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Vehicular ad hoc routing protocol with link expiration time (VARP-LET) information

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Vehicular Ad Hoc Routing Protocol with Link Expiration Time (VARP-LET) Information

By

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Declaration of Co-Authorship / Previous Publication

I hereby declare that this thesis incorporates one original paper [C1] that is included in Chapter 3 of the thesis. The paper has been co-authored with B. K. Singh under the supervision of Professor Dr. K. E. Tepe, as follows:

Thesis Chapter	Publication title/full citation	Publication status
Chapter 3	Reliable coverage area based link expiration time (LET) routing metric for mobile ad hoc networks	Accepted for publication in ADHOCNETS 2009

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Abstract

This thesis presents a vehicular ad hoc routing protocol that uses link expiration time (LET) information in selection of routes. The proposed protocol is named as VARP-LET, which uses LET information to increase reliability and stability of the routes. LET information is used selectively in the route discovery mechanism to reduce the routing control overhead. In addition to LET a Route Break Indicator (RBI) message is introduced. RBI is generated when a link breakage is about to occur. A source node on receiving the RBI signal preemptively stops sending data packets through a route before it breaks. This provision decreases the packet loss. The effectiveness of LET and RBI is tested via network simulations with NS-2. These simulations show that VARP-LET protocol increases packet delivery ratio by 20.7% in street section mobility model and by 30% in highway mobility scenario compared to regular AODV protocol. It is also shown that the protocol significantly reduces frequent route failure and routing overhead.

In memory of my father, Muhammad Nisar Khan,
and of my daughter Mehnoor.

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In the name of God, Most Gracious, Most Merciful

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Abbreviations

AODV	Ad Hoc On-Demand Distance Vector
CBR	Constant Bit Rate
CGSR	Clusterhead Gateway Switch Routing
CH	Cluster Head
DARPA	Defense Advance Research Project Agency
DCF	Distributed Coordination Function
DSDV	Destination Sequence Distance Vector
DSR	Dynamic Source Routing
DSRC	Dedicated Short Range Communication
FN	Forwarding Node
GPS	Global Positioning System
GPSR	Greedy Perimeter Stateless Routing
IEEE	Institute of Electrical and Electronic Engineers
IETF	Internet Engineering Task Force
INTC	Intersection
ITS	Intelligent Transportation System
IVC	Inter-Vehicle Communications
LAN	Local Area Network
LCC	Least Cluster Change
LET	Link Expiration Time
MAC	Medium Access Control
MANETs	Mobile Ad Hoc Networks
MN	Mobile Node
NAM	Network Animator

NS	Network Simulator
OTcl	Object Oriented Tcl
PBR	Prediction-Based Routing
PDA	Personal Digital Assistance
QoS	Quality of Service
RBI	Route Break Indicator
RCA	Reliable Coverage Area
RERR	Route Error
RR	Route Request
RWP	Random Way Point
S_A	Area Covered by Node A
S_B	Area Covered by Node B
UDP	Unigram Data Protocol
V2V	Vehicle-to-Vehicle
VANETs	Vehicular Ad Hoc Networks
WWAN	Wireless Wide Area Network
GHz	Giga Hertz

Chapter 1: Introduction

Vehicular ad hoc networks (VANETs) is one of the applications of ad hoc networks. Modern wireless network technologies integrated with ad hoc networking have made it possible to develop a short range communication between vehicle-to-vehicle (V2V) communications on the road. Several projects like CAR-2-CAR communication consortium [1], CarLink [2] and Fleetnet [3] are aimed at developing an intelligent wireless service platform for the vehicle's road safety and for the passenger's comfort services. Recently, Dedicated Short Range Communication (DSRC) protocol has been proposed for inter-vehicle communication in North America. DSRC is an allocation of 5.9 GHz licensed band comprising of seven channels for intelligent transportation systems (ITS) applications, out of which one is dedicated for the V2V communications. Moreover, modern vehicles equipped with navigational devices such as Global Positioning System (GPS) which provides the mobility parameters like position, direction of motion and speed of the vehicles. The main goal of these projects and standards are to develop an ITS for passenger's safety and comfort applications.

The network architecture [4] proposed for VANETs mainly divided into three categories: (1) Fixed cellular gateways or wireless WAN (WWAN) access point where vehicles directly communicate with these access points. To install these fixed access points on every site of the road is not feasible and are very costly, (2) Hybrid wireless architecture uses the WWAN access point only at certain points and in between those access points an ad hoc communication is used between vehicles, and (3) The ad hoc V2V communications require no fixed access points to communicate. The vehicles equipped with wireless network card can spontaneously set up an ad hoc network among the vehicles. In this dissertation we will be focusing on ad hoc V2V communications networks also known as VANETs.

1.1 Motivation

Ad hoc networks can provide temporary and quick network access economically and have applications in military, distributed and collaborative computing, wireless sensor networks, and hybrid wireless network architectures [5] and [6]. Recently ad hoc networks find its application in vehicular communication system, in which nodes are vehicles. In this context, focus of CAR-2-CAR communication consortium [1] is to create and develop a European industrial standard for V2V communication system.

Researchers have categorically defined VANETs as class of mobile ad hoc networks (MANETs) [7] and [8]. VANETs, like that of MANETs, have no-centralized mechanism, self organized, short radio transmission range and every node acts as a router or relays to the next node. Thus, V2V communications or inter-vehicle (IVC) communications is possible. Moreover, VANETs has some unique characteristics that distinguish themselves from MANETs [4] and [9]: (1) The mobility is highly dynamic, as vehicles move at relatively very high speeds, (2) The nodes' mobility is not random where as it is predefined and follows a specific path, and (3) The energy constraint is not an issue, therefore, an additional hardware such as GPS can be installed in vehicles. GPS can provide the mobility parameters like, direction of motion, speed, and location information.

Ad hoc networks still face various challenges [5], such as routing, scalability, multipath, multicasting, and energy management. Routing is one of the most challenging tasks in ad hoc networks, especially for VANETs, where high relative velocity among vehicles changes the network topology frequently.

There are number of routing protocols proposed for MANETs. These protocols can be broadly classified into two groups [5] and [10]: (1) proactive and (2) reactive. Proactive routing protocols such as Destination Sequence Distance Vector (DSDV) [11] and wireless routing protocol [12], maintain a global view of the network topology by exchanging complete routing tables periodically among the nodes. This periodic updates are flooded throughout the network which generates a large number of overhead packets in the network and hence consumes a large bandwidth and energy. Therefore, proactive routing protocols are unsuitable for MANETs. Reactive routing protocols do not maintain a global view of the network topology all the time. These protocols work and obtain a path when it is needed. That is why reactive routing protocols are scalable and consume less bandwidth than proactive routing protocols. These make reactive routing protocols very suitable for MANETs. Two of the popular reactive protocols are Ad hoc On-demand Distance Vector (AODV) [13] routing and Dynamic Source Routing (DSR) [14].

Routing protocols defined for MANETs cannot be directly applied for VANETs. The factors that greatly affect the performance of these protocols are the mobility constraint, driver behavior and high mobility in VANETs [9]. And as a result, some of the problems associated with the routing that are explained in [9], [15], and [16] are: (1) Link stability (link lifetime), (2) Small effective network diameter, i.e., unsuitability of the minimum hop metric for route selection, (3) Highly dynamic topology. The link stability or reliability greatly depends on how long a route may exist during data transmission time. Link lifetime has a great impact on QoS performance of the routing protocol [16], [17], and [18]. That is why, routing protocols in VANETs should be capable of selecting routes that are long lasting in order to minimize route breakages. Researchers have proposed various protocols that select the most stable route under highly dynamic environment. In general, some of these protocols are based on flat architecture and some on hierarchical architecture. Proactive and reactive protocols are the example of flat routing scheme whereas clustering-based routing protocols comes under the category of hierarchical routing scheme [19] and [20]. In [20], the authors survey and present a comprehensive description and performance evaluation of various clustering based routing protocols. In clustering based schemes, a group of adjacent nodes, according to some rules, form a cluster and the network is then composed of various clusters. Each cluster is composed of one cluster head and a number of ordinary nodes. The cluster head forwards a route request (RR) packet on behalf of ordinary nodes from one cluster to another through a node called gateway node. The routing protocols proposed in [21] and [22] are based on clustering scheme, these protocols are capable of selecting a stable cluster head and a stable gateway node. In some clustering schemes nodes are required to exchange HELLO messages in order to get a global view of the network and to determine a stable cluster head and a stable gateway node. This periodic exchange of the HELLO messages will generate extra overhead in the network.

In flat network architecture, the routing protocol selects intermediate nodes to form a route. Selection of stable routes is important under mobility environment and some of the stability based route selection techniques are explained in [17], [23], and [24]. The link stability in these protocols relate directly with the link lifetime between the nodes. In general, if the path duration is longer the performance of the protocol will be better in terms of throughput and overhead. The routing protocols described in [17] and [24] predict the link lifetime based on some probabilistic approaches. Probabilistic approaches need to estimate the current and future positions of the nodes in order to estimate the link lifetime which is computationally complex and require high degree of accuracy. The protocols presented in [21] and [23] determine the link lifetime using a navigational system, like GPS, while selecting a stable route.

Using minimum hop metric causes problems in MANETs [15]. Reactive routing protocols like AODV and DSR use minimum hop metric for route selection this is why they do not perform well in MANETs. A new metric that captures the effect of mobility should be used in routing protocols that are used in MANETs and VANETs.

The links in VANETs experience frequent breakages. These frequent link breakages contribute to route failures. Those failures force source node to re-initiate route discovery mechanism. That mechanism increases the network overhead and decreases throughput.

1.2 General problem statement

Since the topology in VANETs is highly dynamic; therefore, the design of an efficient routing protocol has two major challenges:

First, routing protocol should be capable of selecting stable and reliable routes with control overhead during route discovery phase. In the selection of stable route, we can estimate the link expiration time and enhance the routing protocol with this information. Second, if the links that are about to break can be detected before it actually breaks, then an alternative route can be established before this breakage. A routing protocol that monitors link status during the route maintenance phase should be more efficient. Most of the reactive protocols like AODV [13] and DSR [14] rely on route error message (RERR), which indicates the link breakage, and is generated by a node after the link actually breaks. The sudden link breakage during transmission can cause loss of data, because the source keeps sending data through the broken link until it receives the message. In [23] and [24], proposed protocols that predicts the link lifetime and re-initiate a new route discovery before the predicted life time. These proposals show that change in the routing mechanism improves the performance. But this predicted link lifetime is estimated during route discovery phase. The dynamic nature of VANETs may change the link lifetime during the use of the route and the prediction may fail. Here, we propose a protocol that monitors the link status' real-time and incorporates this status in its operation.

1.3 Contribution and applicability

In the light of the above discussions, this thesis will present an efficient prediction based routing protocol that uses the link expiration time (LET) information to select the most suitable and reliable route. The proposed routing protocol is called Vehicular Ad Hoc Routing Protocol with LET information (VARP-LET). One of the promising ad hoc reactive protocols namely, Ad hoc On-demand Distance Vector Routing (AODV) [13] has been modified to implement VARP-LET. In the VARP-LET, the LET information is used to select the intermediate nodes. The nodes having a larger value of LET will be selected; therefore, the selected route is more robust under mobility environment. In VARP-LET a reliable coverage area metric (RCA) is introduced, the nodes lying within this area are referred to as reliable nodes. On receiving a route request (RREQ) message, only those nodes that are considered reliable will take part in route selection. This helps to reduce the un-necessary re-broadcast from those nodes that are un-reliable in terms of

LET. Further, VARP-LET uses the real-time calculation of link lifetime, before forwarding the data packets, and generates route break indicator (RBI) message before the link breaks. An RBI message is generated during the route maintenance phase. Hence, VARP-LET continuously monitors the link status and predicts links that are near-to-be-broken. If near-to-be-broken link is detected a precursor node will be informed about the possible link breakage. The RBI message is then propagated towards the source node. The source node after receiving the RBI message stops sending the data packets via the near-to-be-broken link. Therefore, a significant loss of data can be avoided. It is shown in this thesis that the introduction of an RBI message with reliable coverage area metric further improves the network throughput and control overhead.

The VARP-LET has the following advantages:

- VARP-LET limits a re-broadcast area in the network which reduces the broadcast overhead.
- VARP-LET selects a stable route faster as there is a lower number of nodes involved in route decision process.
- VARP-LET does not depend on the global information of the network. That means it uses information that is locally available at every node.
- VARP-LET selects a stable route that last longer with as few hops as possible.
- VARP-LET detects link breakage ahead of time.
- VARP-LET shows, through simulation results, that at relatively high speeds of nodes, it outperforms AODV protocol, whereas at relatively low speeds, VARP-LET does not deteriorate any of the basic properties of AODV.

1.4 Thesis organization

This thesis consists of 4 Chapters. Motivation, the problem statement and contributions were presented in this chapter. Chapter 2 comprises of a background which includes: brief overview of the mobility models, challenges in VANETs, Ad hoc On-demand Distance Vector (AODV) routing protocol, a review of routing protocols in VANETs, and NS-2 simulation platform. In Chapter 3, a new routing protocol Vehicular Ad Hoc Routing Protocol with Link Expiration Time Information (VARP-LET) is introduced. An analysis of additional coverage vs. LET is investigated in related work. Then, reliable coverage area based LET (RCA-LET) metric for selecting a reliable link is introduced in that Chapter. In Chapter 4, the summary of this work and future research is presented.

