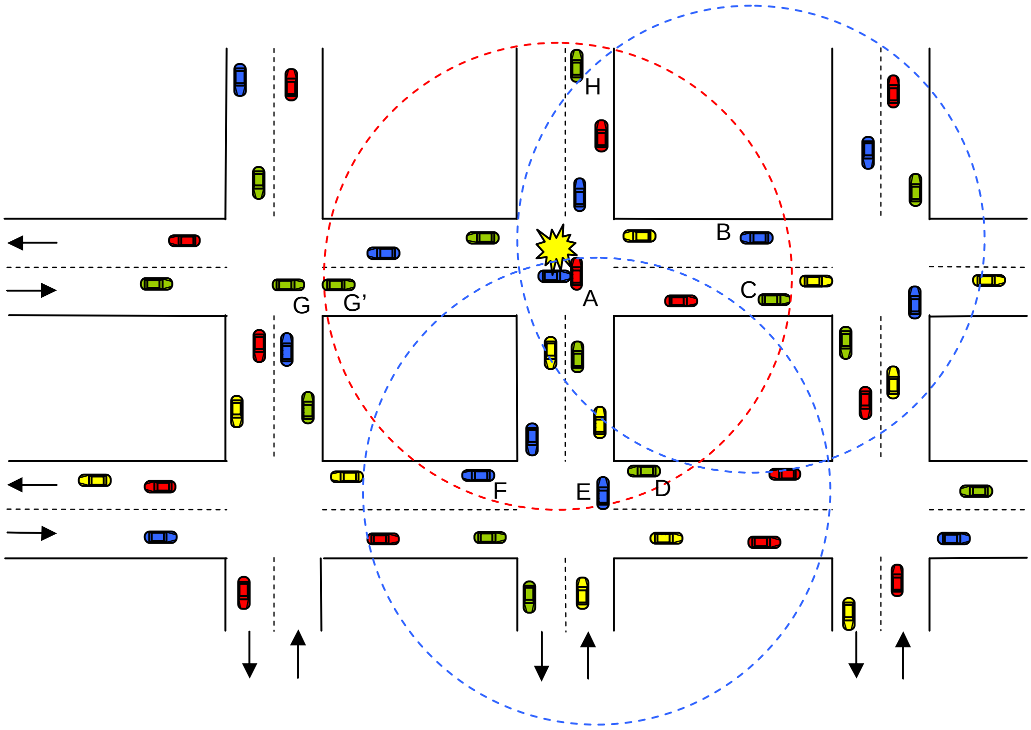


Figure 3.4: A two-dimensional city street scenario

updates of neighbor list and sender list is required. If used with periodic retransmissions, it may cause some redundant retransmissions when network is not fragmented. Since we use the concept of a zone of relevance and zone of forwarding instead of geocast region and forwarding region, the vehicles moving in opposite direction can be easily used as message ferry by changing the geographic criteria of zone of forwarding.

3.6 Spreading and Implicit Acknowledgement

A node receiving a geocast message may retransmit the message with the objectives of spreading or delivering the message, as noted in Section 3.2. In [16, 17, 18] a one-dimensional road is assumed with corresponding one-dimensional zone of relevance. The distance-based backoff algorithm proposed is designed for spreading and delivering of the message in such a scenario. However, those algorithms fail to consider the problems of implicit acknowledgement and flooding in a more realistic two-dimensional scenario.

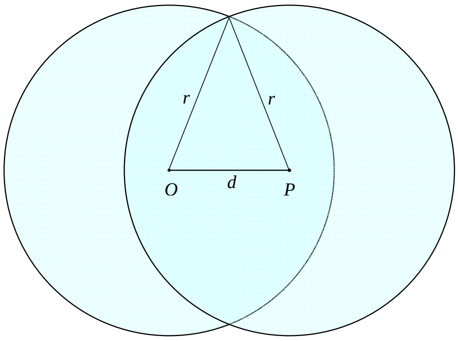
Consider a two-dimensional scenario shown in Fig. 3.4, set on a city street network. Node A generates a geocast message to warn about the crash, with a zone of relevance and zone of forwarding restricted to the vehicles moving towards A and covering the entire region shown in the figure. If node A treats the transmission from node E and/or node B as an implicit acknowledgement, it may fail to ensure the spread of the message in all directions since the network is fragmented towards left where node G is just outside coverage area of A. However, if node A continues to retransmit, G eventually comes within the coverage area and the fragmentation can be overcome. Thus, we need a criterion for implicit acknowledgement that will make the forwarding algorithm robust to temporary network fragmentation, but that, at the same time, will reduce redundant transmissions.

In a two dimensional scenario, the distance-based backoff prefers the nodes towards the edge of the "transmission range" to take on the role of a relay. However, to spread the message throughout the two-dimensional zone of relevance the relay nodes should be selected such that they are best positioned to cover substantially new regions of the zone of relevance. A node should continue to retransmit a message until it receives an implicit acknowledgement from other relay nodes such that the message has a high probability of spreading as well as delivering. At the same time, the number of retransmissions should be minimized to reduce contention with other transmissions. If the current node receives the same message from relays that cover a major portion of its own coverage area, there is a high probability that other nodes in the coverage area would have received the message from either the current node or one of the relays. The ratio of the area of overlap of coverage area or coverage disk of two nodes with respect to their average coverage area is called *coverage ratio*. If the relays have a small angular distance among themselves with respect to the current node, the probability of spreading the message is low. Hence, the angular distance and the coverage ratio of the relays should be greater than certain thresholds to ensure spreading and flooding of the message. Let us call these thresholds the *angular threshold* and the *coverage ratio threshold* respectively.

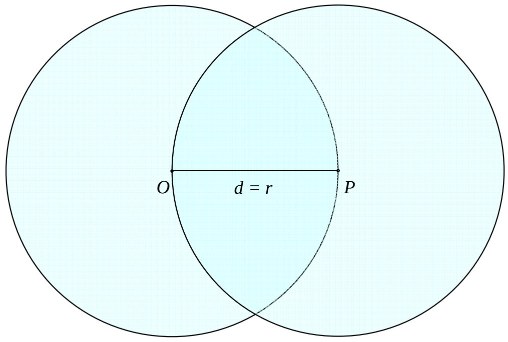
We will next show that there should be a ceiling on the coverage ratio threshold.

3.6.1 Area of Overlap of Coverage Disks of Two Nodes

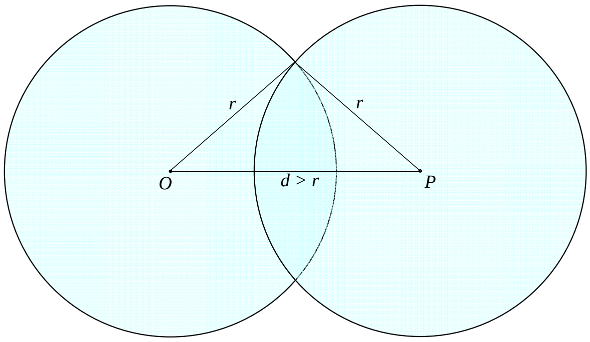
For the purpose of this section we assume a disk model of radio transmission range, where all the nodes within a certain distance from the transmitter receive all the packets and all the nodes with more than that distance from transmitter do not receive any packets. We will show later that the results we obtain with this assumption can be used even when the assumption is not true.



(a) Two nodes at a distance less than transmission range



(b) Two nodes at a distance equal to transmission range



(c) Two nodes at a distance greater than transmission range

Figure 3.5: Various cases of overlap of Transmission Ranges of two Nodes

Let all the nodes have a transmission range r. Let node O be the transmitter. We assume that if a node is within the coverage disk of O (i.e., a disk with O as the center and radius r) it can receive the signal, while if it is outside the disk it cannot receive the signal. Figure 3.5 shows various cases of two nodes O and P, and the overlap of their coverage disks for various distances d. The area of overlap of coverage disks of two nodes, or the coverage ratio, is inversely related to the distance d between the nodes. As the distance increases, the coverage ratio decreases and vice versa. The coverage ratio is minimum (or zero) when $d \geq 2r$, and is maximum (or 1) when $d = 0$. Please note that when $d > r$, as shown in Fig. 3.5 (c), the two nodes cannot receive transmissions of each other.

We are interested in finding the area of overlap of coverage disks of two nodes

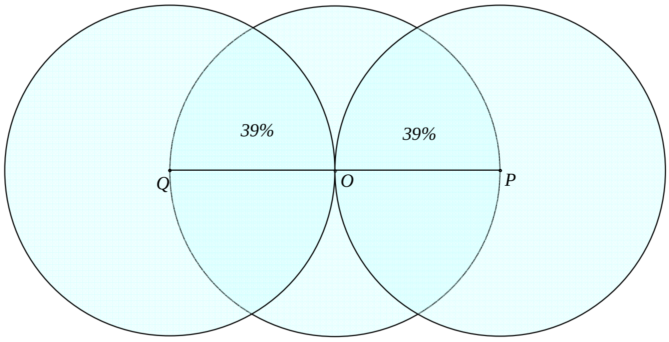


Figure 3.6: Two nodes on the edge of center node's transmission range

when $d \leq r$, i.e., when they are within each other's transmission range. We can see that this area is minimum when $d = r$, and maximum (equal to the area of the disk) when $d = 0$. Hence, the minimum area of overlap of two node's coverage disk when they are within each other's transmission range is found using equation (A.20) substituting d by r.

$$A_{intersection} = 2r^2 \arccos\left(\frac{1}{2}\right) - \frac{\sqrt{3}}{2}r^2 \tag{3.6}$$

$$= \frac{2\pi r^2}{3} - \frac{\sqrt{3}}{2}r^2 \tag{3.7}$$

The area of coverage disk is,

$$A_{disk} = \pi r^2 \tag{3.8}$$

The area of overlap of coverage disk, as a fraction of coverage area is given as,

$$P_{overlap} = \frac{A_{intersection}}{A_{disk}} \tag{3.9}$$

$$= \frac{2}{3} - \frac{\sqrt{3}}{2\pi} \tag{3.10}$$

$$\approx 0.391 \tag{3.11}$$

3.6.2 Ceiling on Coverage Ratio Threshold

A scenario for geocast on a straight road is shown in Fig. 3.6. Let Q, O and P be nodes moving along a straight road in the same direction. If node Q transmits a packet, the

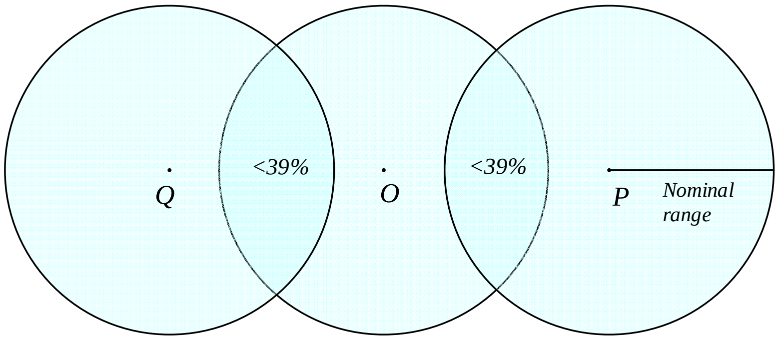


Figure 3.7: Three nodes with their nominal transmission ranges

distance-based backoff algorithm will ensure that node O becomes the relay and forwards the packet. The packet transmitted by O would be further relayed by node P, irrespective of the number of nodes between O and P. The relay by P will also be received by node O. Substantial portion of the coverage disk of O is covered by the transmissions of nodes P and Q, thus flooding the disk. The relay by P should be treated as an implicit acknowledgement, stopping retransmissions by O as the message can be considered to be spreading through zone of relevance as desired.

