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Road-based proactive routing protocols for vehicular networks

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ABSTRACT

ROAD-BASED PROACTIVE ROUTING PROTOCOLS FOR VEHICULAR NETWORKS

by
Neeraj Mahadevrao Rajgure

Vehicular networks are formed by vehicles communicating in an ad hoc manner or through cellular and IEEE 802.11 base stations. Routing in vehicular networks is challenging due to highly dynamic network topologies. Previous research done at the UbiNetS lab at NJIT has proposed the idea of Road-Based using Vehicular Traffic information (RBVT) routing. In RBVT, routes are sequences of road intersections, and geographical forwarding is used for sending packets between the intersections.

This thesis proposes two proactive RBVT protocols (RBVT-P and RBVT-PS) for city-based Vehicular Ad hoc NETworks (VANETs). RBVT-P is a completely distributed protocol that unicasts connectivity packets in the network to find the road-based topology graph. This graph represents a real-time view of the roads with enough vehicular traffic to ensure connectivity between intersections and is disseminated to all nodes. RBVT-PS uses a similar concept, but the road connectivity information is gathered and sent separately to a server via cellular links. The server centrally computes the connectivity graph and disseminates it to the nodes in the network.

The proposed protocols are compared against existing routing protocols. Simulation results for city scenarios show that both RBVT-P and RBVT-PS perform better than the existing protocols, with reduction in end-to-end delay as much as 85% and increase in delivery ratio as much three times. RBVT-PS reduces the delay three times and increases the delivery ratio by 10% when compared with RBVT-P.

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by
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To my family and friends who gave me support that made my dream come true. To my beloved wife Sheetal who kept me on track. To Dada who always believed in my abilities.

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CHAPTER 1

INTRODUCTION

In recent years there has been a growing interest in field of vehicular networks, primarily due to the advancement in technology and need for safety and entertainment applications. The current generation of vehicles have embedded computers, GPS receivers, and number of sensors, whereas the next generation of these vehicles will potentially have short-range wireless network interfaces and wireless access to the Internet. The Federal Communications Commission (FCC) has allocated 75 MHz of spectrum 5.9 GHz for the vehicle to vehicle and vehicle to road side facility for *Dedicated Short Range Communications* (DSRC) [54] in the United States. These capabilities support a wide range of applications that can be divided in two categories (a) safety and (b) non-safety. The safety applications include accident avoidance [37], [40], Co-operative driving [4] and police and fire vehicles communicating with each other for safety purposes. The non-safety applications include, traffic information for smooth traffic flow [38], file sharing for entertainment [39], comfort applications like toll service and accessing the Internet. A vehicular network in general is a network of vehicles that can communicate with each other; the network could be formed by use of infrastructure such as cellular or road side fixed equipment or on-the-fly in an ad hoc manner. The vehicular network that is formed in ad hoc manner without need of infrastructure is called a *Vehicular Ad-hoc NETwork* (VANET).

One of the core issues of vehicular networks is designing efficient and scalable routing protocols. Such protocols are needed for most of the above applications to come to reality. The development of new routing protocols is important because not only will they enable the addition of new dimensions to the vehicle through various applications in areas such as vehicular safety, but they will also transform it from being a mere transportation means to a smart vehicle. The requirements of routing protocol in VANET are significantly different than what they are in wired network or *Mobile Ad hoc NETwork* (MANET). Some of the major differences in VANET are (i) Mobility: due to which the topology is highly dynamic, (ii) Road layout: a node moves on the road, which constraint the packet to follow the road path, and (iii) Obstacles: due to which the communication on close-by parallel streets is restricted.

In past, the research has been focused on finding variants to MANET protocols and changing some of their parameters (to overcome issue of highly dynamic topologies) or developing reactive/geographical VANET protocols. Some of these protocols [33][34] do use the right approach of using road intersections as part of their routes but fail to use the real time traffic information or propose an expensive solution of deploying infrastructure such as deploying sensors to get the real-time traffic information.

The research group in the UbiNetS lab at NJIT proposed *Road-Based using Vehicular Traffic* (RBVT) routing [2]. As the name suggests, RBVT leverages real-time vehicular traffic information to create road-based routes. The created routes are successions of the road intersections that have, with high probability, network connectivity between them. A packet between consecutive intersections is forwarded using Geographical routing; this approach decouples routes from individual node movements. There are two main advantages in RBVT: (a) adaptability to topological changes by incorporating real-time vehicular traffic information and (b) stability in route by use of road-based routes and geographical forwarding.

This dissertation studies the effectiveness of RBVT proactive protocols in city-based environment. Proactive protocols are also referred to as table driven protocols. These types of protocol maintain route and periodically distribute updates throughout the network. The contributions of this dissertation consist of two proactive routing protocols designed and simulated, specifically for VANET. One of them is totally distributed, namely *Road-Based using Vehicular Traffic - Proactive* (RBVT-P), and other uses cellular network and a server for the control plane, namely RBTV-PS.

RBVT-P periodically generates connectivity packets that visit the connected road segments (a road segment is "connected" if there are enough vehicles to forward the packet between the two intersections that define this segment) and stores the graph of the roads function of the real-time vehicular traffic. As the connectivity packet returns to its originator segment, the gathered connectivity graph is disseminated to all nodes in the connected network. Subsequently, each node individually computes its shortest path to all the other road segments using this graph. When the need for data transfer occurs, unlike the reactive protocols, available route can be directly used for communication instantaneously without any future delays to find the route.

Many times a cellular link would be available, to see how RBTV-P would work if the control plane (i.e., routing traffic) is routed across the cellular link whereas data is transmitted over the Wi-Fi link in ad hoc manner. This other proposed protocol is called as *RBVT-P with Server* (RBVT-PS). Novelty of these proposed solutions come from the use of real-time traffic information and the way route between the source and destination is created. Unlike the MANET protocols, both the proposed protocols use road intersections as a part of route. Road intersections are stationary; having them in route is more advantageous than having a moving vehicle. The difference with respect to other VANET protocol is that the proposed solutions use real-time traffic information rather than the historic data. The use of road intersection as the guiding point helps when a moving vehicle goes out of range from the guided point. This vehicle (that moved out of range) can be replaced with other vehicle near the road intersection to forward the packet towards the destination. The need for such mechanism arises due to the highly dynamic changes in the topology. The proposed protocols being proactive are expected to be better in terms of end to end delay i.e. lowering the delay of end to end communication.

The simulation results for the RBVT-P protocol shows that it performs better than the MANET reactive protocols (GPSR [18], AODV [6]), one of MANET proactive protocol (OLSR [7]) and a VANET protocol (GSR [33]) in both delays and in delivery ratio, which shows that it applies well to the thesis claim. RBVT-P being a proactive protocol, is supposed to have a lower end to end delay compared to reactive protocols. The noticeable fact here is that it also outperforms OLSR, a proactive protocol with a difference of 50%. RBVT-P and RBVT-PS both not only outperforms the reactive protocols in delay but also have a higher delivery ratio with low overhead. Usually there is a trade-off between delay and delivery ratio and protocols are good in one of the two aspects. The reason for proactive RBVT protocols to be good in both the aspects is due to novel idea of using road intersections as the part of routes instead of binding it to the car nodes. In the comparison between RBVT-P and RBVT-PS, as expected RBVT-PS have better results than RBVT-P in end to end delay and delivery ratio. RBVT-PS has half the delay and 10% higher delivery ratio than that of RBVT-P. This better performance of RPVT-PS over

RBVT-P is attributed to the control plane communication over the cellular link.

The rest of the document is organized as follows. Next chapter reviews the background, describes the terminologies and illustrates the related work in VANET. Chapter 3 discusses the basic design of RBVT; chapter 4 describes RBVT-P and RBVT-PS along with the simulation results, all assumptions are also stated in that chapter. Simulation results are analyzed in chapter 5. The thesis concludes with conclusion in chapter 6.

CHAPTER 2

BACKGROUND

2.1 Categories of Vehicular Communication

Vehicular communication can be categorized in following three categories:

Cellular, Opportunistic using Wi-Fi Base station (infrastructure based), Ad hoc using Wi-Fi (or Dedicated Short Range Communications DSRC)

2.1.1 Cellular

In this type of network the nodes uses the cellular link [20, 11] for communication and in some cases can also use direct vehicle to vehicle communication for maintaining the information about the neighbors.

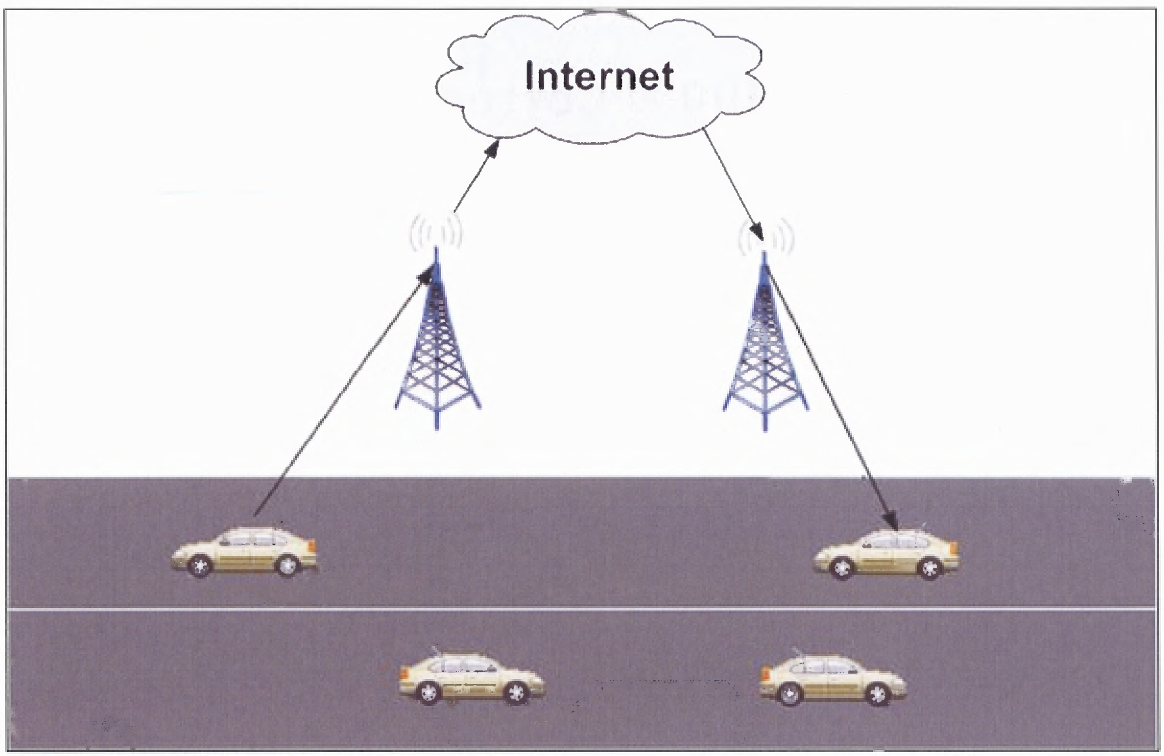

Figure 2.1 Car A communicates with car B using the cellular infrastructure.

A *Location-based Channel Access* (LCA) protocol [20] can be used in inter -vehicular communication network for various applications to achieve *Intelligent Transport System* (ITS). This scheme provides a dynamic decentralized access to the channel in the network. The basic idea of the scheme is to allocate each node a channel depending on its current location. The geographical area is divided into cells, depending on these cell coordinates, the channel is acquired by the node. When the node has to communicate, it finds its location from a positioning system (such as GPS); using this location it fetches the cell to which it belongs. Querying the mapping (present in memory) the node finds the channel identifier over which it communicates to other node.

In recent years, commercialized products [11, 12, 53] provide uninterrupted internet connection or remote services on mobile vehicle. OnStar [53] has a build-in GPS system that knows the precise position of the vehicle at every time. If the vehicle or the driver gets into any problem, vehicle data along with GPS location is gathered and sent over the cellular link to the call center automatically, where the agent can assist the driver.