Chapter 2: Background

2.1 Overview of mobility models

The mobility adds complexity in routing decision process. In order to understand how a routing protocol behaves and performs, mobility models that mimics movement pattern of mobile nodes (MNs) must be developed. Broch et al. [25] evaluated the performance of reactive and proactive protocols under the random mobility model and showed that mobility does impact on routing performance. Recently Gomes et al. [26] evaluated the performance of Ad Hoc On Demand Distance Vector (AODV) routing protocol using different mobility models. It was shown that the mobility models impose a severe restriction on link connectivity. Therefore, in order to design an efficient routing protocol in ad hoc networks its performance should be evaluated for a specific mobility model that is designed for. In this section a brief overview of different mobility models used for MANETs is presented. For a complete reference reader is advised to visit [27] and [28]. Mobility models can be viewed based on the movements' pattern of mobile nodes. For example, the mobility model that describes the movement of each MN independently is termed as entity mobility model. And the mobility model in which MNs move in a group is termed as group mobility model. In this section some of the most popular entity mobility models (also relevant to this thesis) used in MANETs is presented.

2.1.1 Random way point mobility model

In this mobility model each MN moves from its current location to a new location randomly with a speed between a pre-defined minimum and maximum speed values and a direction angle between 0 and 2π respectively. Each MN after covering a certain distance stays for a certain period of time which is known as pause time. Once this pause time elapsed an MN again chooses a new direction and a speed randomly. Figure 2.1 shows a 300mx600m simulation area where an MN is moving under the random way point model (RWP).

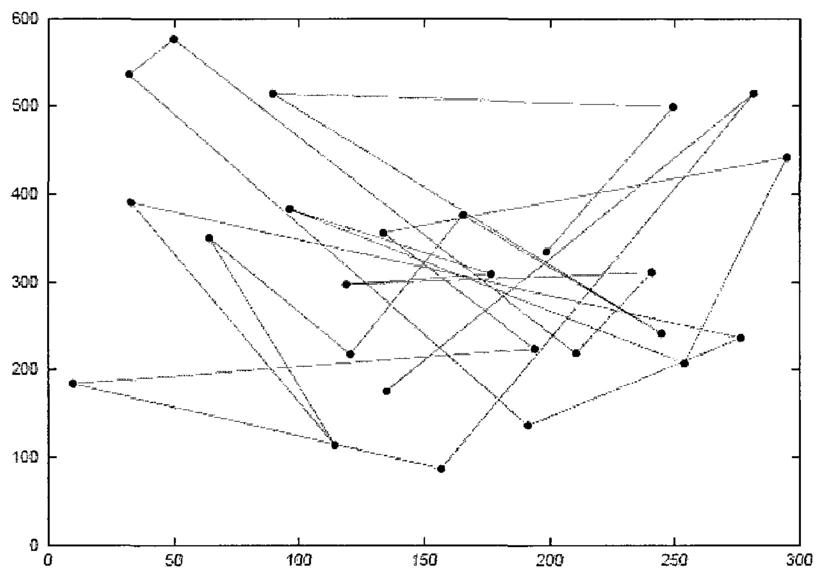

Figure 2.1: MN's movement pattern using random waypoint mobility model

RWP mobility model is the most widely used model in MANETs. It is a memoryless mobility model, that means, an MN's new direction and speed is independent of the old direction and speed.

2.1.2 Random walk mobility model

Random walk mobility model is another widely used memoryless mobility model in ad hoc networks. In this mobility model, pause time is set to zero, therefore, an MN after covering a certain distance chooses a new direction and speed without staying at that point. Thus, this model generates an unrealistic movement of the mobile nodes which include sudden stops and sharp turns. Figure 2.2 shows a typical MN's movement under this mobility model.

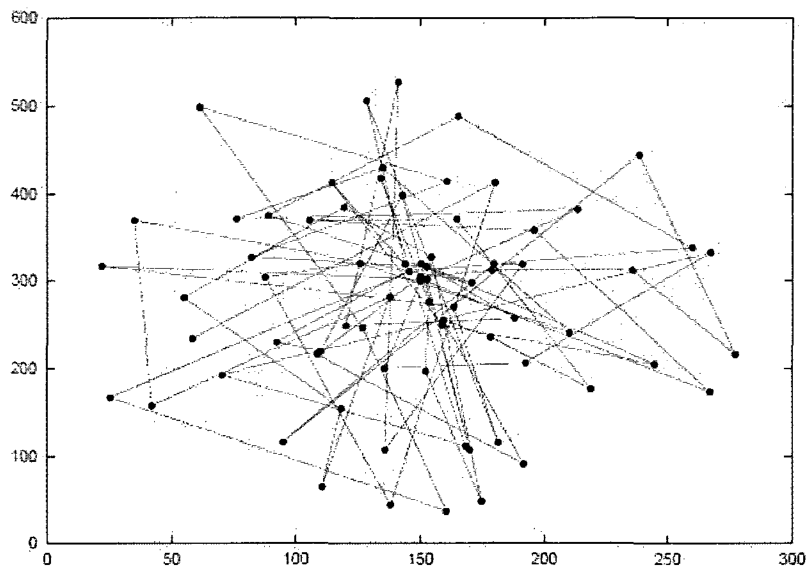

Figure 2.2: MN's movement pattern using random walk mobility model

2.1.3 Gauss-Markov mobility model

In this mobility model, a sudden stop and a sharp turn is eliminated. This model has memory, i.e., a new speed and direction of an MN depends on the old speed and direction. The new value of speed and direction chosen by an MN is tuned through a tuning parameter, which varies the randomness of these values, i.e., a new velocity v_n of the MN at time n based on [27] is given by

$$v_n = \alpha v_{n-1} + (1-\alpha)\mu + \sqrt{1-\alpha^2} * x_{n-1} \quad , \tag{2.1}$$

where $0 \leq \alpha \leq 1$ is a tuning parameter, μ is a mean value of v_n as $n \to \infty$, and x_{n-1} is a Gaussian random variable. For $\alpha = 0$, total random values are obtained and for $\alpha = 1$ linear motion is obtained.

2.1.4 Manhattan Grid mobility model

This mobility model represents the street section network where MNs are forced to move in a grid. The streets are shown along vertical and horizontal axis. This model can be used to emulate the movement pattern of vehicles in an urban area. Figure 2.3 shows the movement pattern of seventeen nodes using the Manhattan Grid mobility model. In this model MNs, at the intersections, can take turn or go straight with certain defined probability.

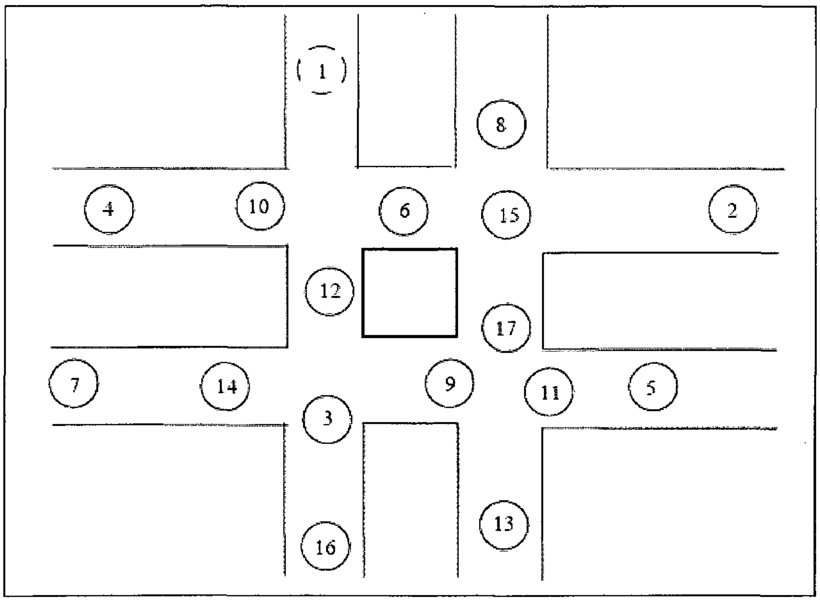

Figure 2.3: MN's movement pattern using Manhattan Grid mobility model

2.2 Routing protocols for MANETs

The complexities and challenges involved in MANETs make the role of a routing algorithm crucial [5] and [10]. Therefore, a number of routing protocols are proposed in the literature for MANETs and their performances are evaluated by the internet Engineering Task Force (IETF)'s MANET working group [29]. Generally, the routing protocols proposed for MANETs can be divided into three categories: (1) Proactive, (2) Reactive, and (3) Hybrid. Proactive routing protocols maintain the global network topology information in each node's routing table. The nodes periodically exchange the routing table information and maintain a fresh route among the nodes. Proactive routing protocol consumes a lot of bandwidth and energy while exchanging the complete routing information among nodes. For that reason, the proactive routing protocols are not preferred for MANETs. Reactive routing protocols, on the other hand, do not need to maintain the global overview of the networks at all time. They find a route by initiating a route discovery phase when it is needed. Even though there is data latency while searching a route by a source node to its destination, these protocols are bandwidth and energy efficient. Therefore, they are preferred for MANETs. The third category of the routing protocols in MANETs is the hybrid protocols which combines the best features of both proactive and reactive protocols [30].

2.2.1 Proactive routing protocols

Proactive routing protocols are also known as table driven routing protocols. As these protocols maintain a complete route path information in memory, i.e., in the routing table of a node, thus, there is a complete and fresh path available at all time. In order to make this information update, nodes need to exchange the fresh information at regular intervals with each other. This is also necessary to respond to any network topology changes at any time. Destination Sequenced Distance vector routing (DSDV) [11] and Clusterhead Gateway Switch Routing (CGSR) [31] are the examples of proactive routing protocols. The DSDV protocol is based on a well known Bellman-Ford algorithm with some improvements and is one of the first protocols proposed in the literature. The DSDV is improved in a way that it needs less convergence time and avoids any routing loops. A sequence number is allocated to every entry in the routing table to provide freshness information. In order to decide a route, the most recent allocated sequence number is used and in case that if two updates have the same sequence number then the route having a lower hop count will be selected. And in order to reduce periodic routing update traffic in DSDV, two types of update packets are introduced: full dump and incremental. In the full dump update packet, complete routing table information is exchanged. This exchange may need multiple network protocol data units (NPDUS). The full dump update packet is used only in case if there is a significant change in the network topology. An incremental update packet contains information about the changes occurred after the last full dump. An incremental update packet's information is usually fit in one NDPU. Therefore, increasing the time period between the full dump and exchanging incremental packet reduces the routing overhead.

Cluster-Head Gateway Switch Routing (CGSR) [31] is another proactive routing protocol. It uses hierarchical network architecture instead of a flat network architecture used in DSDV protocol. In the CGSR, a different number of nodes grouped together to form a cluster. For each cluster there is a cluster head (CH) which controls all the nodes in the cluster. Within a cluster other nodes are defined as cluster members and gateway nodes. The cluster members are the members of a cluster and are located at one hop away from a cluster head. The gateway nodes act as a communication gateway between two clusters and should be in the communication range of each other. Each member node will send its data packets to its CH, which route the packet to the next cluster via gateway node and so on until the data packet reach to the CH of the destination node. Figure 2.4, shows a typical routing scenario under CGSR, where node 1 is source and node 8 is destination.

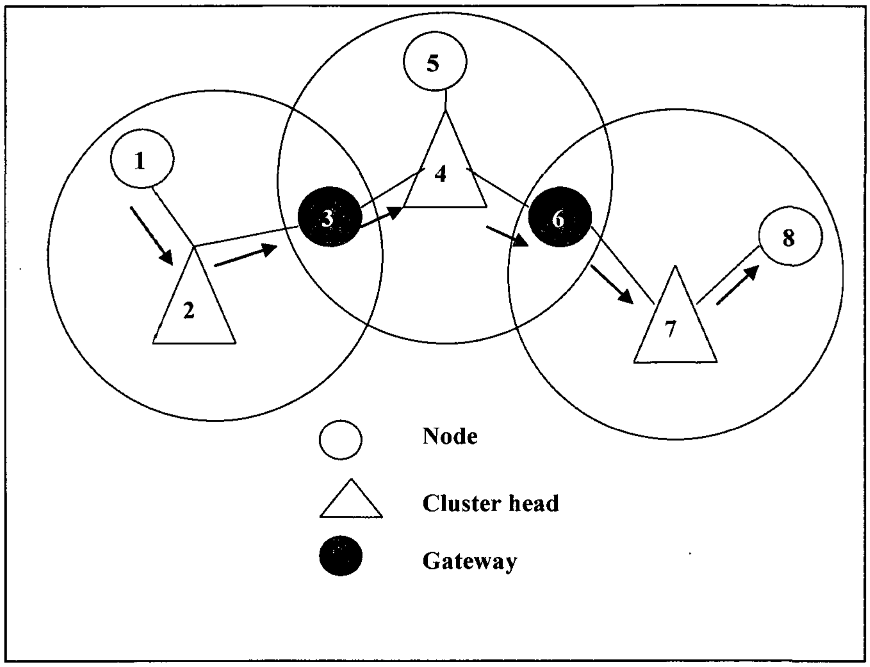

Figure 2.4: CGSR: routing from node S to D

In CGSR protocol each member node employed with DSDV protocol within a cluster. Therefore, each node maintains two tables; member table and routing table. Member table contains the list of CHs of each cluster in the network; whereas the next hop towards the destination is decided by routing table.