From equation (3.11) we know that nodes Q and P cover approximately 78% of node O's coverage area. If relay nodes Q and P were any closer to node O than shown, the coverage ratio would be higher than 78%. However on a straight road with very high density of nodes, there is a high probability that the relay nodes would be as shown in Fig. 3.6. If the coverage ratio threshold is higher than 78%, node O will keep on retransmitting the message without any gain in spreading or flooding of the message. To avoid this scenario, the coverage ratio threshold should not be more than 78%:

$$x \leq 0.78 \tag{3.12}$$

3.6.3 Angle as a Proxy for Coverage Ratio

At the beginning of this section we had assumed a circular disk model for radio transmission range. This model is not very realistic as it does not take into account factors such as fading, path loss, interference, radio obstacles, etc. However, it is very difficult to estimate the coverage area using the complex but more realistic radio model. In reality,

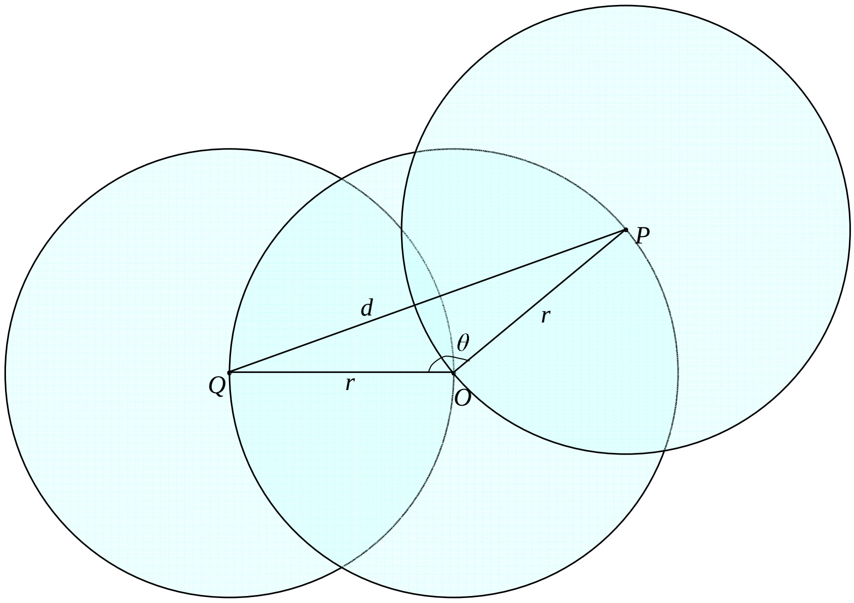


Figure 3.8: Two nodes on the edge of center node's transmission range, forming an angle θ at the center node

a node outside nominal transmission range may receive a packet while a node within the nominal range may not receive it. Such a case is shown in Fig. 3.7. Both nodes Q and P receive packets from node O, and vice versa, even though they are outside O's nominal transmission range. In such a case, the coverage ratio calculated using coverage disks with nominal transmission range would be less than 78% even though the relay nodes are quite well positioned for spreading the message.

Thus, even if we assume the disk model, our coverage ratio calculation may give less than ideal results. The success of coverage ratio criterion depends on very accurate estimation of actual transmission range. Not only is this difficult, the actual transmission range may change with time, and may not be circular in shape.

To overcome these difficulties we propose to use an angle based criterion for forwarding decision as a proxy for coverage ratio. We look at the angle the other relay nodes make at the current node and map that onto a minimum coverage ratio. For example, 180^o is mapped to a minimum 78% coverage ratio - if the two relay nodes make 180^o with the center node they will cover at least 78% of the center node's coverage area.

Let us consider a more general case shown in Fig. 3.8. Nodes P and Q make an angle θ with the center node O. Let our desired coverage ratio threshold be x. What should be the minimum value of θ for the minimum coverage ratio to be more than the threshold x. We need to find an angle θ such that the area of intersection of disks P and Q should not be more than $(0.78 - x)$, i.e.,

$$A_{P\cap Q} \leq (0.78 - x)A_{disk} \tag{3.13}$$

$$A_{P\cap Q} = 2r^2 \arccos\left(\frac{d}{2r}\right) - \frac{d}{2}\sqrt{4r^2 - d^2} \tag{3.14}$$

where d is the distance between nodes P and Q.

Without loss of generality, we can assume the disks to be unit circles, or the transmission range r to be 1. Thus, equation (3.13) becomes,

$$2\arccos\left(\frac{d}{2}\right) - \frac{d}{2}\sqrt{4 - d^2} \leq (0.78 - x)\pi \tag{3.15}$$

where $0 < d \leq 2$.

Now, from the Fig. 3.8 we can see that the distance d and angle θ are related by these equations,

$$d = 2r\sin\left(\frac{\theta}{2}\right) \tag{3.16}$$

$$\theta = 2\arcsin\left(\frac{d}{2r}\right) \tag{3.17}$$

Thus, from equations (3.15) and (3.17) we can find a value of θ such that the minimum coverage ratio is above the coverage ratio threshold. Once, this value of θ is found, it is used in place of the coverage ratio threshold in the geocast protocol. The calculation of θ is one-time, and significantly reduces the complexity of calculating coverage ratio by each node by replacing it with simple calculation of angle between three nodes.

We propose to use the angle θ_{min} as a threshold for accepting a packet as an acknowledged and to stop retransmissions. Thus, when a node receives a message from two other nodes that make an angle $\theta \geq \theta_{min}$, the message will be considered to be acknowledged and spreading in desired direction and it will be recognized that a retransmission will not significantly add to the coverage, and hence all retransmissions of that message will be canceled.

3.7 Collision Avoidance

While the distance-based backoff mechanism manages to relieve contention in a network with fairly sparse node distribution, in a dense network there might be collisions caused by nodes being located at similar distances from the sender. This scenario can be easily visualized in a traffic congestion, a traffic signal or a parking lot. Hence, there is a need to have a mechanism to avoid collisions between transmissions of nodes that have distance-based backoff time close to each other's. To reduce the probability of collisions we propose a collision avoidance scheme:

$$BO_r(CW) = rand(CW_{min}, CW_{max}), \tag{3.18}$$

where, BO_r is the random component of backoff time, CW_{min}, CW_{max} are the minimum and maximum collision window respectively, and $rand(a, b)$ is a function that generates a random number uniformly distributed between a and b. We determine the optimal value for the parameters in (3.18) through simulations in Chapter 4.

3.8 Priority Classes

In Section 1.1 we have identified various applications of geocast in inter-vehicle communication. It is expected that the requirements of various applications from the network layer would be different. The safety applications may demand real-time service with extremely low delays, while traffic monitoring applications may not be affected much by delays but may require higher throughput. Hence, we propose to build priority classes for geocast messages and maintain separate queues for each class with associated backoff given by:

$$BO_p(p) = S_p \cdot p, \tag{3.19}$$

where, BO_p is the priority term in the backoff time, S_p is the delay increase due to reduced priority, and p is the priority of the packet and can be zero or positive. The lower the value of p, higher is the priority of the packet.

3.9 Time-Persistence

In Chapter 2, we have discussed the work by Maihöfer et al. [35] where three approaches to providing a time stable or persistent geocast are discussed. We reject the server approach as it requires a fixed infrastructure, and the election approach as it introduces election overhead. The neighbor approach is the best suited for our completely distributed approach to geocast algorithm. We propose two approaches towards achieving a time persistent geocast: (a) periodic rebroadcast (flooding) and (b) periodic geocast. Both these approaches are discussed below.

3.9.1 Periodic Rebroadcast

In this approach, as implied in [35], each node sets a persistence timer on receiving a new geocast message. At the expiry of the timer, the message is simply broadcasted without any expectation for implicit acknowledgement. This approach effectively results in flooding the zone of relevance periodically. The advantage of this approach is that it is very simple.

3.9.2 Periodic Geocast

We propose this approach of periodic geocast from one or more nodes to the rest of zone of relevance using the distance-based backoff forwarding algorithm of Section 3.4. Since, the forwarding algorithm reduces redundant transmissions, this approach may result in more efficient delivery of the message if the total hops in ZOF and ZOR is less than the total number of nodes in the ZOR.

The choice of angle criterion for implicit acknowledgement and the normal rectangle shape of the zone of relevance may result in the node or nodes at the edge of the ZOR/ZOF never receiving an implicit acknowledgement. Hence, these nodes continue to retransmit according to the scheme given in Section 3.5.2. Since the remaining nodes have received an implicit acknowledgement for this message, they simply ignore the retransmissions. However, if the information about received acknowledgements is removed periodically, then the other nodes will treat the retransmissions as a fresh geocast message and forward it accordingly.

3.9.3 Efficient Periodic Rebroadcast

The periodic rebroadcast approach suggested in 3.9.1 is simplistic and naive. Since periodic broadcast by all the nodes within the ZOR constitutes unrestricted flooding of the ZOR, the approach has all the inefficiencies and redundancy associated with flooding. We propose a simple modification to reduce the redundancy. Each node sets a persistence timer on receiving a new geocast message. However, upon the expiration of the timer, only those nodes that have not received a transmission of that message recently, i.e., within recent time threshold for persistence T_{R_p}, broadcast the message. To determine the value of T_{R_p}, we propose the following formula:

$$T_{R_p} = \epsilon \frac{R_{tx}}{V_{max}} + rand(CW_{min}, CW_{max}), \tag{3.20}$$

where, ϵ is the sensitivity factor, R_{tx} is the nominal transmission range, V_{max} is the maximum velocity of the vehicles, CW_{min} and CW_{max} are the minimum and maximum collision window respectively, and $rand(a, b)$ is a function that generates a random number uniformly distributed between a and b.

Thus, with proper values of , R_{tx} and V_{max}, a new node entering the ZOR can be expected to receive a transmission of the geocast message $1/\epsilon$ times before it reaches one hop distance into the ZOR.

3.10 Summary

A finite state machine for the Distributed Robust Geocast is shown in Fig. 3.9. On receiving a packet a node examines the geocast header and checks if it belongs to either the ZOR or the ZOF. If not, the node just discards the packet. If the message has been received for the first time and the node is in ZOR, the message is pushed up to the higher layer and its source VIN and packet sequence number are recorded in a $UniqueMessageBuffer$. The message is scheduled for transmission after a backoff time that includes the distance, collision avoidance, and priority components. A persistence timer is also started. If an implicit acknowledgement is received before the scheduled transmission time, the transmission is canceled. At the time of transmission of the message, a retransmission is scheduled after the maximum backoff time $MaxBO$.