Cellular networks get constrained to the areas of Cellular connectivity. The good feature of these networks is that they use existing infrastructure, but due to the dependency on infrastructure these solutions do not remain cost effective.

2.1.2 Opportunistic using Wi-Fi Base Station (Infrastructure Based)

This type of network requires deployment of new infrastructure [10, 13, 14, 15, 16] for the network communication. The infrastructure may include roadside equipment, remote servers, access points, cameras, onboard sensors and static roadside sensors.

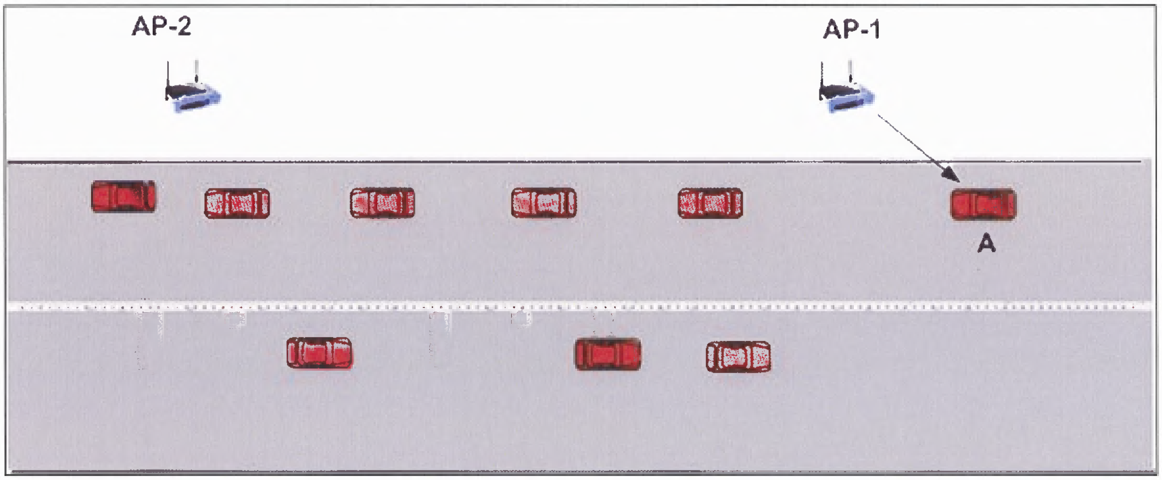

Figure 2.2 (a) The source Access point (AP-1) downloads file to a moving vehicle A.

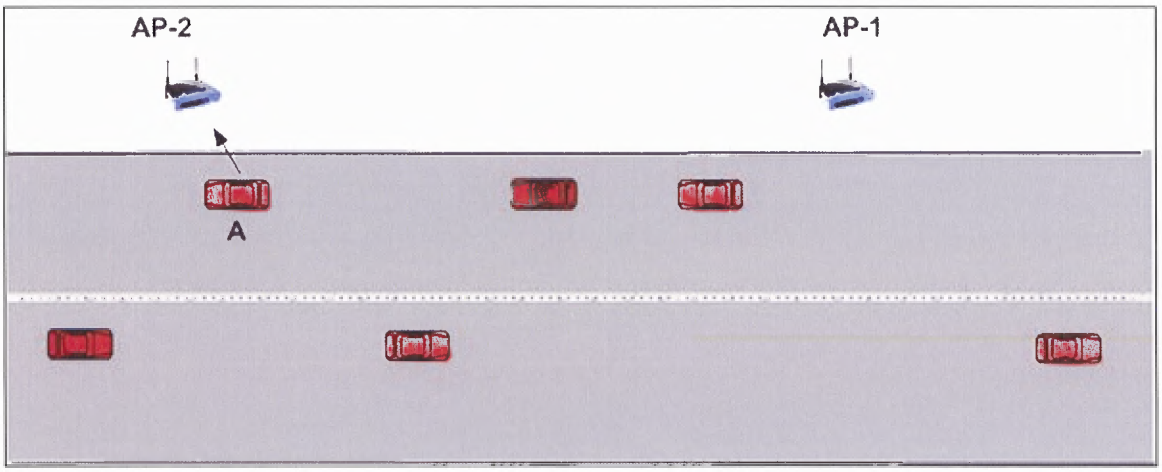

Figure 2.2 (b) The moving vehicle "A" reaches in the range of destination Access Point (AP-2) and uploads file to it.

Communication between two roadside equipments (called as access points) using the vehicular traffic is presented in [16]. Refer figure 2.2 (a) and 2.2 (b); when an access point (source AP-1) wants to send a file to other access point (destination AP-2) then AP-1 continuously transmits beacons in the available range. After establishing the handshake with passing by vehicle (A); AP-1 transfers the data to A that has to be sent to AP-2. If vehicle "A" goes out of range before whole file was transmitted, then S finds another vehicle using the same procedure and continues sending remaining parts of the file. Soon after vehicle "A" comes in the range of AP-2, it starts delivering the data to the AP-2. Similarly the remaining parts of the file are delivered by other passing vehicles.

Mobile Internet Access in FleetNet [10] proposes architecture for Internet Integration, a way by which the user in ad hoc inter-vehicle communication (IVC) can access the Internet. As the proposed solution not only provides Internet access to the vehicle but also lets other nodes on Internet to access services provided by this node so a fixed IP address for a particular vehicle is required. As the number of vehicles is too high using IPv4 does not help, therefore the solution uses IPv6. The TCP/IP communication requires a fixed network topology and reliable links for an efficient communication between the end points. The TCP/IP protocols are insufficient in handling mobility aspect of the vehicular network. As the vehicle node will move in and out of the range of gateways, the previously established connection with the internet host or unavailability of the vehicle node at certain times will terminate the TCP connection due to timeouts. To over come these drawbacks the authors propose an architecture called as MOCCA (Mobile CommuniCation Architecture). As seen in Figure 2.3, by use of the proxy between the gateway and the Internet cloud the vehicle received Internet access and also can provide Internet services to other hosts in Internet.

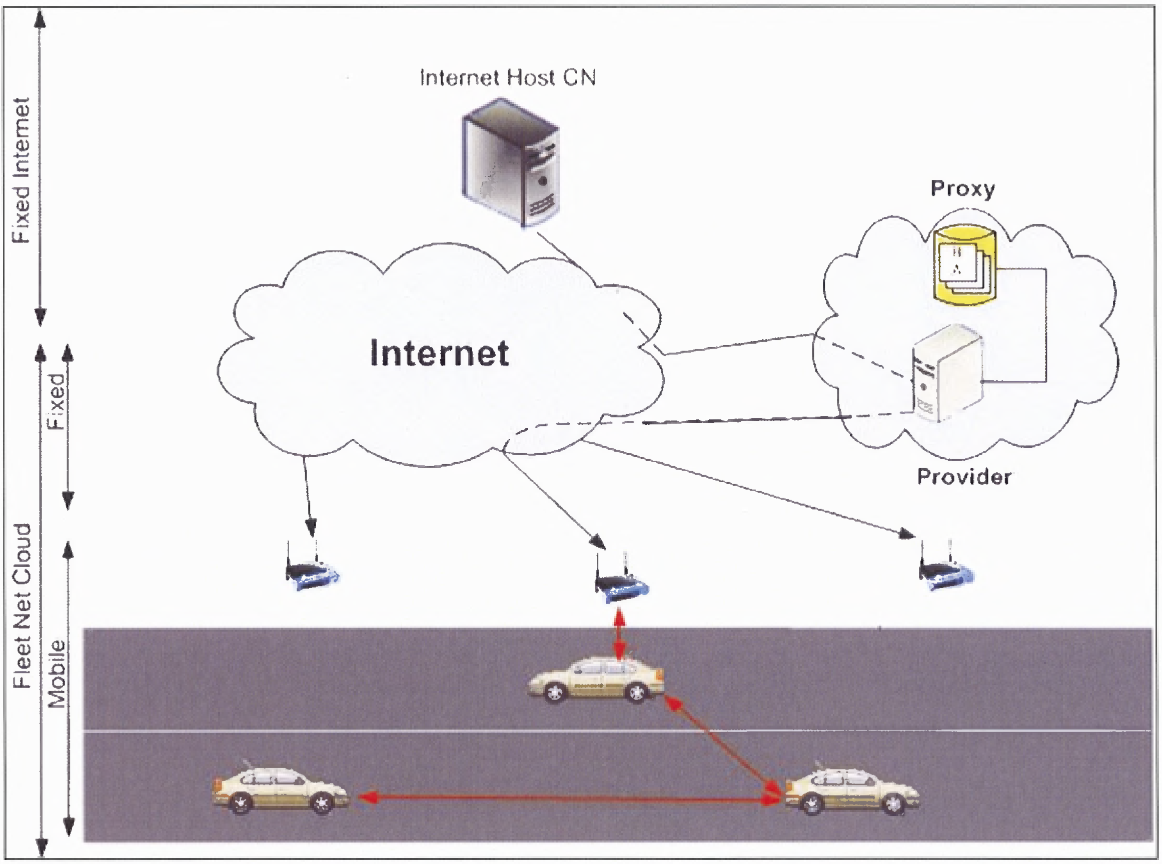

Figure 2.3 MOCCA's proxy based communication architecture.

Another application proposed by CarTel [13] has sensors coupled to cars. When the vehicle is on the move the sensors will gather various data (Environment related, civil infrastructure, etc). The collected data can be stored in the local database, when the vehicle comes in the range of infrastructure device like Internet access point; it transfers the collected data to the server. The server can process the data and make it available for analysis.

Even after their high benefits, these networks remain unattractive due to their high cost for installation and maintenance of the new infrastructure.

2.1.3 Ad hoc using Wi-Fi or Dedicated Short Range Communications (DSRC)

Vehicular Ad hoc NETwork (VANET) is formed by communication between vehicles and in some cases along with the roadside infrastructure. VANET are a form of *Mobile Ad hoc NETwork* (MANET) but differ substantially from them.

The following table mentions the differences between VANET and MANET.

Table 2.1 Comparisons between VANET and MANET

VANET	MANET
Vehicle follows a well defined path.	The mobile device has a fairly random motion (except in some exceptional cases like Robots in which the path may be predictable).
There is no battery life constraint.	Mobile devices have a constrained battery life.
At a given time there can be large number of nodes in a network.	In MANET the number of nodes participating is limited as compared to VANET.
Due to the network dynamics changes and speed of vehicles, frequent connectivity loss is usual in VANET.	It's usually uncommon to have frequent disconnections.

These types of networks are formed on-the-fly by the communication between vehicles. Due to use of de-centralized approach these networks have advantage of not requiring any infrastructure. Some of the envisioned applications include Monitoring the traffic [4], Context aware-Services [9], Alert Dissemination [41] and Peer-to-Peer [5, 21] systems.