2.2.2 Reactive routing protocols

Reactive routing protocols are also known as source-initiated on-demand routing protocol. The two very promising and popular reactive routing protocols are DSR [14] and AODV [13]. DSR is designed to reduce bandwidth taken by control packets in MANETs [5]. There are two phases in the operation of DSR: (1) route discovery phase, (2) route maintenance phase. In route discovery phase the source node will broadcast a route request (RREQ) packet on-demand to find a route towards the destination, only if it does not have a route in its cache to the destination. If a source node (or any intermediate nodes after receiving an RREQ packet) has a route to the destination, it will use that route to send a packet. Each intermediate node, after receiving the packet, will append its address in the packet and then re-broadcast the request. This process will continue until the packet is received at the destination. The destination, on receiving the RREQ, will generate a route reply (RREP) packet back towards the source node. In DSR, a RREQ packet size increases with the increase of the network size so it is not as scalable as that of AODV [10]. This is one of the reasons for choosing an AODV algorithm as a base in the proposed routing in this thesis.

Route error (RERR) packet is used for route maintenance. When a link breaks the node which detects the link failure will initiate an RERR packet. The RERR packet is propagated back towards the source node to inform about the link breakage. DSR also keeps a redundant route path to the destination and can use this path if a current route fails. As mobility makes the network topology very dynamic; therefore, a redundant route can become a stale during the route maintenance phase.

2.3 Ad Hoc On-Demand Distance Vector (AODV) routing protocol

As the proposed routing protocol in this thesis is based on AODV algorithm, for that reason, AODV is described in detail in this section. AODV is based on DSDV algorithm but it is improved to minimize the broadcast and transmission latency. The authors classified AODV as a pure on-demand route acquisition system [13] because routing information is maintained by the nodes that lie on an active path. The following are the primary objective of the protocol as stated in [13].

- To broadcast the discovery packets only when needed.
- To distinguish between local connectivity management neighborhood detection and general topology maintenance.
- To disseminate information about changes in local connectivity such as HELLO messages, to those neighboring mobile nodes that are likely to need the information.

Like many other reactive routing protocols AODV uses two phases in its operations: (1) route discovery phase (2) route maintenance phase. In the first phase, the protocol discovers a route to its destination. In the second phase, a broken link is detected and informed to the source node.

2.3.1 Route discovery phase

In this phase a source node will find a route to the intended destination. If a source node has a packet to send to some destination, if it does not have a route to the destination, it will broadcast an RREQ packet to its neighbors. The neighbors after receiving the RREQ packet will forward it to their own neighbors by increasing the hop count field of the packet. The neighboring nodes will re-broadcast RREQ during time slot $[0ms, 10ms]$ randomly. This process continues until the RREQ packet reaches the destination node, as shown in Figure 2.5 (a). After receiving the RREQ packet by the destination node a RREP packet is generated back towards the source node and is shown in Figure 2.5 (b).

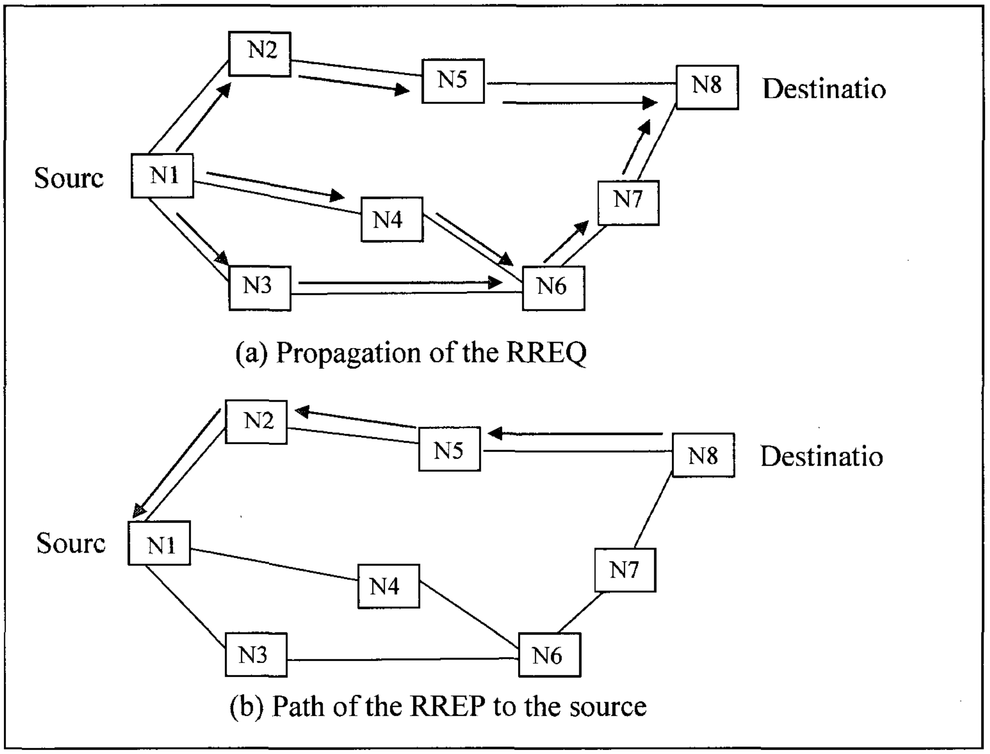

Figure 2.5: AODV route discovery

The RREQ packet contains the following fields; source address, source sequence number, broadcast ID, destination address, and hop count. The RREQ packet is uniquely identified by the sequence number and the broadcast ID. Each intermediate node maintains its own sequence number and broadcast ID. When a node initiates an RREQ process again, a broadcast ID is incremented. As the RREQ packet propagates in the networks, each intermediate node will record the address of its neighbor through which the RREQ is received. It automatically sets up a reverse path as shown in Figure 2.6. The intermediate node will discard any redundant RREQ packet after the first one received from the same neighboring node for the same destination node. The destination node on receiving the RREQ packet or any intermediate node having a fresh route towards the destination unicasts a RREP packet back towards the destination node. The freshness of a

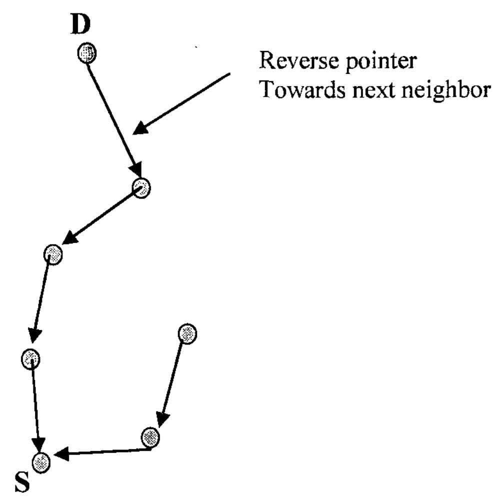

Figure 2.6: Reverse path formation.

route is decided by the value of a source sequence number. The RREP packet propagates to the source node by using the reverse path that is already created. And as the RREP packet propagates back to the source node a forward pointer is created by the intermediate nodes as shown in the Figure 2.7.

Each intermediate node, after receiving the first RREP packet, forwards the RREP packet back towards the source node. If an intermediate node receives more than one RREP packet for the same source, it updates its routing table and forwards only if it has a larger sequence number. In the event of a same sequence number, a smaller hop count is preferred.

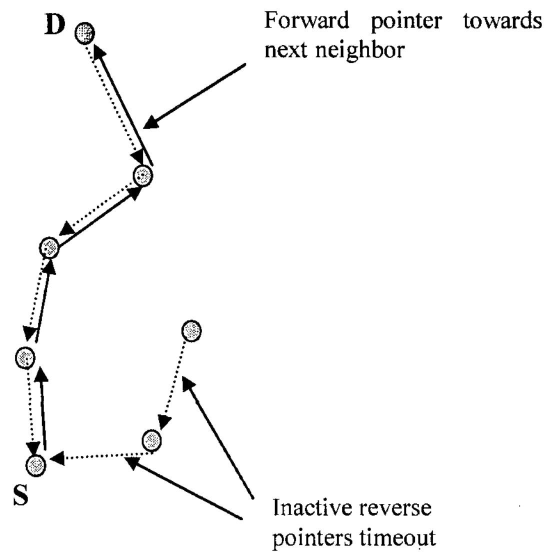

Figure 2.7: Forward path formation

2.3.2 Route maintenance phase

In this phase, a link breakage is detected which mainly occurs due to any change in the network topology. In AODV-LL (Logical Link), a link breakage is detected by using an acknowledgment packet sent by a MAC layer protocol such as IEEE 802.11 Wireless LAN. In AODV-LL version, a HELLO message is not used to find the link status. If a link breakage occurs because of a source node's move, it re-initiates a route discovery mechanism to find a new path to the destination. If a link breaks due to an intermediate node's move, the node that detects the link breakage will inform its precursor node by initiating an unsolicited route reply packet with hop count set to infinity. This unsolicited route reply packet is also called route error (RERR) packet. The RERR packet is subsequently relayed by the nodes towards their own neighbors. This relaying continues until all the active nodes are notified. The source node, on receiving the RERR message, can then re-initiate a new route discovery if it still needs to send packets to the destination node.

2.4 VANETs' challenges

The routing protocols in VANETs face unique challenges that distinguish these protocols from that of MANETs [9]. The high relative speed of vehicles, driver's behavior, constraints on mobility together make the unique characteristics in vehicle-to-vehicle (V2V) communications. Blum et al. [9] shows through simulations results that the VANETs are fundamentally different from MANETs. The following are the important challenges in VANETs, which should be taken into consideration for designing a protocol for such networks [4] and [9]: (1) Highly dynamic topology, (2) Frequent network fragmentation, (3) Small effective network diameter. As the vehicles move at relatively high speeds, the network topology changes very frequently. These topology changes lead to frequent link breakages, this leads to routing protocol to find new routes. Rediscovering new routes increases the routing overhead. The link lifetime depends on the direction of movement of the vehicles. The vehicles moving in the opposite direction will remain in contact for a small duration of a time. On the other hand, vehicles moving in the same direction may provide a longer link lifetime. It is stated in [9] that in VANETs, due to mobility constraint in the network, even the vehicles traveling in the same direction provide on average one minute of link life time. And the effects of short lived routes become even worse when number of hops between source and destination gets larger. That is why an efficient routing protocol design for VANETs should be able to address the mobility related challenges.

Due to high mobility and topology changes, there occurs a fragmentation in the networks. During this period a chunk of mobile group may not get access to the desired nodes in the nearby region. The impact of network fragmentation is higher if the node density is lower. Zong et al. [32] propose a relaying technique for successful delivery of the message. The moving node keeps a message temporarily in its cache while waiting for an opportunity to forward further. Another solution is to deploy fixed relay nodes (access points) at certain points along the road to keep the connectivity [9].

In VANETs, there are frequent link breakages that cause many routes disconnected before they are actually used; thus, a route may cease to exist just after it was discovered.

Reference [9] reported a poor nodal connectivity in VANETs due to highly mobile vehicles. Reactive protocols like AODV, and DSR uses a minimum hop metric for route selection. It is stated in [15] that minimum hop-count metric is not always a good choice for route selection, especially under mobility.

Because of the limitations mentioned above, VANETs require efficient routing protocols with following characteristics: Distributed, stable route, loop-free route discovery, quick route maintenance, and minimum control overhead.

- Distributed: As the network topology is highly dynamic in VANETs; therefore, routing protocols in such networks must be distributed because centralized routing is susceptible to single point of failure.
- Stable route: The stable and reliable route is a key to an efficient routing protocol in high mobility circumstances. The more stable routes reduce link breakages in the network. Therefore, in VANETs, routing protocols must be capable of selecting long lasting routes.
- Loop-free route discovery: For a dynamic network like VANETs, a transient route commonly exists. A routing protocol for this kind of network should be capable of detecting and eliminating routing loop as soon as possible.
- Quick route maintenance: Highly mobile nodes can break links frequently. An efficient routing protocol should be able to detect link failures as quickly as possible. An early detection of link breakage should be an efficient technique in highly mobile environment.
- Minimum control overhead: Frequent link breakages increase routing overhead for initiating a route discovery process over and over again. The routing selection for a more stable and reliable route can reduce the control overhead in the network.

2.5 Review of routing protocols in VANETs

The routing protocol defined for MANETs behave poorly in VANETs. The researchers proposed various different routing protocols for VANETs [4] and [8]. These protocols can be broadly classified as: (1) Position-based routing, (2) Prediction-based routing, and (3) Clustering-based routing.

2.5.1 Position-based routing

In position-based routing (also known as geographic routing), the location or position of a destination is known to the source. If a source node needs to send a packet toward the destination, it will forward the packet towards an intermediate node which is close to the destination. Hence, forwarding data packets is based on greedy forwarding routing technique. One of the known position-based routing protocols is Greedy Perimeter Stateless Routing (GPSR) [33] protocol. In GPSR, each node exchanges its position information with its neighboring node through a beacon signal and a source node knows the destination position through a location service mechanism. GPSR employs the perimeter algorithm to deal with the local minimum, i.e., when there is no node other than source node close to a destination point. The local minimum problem mainly occurs at the junction point on a road. The intermediate node may forward data packet in the wrong direction other than that where destination node is located. The perimeter algorithm is employed at the time when local minimum does occur. The packet then traversed back and forwarded in the right direction. In GPSR, the local minimum problem may occur frequently, so the packet has to travel a longer path which in turn adds a delay in the network. In order to avoid the local minimum problem, the authors in [34] proposed Geographic Source Routing (GSR). GSR uses a digital street map in the city environment to get the global knowledge of the city topology. GSR by using Reactive Location Service (RLS) knows the destination position. By combining this information, the source node employs the Dijkstra's shortest path algorithm through the junctions that the data packets have to be traversed toward the destination. In between junctions, the packet is forwarded in a position-based fashion. Another position-based routing protocol named as Multi-Hop Routing Protocol for Urban VANETs (MURU) [24] is recently proposed. MURU is based on GPSR. A new metric "expected degree of disconnection" (EDD) is introduced in MURU. EDD takes into consideration the quality of a route based on factors like vehicle speed, location and trajectory. EDD is based on probabilistic scheme used to estimate the link lifetime after which the link might be broken. Thus, a route with a low EDD value is chosen. In MURU, an RREQ packet on its way towards destination cumulates the EDD value of the path discovered.