The message is regularly retransmitted at maximum backoff time, and the number of retransmissions are counted. When the number of retransmissions reach the maximum retransmissions $MaxReTx$, the retransmission counter is reset and the next retransmission is scheduled after the long backoff time $LongBO$. Each received packet's message ID is recorded along with the sender's VIN and position in a $RecentMessageBuffer$. This

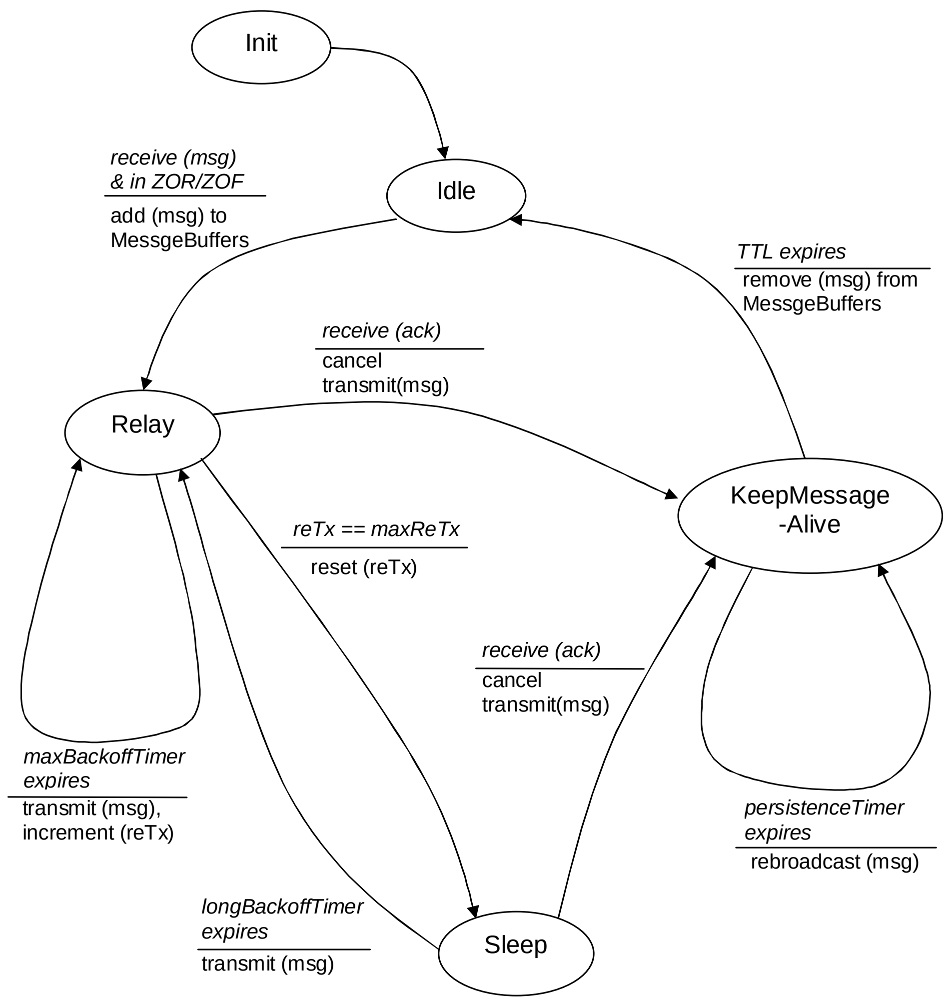


Figure 3.9: Finite state machine for distributed robust geocast

buffer is used to determine when a message is acknowledged using the criterion developed in Section 3.6. Once a message has been acknowledged, it is marked as such in the $UniqueMessageBuffer$, and future receptions of the message are ignored. At the expiry of persistence timer, a node just transmits the message once, without expecting an acknowledgement. A message is discarded if it's time-to-live has expired, any scheduled transmissions are canceled and the message details are dropped from the $UniqueMessageBuffer$ and $RecentMessageBuffer$.

Chapter 4

Performance Evaluation

In this chapter, we evaluate the performance of Distributed Robust Geocast (DRG) discussed earlier. The simulation models used for network and vehicle traffic simulation are discussed in the section on simulation environment. The values of some of the parameters of DRG are selected for a typical scenario. Then the performance is evaluated for a collision warning application on both highway and city scenarios. The performance for traffic monitoring is evaluated next in city scenario. The protocols used for comparison of performance of DRG are discussed first along with the metrics used for measuring performance.

4.1 Protocols for Comparison

4.1.1 Flooding

We use simple flooding as the most simple algorithm to compare performance of our algorithm. In a simple flooding each node on receiving a new message rebroadcasts it once. In our implementation of flooding for geocast, we use zone of relevance to restrict the flooding to the relevant nodes. We also use a collision avoidance scheme based on random slot based backoff to avoid collisions caused by all receiving nodes rebroadcasting simultaneously. On receiving a new message each node selects a contention window CW

using:

$$CW = rand(0, CW_{max}) \cdot S_t, \tag{4.1}$$

where, CW_{max} is the maximum number of slots for the contention window, S_t is the fixed slot time, and $rand(a, b)$ is a function that generates a random number uniformly distributed between a and b. The values of CW_{max} and S_t are selected through simulations on a typical scenario.

4.1.2 ROVER

A more complex protocol, robust vehicular routing (ROVER) [38], is used as a representative of the explicit route setup approach for performance comparison. ROVER is a reactive protocol, based on AODV, that floods the control packets but not the data packets. The data packets are unicast, potentially increasing efficiency and reliability. The objective of ROVER is to build a multicast tree from the source vehicle to all the vehicles within the zone of relevance. The route request, RREQ, is flooded in the entire ZOR and ZOF. Each node within the ZOR replies to the RREQ by unicasting route reply, RREP, message to the node from which it first heard the RREQ. Unlike AODV, the RREP messages are not sent back to the source, but are used to build the local route tree. Once the multicast tree is built the data packets are disseminated down the tree.

For traffic monitoring application we define two more performance metric. These are discussed in Section 4.4.

4.2 Simulation Environment

We use the network simulator SWANS based on the simulation engine JiST [19], along with the STRAW [20] module for evaluating our protocols. JiST/SWANS is a wireless simulator, similar to ns-2 and GloMoSim, capable of simulating large networks. SWANS has radio propagation models including disk model (i.e. no fading) and Rayleigh fading. It has an IEEE 802.11 module for MAC layer. The network layer is based on IPv4, and routing implementations for AODV, DSR and ZRP. Both UDP and TCP implementations for transport layer are available.

STRAW is a mobility model for vehicles on city streets. STRAW uses map data for real cities from the Topologically Integrated Geographic Encoding and Referencing (TIGER) system available from the US Census Bureau Geography [39]. STRAW uses a car-following model to model mobility of vehicles within a road segment. Vehicles encounter stop signs or traffic signals depending on the class of the road; the timings of traffic signals are also controlled based on the road class. An admission control mechanism, based on the room on the next road segment, is used to model mobility at an intersection. The vehicle route planning can be done by specifying an origin-destination pair, or vehicles can move randomly by selecting a random direction at an intersection. Since, SWANS and STRAW are academic projects, far from fully developed and functional simulators, we made several modifications and additions for our simulations. The most important ones are discussed below.

4.2.1 Lane Changing Model

Since, the version of STRAW that we used only had a car following model without lane changing behavior, on a multi-lane road a vehicle would slow down or stop if the vehicle in front does so, even when there would be empty adjacent lanes. This caused an unrealistic mobility pattern for multi-lane roads. Hence we implemented a lane changing behavior based on a model proposed by Kesting et al. [21]. The model, minimizing overall breaking decelerations induced by lane changes (MOBIL), proposes that a vehicle changes lanes when:

- the potential new target lane is more attractive, i.e., the “incentive criterion” is satisfied, and
- the change can be performed safely, i.e., the “safety criterion” is satisfied.

The safety criterion is satisfied, if the braking deceleration acc' imposed on the back vehicle B' of the target lane after a possible change does not exceed a certain limit b_{safe}, this means, the safety criterion

$$acc'(B') > -b_{safe}, \tag{4.2}$$

is satisfied. Here, $acc'(B')$ is the acceleration of the back vehicle on the target lane after a possible change.

To asses the incentive criterion, the self advantage on the target lane, measured by the increased acceleration (or reduced braking deceleration), is weighed against the disadvantage imposed to other drivers, again measured by the decreased acceleration or increased braking deceleration for these drivers. The disadvantage imposed on other drivers are weighed with a politeness factor p whose values are typically less than 1, resulting in following incentive criterion:

$$acc'(M') - acc(M) > p\left(acc(B) + acc(B') - acc'(B) - acc'(B')\right) + a_{thr}, \qquad (4.3)$$

where, acc is the actual acceleration of a vehicle, acc' is the acceleration after a potential lane change, M is the vehicle considering lane change before the change and M' is the vehicle after the change, while B and B' are the back vehicles before and after the potential change respectively, and a_{thr} is the lowest acceleration capability of any vehicle and helps avoid oscillations between lanes.

Thus, a vehicle considers the advantage to self $acc'(M') - acc(M)$ from lane change against the disadvantage to the existing back vehicle $acc(B) - acc'(B)$ and the new back vehicle $acc(B') - acc'(B')$ to arrive at a decision about the lane change. In our implementation, we prefer a lane change towards a left lane though a right lane change for overtake is not prohibited. The politeness factor p is set at 0.5 and a_{thr} is $0.2m/s^2$ as suggested in [21]. The safe deceleration for lane change, b_{safe}, which has to be less than the maximum deceleration allowed, is set at $1m/s^2$.

4.2.2 Other Modifications

One of the most significant modification we had to make was to modify various modules of SWANS to work with the geographical addressing. For implementing flooding, we modified the IPv4 header to include the geographic address of destination, i.e., the zone of relevance. Instead of an IP address, the nodes were identified with a vehicle identification number (VIN). The header for DRG packets included the ZOR, the source and the sender position.

By default, STRAW places vehicles randomly on the road segments. To ensure repeatability this was modified such that vehicles can be placed at specific road segments. STRAW also uses real road maps by default. Since the objective of the investigations was to evaluate the proposed routing protocol, we wanted to have a very simple road model to avoid any effects caused by the specific road map used. Hence, highway and city street roads were created in the TIGER format and were used for the simulations.

Originally, in STRAW, the drivers do not react as a function of the information received from the other drivers. In our system, a driver that receives an emergency message breaks in order to avoid collision, or changes the lane if possible, or re-routes if it has a chance, i.e., if an appropriate exit exists.

4.3 Collision Warning Application

We use a collision warning application as a representative for the safety applications identified in Section 1.1. In this application, if a vehicle is either involved in or detects a collision or breakdown, it sends a warning message to vehicles behind it. A suitable zone of relevance (ZOR) is determined by the application. In our simulations, the ZOR is rectangular with a length L and width W. The minimum length of ZOR, L_{min}, should be the safe braking distance for vehicles at the maximum allowed speed, while the minimum width, W_{min}, should cover all the lanes on the road moving in the direction of the collision. The ZOR also specifies the maximum deviation of the direction of a vehicle from the direction of the source vehicle. For our simulations we allow a deviation of 180^o, i.e., all the vehicles within the area specified by L and W are part of the ZOR, regardless of their direction. The zone of forwarding (ZOF) is defined by adding 15 meters to the bounds of ZOR.

The performance on collision warning application is evaluated on two scenarios: a straight highway and a city street network. The metrics measured for evaluating performance are described next.

4.3.1 Performance Metrics

To evaluate the performance of our protocols we identify the following metrics.

- *Packet Delivery Ratio (PDR)* is the ratio, as percentage, of the number of nodes receiving the packet and the number of nodes that were supposed to receive the packet. It gives a measure of the reliability of routing protocol by showing its effectiveness. When a source generates a new geocast message for a particular ZOR, a list of nodes belonging to that ZOR is created and this is used to identify the nodes that are supposed to receive the geocast message.

- *End-to-End Delay* is the time delay between the time a geocast message is sent by an application at the source node to the time the application running on receiver node receives the message. Since the processing time between network and application layer is small and constant for all node in our simulations, the average end-to-end delay provides a measure of delay in delivery caused by the network layer as a measure of time-efficiency of the routing protocol.

- *Overhead* is the ratio of the number of network layer bytes transmitted to the number of bytes sent by the application layer for a unique message. The overhead provides a measure of efficiency of the routing protocol in reducing redundant transmissions for restricted flooding based protocol.

4.3.2 Sensitivity Analysis of DRG Parameters

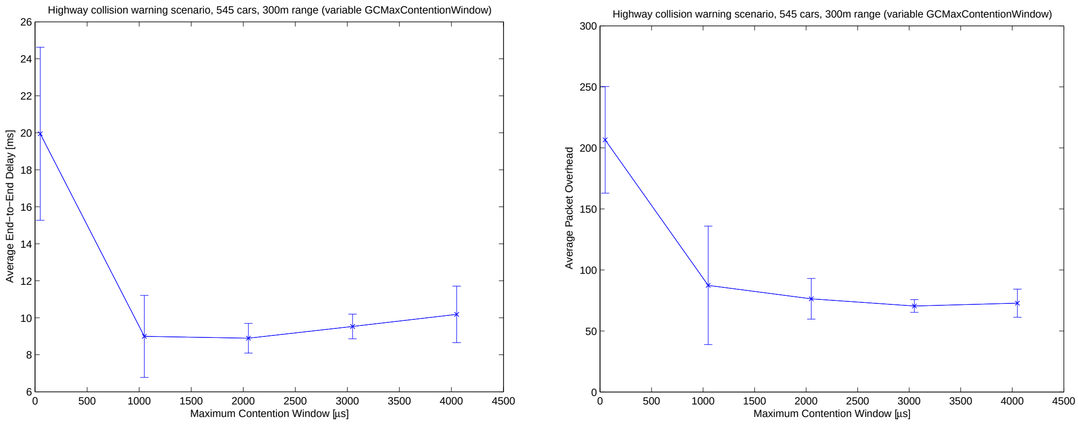
In this section, we present a sensitivity analysis of some of the parameter of DRG and select the optimum values for DRG parameters. Some values are selected using simulations on typical scenarios, while the rest are based on the formulae given in Chapter 3.