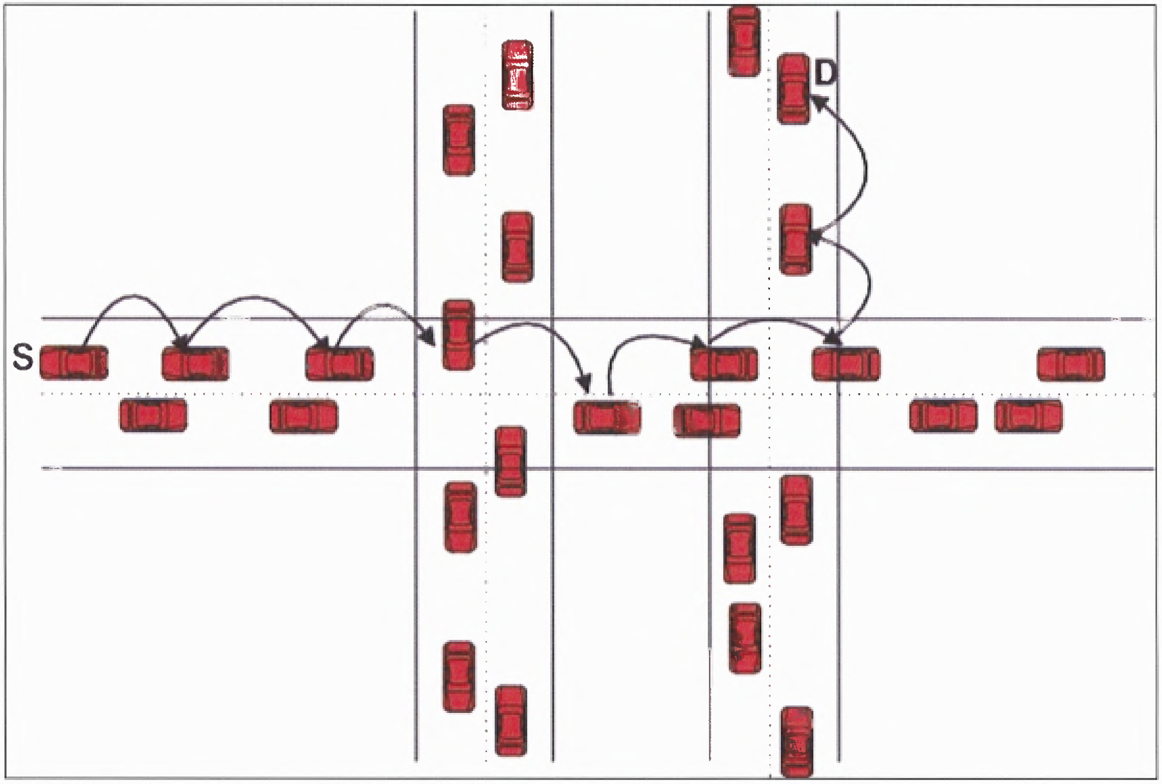

Figure 2.4 The source communicates with destination by use of intermediate nodes, the path is created dynamically.

TrafficView [4] is a system which can be used by the drivers in the vehicles to know the real-time traffic ahead of them (beyond the physical seeing capability). The authors propose a device which can be embedded in a vehicle. The vehicles that are equipped with these devices can communicate with each other. The traffic information gathered is periodically disseminated. The received information is stored in the local dataset where the node validates it; later in the next broadcast cycle disseminates it further to the other nodes.

A solution for peer–to-peer (P2P) system in VANET is described in [5]: A file contains multiple blocks (e.g., A, B, C and D). These blocks are independent and can reside on different nodes. When a file is requested by a user (source), the protocol broadcasts a request to its first hop neighbor with the name of the blocks it requires. The neighboring node having one or more blocks responds back to the source node with the block names present with them. The source node on receipt of all responses computes the missing blocks and sends back the request for the missing blocks again to its first hop neighbor. If the first hop neighbors do not have those blocks they forward the request to respective first hop neighbors. The process continues until, all the blocks for the requested file is received by the source. The source creates route between itself and each node possessing one or more blocks for the file transfer to take place. If required, the file transfer takes place in a multi-hop manner.

The glaring trade off of these networks is the Security concern due to the lack of central control. The advantages include scalability and low infrastructure needs.

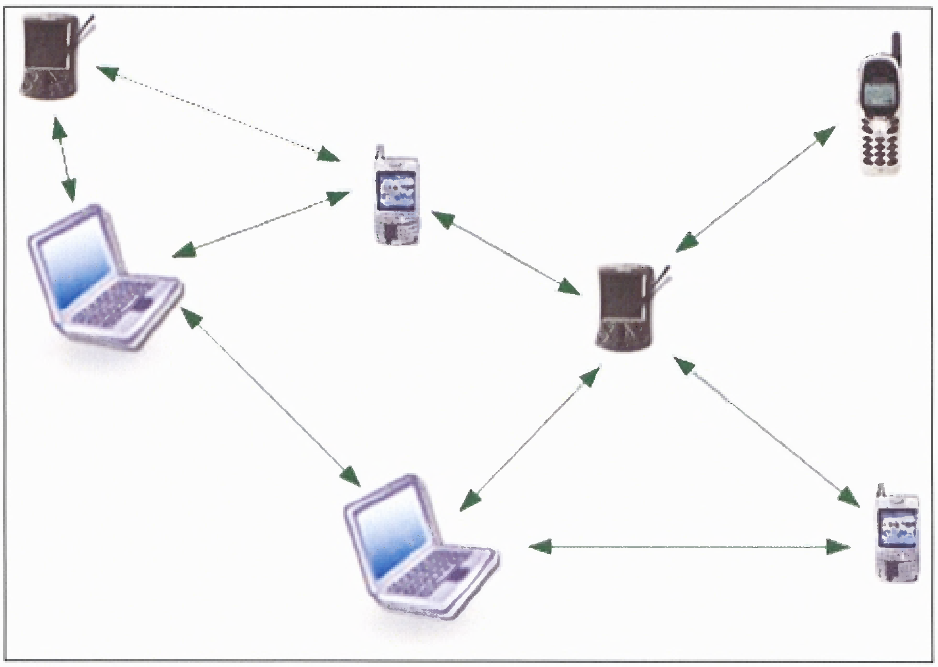

Figure 2.5 Formation of mobile ad hoc network.

2.2 Routing in Mobile Ad hoc NETwork (MANET)

MANET is a collection of wireless mobile nodes that form a network without any need for infrastructure or central administration. Various protocols [17, 18, 19] and applications such as EZCab [3] and Peer to peer networking [8] have been proposed for MANET. The IETF MANET working group [55] is formed to standardize the routing protocols for MANET. The protocols in MANET can be categorized as Reactive, Proactive and Hybrid. Each of these types has their own applications; the correct protocol for an application depends on how delay sensitive the application is, and the amount of network overhead that the application can afford.

2.2.1 Reactive

In reactive protocols the route discovery to the destination node is initiated when, the source node has data to send to the destination, for this reason these protocols are also called as "On Demand" protocol. The proposed protocols [6, 17, 24] follow the same technique; the advantage of having route discovery when required, reduces the overhead of message exchange. Typically these message exchanges are required so that the route be proactively maintained. If there is no maintenance of route, then that adds a delay to the delivery of first packet and to every first packet after the route break. The other disadvantage is that all the packets sent in the period between the route break and the source realizes it; are dropped decreasing the performance of these protocols.

AODV [6] proposed a reactive routing protocol that does route discovery when needed by a node. The neighbors list is kept updated by use of Hello beacon. When the source node wants to transmit data it checks routing table to find whether valid route to destination node exists. If no such route exits, it broadcasts a RREQ packet on the network. The node that receives the request packet queries its routing table to find if a valid route to the destination exists, if a valid route exists this intermediate node returns with the RREP message else the node forwards the request (RREQ) to its neighbors and so on till the destination node receives it and replies back with RREP packet. Only the nodes on the currently active path update the routing table; that makes AODV a truly On-Demand routing protocol.

The Dynamic Source Routing in Ad hoc Wireless Network [17] is another reactive protocol for MANETs. The route discovery (if the route is not present in the cache) is started when the source node wants to send data to the destination node. When an intermediate node receives a packet it updates the cache for the routing related information that can be used in future. Unlike AODV, DSR is a source routing protocol i.e. the source stores the whole route up till the destination in the packet. This stored route indicated the intermediate nodes the packet should move through, due to which all the nodes in the ad hoc network need to know the topology of the network.

2.2.2 Proactive

In contrast to reactive routing protocols the proactive protocols [7, 32] try to maintain a path between every node to every other node in the network. The advantage of proactive protocols is they usually do not cause delay in first packet as the route to the destination node already exists in the routing table. The situation when route break occur the node may have an alternate route to the destination. When the source node does not have any route at a given instance, it cached the packet at source node itself to avoid dropping of packets by intermediate node. Maintaining routes adds overhead on the network. Proactive protocols do not need the route discovery process when the data for transfer is available as it maintains a route in the routing table for every possible node in the network. The advantage of using proactive routing is the decrease in time delay when the source wants to transfer data to the destination.

The rfc 3626 for OLSR [7] proposes the protocol that maintains routing table by exchanging topology information. Each node that advertises the routing table sends the information of its links with its neighbors which are in multi point relay. Multipoint Relay (MPR) is chosen by group of nodes which announces the topology information in its control packets. The control packets do not have to be transferred reliably as they are often generated. Hello messages are passed between the nodes to select the MPR. The hello messages received for maintaining connectivity between the neighboring nodes are not forwarded to the next hop to avoid flooded in the network.

DSDV (Highly Dynamic Destination-Sequenced Distance-Vector Routing) [32] is also a table driven protocol. The routing tables are stored and maintained at each node of the network. After a time interval each node advertises (broadcast or multicast) the update that it is aware of except for the ones that are about to expire. The shortest route (in terms of hops) is used when multiple routes from one node to other are present.

2.2.3 Hybrid

Hybrid protocols are those that combine advantages of both proactive and reactive protocols; the basic aim is to get a balance by reduce delays that occur in reactive protocols and control overhead that are present in proactive protocols. The usual technique that is used is by dividing the area in grids or zones. At zone level proactive approach (table driven) is employed and for interzone communication reactive approach is used (on demand). These types of protocol [25, 26, 27, 28] try to create a balance by taking advantage of both the approaches, they can be further classified as node centric [26, 27] and cluster centric [28, 29, 30].

Zone Routing Protocol [25] is one of the Hybrid protocols which use a proactive approach for local neighboring nodes and reactive approach when the data has to be transferred between zones. It reduces the network overhead caused by either approach. The search for destination which is at global level can be preformed quickly by querying selected nodes in the network. The protocol uses a method called as boarder-casting instead of broadcasting for the request packet (RREQ) like in cases of AODV [6], which reduces the overhead that is caused by reactive protocols while formation of route between the source and destination.

Some of the other protocols employ the same scheme with some variation; the TZRP [31] uses the two zone concept which aims at separating the ability of the protocol to adapt to the traffic characteristic and mobility. The other variation is in the node centric protocols such as [27] in which some nodes are designated as special nodes. The route between the special node and ordinary node is maintained in proactive way whereas the route between ordinary to ordinary nodes is discovered reactively.

2.3 Routing in Vehicular Ad hoc NETwork (VANET)

VANET is a type of vehicular network which operates without any need of infrastructure in an ad hoc way. A number of protocols have been proposed in VANET based on different environment like City [33, 34] and Highway [61]. The different forwarding schemes topological [7] or geographical [34] are used by these protocols to transfer data packets. Topological differs from geographical routing by its node centric approach, where as in geographical routing the next hop node is selected on the fly. Topological routing is not suitable for VANET, due to high node movement which causes frequent connectivity losses.

One of the proposed protocols [33] for VANET uses the position based routing method. The source broadcasts a "position request" packet with destinations node identifier when it wants to transmit data to the destination, on receipt to this packet by destination node, it replies back with the "position reply" packet to the source node. While broadcasting, the protocol avoids the problem of extensive flooding and well-known broadcast storm problem [35] by optimizing the broadcasting. The source node stores the intermediate road intersection information in the packet header so that the data can be transferred to the required destination. The packet transfer between the intersections is done in a greedy way.

GyTAR [34] propose improvement to other protocols [42, 43] in two areas, (a) Junctions selection and (b) forwarding data. The destination discovery packet uses a mechanism that assigns score to each candidate junction in the vicinity of current junction. The scores depend on the densities of the road and other factors. The packet is forwarded to the junction that gets highest score. While sending the data packets the sender marks it with discovered destination junction. An intermediate node decides the next hop from its table of neighbors. This table is updated when the hello packet are received. The hello packet contains information such as current position, direction and velocity. This information helps a node to predict the latest position of the next hop.

CHAPTER 3

Overview of Road-based Routing using Vehicular Traffic Information (RBVT)

Road-Based using Vehicular Traffic (RBVT) routing [2] protocols leverage real-time vehicular traffic information to create road-based paths. The created routes are sequence of the road intersections that have, with high probability, network connectivity between them. Geographical forwarding is used for forwarding a packet between the consecutive intersections; this approach decouples routes from individual node movements. RBVT routing has two main advantages: (a) adaptability to topological changes by incorporating real-time vehicular traffic information and (b) stability in route by use of road-based routes and geographical forwarding.