As MURU, like any other position-based routing protocol, forwards the packet towards the node close to the destination node. The source node first finds the shortest trajectory and then initiates an RREQ packet to be forwarded through this trajectory. The RREQ packet is broadcasted to the rectangular broadcast area which encloses the shortest trajectory between source and destination. The nodes lying within the broadcast area will respond to RREQ only for finding a route to the destination. Nodes outside the broadcast area will drop the RREQ. Simulations results show that MURU provides good routes with reasonable overhead and delay. The authors in [35] propose GVGrid protocol, which employs the divide-and-conquer rule. The GVGrid assumes that the global network topology is known by the nodes, which are equipped with GPS system. The protocol uses this information, and divides the geographic area into small squares called as grids. The GVGrid then creates a request zone, which is a rectangle area comprises of the grids. The request zone includes the grids of the source and the destination node. The source node initiates a route discovery phase by forwarding an RREQ packet to the selected nodes in the neighboring grid close towards the destination grid. The receiving nodes forward the RREQ packet to their selected nodes in their neighboring grid. There is representative node selected by GVGrid protocol. The representative node is located in the destination grid. The RREQ packet contains the sequence of the forwarding nodes and their corresponding grids while traveling to the destination grid. The representative node on receiving the RREQ sends an RREP through a route that is more stable. The representative node estimates the stability of the route by preferring nodes which are moving in the direction from source to destination at the same speed on the same roads. It is stated in [8] that the link delay analysis is required in the GVGrid.

One of the known problems related with the position-based routing protocol is that an efficient location service mechanism is required. In GPSR, in order to keep up-to-date the destination's location information, the client-server architecture is employed which adds an extra cost. In addition, the nodes exchange their position information through beacon signals. These beacon signals generate a large amount of protocol overhead. GSR needs RLS service mechanism to get the destination location information. In MURU, the authors assumed that an efficient location service mechanism is present. MURU's performance is highly dependent on the accuracy of the location service mechanism. Nevertheless, the location based scheme may increase the system throughput [36]. But finding the physical position of nodes, especially when the network is highly dynamic is very challenging.

2.5.2 Prediction-based routing

Prediction-based routing protocols proposed in the literature mainly based on topology based routing protocols. AODV and DSR are the example of topology routing protocols and are specifically designed for MANETs. DSR keeps a redundant path in its cache which is utilized in case if the active route fails. AODV does not keep any redundant route; thus only relies on one discovered route. In the event when the active route fails, AODV reinitiate a route discovery process again. In [37] the authors propose an AODV-BR protocol which keeps back up route in the routing table. The nodes in AODV-BR use the RREP packets to create the alternate route. The nodes that are not part of the active route promiscuously listen to the RREP packets not directed towards them by their neighbors. They record that neighbor towards the intended destination and create the alternate path. And in the event of the link failure, the alternate path is utilized by the intermediate nodes to forward the data packets to its destination. As said earlier that in VANETs the highly dynamic topology may stale the route information. Thus, under high mobility environment the alternate route may stale before it is utilized. This is also shown in [37] that there are packet losses in AODV-BR because of mobility. Further, Santos et al. [36] show that topology based routing (e.g., AODV and DSR) perform poorly in various traffic conditions in VANETs. The route established by an AODV can break very frequently when the node mobility is high. Therefore, to reduce the link breakages and to improve the network performance, Namboodiri et al. [38] present two prediction-based routing protocols PRAODV and PRAODVM. The authors considered routing from vehicle to the moving gateway on the road. The proposed protocols use GPS information like velocity and position information to predict the link lifetime. PRAODV prefers the minimum hop metrics as that of AODV but preemptively construct a new path before the expiry of the predictive lifetime of the previous path. PRAODVM selects a route with maximum predicted lifetime. Simulation results show a slight improvement in terms of packet delivery ratio of these protocols. PRAODV uses the same minimum hop metric as that of AODV; hence, the chance of a route breakage is high under mobility. On the other hand, PRAODVM prefers a route whose predicted lifetime is the maximum. In PRAODVM, the link lifetime is calculated based on the information of a route reply (RREP) packet. As the RREP packet is generated by the destination node; therefore, the destination node has to generate the RREP packet for every received RREQ packet back towards the source node. The source node then chooses the route with a maximum calculated link lifetime. The generation of a RREP packet for every received RREQ packet increases the routing overhead in the network.

Namboodiri et al. [23] proposes a Prediction-Based Routing (PBR) protocol which is specifically designed for the highway scenario. The PBR uses the best features of both PRAODV and PRAODVM. The authors in [23] propose an idea of mobile gateway nodes which are equipped with wireless WAN connections that can act as internet connections for the vehicles. As installing fixed gateways alongside the roads are costly, especially on the highways. PBR uses the mobility parameters like speed, direction of motion and position information, which are obtained from GPS, to predict the link lifetime of a route. If a source node needs to find a route to a gateway node and if it does not have a route to the gateway, it broadcasts an RREQ packet. The intermediate nodes will re-broadcast the RREQ after inserting its own parameters to the next node. Each intermediate node will also amend its direction of motion in the RREQ. When the RREQ reaches the destination node an RREP packet is generated. The PBR like PRAODVM calculates the link lifetime based on the information of the RREP packet and prefers the route having a longer link lifetime. The PBR like PRAODV preemptively construct a new route before the expiry of the predicted lifetime of the old route. The high topology dynamics of the VANETs can break the route sooner or later as compared to the link lifetime predicted, initially, during the route discovery phase. For that reason, the real-time calculation of the link lifetime should be more efficient.

2.5.3 Cluster-based routing

Cluster-based routing creates a virtual network infrastructure. A group of nearby nodes combines to form a cluster. Each cluster selects a cluster head (CH), which is responsible for intra- and inter-cluster communication and controls the group of nodes in the cluster known as ordinary nodes. The cluster gateway (CG) (if selected) is responsible for inter-cluster communication. Cluster-based routing protocols are primarily designed to provide scalability in the network and efficiency in a dense network. The stability of a CH is very important and a key factor in cluster-based routing. One of the earlier cluster-based routing protocol proposed in the literature is CGSR [31]. To elect a CH for the cluster, a distributed algorithm is used in CGSR. The algorithm selects CH with lower ID (LID). The LID node is responsible for broadcasting an ID to the one hop neighbors. As a result one hop clusters are formed. In CGSR, there are frequent CH changes occur. The CH gives up its position if another LID node joins the cluster. Further, the highly dynamic topology in VANETs can cause frequent CH changes in CGSR within a cluster. In order to mitigate the frequent CH changes, a least cluster change (LCC) algorithm [39] is proposed. In this algorithm, CH does not give up its position unless there is another CH move into its range. The authors [22] proposed a cluster-based multi-channel communications protocol. The proposed protocol efficiently utilized the DSRC allocated channels in vehicular networks. The protocol selects CH during election procedure based on some rule. The elected CH is then responsible for allocating the channels for different applications within a cluster. The main goal of the protocol is to ensure the timely delivery of the safety messages among the vehicles. Mobility-based clustering (MOBIC) is another cluster-based routing protocol which elects CH based on the local mobility characteristics [40]. MOBIC selects CH which has lower relative velocity among the nodes within a cluster; thus, the protocol is capable of selecting stable CH in terms of mobility. MOBIC uses received signal power to indicate the lower relative velocity. (i.e., the power difference between two consecutive received messages). Hence, in MOBIC there are exchange of messages among the nodes within a cluster for selecting a stable CH. It is stated in [21] that MOBIC can provide a more stable CH as compared to LCC at the cost of higher controlled messages. The authors [21] proposed two cluster-based algorithms for selecting a stable CH and a stable CG: (1) dubbed dynamic Doppler velocity clustering (DDVC), and (2) dynamic link duration clustering (DLDC). DDVC uses a new metric called Doppler value (DV). DV finds the relative velocities between the nodes from Doppler shift, by considering the effects of approaching or receding nodes. The authors stated that the approaching nodes can remain in communication range for a larger time as compared to that of receding nodes. DDVC uses the ratio of the transmitted signal frequency to the received signal frequency. For approaching nodes, the ratio is smaller where as the ratio for receding nodes is higher. Based on this information the algorithm selects the more stable CH that can stay longer in the cluster. The DLDC algorithm uses mobility parameters from GPS devices installed in vehicles. The algorithm employs the inverse of the link duration as a cost metric. The CH that has lower cost value within the cluster is selected. The lower cost metric value means more stable CH.

In VANETs, the rapid topology changes affect the nodal connectivity. Thus, links break very frequently. Consequently, the cluster head and the cluster gateway created by cluster-based schemes are short lived to provide a stable communication with low overhead. Further, it is stated in [22] that due to the high mobility of the vehicles, the clustering-based algorithm cannot provide guarantee for a stable cluster topology. In short, cluster-based routing schemes can provide scalability for large and dense networks, but rapid topology changes of VANETs increase the delay and the routing overhead for forming and maintaining the clusters by using these techniques.

2.6 Network Simulator

The network simulator (NS-2) is a discrete event simulator and is widely used in the networking research especially in ad hoc networks. In 1989 Cornell University, Ithica, New York [41] started the work on NS-2 as a variant of the REAL network simulator. In the following years, the Defence Advance Research Project Agency (DARPA) has supported the development of NS-2 through the Virtual Inter-network Testbed (VINT) project at Lawrence Berkeley Laboratory (LBL), Xerox Palo Altto Research Center (PARC), University of California at Berkeley (UCB), Information Science Institute (ISI) of the University of Southern California (USC) and Collaborative Simulation for Education and Research (CONSER) by The National Science Foundation (NSF). Many researchers contributed to NS-2, especially the wireless code which was contributed by researchers working at UCB at Daedelus and Carnegie Mellon University (CMU) with Monarch projects and Sun Microsystems. NS-2 can simulate Transport Control Protocol (TCP) and User Data Protocol (UDP), traffic source behavior such as File Transfer Protocol (FTP), telnet, web, constant bit rate (CBR), router queue management mechanisms such as drop tail, routing algorithms such as Dynamic Source Routing (DSR), Ad hoc On-demand Distance Vector (AODV), Destination Sequence Distance Vector (DSDV) and MAC protocol like IEEE 802.11 [42]. NS-2 is an open source simulator and it is evolving continuously through research and development.

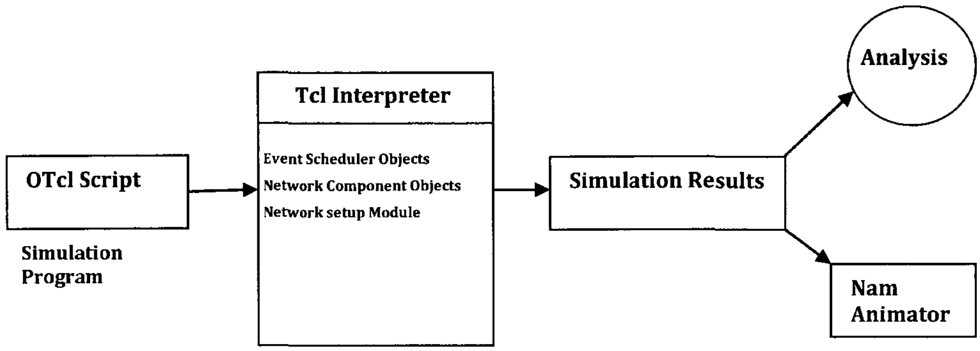

Figure 2.8: NS-2 model

There are two programming languages used in NS-2; an object oriented simulator written in C++ and Object Tool Command Language (Otcl): Tcl script language with Object oriented extensions developed at Massachusetts Institute of Technology (MIT). It has a rich set of library for network and protocol objects. NS-2 consists of two class hierarchies: the compiled hierarchy written in C++ and the interpreted one written in Otcl. Figure 2.8 shows a simplified model for NS-2. It has an object oriented Tcl (OTcl) script which consists of a simulation event scheduler and network component object libraries, and network setup libraries. Users of NS-2 program in OTcl script language setup and run a simulation network. The trace file is used to record the detail of each packet which has a unique identification. Trace file stores all the events related to a packet such as when it was generated, its size, what was the source node of that packet and when it reached the destination. Network Animator (NAM) can show graphically the network activities in terms of packet drop, mobile node movement, and other network parameters.

2.7 Wireless network model

Monarch project of Carnegie Mellon University, contributed to the implementation of wireless network extension of NS-2. New elements were added to NS-2 are the physical, MAC and routing layers. These elements make it possible to construct detailed and accurate simulations of wireless subnets, LANs, and multi-hop ad hoc networks [43]. The logical view of node connections using the CMU Monarch extensions to NS-2 is shown in Figure 2.9.