The maximum distance-based backoff $MaxBO_d$ is calculated using (3.4), with the propagation and processing delays assumed to be negligible or nearly constant. We use IEEE 802.11 implementation as the MAC layer, and assume a low bit rate of 2 Mbps since all the transmissions are broadcast. Our selected $MaxBO_d$ of 10 ms supports frame size of up to 1250 bytes.

The angle criterion θ for implicit acknowledgement for 75.5% coverage ratio is found to be 135^o using (3.15) and (3.17). The nominal transmission range R_{tx}, or R_D in (3.2), is based on either a disk model or a Rayleigh fading model. More details on selecting transmission range are given in Appendix C.

The rest of the parameters are selected on the basis of simulations on the typical highway collision warning scenario as discussed in Section 4.3.3. For the typical scenario, DRG delivers message to all the relevant nodes for all the tested parameter values. Hence, the PDR is not shown here.

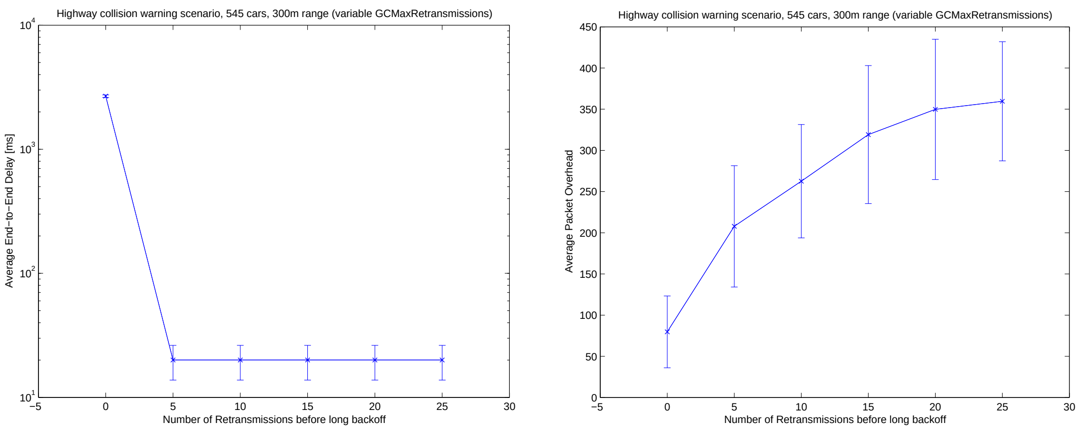
Figure 4.1 shows the the effect of various collision window sizes on the end-to-end delay and overhead of DRG. The average end-to-end delay drops as the CW_{max} is increased



(a) (b)

Figure 4.1: The average end-to-end delay (a) and overhead (b) as a function of collision window size

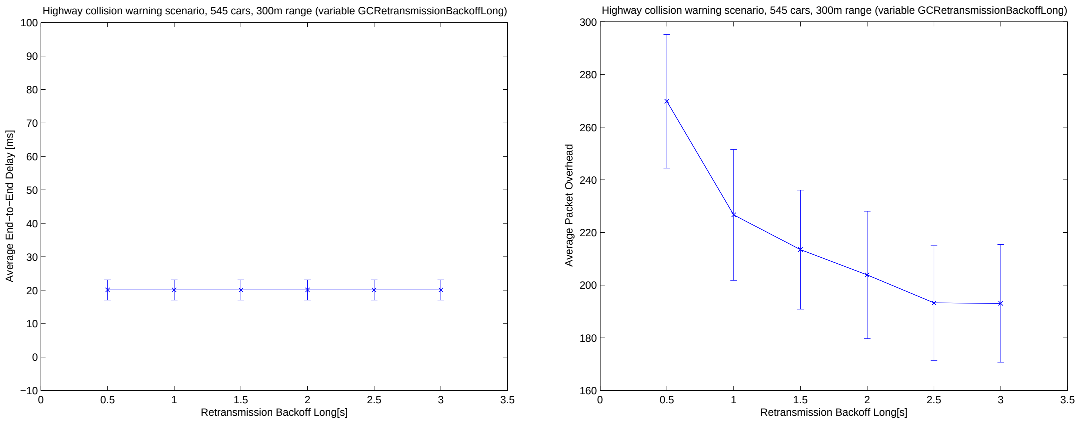
from 50μs to the order of a millisecond, a result of reduced collisions and increased number of successful transmissions. However, with $CW_{max} > 2$ ms the delay slowly increases as higher collision windows result in higher backoff at relays. The packet overhead also reduces as the collision window size is increased. We select a maximum collision window of 2 ms.



(a) (b)

Figure 4.2: The average end-to-end delay (a) and overhead (b) as a function of number of retransmissions before long backoff

The number of retransmissions of the geocast message to overcome errors of wireless communications or collisions, $MaxReTx$, has to be limited to reduce redundancy. However, a certain number of retransmissions may be necessary to ensure delivery. The end-to-end delay and overhead for various $MaxReTx$ thresholds are shown in Fig. 4.2. When short-term retransmissions are not used, i.e., $MaxReTx = 0$, the end-to-end delay is extremely high because the packets lost due to errors are received only from retransmission after a long backoff. This shows that there can be significant loss of packets due to errors or collisions, and that a burst of retransmissions can help reduce the end-to-end delay. However, a longer burst of retransmissions result in higher overhead. We chose a $MaxReTx$ of 5 to ensure delivery and contain overhead.



(a) (b)

Figure 4.3: The average end-to-end delay (a) and overhead (b) as a function of long backoffs

The long backoff, $LongBO_d$, reduces redundant transmissions, and thus, lowers the overhead. However, as shown in (3.5), there is a ceiling on maximum value of $LongBO_d$, especially for safety applications. As shown in Fig. 4.3, the overhead is optimum for long backoff of 2.5 seconds. This is within the ceiling given in (3.5) for a maximum velocity of 120 kilometer per hour and the minimum transmission range of 100 meters. The end-to-end delay is not significantly affected by the long backoff as the network remains well connected in our typical scenario.

4.3.3 The Highway Scenario

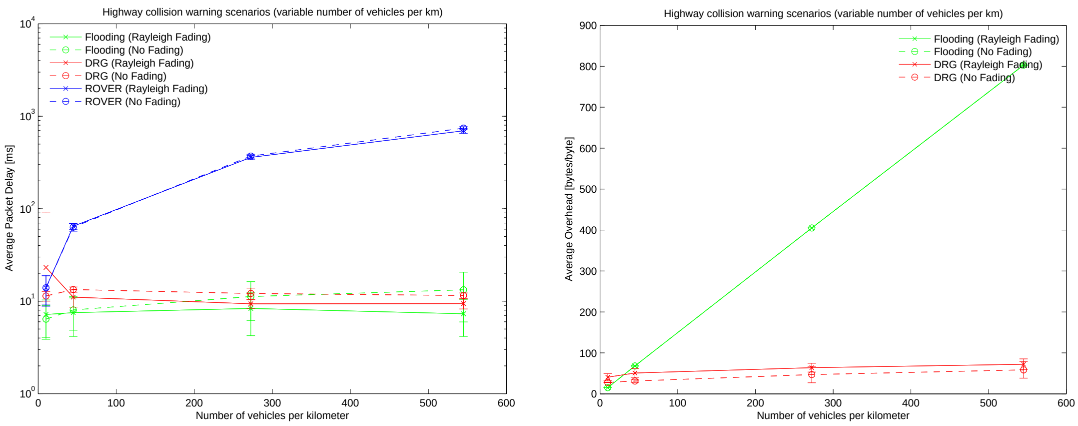
We use a straight highway 10km long and with 3 lanes in each direction. The maximum speed allowed on the highway is 120 kilometer per hour. The vehicles are placed at a regular distance depending on the density of the vehicles. The lead vehicle stops abruptly three seconds into the simulation and generates a single collision warning message.

The ZOR starts at the colliding vehicle and extends to 150 meters on either side. The length of the ZOR is varied from 500 meters to 3500 meters. We also evaluate the performance by varying the vehicle density and the nominal transmission range. The simulation parameters and their values are shown in Table 4.1. The default values are in the parenthesis.

Table 4.1: The simulation parameters and their values for the highway scenario

Parameter	Values
Number of vehicles per km	10, 45, (272), 545
Transmission range [m]	100, 200, (300), 400
Length of the ZOR [km]	0.5, (1.5), 2.5, 3.5

Vehicle Density



(a) (b)

Figure 4.4: The average end-to-end delay (a) and overhead (b) as a function of vehicle density

The effect of vehicle density on the end-to-end delay and overhead is shown in Fig. 4.4. For a protocol like ROVER, which is based on explicit route setup, a higher number of nodes require more control packets. With a given coverage area, a higher node density causes more contentions or collisions, resulting in a higher end-to-end delay. However, for broadcast based protocols like Flooding and DRG the increase in contention is not very significant.

The number of transmissions for Flooding is of the order of $O(n)$, where n is the number of nodes in the ZOR and ZOF. Hence, the overhead for Flooding increases linearly with the node density. Due to the distance-based backoff mechanism in DRG, the number of transmissions for DRG is of the order of $O(k)$, where k is the number of hops in the ZOR and ZOF. Thus, the number of transmitting nodes are not significantly affected by node density. Hence, DRG scales much better than Flooding.

The PDR for Flooding and DRG, as shown in Fig. 4.5 (a), is 100% since the network remains connected even for low vehicle density. However, ROVER gives a lower PDR (90%) for low vehicle density as the routing tree breaks easily at low densities.