3.1 Route Construction

Routing is a process of moving packets through the network. It consists of two separate, but related, tasks: (a) Defining paths for the transmission of packets through the network and (b) Forwarding packets based upon the defined paths. The tasks are achieved with the help of routing table. RBVT [2] being proactive protocols the routes table are updated for every know change of topology. Usually the protocols [6, 7, 32] that have been derived from MANET use node centric approach, these protocols do not work well due to the dynamic nature of the network. The other protocols [33, 56, 57, 58] use the road-based approach, these protocols use the right approach but most of them [33, 58] do not factor in the current road traffic and rather try to use the shortest distance to reach from source to destination, which currently may not have any traffic. The protocols fail to consider traffic flow; some of the protocols [57, 34, 59, 60] try to work around this problem by using historic data. Due to the events such as road constructions or traffic redirections which are not rare, the historical data does not remain an accurate indicator of the current road traffic flow.

The RBVT [2] protocols use road intersection as their building block. When a source wants to transfer data to the destination, instead of tying particular nodes to the route towards the destination it uses the road intersections. As long as the road segments remain connected it does not matter if the connectivity between the individual nodes on a road segment exists. The fault in binding a particular node to a route is due to the node movement, it may not remain in the sight of the route.

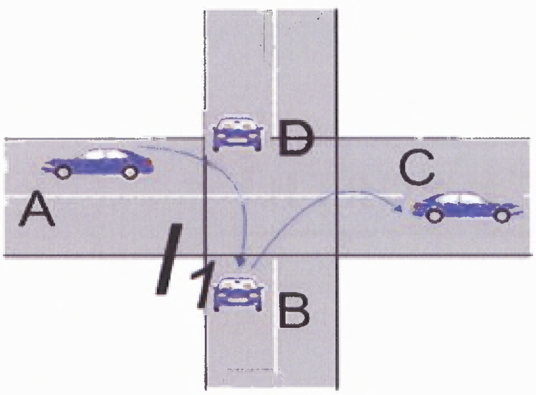

Figure 3.1 (a) At time t, node "A" can reach "C" through "B".

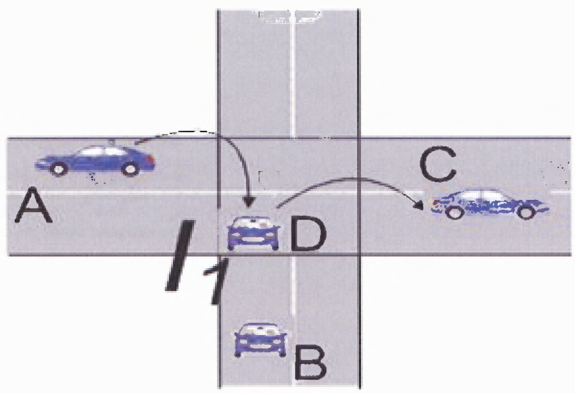

Figure 3.1 (b) At time t + 1, node "A" could have reached "C" through "D".

The above figure shows how useful it is to use the road intersection as the intermediate point rather that binding the next hop as a particular node; if the route was bound to intermediate node "B" there would be a route break when node "A" would want to communicate with node "C". This is the major reason why the proactive MANET algorithms like OLSR [7] fail to perform well in VANET. The RBVT protocols use the road intersection as the guiding point, in the above e.g. if the node "A" wanted to send data to node "C" it would have bound the path to intersection "I1" instead of node "B". Later on at time t+1 node "A" would have found node "D" to forward the packet to node "C".

3.2 Forwarding

A node periodically broadcasts hello messages; the receiving node updates its neighbor table using the information provided in hello message. If a hello message is not received from a particular neighbor within a time interval the entry is purged; non-receipt of hello messages is a strong indication that the other node is travelled out of communication range. When the source node wants to transmit data to destination node, it queries the routing table for the available routes to the destination; if there are multiple routes from the source to destination, the route with minimum number of intersections is used. This desired route is stored in the packet for reference of the intermediate node. The protocol uses loose source routing to forward data packets in order to improve the routing performance. The intermediate nodes are free to change the path in the packet if they have latest connectivity information. The node that stores or updates the route information in the packet also writes the timestamp of the connectivity graph that was used for determining this route. The intermediate node compares its connectivity graph timestamp to decide if a better routing decision can be made. Due to the high volatility there could be route breaks, in such cases the intermediate node tries forwarding the data packet using geographical forwarding method until it reaches a node that has fresher information and there exists a route from that node to the destination; this newly found route is updated in the packet and forwarded further towards the next intersection. In between intersections the packet is forwarded using geographical forwarding; this is advantageous as the node always selects the farthest possible neighbor node to forward the packet.

In this class of routing there are particularly two advantages: (a) it is adaptive to network topology changes by using real-time vehicular traffic information and (b) the stability of route through road-based routes and use of geographical forwarding.

CHAPTER 4

RBVT-P and RBVT-PS

4.1 Proactive RBVT

The proposed solution (RBVT-P and RBVT-PS) are different from other VANET protocols as they proactively maintain the graph of the connected road segments at each node which gives the real-time view of the network. Being a proactive protocol it is more suitable for delay sensitive applications such as real-time voice, video or online gaming.

The proactive RBVT assumes that each car node is equipped with digital maps (e.g., Tiger Line database [22]), a Global Positioning System receiver (provides location and time synchronization), a navigation system that maps GPS positions on roads and a location service such as [44] that the source can query before sending the data to destination node. No assumption is made as to the symmetry of the links. In addition to above, the second proposed solution also assumes a cellular link between each car node and the server.

4.2 RBVT-P

RBVT-P is a proactive routing protocol for VANET; it periodically discovers and disseminates the real-time road connectivity graph. The source node uses the connected shortest available path to the destination. The path consists of intersections that are found connected in the real-time view. RBVT-P uses a location service, to find the destination position. Due to the dynamic nature of the network, RBVT-P does not bind the forwarding of packets to a particular node like AODV (which are node centric).

4.2.1 Topology Discovery

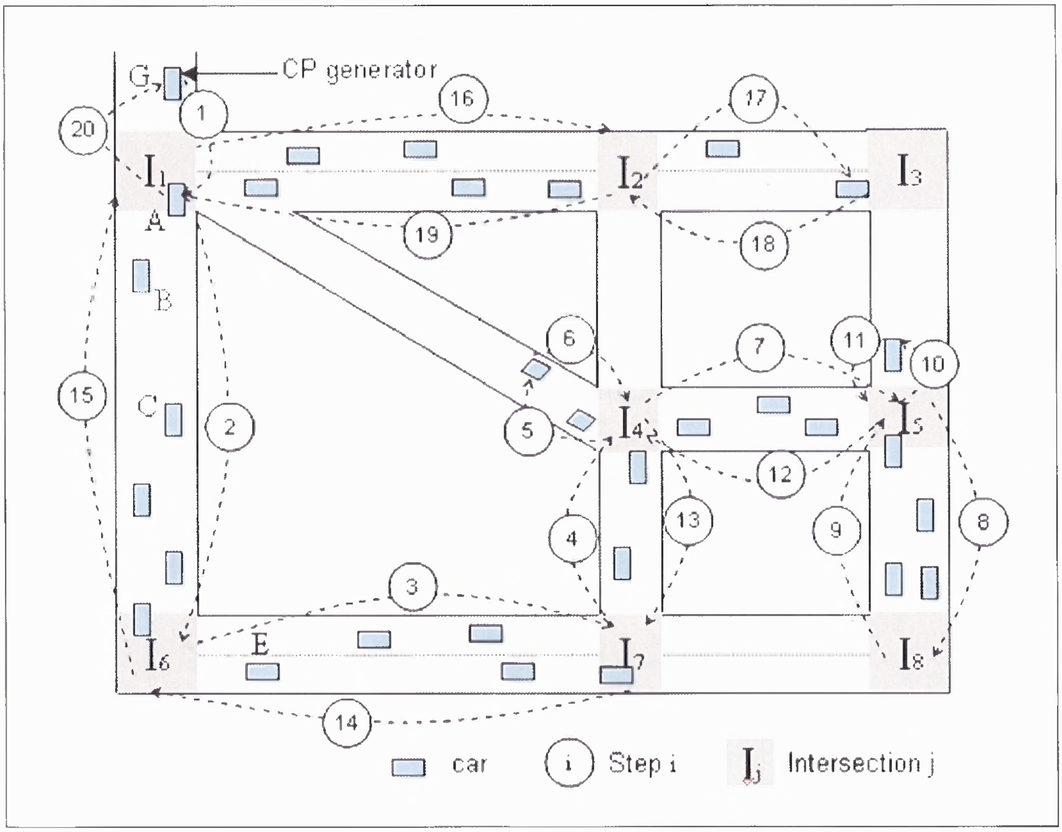

Figure 4.1 The topology discovery by use of CP.

The topology is discovered by use of *Connectivity Packet* (CP). The CP is a packet that traverses the connected road segments and stores the visited intersections in it. This information is later used to create the connectivity graph which is then disseminated in the network to other nodes. The CPs are generated periodically by a number of randomly selected nodes in the network. The CP packet traverses the road intersection by use of algorithm similar to DFS graph traversal, as the packet moves from one intersection to other intersection the road segment is marked as connected otherwise as un-connected. The CPs are periodically generated by a CP generator node, they are unicasted to discover the network topology. Figure 4.1 demonstrates step by step path of one CP showing how it sequentially visits connected road segments and records the segment information that has enough vehicular traffic. A point to note, that the CP traversal is not expected to end at the same vehicle node that initiated it; rather it ends at the same road segment from which it was initiated at.

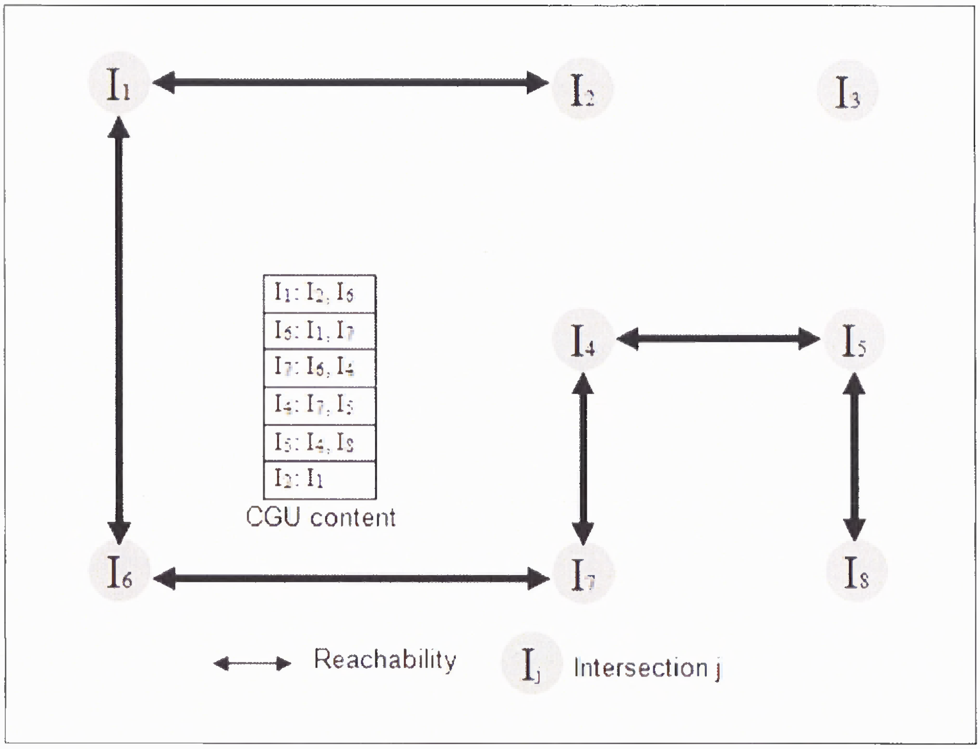

Figure 4.2 The connectivity graph generated after the traversal.