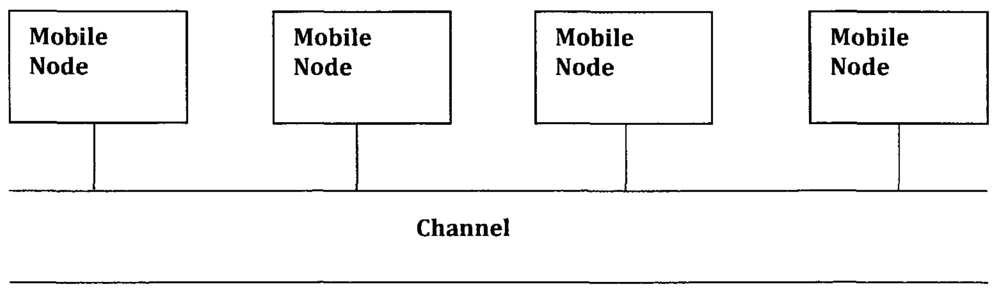

Figure 2.9: Logical view of mobile node connection

Each mobile node acts as an independent entity which might have one or more network interfaces attached to a channel. The channel acts as the link that carries packet between mobile nodes. Every packet transmitted to the channel has a copy distributed to all the network interfaces on the channel. Each interface then uses a radio propagation model to determine if it can receive the packet. Mobile nodes are responsible for computing their position and velocity as a function of time.

The mobile node architecture of NS-2 is shown in Figure 2.11. Each arriving packet from the channel is stamped by the network interface with the receiving properties and then invokes the propagation model. Based on the propagation model and the receiving properties the network interface determines if the node can receive the packet or not. If it can receive the packet, the packet is handed to the MAC layer where it determines if the packet has an error or arrives collision free. If it has no error and arrives collision free, the MAC layer hands the packet to the mobile node's entry point. At this point if the node is the final destination of the packet, the address demux will hand the packet to the port demux, and then to the proper sink agent. If the node is not the packet's final destination, it will be handed to the default target of the address demux, and the routing agent will assign the packet a next hop address and pass the packet back to the link layer. If the next hop address is an IP address, the Link Layer (LL) object queries the ARP object to translate the IP address to a hardware address. On getting the hardware address, the packet is inserted into the interface queue (IFq). The MAC layer takes packets from the head of the interface queue and sends them to the networking interface (NetIF) at the right time.

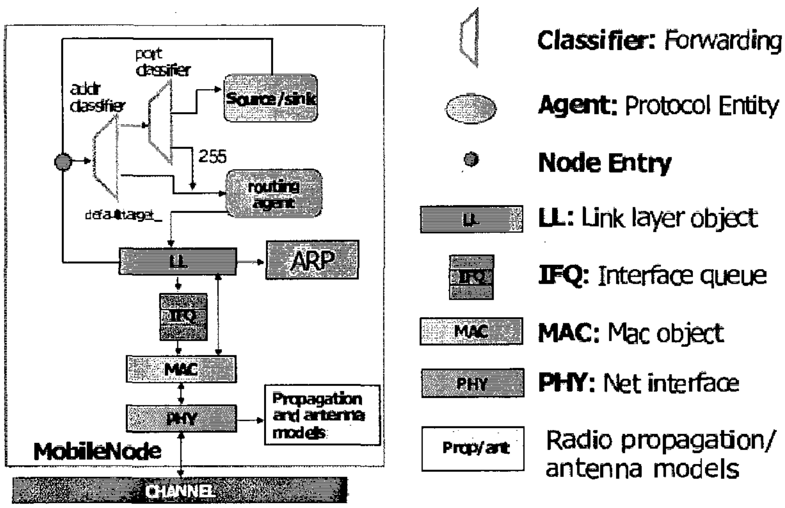

Figure 2.10: Portrait of mobile node

2.8 Summary

In this chapter, the most widely used mobility models in Ad Hoc Networks were highlighted. Proactive and Reactive routings of MANETs were explained. Ad Hoc On-Demand Distance Vector (AODV) routing described in detail and the mobility effect on AODV is described. The challenges and the features of routing protocols in VANETs were discussed. A review of routing protocols in VANETs was presented and their limitations were highlighted. The above discussions lead to the following:

1. During route discovery phase, the nodes which are highly mobile and unstable (in terms of link lifetime) can be differentiated and restricted for route selection process. Therefore, suppression of unnecessary re-broadcast from these nodes reduce the routing overhead which in turn also minimize the route acquisition time.
2. In VANETs, a vehicle's mobility can change the predicted Link Lifetime which was calculated during the route discovery phase. Thus, a real-time calculation for link lifetime to predict a link breakage should be an efficient choice.

The next chapter will be focused on the design of a new routing metric and its implementation in the proposed routing protocol for VANETs.

Chapter 3: Vehicular ad hoc routing protocol with link expiration time information (VARP-LET)

3.1 Introduction

Finding a stable and a reliable path in VANETs leads to avoidance of a frequent disconnection of the path and increases the system throughput. As vehicles are traveling fast which make network highly dynamic, therefore, they need to form and maintain a network automatically. Node mobility increases complexities of routing even further due to frequent link breakages. These link breakages increase routing control overhead and reduce efficiency of the protocol due to increase in frequency of the route discovery process. The link expiration time (LET) information can be used to select the route that last longer. Thus, it leads to reduce in the amount of controlled packet overhead generated in the network and hence improves bandwidth utilization. For that reason, treatment of link breakages in VANETs is very important.

There are a number of proposals in the literature to address this problem. Reference [44] proposes Associativity-Based Routing (ABR) in which each node periodically transmits beaconing ticks to identify itself. The metric used for route selection is the number of ticks received at the receiving node. If a large number of ticks are received, then the route is considered stable. However, there is a substantial increase in overhead in ABR due to these periodic beaconing signals. Another adaptive protocol is Signal Stability-Based Adaptive Routing (SSA) [45] which uses signal strength as a metric to select the most reliable route. It selects links with higher signal strength. However, higher signal strength is an indication of shorter distance between two nodes. Therefore, nodes close to each other in the route selection process will increase the hop count between the source and the destination, which in turn increases end-to-end delay in the network. References [46] and [47] present an algorithm that is useful for link stability estimation when the node's movements are random. Link properties in this algorithm are based on a random way point mobility model. Reference [48] presents an algorithm that analyses the link lifetime and expected link change rate by using a distance transition probability matrix. Link properties in this algorithm are based on the smooth mobility model. The algorithms, mentioned in [46], [47], and [48], are based on probabilistic approaches.

The reliable distance based routing metric for reliable route selection in the AODV protocol is investigated in [15] and an optimized AODV (O-AODV) protocol is proposed. In O-AODV, neighboring nodes that lie farther than reliable distance (which is less than transmission range) are not considered during route selection by a node. As links between the nodes present within a reliable distance are still decided on the basis of the minimum hop criteria of AODV, thus this metric tries to select the next hop neighbor that lies near the periphery of the reliable distance region of a node. Therefore, the chances of early breakage of a route increase greatly even with a small increase in the relative speed of the mobile nodes.

The proposed routing protocol in this thesis is based on link lifetime prediction known as link expiration time (LET). It uses LET information to select route that has a higher LET value with as few hops as possible. Imposing the few hops condition is needed as it controls the end-to-end delay of the transmitting packets (seen later in simulation results). One way, for selecting route that has higher LET value, is to let all the nodes in a network re-broadcast and then selects a route through the nodes that last longer. This increases the system overhead as broadcast consumes more of the bandwidth of the system. The other way, is to limit nodes re-broadcast to only those nodes which are reliable in terms of their position and relative velocities to that of the transmitting node. That is why the routing metric in VANETs' routing protocol needs to co-operate with location as well as mobility. In this context, a new reliable coverage area based LET (RCA-LET) routing metric is introduced. This metric helps in selecting reliable as well as relatively more stable links. The outer periphery of RCA helps to avoid frequent link breakage by avoiding nodes on the edge of transmission range, while the inner periphery of RCA helps to minimize end-to-end delay by avoiding closely spaced nodes. This routing metric is implemented in the proposed routing protocol and is tested via simulations.

3.2 VARP-LET protocol overview

The proposed routing protocol is named as vehicular ad hoc routing protocol with link expiration time information (VARP-LET). There are two phases in VARP-LET (like that of AODV protocol): (1) route discovery phase, and (2) route maintenance phase. In the route discovery phase the protocol uses RCA-LET routing metric that selects a route which is more stable and long lasting. In this phase the nodes which are more reliable are selected to take part in a route selection process. The reliability of the nodes depends on their positions in the transmission range, direction of motion and relative velocities to that of the transmitting node. The transmission range occupied by those nodes is defined as a reliable coverage area. The nodes lying outside the reliable coverage area are not allowed to take part in route selection process and will suppress their re-broadcast in the presence of reliable nodes. This suppression for unnecessary re-broadcast helps to reduce the overall control overhead in the network and provide a faster route selection process as compare to those if all the nodes were allowed to take part in a route discovery phase. In the route maintenance phase, after the stable route is selected in phase 1, each active node keeps on checking its link status before forwarding the data packets. The process involve for checking the link status is based on a real-time calculation of the LET instead of relying on the value of the link lifetime initially estimated during the route discovery phase. The calculated value of the LET is used by the active node to initiate a unicast route break indicator (RBI) message to inform the precursor node about an early breakage of the link. The RBI message propagates towards the source node via each precursor node of the active path. The source node on receiving the RBI message will stop sending the data packets through that path. This process of an early indication of link breakage to the source node will help to avoid the data packets loss that would have been lost if the source node is informed after the route breakage. The source node can re-initiate a route discovery phase to find a new path towards the destination.

3.3 Related work

Before explaining the RCA-LET routing metric, the following background related work need to be discussed.

3.3.1 Coverage area analysis

An additional coverage area analysis is comprehensively presented in [49] for a static network. In this subsection, we describe some of those results that are pertinent to our work. The additional area coverage depends on the distance between two nodes and the transmission radius. Figure 3.1 illustrates this dependency between the distance and transmission radius. Let us consider two nodes A and B located at a distance of d meters (m) apart, and their transmission radii is r (m).

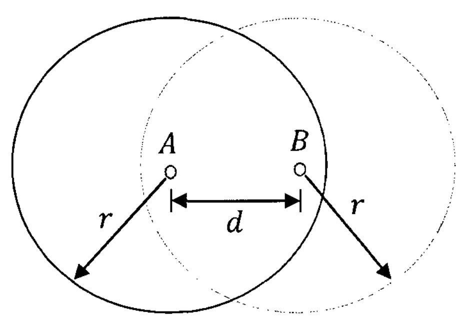

Figure 3.1: Coverage area analysis for static network

Here, A is sending a message and B is forwarding this message. Let S_A and S_B be the area covered by the nodes A and B, respectively. The additional area that node B can cover is shaded, denoted by S_{B-A}, and given by

$$|S_{B-A}| = |S_B| - |S_{A\cap B}| = \pi r^2 - INTC(d) \tag{3.1}$$

Here, $INTC(d)$ is the intersection area of two circles centered at two points located at a distance of d apart, and is given by

$$INTC(d) = 4\int_{d/2}^{r} \sqrt{r^2 + x^2}\, dx \tag{3.2}$$

For $d = r$, the additional coverage is the largest, and is given by

$$\pi r^2 - INTC(r) = r^2\left(\frac{\pi}{3} + \frac{\sqrt{3}}{2}\right) \approx 0.61\pi r^2 \tag{3.3}$$

Equation (3.3) shows that a node lying at the edge of transmission range of the previous node can provide an additional 61 percent coverage over what has already been covered by the previous node.

The above discussion is valid for static networks. However, mobile networks offer different challenges. Figure 3.2 illustrates the effect of mobility on an additional coverage area. Forwarding node (FN_c), located inside the transmission radius of mobile node (MN), provides the largest additional coverage for MN's messages. However, being a border node, it can move out of transmission range of MN any time, and how long it can serve for MN depends on its relative speed and direction.

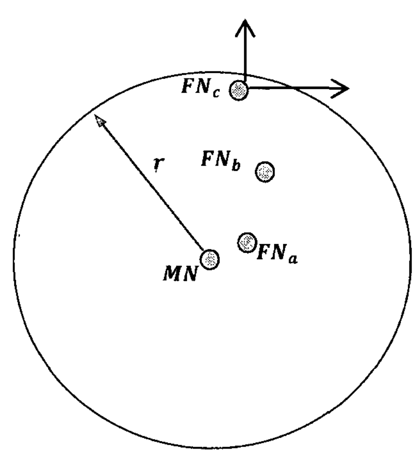

Figure 3.2: Coverage scenario under mobility

In contrast to this, being close to MN, FN_a provides less additional coverage area, but it can remain in contact with MN for a longer period of time. Similarly, FN_b is located in the middle of transmission range of MN; thus, it gives a compromise between additional coverage area and time to remain in contact with MN. This tradeoff is investigated further in selecting the forwarding node in Section 3.4.

3.3.2 Link expiration time

The link expiration time (LET) is the time for which two mobile nodes can remain in contact with each other. To find the estimated LET in our proposed routing metric, we used the following formula as given in Reference [50],

$$Dt = \frac{-(ab+cd)+\sqrt{(a^2+c^2)r^2-(ad-bc)^2}}{a^2+c^2} \qquad (3.4)$$

Here, a, b, c and d are given as follows:-

$$a = vicos\theta i - vjcos\theta j$$
$$b = xi - xj$$
$$c = visin\theta i - vjsin\theta j$$
$$d = yi - yj$$

Here, i and j are two mobile nodes that have r (m) as their transmission or LOS range, vi and vj are their velocities, θi and θj are their direction of motion, and (xi, yi) and (xj, yj) are their positions respectively. This information can be obtained if the mobile nodes are equiped with a GPS system.