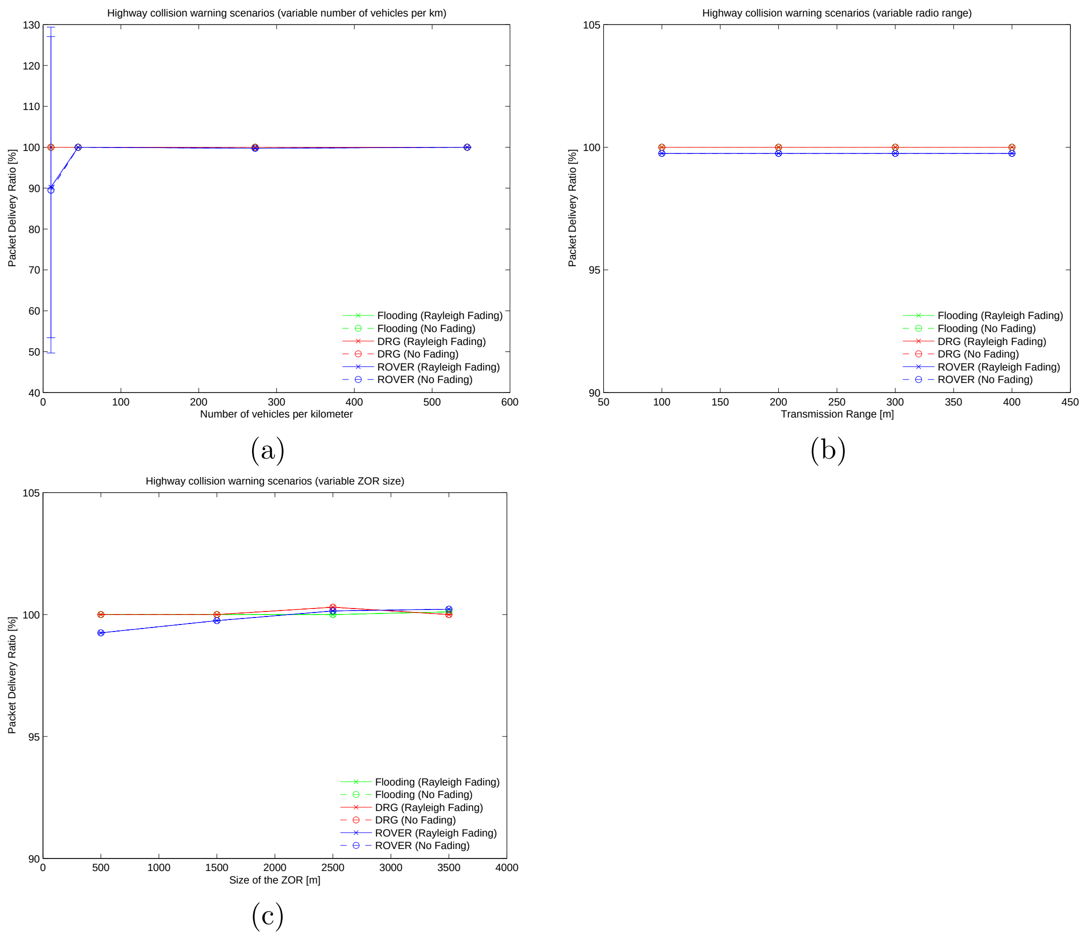
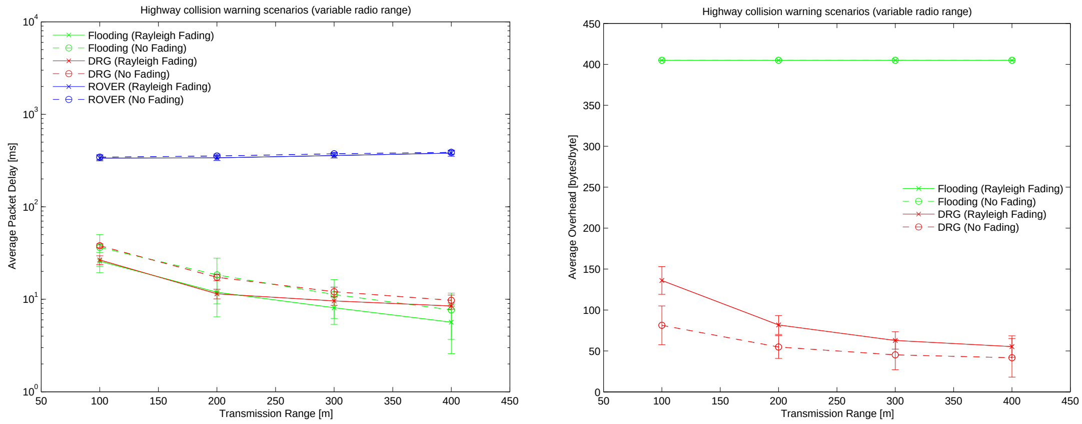


Figure 4.5: The packet delivery ratio as a function of (a) vehicle density, (b) transmission range and (c) ZOR length



(a) (b)

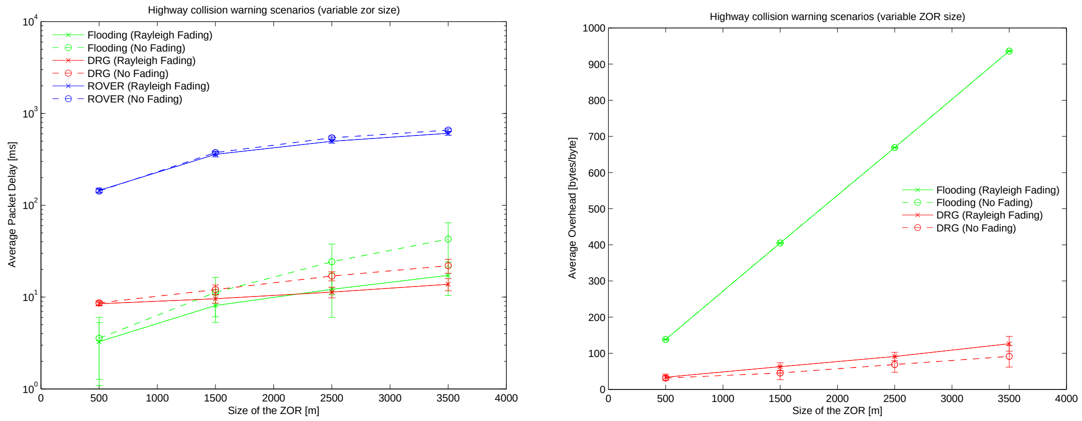
Figure 4.6: The average end-to-end delay (a) and overhead (b) as a function of transmission ranges

Transmission Range

Figure 4.6 shows the influence of transmission range on the average delay and overhead for various protocols. Since ROVER needs to setup a route before the data packet can be transmitted, and since RREP packets are unicast by each node, a bigger transmission range causes contention among higher number of nodes. Thus, it takes more time to setup the route for a larger transmission range. Flooding and DRG directly transmit the data packets, thus a larger transmission range results in a smaller number of hops and hence, a lower delay.

The overhead for Flooding remains constant, irrespective of the transmission range, as long as the number of nodes in the ZOR and ZOF remain the same. However, since the overhead for DRG depends on the number of hops, larger transmission range reduces the overhead.

The PDR as a function of transmission range is shown in Fig. 4.5. Both Flooding and DRG deliver the geocast message to all the nodes within the ZOR, resulting in 100% PDR. ROVER also has a nearly 100% PDR. The PDR for any of the protocol is not sensitive to the transmission range values used in our experiments.



(a) (b)

Figure 4.7: The average end-to-end delay (a) and overhead (b) as a function of ZOR size

Zone of Relevance

The effects of a bigger zone of relevance on the end-to-end delay and overhead is shown in Fig. 4.7. A bigger ZOR not only increases the number of nodes in the ZOR, it also increases the number of hops required to propagate a message through the ZOR. Thus, the delay for all the protocols increases with the length of the ZOR. However, the increase in delay for DRG is at a much slower rate than either Flooding or ROVER.

Since the number of nodes within a ZOR increases linearly with the length of the ZOR, when the nodes are distributed uniformly in the network, the overhead for Flooding also increases linearly with the ZOR. On the other hand, the overhead for DRG increases at a rate equivalent to the ratio of the length of the ZOR and the transmission range. In other words the overhead increases with the number of hops.

The PDR, as shown in Fig. 4.5, is 100% for both Flooding and DRG for all lengths of ZOR in our experiment. The PDR for ROVER is slightly lower (99.25%) for a smaller ZOR size. This may be due to a vehicle moving out of ZOR by the time the route is setup.

4.3.4 The City Scenario

We use a city scenario with a relatively sparse network and short transmission ranges to evaluate the performance of the protocols. The city is a grid of 2km x 2km, streets placed 100 meters apart and perpendicular to each other. The vehicles are placed randomly. The vehicle that sends the collision warning message is always placed at the center of the grid. This is in contrast to the highway scenario, where vehicles are placed at regular distance. The ZOR is a square with the source node at the center. With a randomly uniform distribution of vehicles in the grid, the ZOR is likely to include a quasi-constant number of nodes. The parameter values for DRG are kept the same as in the highway scenario, except the maximum retransmission threshold, $MaxReTx$, which is set at 2 instead of 5. In order to show the effect of time-persistent geocast, we set the time-to-live (TTL) to 15 seconds for DRG. The default value of TTL for Flooding is 64 hops. The performance is evaluated for various simulation parameters including the node density, transmission range and the size of the ZOR. The simulation parameters for the city scenario with their corresponding values are shown in Table 4.2. The default values are in parenthesis.

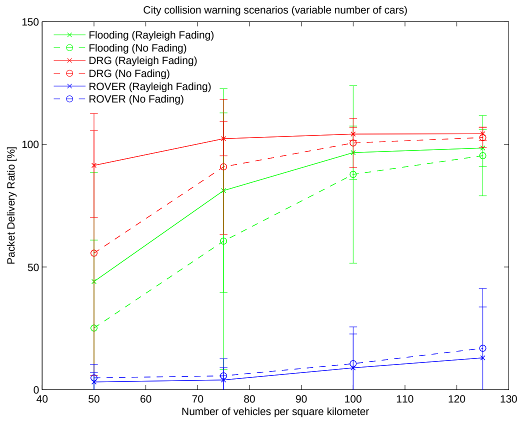
Table 4.2: The simulation parameters and their values for the city scenario

Parameter	**Values**
Number of vehicles per km^2	50, 75, (100), 125
Transmission range [m]	100, 150, (200), 250
Size of the ZOR [m x m]	500x500, 750x750, (1000x1000), 1500x1500

Vehicle Density

The effect of vehicle density in a city scenario on the performance of Flooding and DRG is shown in Fig. 4.8. The PDR for ROVER is very low as the links break frequently in a two-dimensional city scenario. The reliability of DRG is much better than Flooding in a scarce network. This is due to the mechanisms used by DRG to overcome temporary network fragmentation. Also note that the PDR is more than 100% for DRG in certain cases, since the geocast message is kept alive for 15 seconds by which time new nodes enter the ZOR and the message is delivered to them.

The DRG delivers to vehicles, once temporarily separated by network fragmentation, when they enter the coverage area of a relay. Since, vehicle movements take much longer time than the time taken by a packet to propagate through a well connected network, the average end-to-end delay is dominated by the time taken by vehicles to bridge network fragmentation in a sparse network. However, as the connectivity improves, the end-to-end delay reduces. The delay still is much larger than that of simple Flooding and ROVER,



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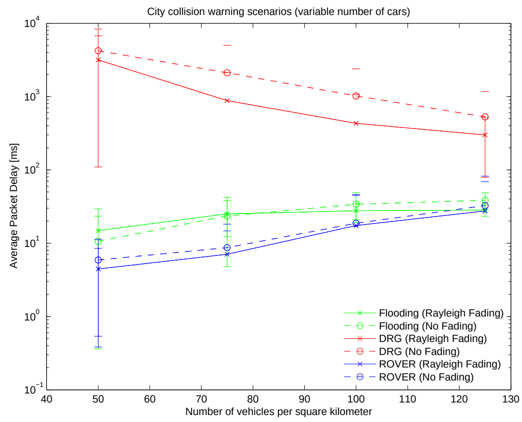

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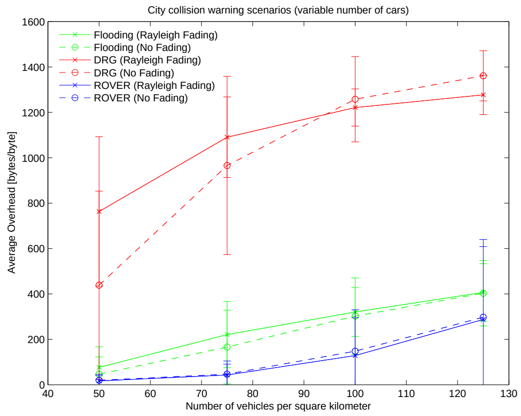
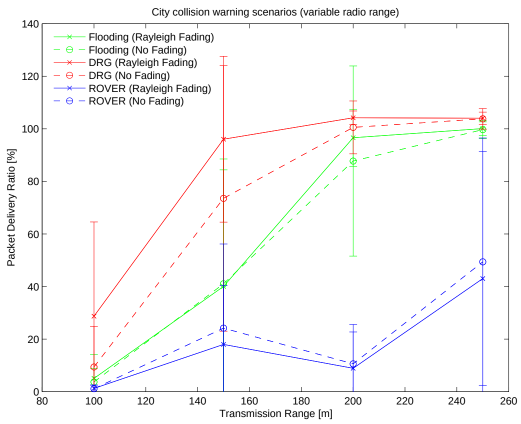


(c)

Figure 4.8: The average packet delivery ratio (a), end-to-end delay (b) and overhead (c) as a function of vehicle density

mainly because the geocast message is kept alive for a long duration, and the message is delivered to nodes which enter the ZOR even after a long time.