4.2.2 Topology Dissemination and Route Computation

The node that finally receives the CP on the generator segment extracts the information in the CP to generate a *Connectivity Graph Update* (CGU) packet and disseminates the CGU to other nodes in the connected network. Figure 4.2 shows the connectivity graph created after the traversal in Figure 4.1. Upon receiving the latest CGU, each node updates its routing table and re-computes the shortest paths to all other connected intersections. One of the fields of each entry in CGU is timestamp, with the use of this field the node determines whether the information it already has or the information the CGU contains is the latest one. The timestamp of each entry is retained in the routing table to identify and remove the stale entries at later point of time.

When the source has to transmit information to the destination it determines and uses the shortest path through the connected intersections. The path is made of sequence of intersections and is stored in the header of the data packet. The packet is forwarded geographically between the consecutive intersections, defined in the path. As described in section 3.1.2 the protocol uses loose source routing so the intermediate node is free to update the path if it has more recent information about the topology. Appendix presents the pseudo-code for topology discovery using connectivity packets and route update process.

4.2.3 Route Maintenance

The RBVT-P generates CP frequently (which in turn generates CGU) that keeps the nodes updated with the topological changes. The CPs are generated from different section of the network so that the information of particular section is gathered by the nodes in that section. The node in an isolated section cannot know the connectivity information about other section till the disconnection between these isolated networks is bridged.

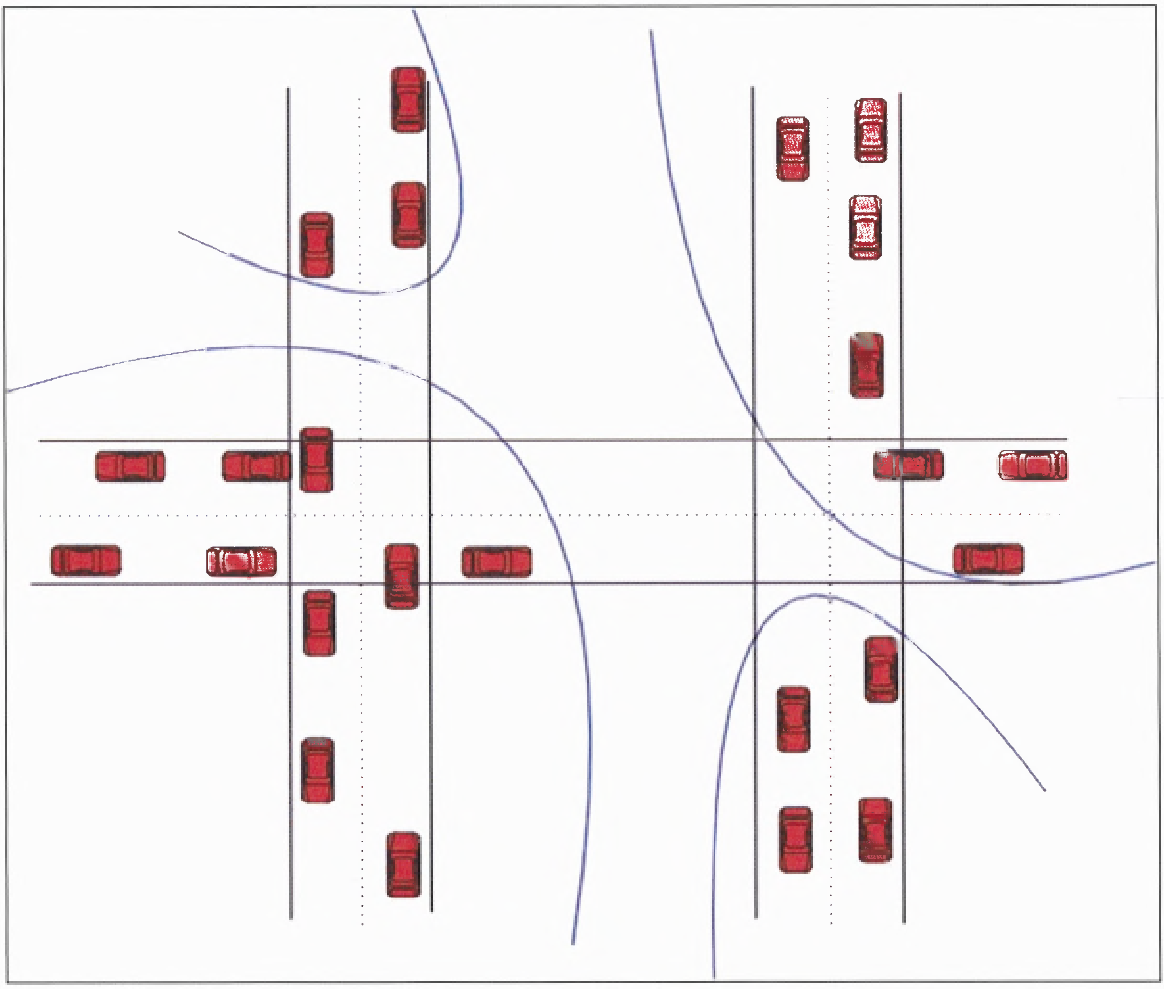

Figure 4.3 Network partitioned due to low density.

The frequency of generating CP would depend on the network size and density of nodes in the section of the network. Higher the density, lower number of packets are required as the probability of finding the replacement node increases. In a CP generation interval, multiple CP are generated to avoid the problem of loosing connectivity information in a CP round when CP packet is lost. The CP passing protocol is not a reliable protocol but a best effort delivery so there are chances of them getting lost.

In general CGU's are influenced in two ways, (a) Time interval at which CPs are generated and (b) Number of CPs generated in CP generation interval. These parameters also determine the quality of topological information gathered. The first parameter depends on the density of nodes in the network and second one would depend on how unreliable is the network.

4.3 RBVT-PS

4.3.1 Design

RBVT-PS like RBVT-P is also a proactive protocol. It uses a concept called as Road Connectivity Packet (RCP) that is similar to CP used in RBVT-P. The car node on the road considers itself the most forward if it does not receive any packet for a timeout interval; similarly it considers itself most backward if it does not find any node to which it can send the RCP. The nodes backward/forward direction is irrespective of the driving direction; each road in the map is assigned a direction that is stored along with digital map in the node. The communication between the node and the server takes place using the Cellular technology whereas the communication between the nodes is through Wi-Fi wireless technology.

4.3.2 Topology Discovery

The most forward node on the road sends the RCP to the node behind it. The intermediate node continues forwarding this packet to the node behind it, eventually reaching the most backward node (no other node behind it on that road which this backward node can communicate). This most backward positioned node on the road sends the gathered connectivity information through its GPRS interface to the server. The connectivity information entry is of the form <StartInterID, EndInterID, ExpirationTime>; where

StartInterID indicates the intersection id from where the connectivity begins, EndInterID indicates the end intersection till the connectivity on the road segments exists and the ExpirationTime indicates the time till the road segments are valid. The expiration time is calculated by addition of Maximum connectivity valid period (protocol configurable value) and current time. The connectivity information is gathered for the segments through which a RCP traveled. The RCP may also implicitly indicate the non-connectivity of two segments the one before the StartInterID and the one after EndInterID to the block of connected segments.

The server receives one RCP from each set of connected nodes; there can be multiple RCPs for the same road depending on the connectivity pattern on the road. For e.g. in Figure 3.1 on road segment S1 of road R3, the five nodes create an isolated network from the nodes on segment S2 on the same road, in these cases there are two different RCPs that are sent to the server from these two sections on the same road. In the figure R1, R2 and R3 indicate roads and S1, S2 and S3 designate the segments on the roads. The pair <Road><Segment> uniquely identifies the segments. The car nodes on the roads are named N1, N2, N3 and N11.

The car N1 being the most forward node on road R1 starts a RCP, every node that has the responsibility to send this packet tries to send it the most farthest possible node so that the discovery of information is faster and this also makes the protocol more efficient. In the example N1 skips node N2 and sends the packet directly to N3 as N3 is in the wireless range of N1. The packet is similarly forwarded to the most backward node (in this case N11), which then sends the packet to the server for re-computing the real-time graph. I1 to I8 indicate the intersections or end points of the roads.

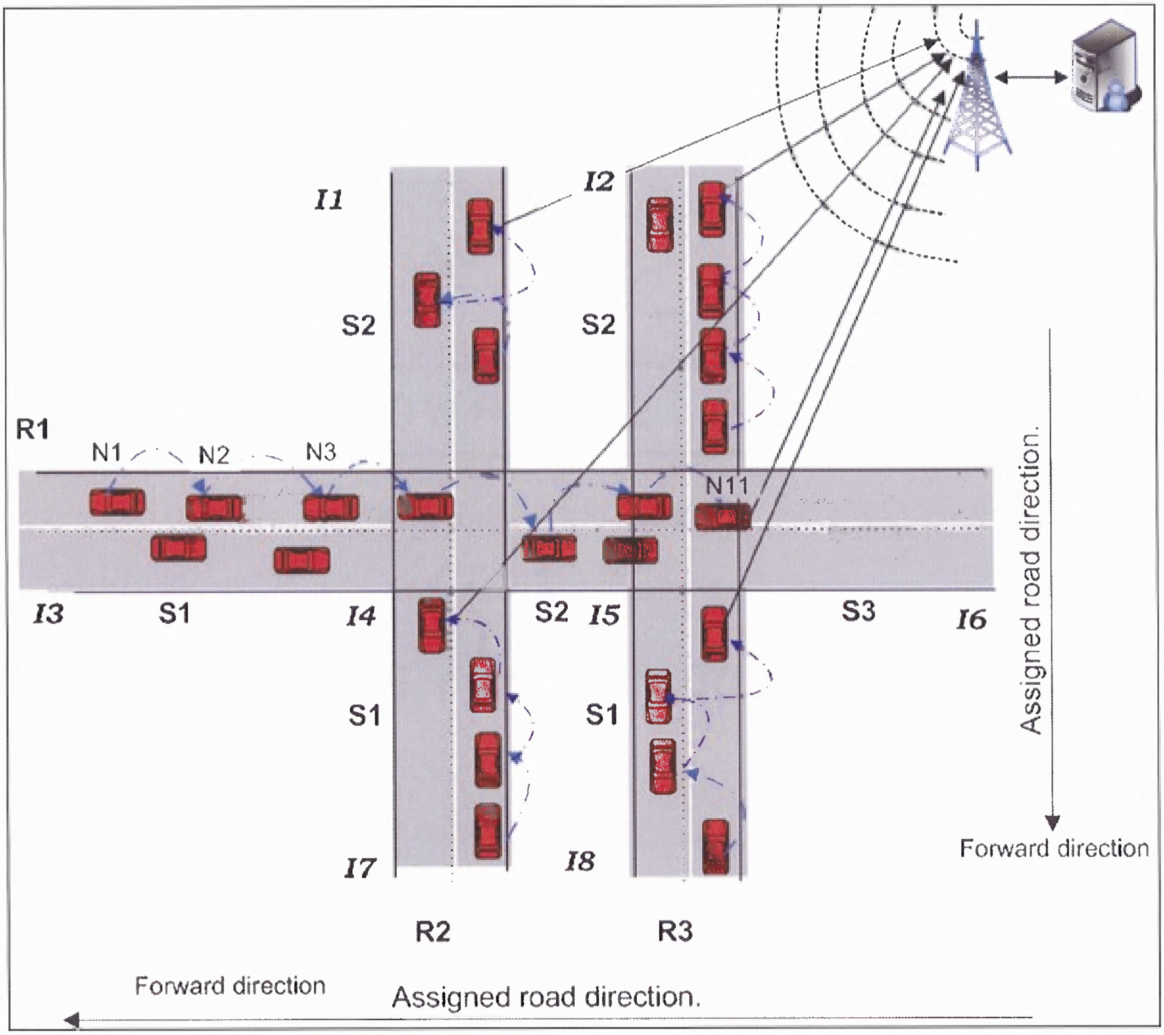

Figure 4.4 Most backward cars on the each road send RCP to server. After computing the real-time graph it is sent to the node which sent this RCP.