3.4 Proposed routing metric description

This section presents a description of the reliable coverage area based link expiration time (RCA-LET) routing metric. This metric assumes that all the nodes have the same transmission radius and are equipped with GPS systems.

The proposed routing metric can be explained with the help of Figure 3.3. In this figure, the transmission range of a mobile node (MN),r, is virtually divided into three regions. The internal region between R_{min} and R_{max} is referred to as *reliable coverage area*. The nodes present in this region are considered as reliable and stable nodes in terms of additional area coverage and LET. The outer region between R_{max} and r is considered as *unreliable coverage area* in terms of LET. The innermost region between R_{min} and the position of MN is considered as an *undesirable coverage area,* in terms of length of route since nodes in this region increase hop count without providing any significant additional coverage area, as per the discussion in Section 3.3.1. The value of R_{min} depends on the compromise between acceptable delay and longevity of a route. However, value of R_{max} depends upon the wireless medium characteristic and the mobility model. The value of these parameters can be tuned to provide desired performance for an application in VANETs.

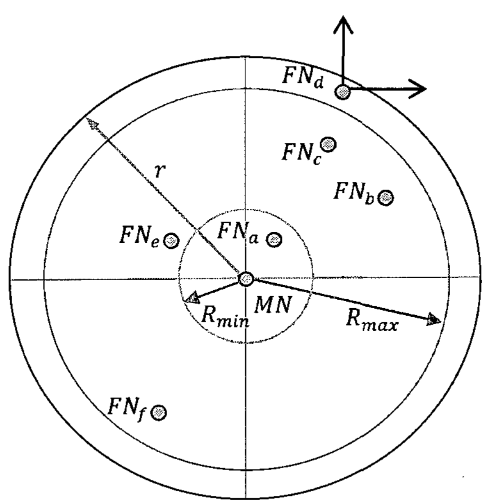

Figure 3.3: Transmission regions of a mobile node

The central theme of our routing metric is that the nodes that lie in an RCA are given the first priority in route selection. However, nodes in an unreliable coverage area and undesirable coverage area are given second and third priority respectively in route formation. A priority scheme is implemented using the concept of waiting interval prior to re-broadcasting of the RREQ message. For example, from Figure 3.3, if MN sends a route request, then the nodes in its RCA (FN_c, FN_b, FN_e and FN_f) respond to that request in a randomly allocated time slot of $[0ms, 5ms]$. Upon hearing a re-broadcast from nodes in RCA during $[0ms, 5ms]$, the nodes lying in unreliable and undesirable coverage areas (FN_d and FN_a respectively) do not respond to route request. Thus, they do not take part in route selection. This helps to avoid unnecessary re-broadcast of RREQ from an unreliable and undesirable coverage area, which in turn significantly reduces routing overhead in the network. However, if there is no node in the reliable region, then, nodes from the unreliable coverage area respond to route request from MN in the next time slot of $[5ms, 10ms]$. Similarly, if there are no nodes lying in the RCA and unreliable coverage area, then nodes from the undesirable coverage area respond to route request in the next time slot of $[10ms, 15ms]$.

3.5 Route discovery phase in VARP-LET

The route discovery phase in the VARP-LET is shown in Figure 3.4.

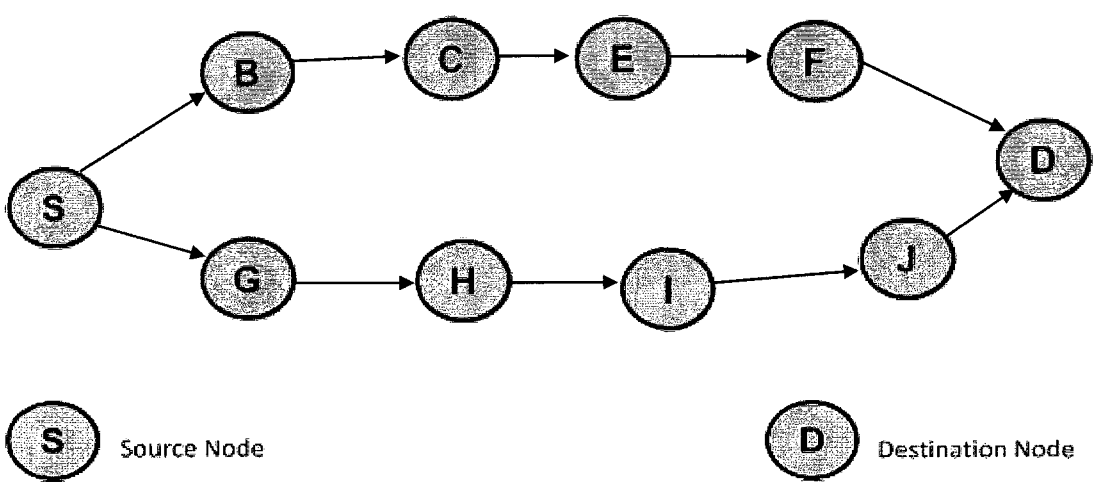

Figure 3.4: Route discovery phase (VARP-LET)

A node calculates its LET value on the basis of its link status with its previous hop node, as given in equation 3.4. At the beginning, the source does not have a valid LET value as it does not have any previous hop node. Therefore, when the route discovery mechanism is initiated by the source node S, the source node broadcasts an RREQ packet with a dummy high value of LET. In general, after receiving an RREQ, an intermediate node calculates its distance from the previous hop node as well as the LET value of the link between itself and the previous hop node. Thus, the nodes from the RCA of the source node calculate their own LET values and compare them with LET value of the just received RREQ packet from the source node. They retain the minimum of these two LET values. Then, these nodes re-broadcast the RREQ packet within $[0ms, 5ms]$ time slot by inserting the minimum LET values in their respective RREQ packet headers. Here, each of the nodes from the RCA of the source node, which takes part in a re-broadcast process, acts as an S node and the group of nodes from their respective RCAs respond to their RREQ packets. This process continues until an RREQ packet reaches its destination. The destination node also calculates its own LET value and compares this value with that of the just received LET value and retains the minimum of these two LET values. Thus, the destination node now has the minimum LET value of the path between itself and the source node. The destination node inserts this minimum value of LET for the path in the route reply (RREP) packet and sends it back towards the source node.

This routing metric always gives emphasis to the best LET value path achieved from the nodes that are present in the RCA. However, if two or more paths have the same LET value, then the path with the lower hop count is chosen. Thus, if the destination node receives an RREQ packet from a different path with a better LET value, then it regenerates the RREP packet and sends it to the source node. After receiving the RREP, the source node updates its routing table and starts sending data packets through the new path.

Figure 3.5 shows a typical route selection scenario. In this figure, node A initiates a route discovery mechanism. Node B and C are present in the RCA of node A. Node D is present in the RCA of both B and C. After receiving a broadcast request from A, B calculates the LET value (minimum) and sends it to D. Then, D compares the just received LET value from B with its own calculated LET value. The node keeps the minimum of these two LET values and inserts it into the RREQ packet header and holds this packet for its random allocated time slot of duration $[0ms, 5ms]$. Meanwhile, before re-broadcast, if D receives a request packet from C, then it compares the just received LET value from C with its own calculated LET value. Thus, if the minimum of the LET values with C is higher than the minimum of the LET values with B (as calculated previously), then discards the path through node B and adopts a path though node C. In this way, the intermediate nodes on the way towards the destination will keep on selecting the best possible path in terms of higher LET values.

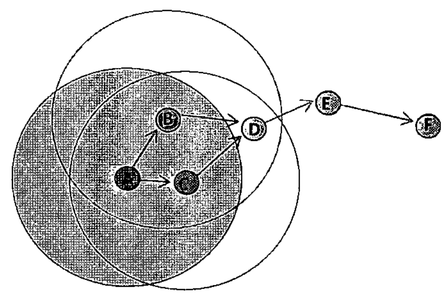

Figure 3.5: A typical route selection scenario

Further, there is a minimum value for LET is set in the route discovery phase, defined as LET threshold (LET_{thr}), each intermediate node has to meet this value before re-broadcasting an RREQ packet. The value is given as below,

$$LET_{thr} = ((NODE\_TRAVERSAL\_TIME \times TTL\_THRESHHOLD) \times 2) + \gamma. \quad (3.5)$$

Here the following are the default values used in AODV

$$NODE\_TRAVERSAL\_TIME = 30ms,$$
$$TTL\_THRESHHOLD = 7,$$

Whereas 2 is a safety factor and γ is a correction factor and its value is set to 0.28.
Using the above values in equation (3.5),

$$LET_{thr} \approx 0.7\text{sec}. \quad (3.6)$$

Note that LET_{thr} is an important parameter. Nodes having LET values equal to or less than LET_{thr} are not allowed to take part in route selection phase. This will further reduce re-broadcast from those nodes which are highly mobile.

3.6 Performance analysis of AODV-RCA protocol (RWP mobility model)

In this experiment only RCA-LET routing metric was implemented in AODV by replacing with minimum hop count metric for route selection process. The route break indicator (RBI) is not implemented yet. Hence, the resulting protocol is named as AODV-RCA. Indeed RBI signal is designed specifically for vehicle's network. As vehicle's motion on the road is linked to the behavior of each driver individually that mostly relate with the traffic density of a road or the road infrastructure. Hence, vehicle's mobility is also characterized as micro-mobility models [51]. This model represents the effects such as smooth speed variation, cars queues, traffic jams etc. Whereas random way point (RWP) mobility model is characterized as macro-mobility models [48] as speed's variation is not smooth and there are sharp turns and sudden stops etc., involved. The purpose of this experiment is to measure the performance of the RCA-LET routing metric by using the most common mobility model RWP in MANETs. The performance of AODV-RCA was tested and compared with traditional AODV [13] and with optimized AODV (O-AODV) protocol [15]. In this scenario the same network is created as that of [15], i.e., The NS-2 simulator is used to create a simulation model. The mobility model is RWP (as defined in Chapter 2). The network model consists of 50 wireless nodes which are randomly distributed over an area of 1200m by 1200m. Thirty (30) pairs of connection are set up in the simulation. Their maximum velocity variation is chosen as (1, 5, 10, 15, 20, 25, 30) m/s. Traffic sources are constant bit rate (CBR) with packet size of 512 bytes and data rate of 1 packet per second. The radio model used is the Lucent's WaveLAN radio whose nominal bit rate is 2Mbps and radio range of 250m. The simulation time set is 400 sec. Each data point is an average of 20 runs.

The performance of traditional AODV, O-AODV [15] and AODV-RCA are compared on the basis of four performance metrics. These are given as below.

- Packet delivery ratio: It is the ratio of data packets received by destination to those generated by a CBR source.

- Number of RERRs: It is the total number of RERR packets during a simulation run. It gives information about frequency of route breakage.
- Normalized routing overhead: It is the number of control packets (RREQ in this case) transmitted or forwarded by all nodes per data packet delivered to destinations.
- Average end-to-end delay: It is the average of durations taken by data packets to reach from their sources to their destinations.

As shown in Figure 3.6, the packet delivery ratio is better in ADOD-RCA as compared to the traditional AODV and O-AODV protocol, specifically at a higher speed. At relatively low speed packet delivery ratio is almost the same in either protocol as there is a less frequent route breakage occurs and selected route might be redundant. But as nodes move faster the AODV-RCA shows better results as compared to other two. This is due to the fact that AODV-RCA considering the LET aspect and selects the route that last longer. Thus, there is a less frequent route breakage in AODV-RCA which in turn increases the system through put.