The higher PDR for DRG in a fragmented network comes at the cost of a higher overhead. The retransmissions to overcome network fragmentation or to keep the message alive add heavily to the overhead. However, the overhead for DRG grows much slower than that of Flooding or ROVER in a connected network. Thus, DRG tends to reduce redundancy, when it is not required to ensure delivery.



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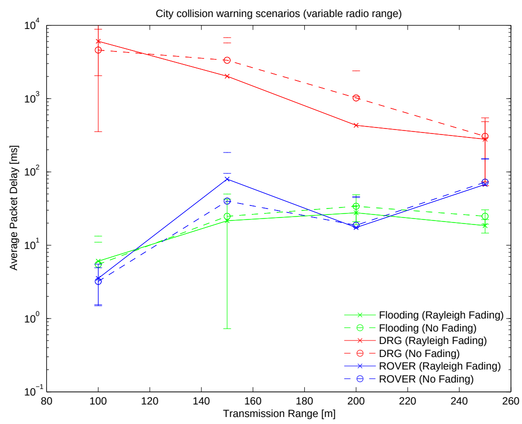

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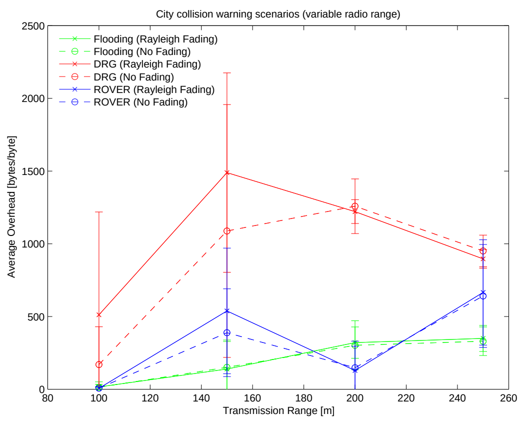


(c)

Figure 4.9: The average packet delivery ratio (a), end-to-end delay (b) and overhead (c) as a function of transmission ranges

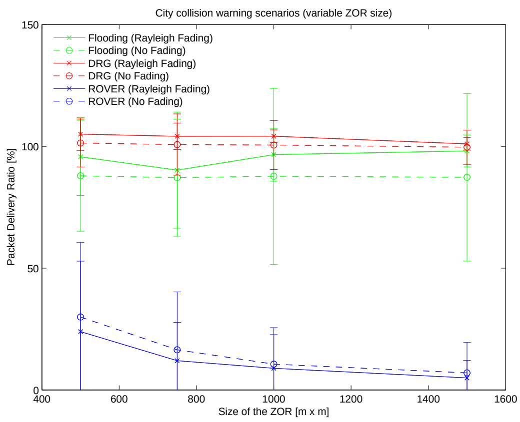
Transmission Range

The sensitivity of performance of DRG and Flooding to the transmission range is shown in Fig. 4.9. Since, the transmission range below a certain limit affects the connectivity of the network with a given node density, the effect of smaller transmission range on PDR is similar to a sparse network. The network is highly fragmented, and even DRG is not able to overcome the fragmentation at transmission range of 100 meters, though it fares better than Flooding. Once a critical level of transmission range (150 meters) is reached the PDR for DRG rises rapidly to be near 100%. At higher transmission range the PDR is more than 100% as the geocast message is delivered to nodes that enter the ZOR after the message was generated.

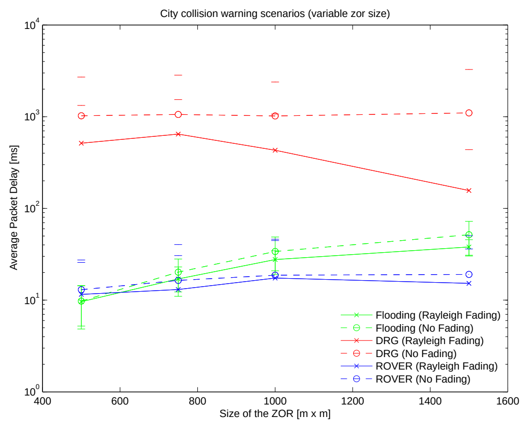
The end-to-end delay for DRG is much higher than Flooding and ROVER as the message is delivered to more vehicles that have overcome temporary network fragmentation. As expected, the delay reduces as the connectivity improves with higher transmission ranges.

The overhead of DRG for transmission range of 100 meters defies the trend and is lower than the overhead at higher transmission range. This is because at 100 meter transmission range the network is so fragmented that very few nodes receive the geocast message and try to overcome the network fragmentation. However, after the critical level of transmission range the overhead reduces as the network connectivity improves.

Zone of Relevance



(a)



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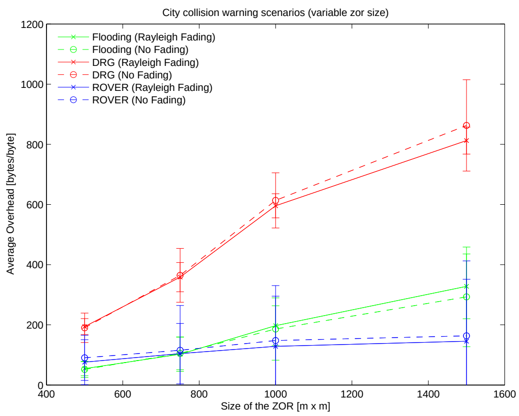

(c)

Figure 4.10: The average packet delivery ratio (a), end-to-end delay (b) and overhead (c) as a function of size of ZOR

The influence of the size of the ZOR on the performance of DRG and Flooding is shown in Fig. 4.10. Since the network is fairly well connected, the PDR is high for both DRG and Flooding. For a smaller ZOR, the PDR for DRG is more than 100% as nodes come within the ZOR after the geocast message is generated. However, for a larger ZOR there is less chance of a new node coming in the ZOR as more area of the city is covered by the ZOR, leaving few nodes outside. Hence, the PDR drops to near 100% for larger ZOR. Since, the connectivity or node density is not affected by changes in the size of ZOR, the PDR for Flooding remains relatively stable. The PDR for ROVER is low as the average lifetime of links and routes in a two-dimensional city scenario is much lower than relatively stable highway scenario. As the number of hops, and as a result, number of links, increase with larger ZOR, the PDR drops for ROVER.

The end-to-end delay for DRG with fading decreases with a bigger ZOR as fewer new nodes enter the ZOR, reducing the number of nodes getting the message after a large delay. The end-to-end delay for DRG without fading remains stable as there are hardly any new nodes to which the message is delivered, as shown by the values of PDR for DRG without fading. The delay for Flooding increases with the size of the ZOR as there are more transmissions and the collisions also increase. The increase in delay, with the size of ZOR, for ROVER is much slower.

The overhead increases with the size of the ZOR as there are more nodes and more hops. Thus, the increase in overhead for Flooding is expected. The overhead for DRG also increases with the ZOR as there are more nodes at the edge of the ZOR that continue to retransmit, trying to overcome non-existent fragmentation, seeking an implicit acknowledgement. The overhead for ROVER increases relatively slowly with the size of ZOR, mainly because of the lower PDR at larger ZOR size.

4.4 Traffic Monitoring Application

We use a traffic monitoring application to evaluate the performance of our protocol for the traffic control class of applications. These applications are characterized by heavy offered load and tolerance for packet loss and delay. Traffic control applications usually involve communications over a fairly large area compared with safety applications. Thus, traffic control applications require the routing protocol to be scalable to a large number of nodes and heavy packet traffic.

We use a simple traffic monitoring application that periodically sends a geocast message with the node's geographic information, like, location, direction and speed. On receiving a traffic monitoring message from another node, the application updates the corresponding information in its traffic monitoring table. Using this table, the node generates a map with the estimated or known positions of other nodes. Thus, using the application a node can get a picture of other vehicles in the region and their distribution. However, unlike the safety application, our traffic monitoring application does not change the node's path based on the available information.

We evaluate the performance in a city scenario with a 2km x 2km grid, roads placed 100 meters apart. The ZOR is a square with the source node at the center of the square. The nodes are placed in the grid randomly, and all the nodes generate a traffic information packet every 5 seconds. The traffic information error and the number of known cars are calculated at only a randomly selected sample of nodes. This is to limit the time and memory invested in keeping traffic state at each node.

4.4.1 Performance Metrics

To evaluate the performance of our protocols we identify the following metrics:

- *Traffic Information Error* is the error in the estimated position of a node and its actual position. This metric gives an indication of how current the received information is. Thus, it is an application layer counter-part of end-to-end delay, though the traffic information error also depends on the predictable mobility of the nodes.

- *Number of Known Cars* is the number of cars a node has received a message from. It indicates the effectiveness of the message delivery.

- *Overhead* is the overhead, as a ratio of the number of network layer packets transmitted to the number of unique messages sent by the application layer. The overhead provides a measure of efficiency of the routing protocol in reducing redundant transmissions for restricted flooding based protocol.

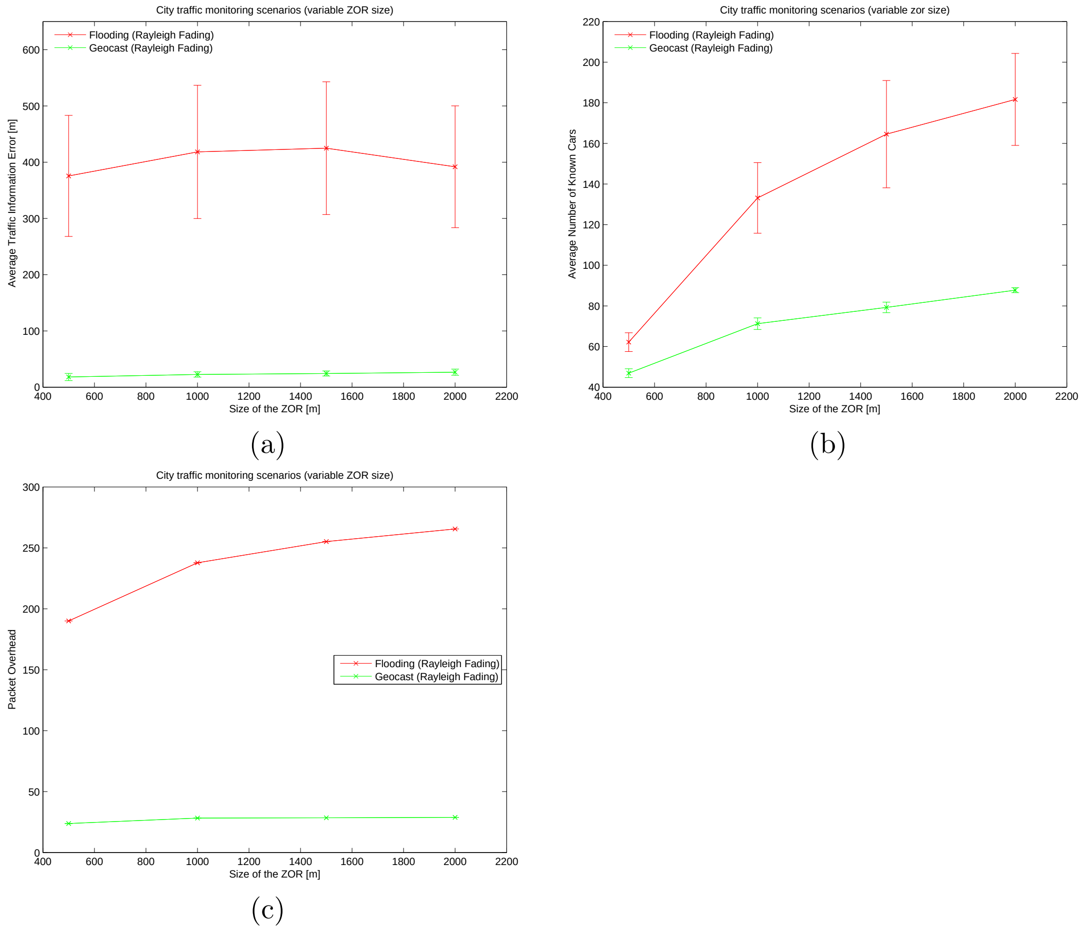

Figure 4.11: The average traffic information error (a), average number of known cars (b), and average overhead (c) as a function of ZOR size

4.4.2 Zone of Relevance

The effect of the size of ZOR on the performance of the traffic monitoring application using different routing protocols is shown in Fig. 4.11. The traffic information error does not increase significantly with the size of ZOR for either Flooding or DRG. The average error however is much smaller for DRG than for Flooding. To a certain extent this is due to the fact that DRG knows about much fewer cars than Flooding. The difference in the number of cars known between Flooding and DRG is a result of different time-to-live (TTL) scales and values. While Flooding uses a hop count based TTL with a default value of 64, DRG uses an actual time stamp for TTL and has a default value of 2 seconds for the traffic monitoring application. However, while DRG knows about half as many cars as

Flooding, its average information error is less than a tenth of Flooding.