4.3.3 Topology Dissemination and Route Computation

On receipt of each RCP the server updates the connectivity graph. In comparison with RBVT-P, this same task is done by the node that finally received the CP from the segment where it was initiated (this indicates that an iteration of connected graph is complete). Once the server rebuilds the connectivity graph, it transmits this graph back to the node that sent the RCP that triggered the graph computation. The node then disseminates this information by broadcasting it to the neighbors. This continues till the most forward node receives the information. Similar to RBVT-P each node then runs Dijkstra's algorithm on the newly received connectivity graph to find the shortest path to all the connected segments in the map. Further on, when a source node wants to transmit data, it stores the connected available shortest path in the packet header. These routes, represented as sequences of intersections, are stored in the data packet headers and used by intermediate nodes to geographically forward packets between intersections.

To give an example of how the above process contribute to the view of a node. In figure 5.1, say node N11 is the last node to send the RCP out of the five RCPs sent to the server. The time difference of the RCP sent should not be more than α, where α is the period between the round of RCP generation. On receipt of RCP from N11, the server recomposes the graph and sends it to node N11. The node views the received graph as shown in figure 5.2, the dotted lines indicate no connectivity between the intersections (or on that segment) and the bold lines imply the connected component of the graph from the intersection I5 at which node N11 is present. The road segment S2 of road R2 is not reachable as there is no node in the connected graph that could communicate with the cluster of nodes that are present towards intersection I1. Similarly as there is no node towards the intersection I6, that intersection remains unconnected from intersection I5. From figure 5.1 it is seen on road R3, the segments S1 (I5 to I8) and segment S2 (I2 to I5) generated two different RCPs, which mean that nodes on those segments are not able to communicate due to the distance between them, but as seen in figure 5.2 the graph is created as showing them connected; the server generated the graph with global view. The nodes at the intersection I5 on road R1 can bridge the gap to forward the traffic between the disconnected segments S1 and S2 on road R3.

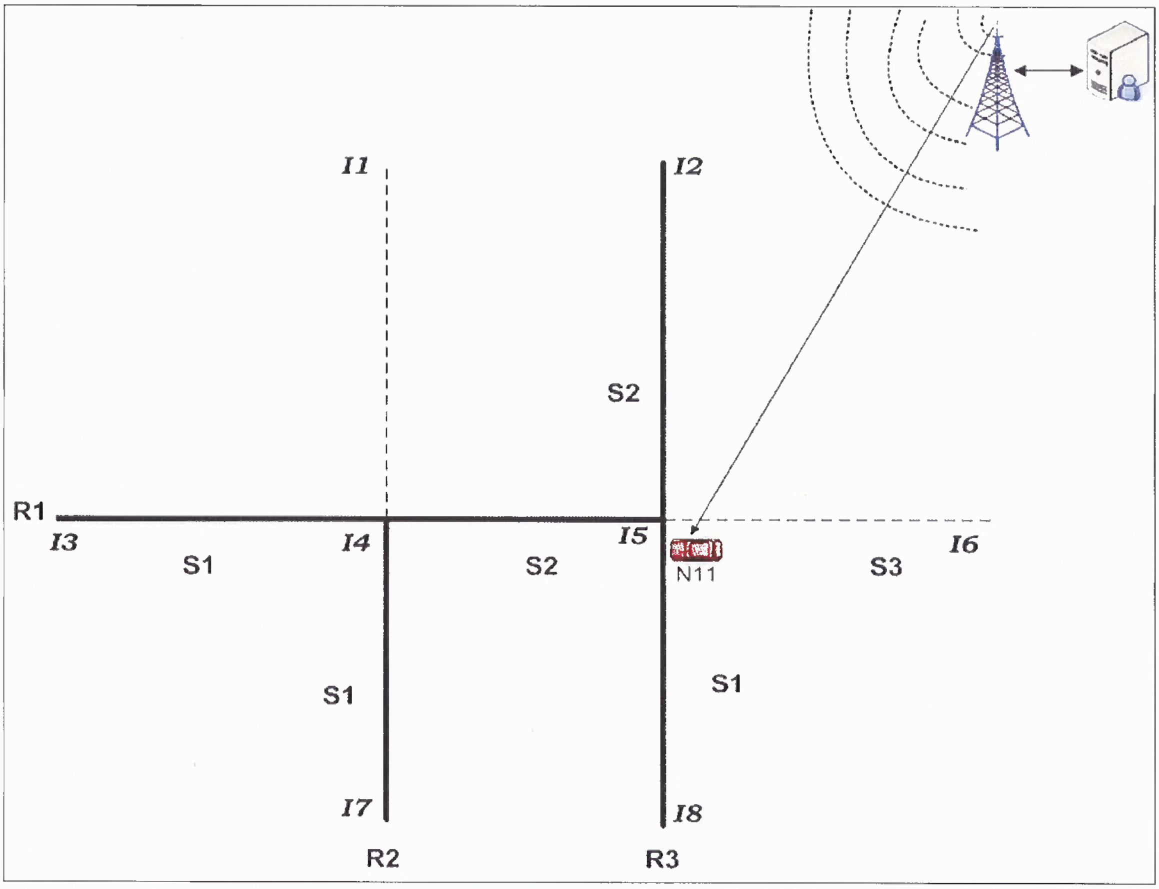

Figure 4.5 View of most backward node on road R1 after receiving the updated connectivity graph from the server.

4.3.4 Route Maintenance

In RBVT-PS, the forward node on the road frequently generates the RCP, which eventually gathers the connectivity information of the road segments that are connected and sends it to the server. The server sends the computed graph to the node that recently reported the connectivity (RCP). This node disseminates the information to its neighbor and those neighbors send it to their neighbors and so on.

CHAPTER 5

PERFORMANCE

This chapter presents the evaluation of the proactive RBVT protocols using the Network Simulator NS-2 [1]. To evaluate the performance, an urban scenario with obstacles (to model buildings) is used. The two proactive protocols RBVT-P and RBVT-PS are compared against four existing VANET/MANET routing protocols. The following, presents the evaluation methodology, the metrics used to compare the protocols, and the analysis of the simulation results.

5.1. Evaluation Methodology

The evaluation consists of two parts, one comparing RBVT-P with RBVT-PS and other where RBVT-P is compared with four existing routing protocols AODV is a MANET reactive routing protocol, GPSR is also a MANET position based routing protocol, GSR is a VANET position based routing protocol whereas OLSR is a MANET proactive link-state routing protocol.

In AODV, a route is created reactively, when a source vehicle node wants to communicate with a destination node. The route creation involves flooding a route request message and recording the sequence of nodes which forwarded the request to the destination node. This sequence of nodes constitutes the path from source to destination. In OLSR, each node maintains sets of 1-hop and 2-hops neighbors and selects some neighbors as multipoint relays. OLSR proactively discovers and disseminates link state information over the multipoint relays backbone. Using this topology information, each node computes the next hop to every other node in the network using shortest path hop count forwarding. GPSR is a position based routing protocol which forwards data packets using greedy geographical forwarding from the source node to the destination node. When a node cannot find a neighbor node closer to the destination position than itself, a recovery strategy based on planar graph traversal is applied. In GSR, every vehicle node is equipped with a GPS receiver and holds a digital map of the region. A source vehicle which wishes to communicate with a destination vehicle creates the shortest path based on the roads layout from its position to the destination position. This route is made of a sequence of road intersections. Data packets are forwarded using greedy geographical routing along this path. No consideration is given to the vehicular traffic.

5.2. Metrics

The evaluation performance of these routing is done using different Constant Bit Rate (CBR) data rates, different network densities and different numbers of concurrent flows. Following are the various metrics to evaluate the performance:

- **Average delay:** This metric defines the average delay occurred for the transmitted data packets that are successfully delivered. The average delay characterizes the latency introduced by each routing approach. For a proactive protocol this is the primary metric, unlike reactive protocols proactive protocols maintain routes between source and destination which leads to reduced delays.
- **Average delivery ratio:** This metric defines the number of data packets successfully delivered at destinations per number of data packets sent by sources (duplicate packets generated by loss of acknowledgments at the MAC layer are

excluded). The average delivery ratio gives the measure of the routing protocol to transfer end-to-end data successfully.

- **Average number of hops:** This metric defines the average number of nodes that are part of successful packet delivery from source to the destination. Historically, the average number of hops was a measure of path quality. This metric is used to study if there is a correlation between the number of hops and average delivery ratio and average delay, respectively.
- **Overhead:** This metric is defined as the number of extra packets per number of unique data packets received at destinations. The number of extra packets consists of routing packets (i.e. routing overhead) and duplicate data packets. Therefore, the overhead measures the total overhead per successfully delivered packet.

5.3. Simulation Setup

The map is 1500 m X 1500 m area extracted from the TIGER/Line database of the US Census Bureau [22]; below figure shows the map used, which is an area of Los Angeles, California.

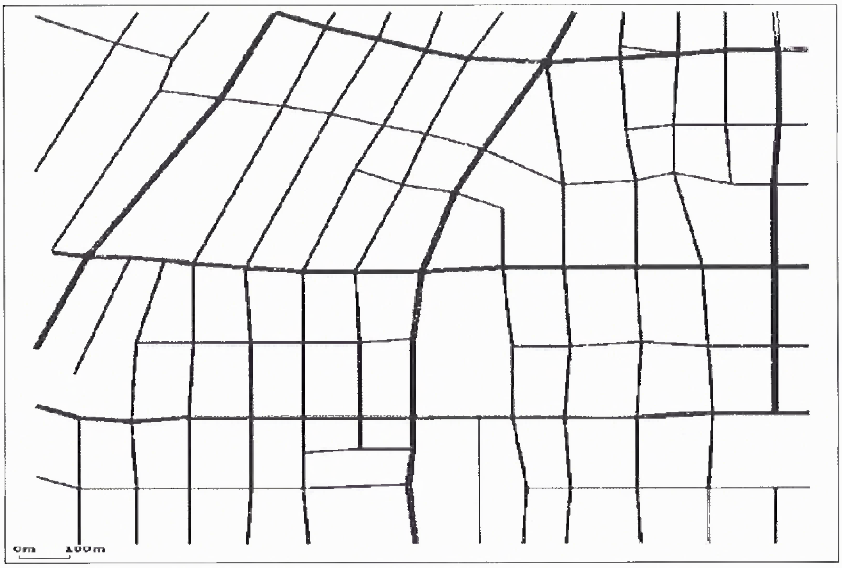

Figure 5.1 City map used for simulations

The evaluation of RBVT protocols is done using Network Simulator NS-2 [1] simulation. The movement of the vehicles is generated using open-source microscopic, space-continuous and time discrete vehicular traffic generator package called as SUMO [45]. SUMO uses a collision-free car-following model [46]. The extracted Tiger/Line map is inputted into SUMO, the information such as road speed limits, traffic lights and number of lanes is also inputted. Not more than one-fifth intersections have traffic lights. The output file from SUMO is converted into the required node movement format of NS-2 simulator.

For the wireless configuration, at the physical layer, the shadowing propagation model is used to characterize physical propagation. The communication range of 400m with 80% probability of success for transmissions is set. Some studies [47] have reported real-life measurements between moving vehicles in the range of 450m and 550m. Additionally, while the DSRC standard specifies a range up to 1000m for safety applications, many non-safety applications are expected to reach 400m [48]. The values path-loss-exponent = 3.25 and shadowing-deviation = 4.0 in equation of Shadowing propagation [49] are used in NS-2.

The obstacle model simulates buildings in a city environment; the contour of each street can either be a building wall (of various materials) or an empty area. Thus for each street border, the signal attenuation value is set to a randomly selected between 0dB and 16dB. For a given pair of transmitter-receiver nodes, the attenuation of the signal at the receiver is computed as follows: first the sum of attenuation from each wall in the direct line of sight between the nodes found; then add the value of the attenuation determined through the shadowing propagation model to it. It is found that the signal attenuation values obtained are comparable to values reported from field experiments at 5.3 GHz [50]. The simulation parameters are summarized in Table 5.1.

Table 5.1 Simulation Setup for UDP data transfer.