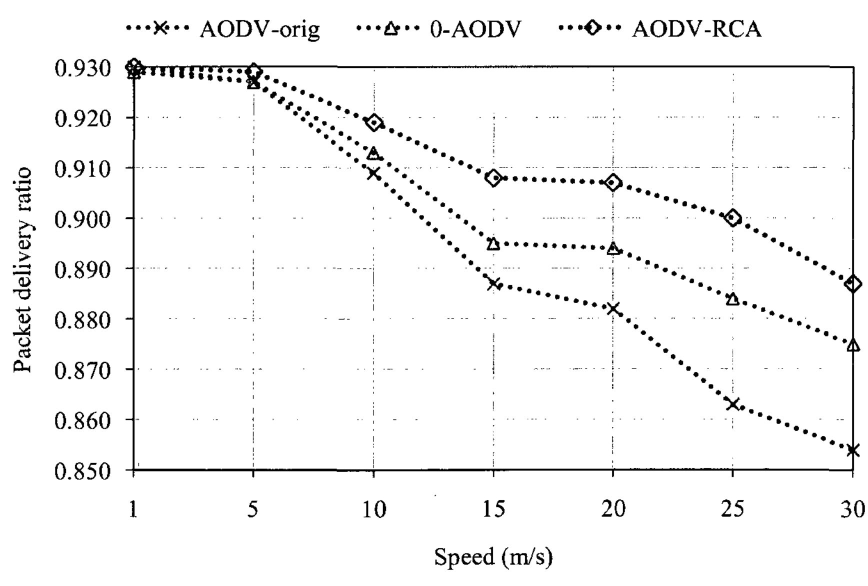

Figure 3.6: Packet delivery ratio (RWP)

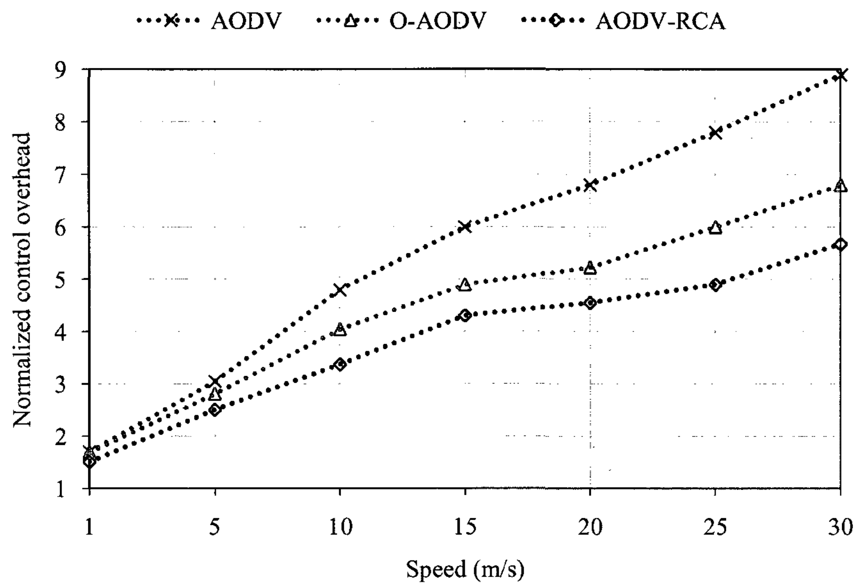

Figure 3.7: Normalized control overhead (RWP)

Consequently, as shown in Figure 3.7, the normalized control overhead is smaller in AODV-RCA. This is due to the facts that 1) there is a less route broken and 2) the unnecessary re-broadcast is suppressed in AODV-RCA. For that reasons there is a significant decrease in routing over head.

Figure 3.8 further affirms the statement that there is a less number of route breakage occurs in AODV-RCA at relatively high speed of the nodes. It is seen that there is a less number of RERR generated in the AODV-RCA as compared to other two routing protocols.

Average end-to-end delay of packet transmission depends on the number of hops between the source and the destination, and the duration elapsed in route formation. Though, the number of hops in AODV-RCA may be more between source and destination for selecting a reliable route. However, there are less frequent route breakages, lower broadcast overhead and faster route selection process due to a smaller number of nodes involved in routing. These factors altogether helps to reduce the end-to-end system delay as shown in Figure 3.9.

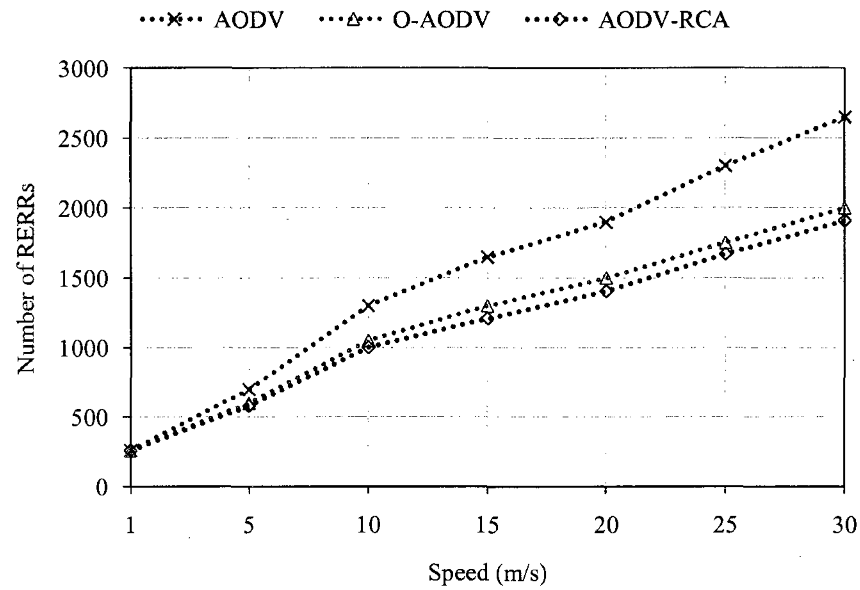

Figure 3.8: Number of RERRs vs. mobility (RWP)

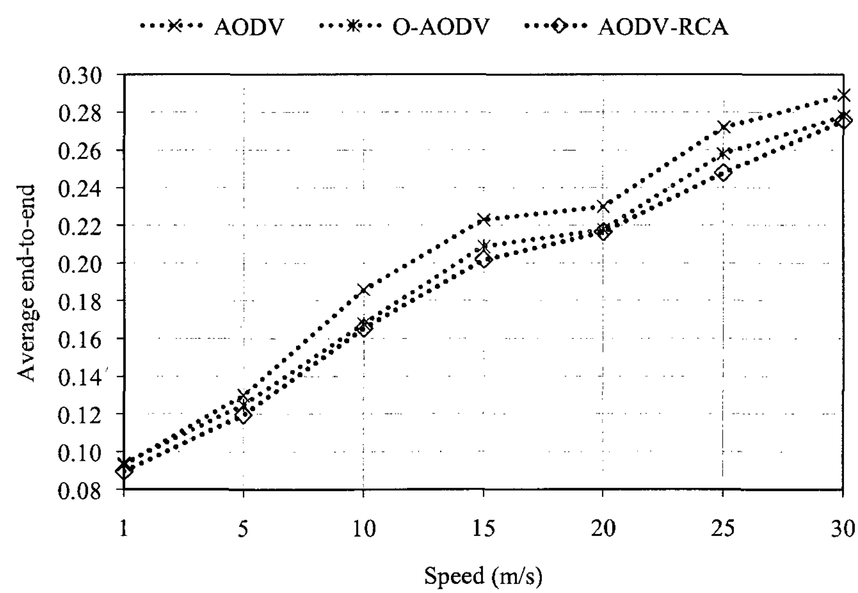

Figure 3.9: End-to-end delay vs. mobility (RWP)

3.7 Route maintenance phase in VARP-LET

During the route maintenance phase each node keeps on checking a link status when it receives a data packet from previous forwarding node. The forwarding node, before sending a data packet to the next hop node, inserts its mobility parameters in the packet header. The next hop node on receiving the data packet, now has all the required mobility parameters i.e., its own and the previous node's parameters. Thus, using an Equation 3.4 the node calculates LET value. The calculated LET value is used by the node to generate an RBI message for near-to-be-broken link. The RBI signal propagates back to the source node and on receiving the RBI signal the source node stops sending data packets through the near-to-be-broken link. And if source node still has data packets for the same destination node it can re-initiate a route discovery process again. The route maintenance phase can be explained from Figure 3.10.

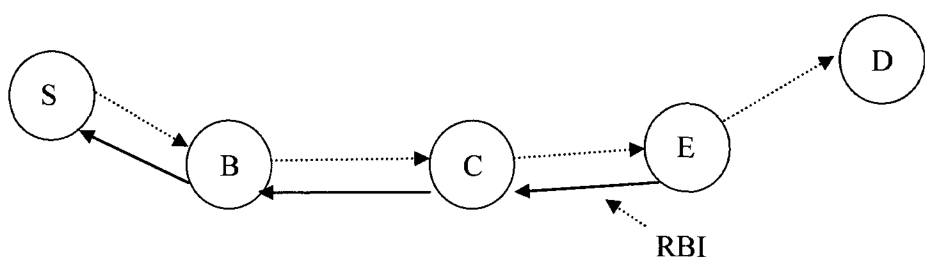

Figure 3.10: Route maintenance phase under mobility

Let S and D is a source and a destination node respectively, having a communication path already set up through intermediate nodes B, C and E. As explained above that each node calculates LET before sending a data packet. Suppose that node E is moving with higher speed than that of node C. When the node E is nearly moving out of the transmission range of the node C, there is a near-to-be-broken link between them. That means LET value between them is small at that instance. And as soon LET value reaches to some specific lower value (define later in this section) node E will send an RBI signal (a unicast signal) back towards the precursor node C. Note that an RBI signal is generated by the node which is ahead of the link. That node is labeled E in Figure 3.10, whereas if the link breaks an RERR is generated by the precursor node which is node C from Figure 3.10. The RBI signal is given a higher priority once it is generated and propagates towards the source node. In the event that if the link between C and E breaks and node C still receiving packets from the same source, for the same destination, and from the same near-to-be-broken link. It generates an RERR message as traditional AODV does. This is also useful in the case if RBI message is lost or not reached to the destination at that instance. The RBI message is generated when

$$\text{LET} \leq (NODE\_TRAVERSAL\_TIME \times HOPCOUNT)\,, \tag{3.7}$$

where $$(HOPCOUNT > 1)$$

Thus, this value depends on the distance (hop count) of the node that generates an RBI from the source node. For example from Figure 3.10, node E is located at the third hop from the source node. Hence in this case node E generates an RBI when it's LET is equal to or less than 90ms.

Also note that HOPCOUNT should be greater than 1 that means, the node that generates RBI should be located more than one hop away from the source node. This is due to the fact that an AODV-LL uses the link layer feedback for detecting a broken link and if a near-to-be-broken link is attached directly with a source node it can detect the broken link immediately after it breaks. For that reason, there is no need to generate an RBI signal from the node located at one hop distance away from the source node.

3.8 RCA-LET with quadrant check

As stated earlier that vehicles move linearly on the road and its mobility is characterized as micro-mobility models. By considering this linearity, the RCA-LET routing metric is slightly modified while implementing in vehicle networks. In the RCA-LET routing metric the preference for route selection is given to nodes which lie in reliable coverage area. In the presence of these nodes the re-broadcasts from the nodes which lie in undesirable coverage area are suppressed in order to avoid un-necessary broadcast in the networks. Now in the vehicular mobility models, the quadrant check scheme is introduced. That checks if nodes are in undesirable coverage area before re-broadcasting. The quadrant check scheme can be explained by Figure 3.11.

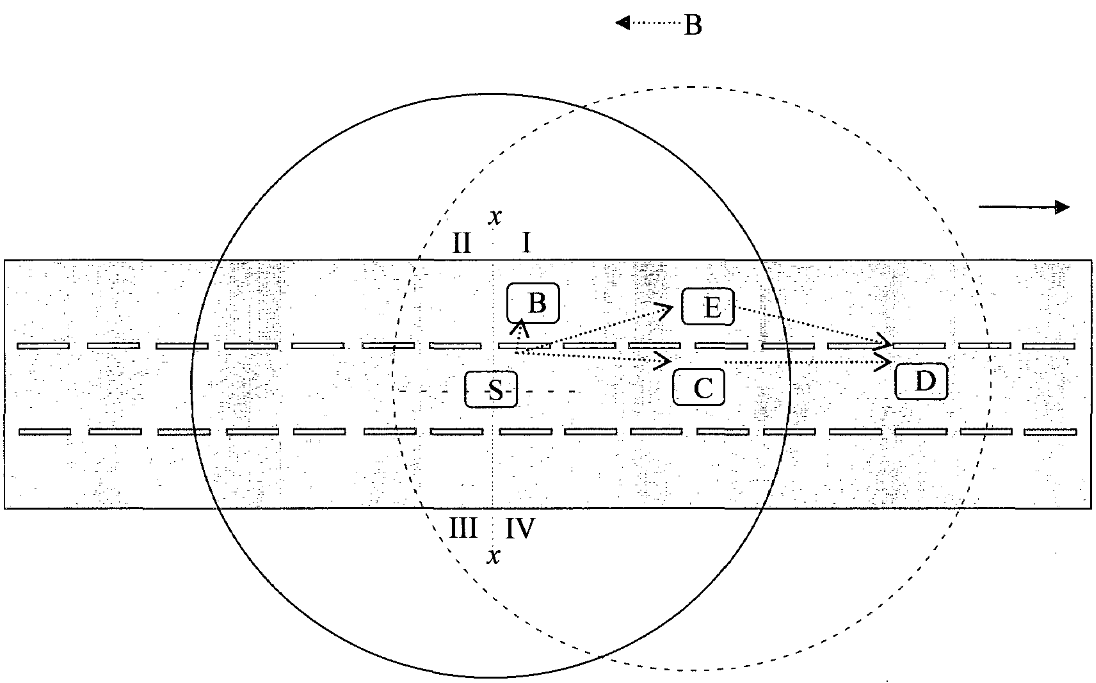

Figure 3.11: Quadrant check suppression technique

Let there are five vehicles moving on a road where S is a source and D is a destination vehicle. The source S initiates a route discovery phase by broadcasting an RREQ packet for the destination D. The intermediate vehicles B, C and E listen to the RREQ broadcast packet from source S. Vehicles C and E being located in the RCA of S will re-broadcast an RREQ packet in the first time slot for destination D (for simplicity only one transmission circle for both C and E is shown). The vehicle B is located in the inner periphery of the transmission range of S still holding the RREQ packet received from S.