The number of nodes within the ZOR increases quadratically with the size of the ZOR when nodes are distributed uniformly in the network. However, since the network size is limited to 2km x 2km, and the source nodes could be located even at the edge of the network, the growth in the number of nodes within ZOR is not quadratic. This can be seen from the growth in overhead for Flooding. The overhead for DRG is much less sensitive to the increase in the size of ZOR, while being at the level of about a tenth of overhead for Flooding. Thus, DRG proves to be more scalable in a heavy load application with high number of nodes.

Chapter 5

Conclusion

In this thesis we have proposed a completely distributed and robust geocast protocol, DRG, that relies on a distance-based backoff algorithm and a novel angle based algorithm to determine implicit acknowledgement. We also propose several modifications to make the protocol robust and more efficient. In contrast to other distributed geocast protocols designed for highway collision warning applications, we present algorithms that work in both one-dimensional and two-dimensional network topology. We have shown through simulations on various scenarios that while the reliability of DRG is comparable or even better than that of the highly redundant Flooding, the overhead is much smaller. DRG is shown to outperform an explicit route setup approach even in a scenario with very little relative mobility. The scalability of DRG is also better as its performance is less sensitive to network size or node density. However, most importantly, DRG adapts itself to fit network topology and ensures a high delivery ratio in a sparse and disconnected network by increasing overhead, while it efficiently delivers the packets in a well connected and dense network.

5.1 Future Work

- The underlying physical model needs to be modified to more accurately represent the radio propagation in a city environment. Radio communication in a typical city street network is replete with radio obstacles, interference and has multi-path radio propagation. Thus, a circular radio model (including fading) is not realistic. A simple way to account for the radio obstacles presented by buildings in a typical city block is to have the length of the city blocks at least twice the transmission range. In this case, when the transmitter is near the middle of the block the vehicles on perpendicular streets cannot receive the transmission. Thus, the connectivity would be somewhat similar to real radio connectivity in a city even when we use a circular radio model.

- In a city scenario, if a node can somehow know that it is at an intersection, as suggested in [34], then it should retransmit the geocast message even if the distance-based backoff mechanism does not require it to do so. This will ensure that the message spreads in all the direction. This modification is useful only when a physical model for city is used for simulations.

- The effect of the angle criterion for determining implicit acknowledgement, proposed in this thesis, on the performance in city scenario should be studied. The angle criterion used in this thesis has been optimized for a highway scenario. However, the effect of the criterion on the overhead and the PDR needs to be explored in a city scenario and an optimum threshold needs to be found.

- The time persistence of geocast can be optimized further to ensure that the new nodes entering the ZOR near the "incident" receive the message before they reach the incident location. The advantages and costs of time persistence geocast also needs further investigation. The overhead caused long time persistence needs to be evaluated against the gain in PDR for nodes entering the ZOR after the message has been disseminated once.

- The effect of MAC layer optimizations also needs to be investigated. It has been observed that even with extensive contention and collision avoidance mechanisms there still are some MAC layer collisions when the default value of minimum collision window (CW_{min}) size for 802.11 is used. However with a higher CW_{min}, the collisions can be reduced.

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Appendix

Appendix A

Intersection of Two Circles

A.1 Area of a Half-lens

The wedge shaped area, with upper boundary defined by the circular arc l, and lower boundary defined by the lines connecting points N, O and P, is called a *circular sector*. The points N, O and P form an isosceles triangle. The area enclosed between the chord $\overline{NO}$ and the circular arc l forms a half convex lens shape, and will be called the *half-lens*.

Let r be the radius of the circle with center at O, c be the chord length, l be the length of the circular arc, h be the height of the arced portion, and d be the height of the triangle ΔNOP.

From Fig. A.1, we know that:

$$r = h + d, \tag{A.1}$$

$$l = r\theta, \tag{A.2}$$

where $\theta < \pi$.

We also know that the triangle ΔNOP is an isosceles triangle, with the length of the sides NO and NP being the radius r of the circle. Hence, the height of the triangle d

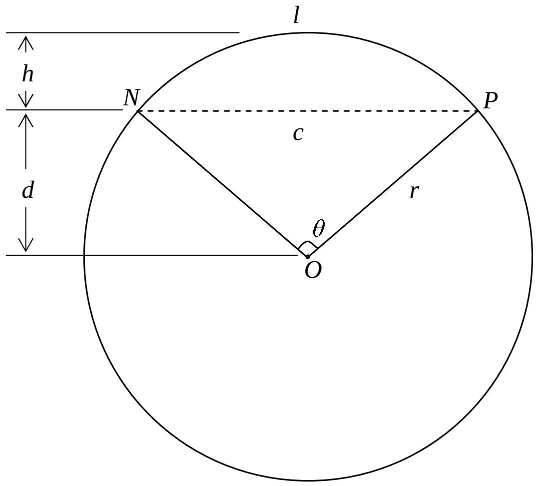

Figure A.1: Area of a half-lens formed by a chord on a circle

is,

$$d = r\cos\left(\frac{\theta}{2}\right) \tag{A.3}$$

$$d^2 = r^2 - \left(\frac{c}{2}\right)^2 \tag{A.4}$$

$$d = \frac{1}{2}\sqrt{4r^2 - c^2} \tag{A.5}$$

The length of the chord is c, given by,

$$\left(\frac{c}{2}\right)^2 = r^2 - d^2 \tag{A.6}$$

$$c = 2\sqrt{r^2 - d^2} \tag{A.7}$$

From equations (A.2) and (A.3), we can write,

$$\begin{aligned} \theta &= \frac{l}{r} \\ &= 2\arccos\left(\frac{d}{r}\right) \end{aligned} \tag{A.8}$$

The area A of the half-lens is the area of the circular sector minus the area of the bottom triangle ΔNOP,

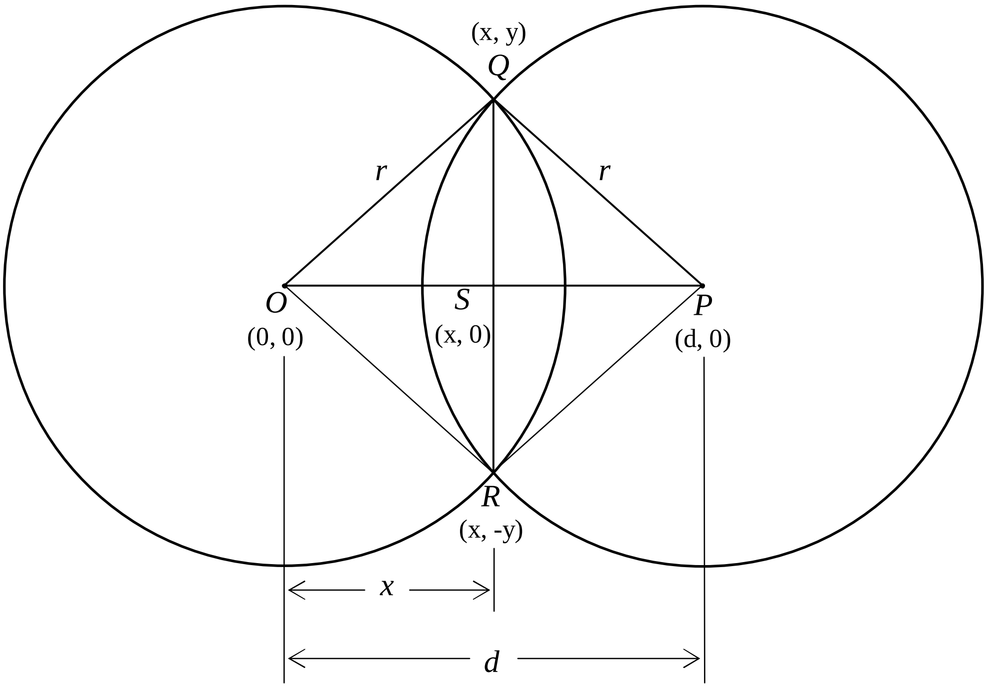

Figure A.2: Area of intersection of two circles

$$A_{half-lens} = A_{sector} - A_{triangle} \tag{A.9}$$
$$= \frac{1}{2}r^2\theta - \frac{1}{2}cd \tag{A.10}$$
$$\tag{A.11}$$

Using equations (A.5) and (A.7) for values of c & d, the area of half-lens is,

$$A_{half-lens} = r^2 \arccos\left(\frac{d}{r}\right) - d\sqrt{r^2 - d^2} \tag{A.12}$$

A.2 Area of Intersection of Two Circles

Let two circles with centers at O and P, each with radius r, intersect each others at points Q and R. We can assign coordinates to O and P as shown in the figure A.2, without loss of generality. It can be seen that the distance d between the two centers O

and P has to be less than or equal to $2r$ for the intersection to have a non-zero area. Since the circles are unique, $0 < d \leq 2r$.

The equations of the two circles are:

$$x^2 + y^2 = r^2 \tag{A.13}$$

$$(x-d)^2 + y^2 = r^2 \tag{A.14}$$

Now, let the two circles intersect each other at two points, Q and R. Hence, at these two points both the equations (A.13) and (A.14) are satisfied. Combining the two equations,

$$(x-d)^2 = x^2 \tag{A.15}$$

Since $d > 0$,

$$x = \frac{d}{2} \tag{A.16}$$

The chord connecting points Q and R has a length $2y$, where y is given by,

$$y^2 = r^2 - x^2 \tag{A.17}$$

$$y = \sqrt{r^2 - \left(\frac{d^2}{4}\right)} \tag{A.18}$$

We can see that the area of intersection of the two circles consists of two half-lens formed by the chord QR. The height of the triangles ΔOQR and ΔPQR, is x given by equation (A.16). Replacing this value of height in the formula for area of half-lens given by equation (A.12), area of half-lens in this case is,

$$A_{half-lens} = r^2 \arccos\left(\frac{d}{2r}\right) - \frac{d}{2}\sqrt{r^2 - \left(\frac{d}{4}\right)^2} \tag{A.19}$$

Hence, the area of intersection of the two circles is,

$$A_{intersection} = 2 \times A_{half-lens} \tag{A.20}$$

$$= 2r^2 \arccos\left(\frac{d}{2r}\right) - \frac{d}{2}\sqrt{4r^2 - d^2} \tag{A.21}$$

Appendix B

Vehicular Traffic Simulators

There are tens of models and simulators available to simulate vehicle traffic on roads. These simulators can be classified as sub-microscopic, microscopic, mesoscopic and macroscopic according to the detail of the simulation. A microscopic simulator is necessary to get details like individual vehicle position and speed. Majority of the microscopic simulators use some kind of car-following and lane-changing models to model the behavior of drivers. Simulators may be based on cellular automaton, fuzzy logic or multi-agent systems. CORSIM seems to be the most capable, low cost simulator, popular among traffic engineers. SmartAHS is an open source simulator with a communication library to simulate inter-vehicle communication. However, its current capabilities are rather limited and it may require extensive programming efforts to simulate a road network. STRAW is a simple microscopic simulator integrated with a network simulator SWANS. Introduction to a few popular traffic simulators is given in this survey, along with their theory of operation and important features. A summary of these simulators is given in Table B.1.