Parameter	Value
Simulation area	1500m X 1500m
Number of vehicles	150-250-350
Number of CBR sources	15
Transmission range	400m
Simulation time	300s
Vehicle velocity	25 – 55 miles per hour
CBR rate	0.5 – 5 packet per second
MAC protocol	IEEE 802.11 DCF
Data packet size	512 bytes
Bandwidth	11 Mb/s
Number of runs	3

5.4. Simulation Results

The RBVT protocols are compared with AODV, GSR, GPSR and OLSR. The AODV implementation is the one provided by Network Simulator NS-2 (which has enabled link layer feedback), the GSR implementation is from [33], the GPSR implementation is from [18] and the OLSR implementation is from [51]. AODV being a MANET protocol does not consider road layout. Unlike AODV, GSR is a VANET protocol and it uses the road layout. As the nodes in the simulation are fast moving nodes to let the MANET protocols to maintain better neighbor accuracy, the hello interval is set to 0.8 seconds and purges the neighbor from the cache after 1.6 seconds of inactivity. For the same reason the topology interval in OLSR is set to 2 seconds. The simulations are carried out with different node densities: 150, 250 and 350. The network with 250 nodes is denser than 150 nodes where as the network with 350 nodes is the most dense.

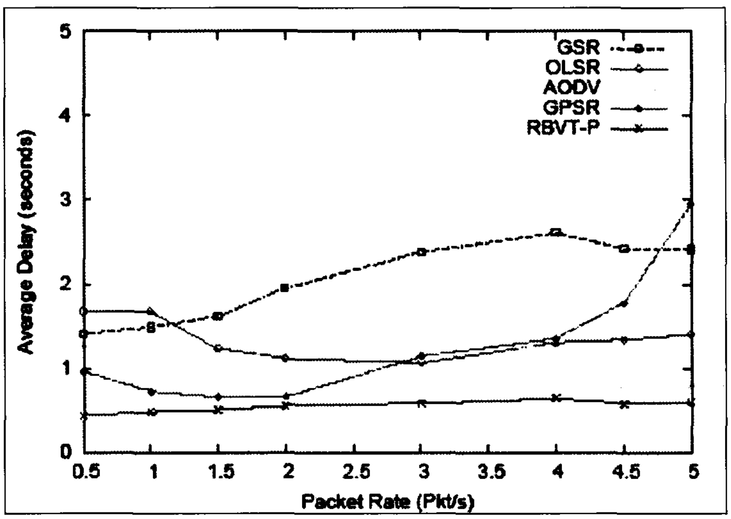

Figure 5.2 Average Delay for RBVT-P, AODV, OLSR, GPSR and GSR with 15 flows and the density of 150 nodes.

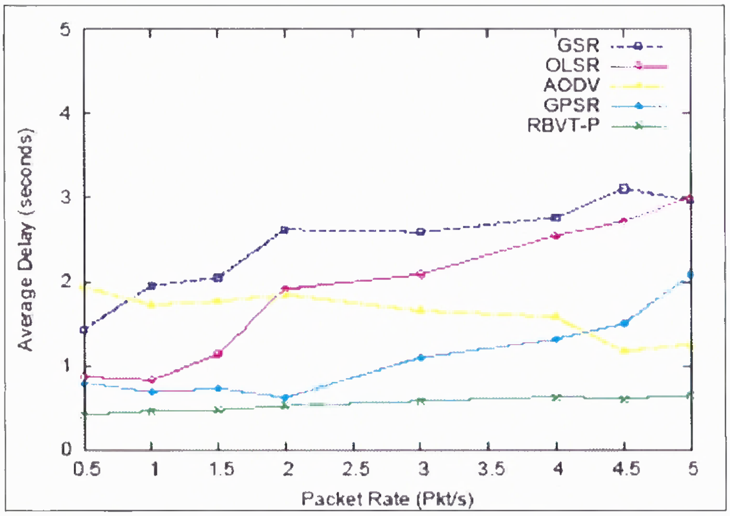

Figure 5.3 Average Delay for RBVT-P, AODV, OLSR, GPSR and GSR with 15 flows and the density of 250 nodes.

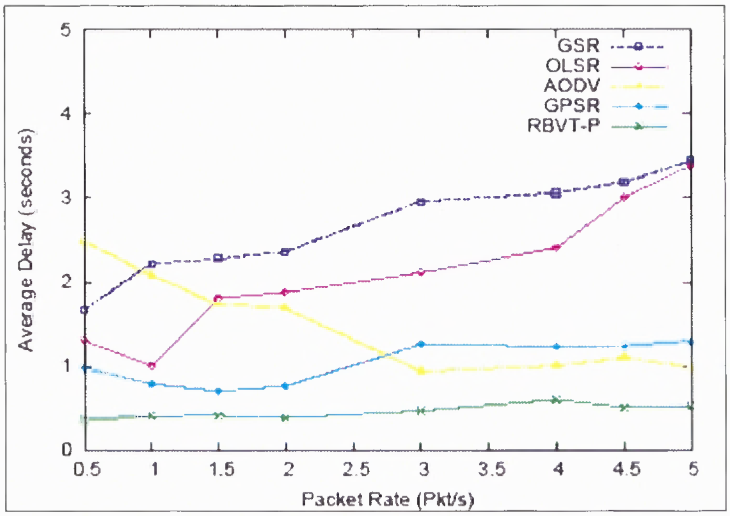

Figure 5.4 Average Delay for RBVT-P, AODV, OLSR, GPSR and GSR with 15 flows and the density of 350 nodes.

Average delay: Figure 5.2, 5.3 and 5.4 show that RBVT-P has the smallest delay of the compared protocols. The advantage that RBVT-P has over the other reactive protocols is the route maintenance that it does as a fact of being a proactive protocol. Unlike RBVT-P, OLSR does not perform in similar manner as it is a MANET protocol and unable to handle the rapid topology changes. Unlike in MANET where proactive protocols appeared not promising [52], proactive road-based protocols with real-time traffic awareness may prove a viable approach in vehicular networks, especially for delay sensitive applications, such as video streaming.

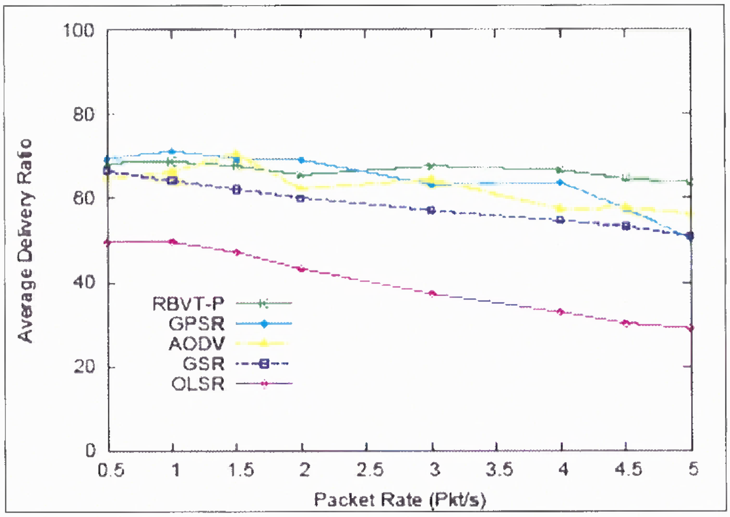

Figure 5.5 Average Delivery Ratio for RBVT-P, AODV, OLSR, GPSR and GSR with 15 flows and the density of 150 nodes.

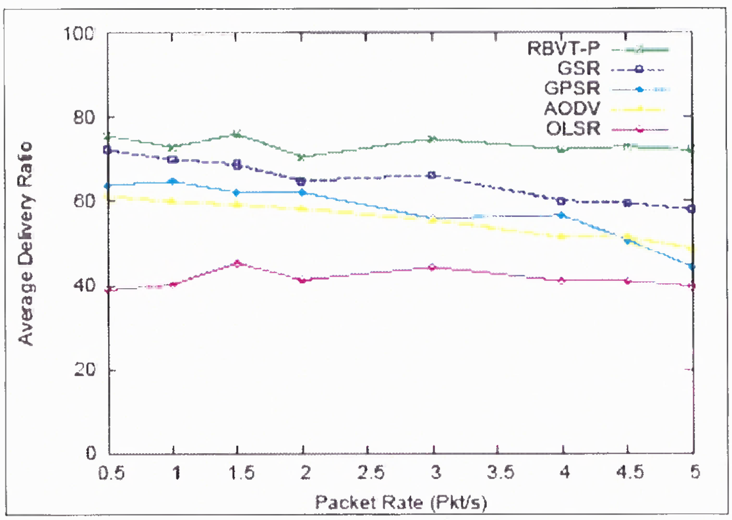

Figure 5.6 Average Delivery Ratio for RBVT-P, AODV, OLSR, GPSR and GSR with 15 flows and the density of 250 nodes.

GSR has the highest delay and is consistently in the growing state. The reason for the GSR's bad performance is due to the absence of quality feedback to the source at the intermediate node. This is because GSR forwards data on road segments selected solely based on the positions of the communication endpoints. This suggests that modification of the path used in GSR triggered by feedback packets may improve the protocol performances.

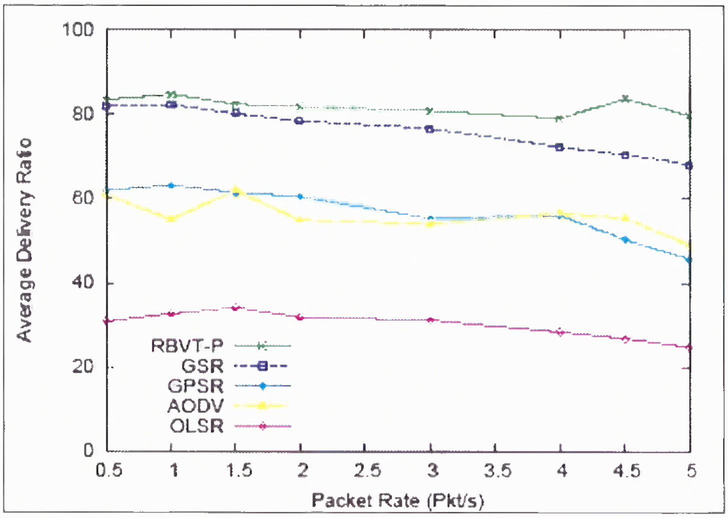

Figure 5.7 Average Delivery Ratio for RBVT-P, AODV, OLSR, GPSR and GSR with 15 flows and the density of 350 nodes.

Average delivery ratio: Figure 5.5, 5.6 and 5.7 shows RBVT-P performs better than other protocols. The simulations are carried out with different node densities: 150, 250 and 350. The network with 250 nodes is denser than 150 nodes where as the network with 350 nodes is the most dense.

Average number of hops: Figure 5.8 plots the average number of hops for packets received at destination for the protocols. This plot is similar for the different network densities so only the results with 250 nodes are presented. The general observation is that greater number of hops does not necessarily translate, as expected, into worse performance. On the contrary, selecting better forwarding nodes leads to better performance (RBVT-P has the highest delivery ratio despite having longer paths).

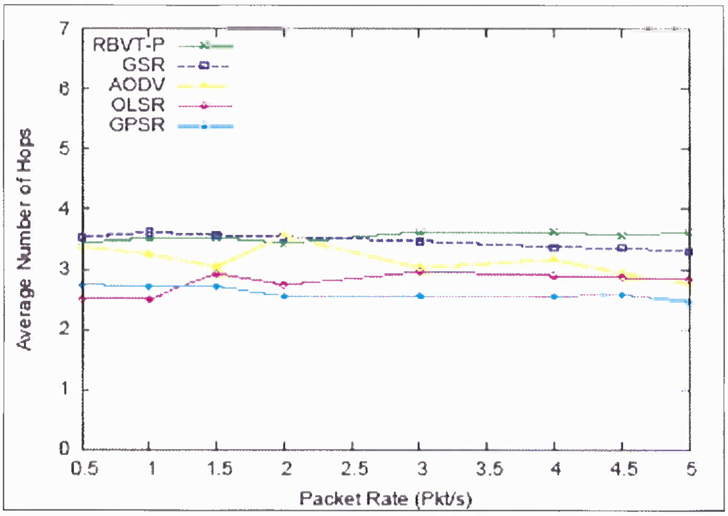

Figure 5.8 Average Numbers of Hops for RBVT-P, AODV, OLSR, GPSR and GSR with 15 flows and the density of 250 nodes.