B.1 CORSIM

CORSIM [40] is a vehicle traffic simulation tool developed by Federal Highway Administration (FHWA) to predict the effect of Advanced Traffic Management Systems (ATMS) concepts and strategies on system's performance expressed in terms of Measures

Table B.1: Summary of various vehicle traffic simulators

Simulator	**Model**	**Environment**	**Features**
CORSIM	Microscopic	Highway and Urban	Easy to use with TRAFED and TRAFVU; Very popular; High capabilities
STRAW	Microscopic	Urban	Based on Java in Simulation Time (JiST); Limited yet simple; Integrated with network simulator SWANS
STRAW Modified	Microscopic	Highway and Urban	A modified STRAW with lane-changing model that works on highways
SimTraffic	Microscopic	Highway and Urban	Very costly; Theory similar to CORSIM
MITSIM	Microscopic	Highway and Urban	No information on availabiliy
SmartAHS/ SHIFT	Microscopic	Highway and Urban	Can also simulate communication; Complex, needs training
SIMONE	Sub-micro & Microscopic	Highway only	Designed for study of Adaptive Cruise Control (ACC)
FLOWSIM	Microscopic	Highway and Urban	Rules designed only for UK roads
PELOPS	Sub-micro & Microscopic	Highway and Urban	Designed for study of ACC like SIMONE

of Effectiveness (MOEs), which include average vehicle speed, vehicle stops, delays, vehicle-hours of travel, vehicle-miles of travel, fuel consumption, and pollutant emissions. The simulation model is capable of representing traffic flow in large urban areas containing surface street networks and freeways and has reasonable computer usage requirements.

CORSIM consists of an integrated set of two microscopic simulation models that represent the entire traffic environment. NETSIM represents traffic on urban streets and FRESIM represents traffic on freeways. Since CORSIM is a microscopic simulator it models the movements of individual vehicles, which include the influences of driver behavior.

Theory of Operation

CORSIM applies time step simulation to describe traffic operations. A time step is one second. Each vehicle is a distinct object that is moved every second. Each variable control device (such as traffic signals) and each event are updated every second. CORSIM is a stochastic model, which means that random numbers are assigned to driver and vehicle characteristics and to decision making processes. The MOEs that are obtained from a simulation are the result of a specific set of random number seeds.

Each vehicle is identified by fleet (auto, carpool, truck, or bus) and by type. Up to nine different types of vehicles (with different operating and performance characteristics) can be specified, thus defining the four vehicle fleets. Furthermore, a "driver behavioral characteristic" (passive or aggressive) is assigned to each vehicle. Its kinematic properties (speed and acceleration) as well as its status (queued or moving) are determined. Turn movements are assigned stochastically, as are free-flow speeds, queue discharge headways, and other behavioral attributes. As a result, each vehicle's behavior can be simulated in a manner reflecting real-world processes.

Each time a vehicle is moved, its position (both lateral and longitudinal) on the link and its relationship to other vehicles nearby are recalculated, as are its speed, acceleration, and status. Actuated signal control and interactions between cars and buses are explicitly modeled.

Vehicles are moved according to car-following logic, in response to traffic control devices, and in response to other demands. For example, buses must service passengers at bus stops; therefore, their movements differ from those of private vehicles. Congestion can result in queues that extend throughout the length of a link and block the upstream intersection, thus impeding traffic flow. In addition, pedestrian traffic can delay turning vehicles at intersections.

Features

Characteristics that change over time,such as signal timings and traffic volumes, can be represented by dividing the simulation into a sequence of user-specified time periods, during which the traffic flows, the traffic controls, and the geometry are held constant. Therefore, the morning rush hour might be simulated with one time period representing pre-rush hour, a second representing rush-hour timing, and a third representing the post-rush-hour flows.

CORSIM also includes a traffic assignment program, which can be used to specify origin-destination volumes that represent the traffic demand over an area for a specified period of time.

CORSIM is capable of simulating most of the prevailing freeway geometries, including multiple-lane freeway mainlines, on/off ramps and connectors to other freeways, variations in grade, radius of curvature and super-elevation, lane additions and lane drops and auxiliary lanes, which are used by traffic to begin or end the lane-changing process or to enter or exit the freeway.

B.2 STRAW

STRAW (STreet RAndom Waypoint) [20] is a mobility model for vehicles on city streets. STRAW uses map data for real cities from the Topologically Integrated Geographic Encoding and Referencing (TIGER) system available from the US Census Bureau Geography. STRAW uses a car-following model to model mobility of vehicles within a road segment. Vehicles encounter stop signs or traffic signals depending on the class of the road; the timings of traffic signals are also controlled based on the road class. An admission control mechanism, based on the room on the next road segment, is used to model mobility at an intersection. The vehicle route planning can be done by specifying an origin-destination pair, or vehicles can move randomly by selecting a random direction at an intersection. Since STRAW does not have a lane changing model, and uses TIGER system to generate road topology on which vehicles move, it is practically limited to traffic simulations on city streets.

B.3 SimTraffic

SimTraffic, developed by Trafficware Corporation, performs micro simulation and animation of vehicle traffic. With SimTraffic, individual vehicles are modeled and displayed traversing a street network. SimTraffic models signalized and unsignalized intersections, and freeway sections with cars, trucks, pedestrians, and busses. Animation is displayed while the simulation is performed. However, SimTraffic needs Synchro — a software for optimizing traffic signal timing and perfoming capacity analysis. Synchro costs $2299 and SimTraffic costs $999, while the combined package costs $1899 to $3099 depending on the version.

Theory of Operation

SimTraffic models traffic at 10 time steps per second versus 1 for CORSIM. It uses the car following model and allows for different driver types. SimTraffic includes the vehicle and driver performance characteristics developed by the Federal Highway Administration for use in traffic modeling. In general, SimTraffic uses CORSIM vehicle and driver performance characteristics as much as possible. In a few cases there are minor differences because the CORSIM values are not published

Features

SimTraffic is capable of simulating both freeway segments and urban streets. However, it cannot model ramp metering, bus stops, bus routes, bus and carpool lanes, light rail, on-street parking, and short-term events. SimTraffic has higher capacity limits than CORSIM as it allows higher number of intersections and vehicles so that larger networks can be simulated.

B.4 MITSIM

MITSIM is a microscopic traffic simulator, and is part of MITSIMLab [41], developed by MIT's Intelligent Transportation Systems (ITS) Program. MITSIM moves vehicles according to car-following and lane-changing models. MITSIM can use either General Motors (GM) or Kazi's car following model. The lane-changing model used is also different from CORSIM. The car-following, lane changing, and event and signal response functions are invoked for each vehicle at a specified interval (e.g. 1 second). Speeds and positions of the vehicles and states of surveillance sensors are updated at a higher frequency specified by the user (e.g. 1/10 or 1/2 second). MITSIM has been used and was validated in the city of Stockholm, Sweden. The network had both freeway and urban sections. There is no information on the availability of MITSIM and its cost.

B.5 SmartAHS/SHIFT

SHIFT [42] is a programming language for describing dynamic networks of hybrid automata. It was developed by California PATH Project to offer proper level of abstraction for describing complex applications such as automated highway systems, air traffic control systems, robotic shop floors, coordinated submarines and other systems whose operation cannot be captured easily by conventional models.

SmartAHS is a specification, simulation and evaluation framework for modeling, control and evaluation of Automated Highway Systems (AHS). SmartAHS is developed using SHIFT, a new programming language with simulation semantics. It is an open source simulator.

Features

SmartAHS has components for simulating communication at physical layer, MAC layer and logical link layer. Communication requires time unit of around 10^{-8} seconds, which results in extremely long simulation time in vehicle traffic. SmartAHS aggregates communication and models it at message level rather than at the bit level. Thus the system (vehicle + communication) can be simulated using "reasonable" time steps. User can also specify the weather condition. However, it is tot clear what variables will be affected by weather. Highway description has to be using the SmartPATH highway description scheme. SmartAHS doesn't seem to have capability to simulate urban street environments, as well as complex freeway networks with ramps.

B.6 SIMONE

The SImulation model for MOtorway traffic with NExt generation vehicles (SIMONE) is a microscopic traffic simulator (developed at either Delft Technical University, Netherlands or Technical University of Hamburg-Harburg) to study the impact of the adaptive cruise control (ACC) driver support system on traffic flow. It simulates a motorway with vehicles equipped with and without an ACC system. SIMONE is capable of simulating individual human driving behaviour based on an individual drivers preferred speed and reaction time.

SIMONE is both a submicroscopic and microscopic simulator since it can not only model speeds and positions of individual vehicles, but also model details like braking in a vehicle, cruise control, etc. SIMONE has also been referred to as macroscopic simulator.

B.7 FLOWSIM

FLOWSIM (Fuzzy LOgic motorWay SImulation Model) is a microscopic model developed by Transportation Research Group at University of Southampton. FLOWSIM was originally developed to investigate driver behaviour on motorways, but has recently been adapted for use on non-motorway roads as well. FLOWSIM is based on car-following, lane-changing models where the driver's decisions are modelled by fuzzy logic reasoning.

B.8 PELOPS

PELOPS (Program for the dEvelopment of Longitudinal micrOscopic traffic Processes in a System relevant environment) was developed at Technical University Aachen, Germany in cooperation with the BMW AG for research and development in future driver assistance systems. PELOPS is a combination of highly detailed sub-microscopic and microscopic traffic models, that permits investigations concerning the longitudinal dynamics of vehicles as well as an analysis of the course of traffic.

Features

PELOPS is orientated towards the fundamental elements of traffic, namely route and environment, driver and vehicle. The route-model covers the entire range from motorways to urban roads, including intersections and traffic-lights. In addition to the geometrical course of the road, the sign postings and the environmental conditions define the state of the route. The vehicle model includes the state of the engine, transmission, clutch, gears, load, engine torque, etc. and is based on cause-and-effect method. The driver behavior is based on car-following, lane-changing models. However, the most important feature is the integration of ACC-controller in the PELOPS simulation environment.

Appendix C

Transmission Range

We have two models for radio transmission range:

- *No fading:* a disk model with all the nodes within a certain distance from the transmitter receiving all the packets and all the nodes with more than that distance not receiving any packets.
- *Rayleigh fading:* a more probabilistic model with signal fading modeled by Rayleigh distribution resulting in some probability distribution for receiving a packet depending on the distance from the transmitter.

The following radio reception power thresholds were found for some common transmission ranges. The experiment was conducted with packets of 160 bytes. A total of 347 packets were sent and the percentage of packets received was monitored. For No fading scenario, the reception threshold was the minimum power at which 100% of the packets were received. For Rayleigh fading scenario, the reception threshold was the minimum power at which at least 70.7% of the packets were received.

Table C.1: The radio reception power threshold for different transmission ranges

Transmission Range (meters)	**Reception Power Threshold** (mW)	
	No Fading	**Rayleigh Fading**
100	-65.5	-67.0
200	-71.5	-73.0
300	-75.0	-77.0
400	-77.5	-79.5
500	-79.5	-81.0
575	-81.0	-82.5