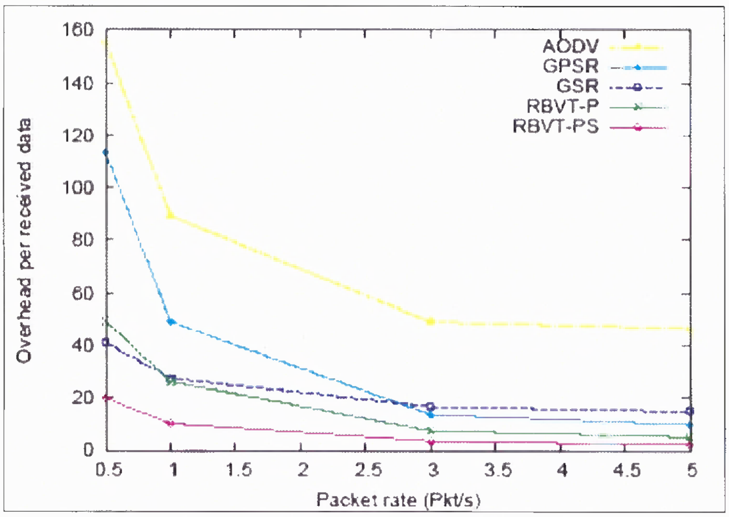

Figure 5.9 Overhead for RBVT-P, RBVT-PS, AODV, GPSR and GSR with 15 flows and the density of 250 nodes.

Overhead: Figure 5.9 shows the overhead caused on the network per delivered packet. AODV has the highest overhead, as when the node detects the broken route it drops the packet and generates a route error message. The frequency of "hello" packets and the route break recovery technique has a greater overhead in GPSR and GSR. RBVT-P suppresses the “hello” packets when the CUG broadcast occurs. In RBVT-PS as the network traffic is split between the Wi-Fi and Cellular interface it has lowest overhead.

5.5. RBVT-P Connectivity Packets (CPs)

The next simulations analyze the parameters that influence the accuracy of the connectivity view of the nodes in RBVT-P. Unless otherwise specified, 250 vehicle nodes are present in the simulations. A number of random nodes generate CPs periodically. A node generates a CP after (1) it verifies that it has not received any CP update for a period at least equal to the CP interval and (2) it executes a boolean function, for which the return value is determined based on the number of desired CPs. A random jitter uniformly distributed over a 1 second interval is applied before transmitting the CP. The CP interval is set at 10 seconds. The evaluation is done for the influence of the number of CPs generated the impact of the geographical dispersion of the vehicle nodes involve in the CP generation and finally the interval between generations of CP.

5.5.1 Number of CPs

To understand the impact of the number of generated CPs on the accuracy of the connectivity map, simulations with different number of CPs generated are run and the differences between the vehicle nodes (local) connectivity view and the simulator (global) connectivity view for every pair of nodes in the network is computed. In this test, the nodes generating the CPs are randomly selected without consideration to their relative positions on the map.

Table 5.2 shows the percentage of vehicle nodes which wrongly believe that there is disconnection with another vehicle based on their local network connectivity view. The observations show that as the number of nodes generating CPs in the network increases, the number of false-negative information between vehicle pairs decreases substantially. Considering that there is a trade-off between a complete real time view and the amount of CP packets that would be required to generate it, 3 CPs is a good tradeoff between accuracy and overhead for this map size and features.

Table 5.2 False-Negative with number of CPs

Number of CPs	1	2	5	10
False-Negative	28.51%	20.36%	14.73%	11.44%

Table 5.3 False-Negative and the position of CP initiators

Type	Near	Spread
False-Negative	25.51%	15.04%

5.5.2 Distribution of CP generator

This section assesses the influence of the geographical distribution of the vehicle nodes which generate the CPs on the accuracy of the connectivity information. For this test, three static vehicles are positioned at specific sections in the map area and use them as initiators of the CPs. In the "Near" case, the vehicles are positioned close to one another and in the "Spread" case; the vehicles are spread on the map area. Each case measures the amount of false negatives between each pair of vehicle nodes and the simulator (global) view of network connectivity.

In Table 5.3, observations are as expected i.e. when the CP initiators are spread on the map; the quality of the connectivity information improves. The fact that the vehicles used in the "Spread" simulation are not moving does not seem to have a noticeable impact. Its results are comparable to those of Table 4.2 where moving vehicles are used.

5.5.3 Interval between CP generation

This test assesses the impact of the value of the CP interval, i.e. the time between the generations of new CPs in the network. Five vehicles are randomly selected to create CP packets and the accuracy of the connectivity view at each vehicle is measure. As with previous cases, this is done by computing the percentage of false negatives between each pair of vehicle nodes and the simulator (global) view of the network connectivity. The number of vehicle nodes is 350.

The percentage of vehicle nodes which wrongly believe that there is disconnection with another vehicle based on their local network connectivity is 47.60% when the interval between CP is 5 sec and 9.13% when the interval between CP is 10 sec. The expectation would be that a smaller CP generation interval would lead to better result. However, this is not the case because a smaller CP interval leads to a higher number of packets in the network (more broadcasts of route update packets), which in turn leads to more packet drops. The significant difference between 5sec intervals and 10sec intervals suggests that an inadequate selection of this parameter can adversely affect RBVT-P protocol performance.

5.6. RBVT-P v/s RBVT-PS

The final comparison is between RBVT-P and RBVT-PS, the simulation uses 250 nodes and 15 CBR pairs.

Average delay: Figure 5.10 shows the end to end delay for RBVT-P and RBVT-PS. RBVT-PS posses' lower delay than RBVT-P for two reasons (a) the traffic in the network gets split due to the addition of cellular link (b) the server can quickly gather and disseminate the CGU to the network. Due to the introduction of server with cellular link there is reduced traffic at the Wi-Fi link also as the node has more accurate view of the network RBVT-PS has reduced delays in data delivery. RBVT-PS experiences three times less delay than RPVT-P.

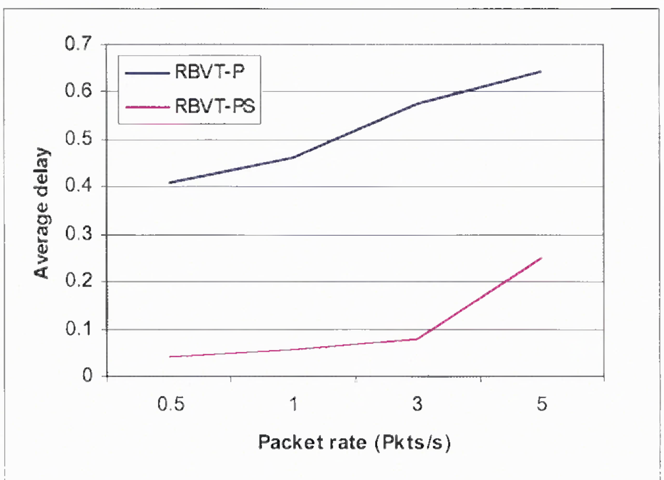

Figure 5.10: Average Delay for RBVT-P and RBVT-PS with 15 flows and the density of 250 nodes.

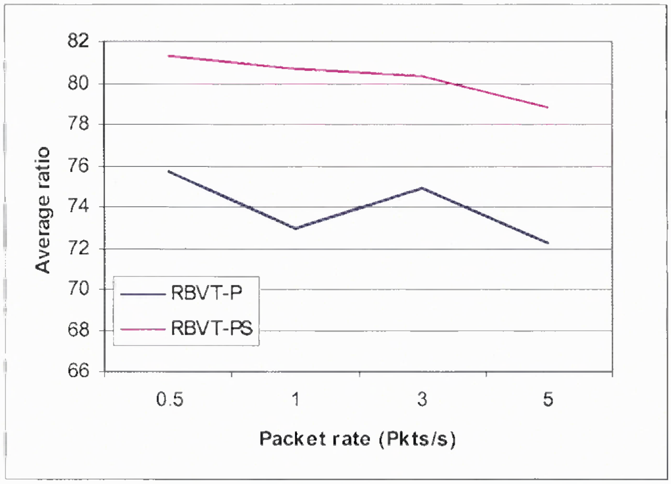

Figure 5.11: Average Delivery Ratio for RBVT-P and RBVT-PS with 15 flows and the density of 250 nodes.

Average delivery ratio: Figure 5.11 shows the average delivery ratio for RBVT-P and RBVT-PS. The RBVT-P demonstrates lower delivery ratio performance than RBVT-PS as in RBVT-P along with the data packets, the connectivity packets (that gather the real-time connectivity graph of the network) and the CGU packets (that disseminate the collected connectivity graph view) participate in network traffic at Wi-Fi interface. RBVT-PS shows 10% gain in delivery ratio this is due to the fact that the control plane traffic of the network is transmitted via cellular link and Wi-Fi link is used for data plane.

CHAPTER 6

CONCLUSION

This thesis presented two proactive RBVT routing protocols (RBVT-P and RBVT-PS) for city-based environments that take advantage of the road topology to improve the performance of routing in VANET. RBVT protocols use real-time vehicular traffic information to create road-based paths between end-points. Geographical forwarding is used to find the forwarding nodes along the road segments that form these paths. Simulation results show that both these protocols (RBVT-P and RBVT-PS), outperform existing approaches such as AODV, GPSR, OLSR and GSR in terms of average delay, average delivery ratio and low overhead. Because the RBVT protocols forward data along the streets, not across the streets, and take into account the real-time traffic on the roads, they perform well in realistic vehicular environments in which buildings and other road characteristics such as dead end streets, traffic lights are present. As cellular link would more commonly be available, RBVT-PS uses a server with cellular communication to show how the performance of RBTV-P can increase if the control plane (i.e., routing traffic) is routed across the cellular link whereas data is transmitted over the Wi-Fi link in ad hoc manner. The overall results demonstrate; distributed applications that generate a moderate amount of traffic can be successfully implemented in VANETs. Furthermore, for delay sensitive applications such as Voice, Video, online gaming proactive RBVT protocols are good choice. Unlike in MANETs where proactive protocols appeared not promising; proactive road-based protocols with real-time traffic awareness may prove a viable approach in vehicular networks.

APPENDIX

ALGORITHM FOR TOPOLOGY DISCOVERY AND ROUTE UPDATE IN RBVT-P

Notation:

n_0: ID of node that originated the CP packet

I_l: Intersection l

I_{ni} : Intersection closest to n_i

(I_l, I_m): Road segment of intersection I_l and I_m

Stack: Stack of road segments to visit

S: Set of all road segments

$RS(n_i)$: Road segment where node n_i is located

α: Waiting time parameter

CP: Connectivity packet

RU: Route update packet

Upon receiving $CP(n_0)$:

if proximity(n_i, I_l) then
    for each (I_l, I_k) do
        if $(I_l, I_k) \notin$ *Stack* then
            Add (I_l, I_k) to *Stack*
        end if
    end for
    if $I_{ni} == I_{n0}$ & $Stack == \Phi$ then
        Broadcast $RU(n_i)$
        Return
    end if
    if $RS(n_i) == (I_l, I_m)$ & (all (I_m, I_k) in *Stack* | marked in *S*) then
        Mark reachability of (I_l, I_m) in *S* /* R-reachable; U-unreachable */
        Remove (I_l, I_m) from *Stack*

end if

Read (I_l, I_m) from top of *Stack*

Forward $CP(n_0)$ toward I_m /* Send to next hop towards I_m */

end if

Upon receiving $RU(n_0)$ from n_j :

if $RU(n_0)$ not seen before then

Update local routing table with $RU(n_0)$ data

Set timer = α * $distance(n_j , n_i)$

else

if $RS(n_i) == RS(n_j)$ then

Cancel timer

end if

end if

Upon timeout

Broadcast $RU(n_0)$

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