As B is allocated a third time slot [10ms 15ms] for re-broadcasting an RREQ packet, so it holds the packet for at least 10ms. As explained in section 3.4, that each node after receiving an RREQ packet calculates its distance from the forwarding node. Hence, B knows its position with respect to x-axis of the S which is quadrant I as shown in Figure 3.11. That means, vehicle B is located ahead of the vehicle S on linear road. For that reason, vehicle B after receiving a re-broadcast from C and E will suppress its re-broadcast only if C or E is present in quadrant I or quadrant IV (ahead of S) as shown. It is due to the fact that as C and E both lie in the RCA of vehicle S and provide a better coverage area and LET with respect to their position, as per discussion in section 3.3.1. However, in case vehicle B is lying in quadrant II or quadrant III i.e., behind vehicle S as shown in Figure 3.12. Though both E and C lying in the RCA of S but ahead of S. That means, both E and C can provide better coverage area only ahead of S. Moreover, as there is no vehicle lying behind S in its RCA that can provide better coverage area in the rear area of S .For that reason, B after hearing a re-broadcast from E and C, will not suppress its re-broadcast. And B is the only intermediate vehicle lying behind S which may provide a route to the destination. This adds robustness in the routing protocol during route selection process. The Quadrant check scheme is not mandatory for RWP mobility models. In RWP the nodes are uniformly or randomly distributed around the simulation area in all direction.

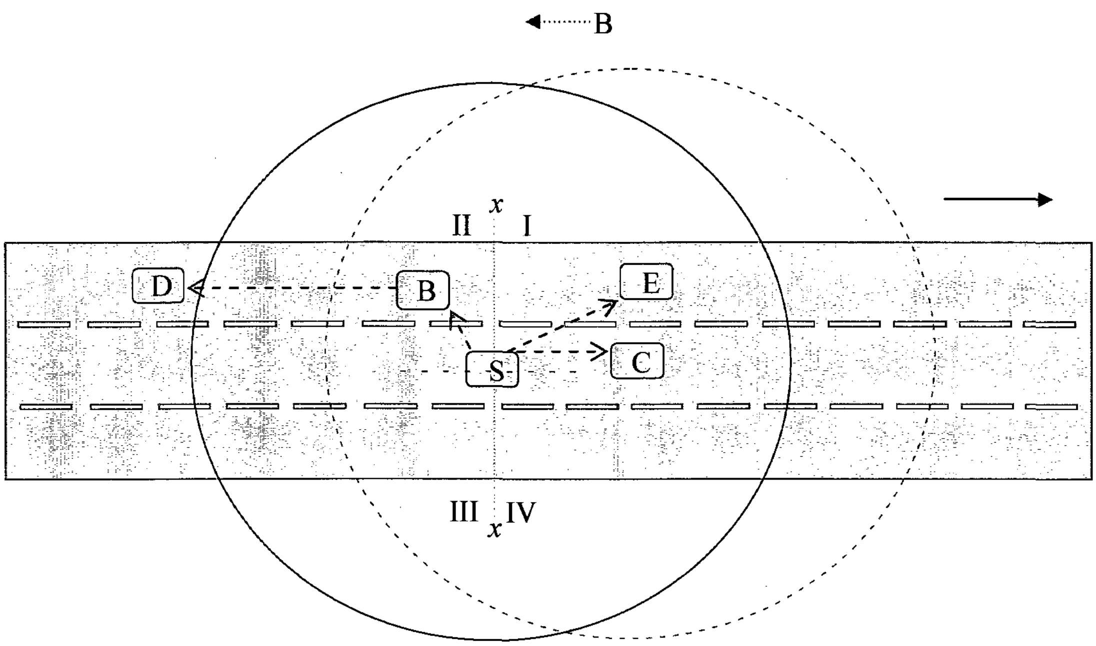

Figure 3.12: Quadrant check non-suppression technique

3.9 Performance analysis (Manhattan Grid mobility model)

In the real world, mobile nodes (*MN*s) such as cars cannot roam freely due to obstacles and traffic regulations. Thus, such *MN*s have more or less similar patterns of travelling in any part of a city. To represent such a mobile scenario, we took the Manhattan Grid mobility model [26] in the simulation. For creating this mobility model, Bonnmotion v1.3a [26] and [27] tool is used. In our simulation scenario, *MN*s are moving at a mean speed (represented as v) of 1 m/s, 10 m/s, 20 m/s, 30 m/s, 40 m/s, and 50 m/s. A grid of ten horizontal and two vertical blocks are taken. The movement update distance is taken as 20 meters. Both the turn and speed change probabilities are taken as 0.1. The minimum and maximum speeds are taken as 0.9v and 1.1v.

Constant Bit Rate (CBR) traffic sources are used in the simulation with a packet size of 512 bytes and data rate of 4 packets per second. The network is composed of 30 nodes moving around a flat rectangular area of 1500m x 300m, where 3 nodes are chosen to be

UDP sources and another 3 nodes are chosen as destination nodes. The channel bandwidth is taken as 2 Mbps. The transmission range of a node is taken as 250 meters. IEEE 802.11 wireless network standard with Distributed Coordination Function (DCF) mode is used for the MAC layer. Simulation time is taken as 400 seconds. Each data point is taken as an average of 15 runs.

In the following discussion, AODV-RCA represents AODV protocol modified with the proposed RCA-LET routing metric in route discovery phase only without implementing an RBI in the route maintenance phase. Whereas, VARP-LET represents a complete protocol, that means, AODV protocol modified with the proposed routing metric and an RBI signal. We compared the performance of traditional AODV, AODV-RCA and VARP-LET as below.

As shown in Figure 3.13, the packet delivery ratio of AODV-RCA and VARP-LET is better than traditional AODV, particularly at higher relative speeds of MNs. It is due to the fact that the traditional AODV experiences frequent route breakage with increasing relative speed of nodes, as the route selection decision in traditional AODV is based on minimum hop routing only. It does not consider the link expiration aspect of a route. Thus, routes selected by AODV break quite frequently as relative speeds of MNs increase. In contrast to this, AODV-RCA and VARP-LET uses link expiration information to select a route. Therefore, though the number of hops in a selected route may be higher in both AODV-RCA and VARP-LET than that of AODV, but the route in this case will last longer which results in a higher packet delivery ratio. VARP-LET gives more better performance than that of AODV-RCA, as it uses an RBI signal for the link which is near-to-be-broken. This helps to avoid the loss of packet which were lost if the link breaks suddenly. Hence, packet delivery ration is improved by 17.22% with AODV-RCA and 20.7% with VARP-LET at a mean speed of 50 m/s.

The argument that the link last longer in AODV-RCA and VARP-LET is further confirmed by observing the number of RERR packets in the network. Figure 3.14 shows

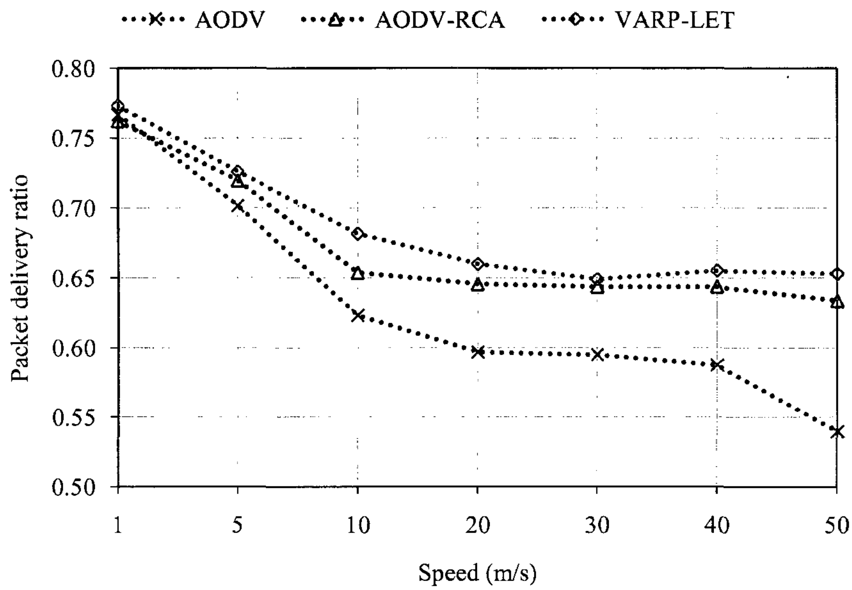

Figure 3.13: Packet delivery ratio vs. mobility (Manhattan Grid)

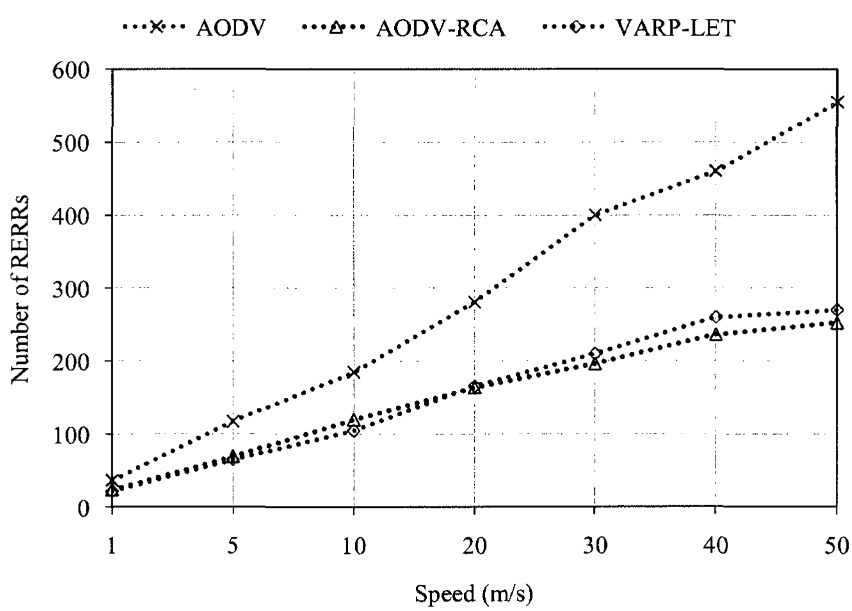

Figure 3.14: Number of RERRs vs. mobility (Manhattan Grid)

that rate of increase in frequency of route breakage with respect to increasing relative speeds of MNs is more in the case of traditional AODV as compared to AODV-RCA and VARP-LET. Note that number of RERR[1] seems to be more in VARP-LET as compared to AODV-RCA. This is due to the fact that the RERR in case of VARP-LET is replaced with RBI, and as stated earlier that the RBI is generated before the link actually expires. Thus, there is always a possibility of more than one link going to expire soon under mobility environment. In that case more than one RBI will be generated to inform the pre-cursor node about the near-to-be-broken link. Whereas RERR signal is generated only after the link actually expires. Further, RERR in VARP-LET may also be generated in case if RBI signal is lost on its way back towards the source node. Therefore, number of RERR plus the number of RBI is higher as shown in Figure 3.14.

As shown in Figure 3.15, rate of increase in normalized routing overhead is less in AODV-RCA and VARP-LET because both use the reliable coverage area concept to determine which nodes take part in route selection. Thus, the number of nodes that take part in route selection is lower in AODV-RCA and VARP-LET as compared to traditional AODV which is based on random broadcast for route selection. It reduces flooding in the network in AODV-RCA and VARP-LET.

End-to-end delay of packet transmission depends on the number of hops between the source and the destination, and the duration elapsed in route formation. As mentioned earlier in this section, the number of hops between the source and the destination are more in AODV-RCA and VARP-LET, as both use the same RCA-LET metric in route discovery phase. It is therefore expected that end-to-end delay will be more in AODV-RCA and VARP-LET. However, there are many factors that compensate for this delay in both AODV-RCA and VARP-LET. These factors are less frequent route breakage, lower broadcast overhead and faster route selection process due to a smaller number of nodes involved in routing. Therefore, as shown in Figure 3.16, as the mean speed of the nodes becomes high such as 40 or 50 m/s, AODV-RCA and VARP-LET gives more emphasis on forming a reliable link that can last longer. For that reason, it starts selecting nodes that are closer to R_{min} in the reliable coverage area. Therefore, average distance between

[1] Combination of RRER + RBI is shown

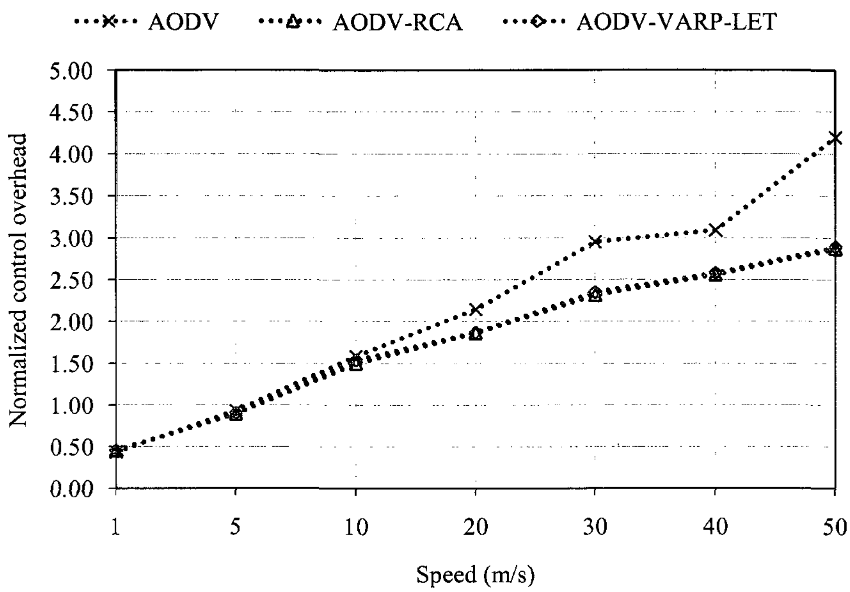

Figure 3.15: Normalized control overhead vs. mobility (Manhattan Grid)

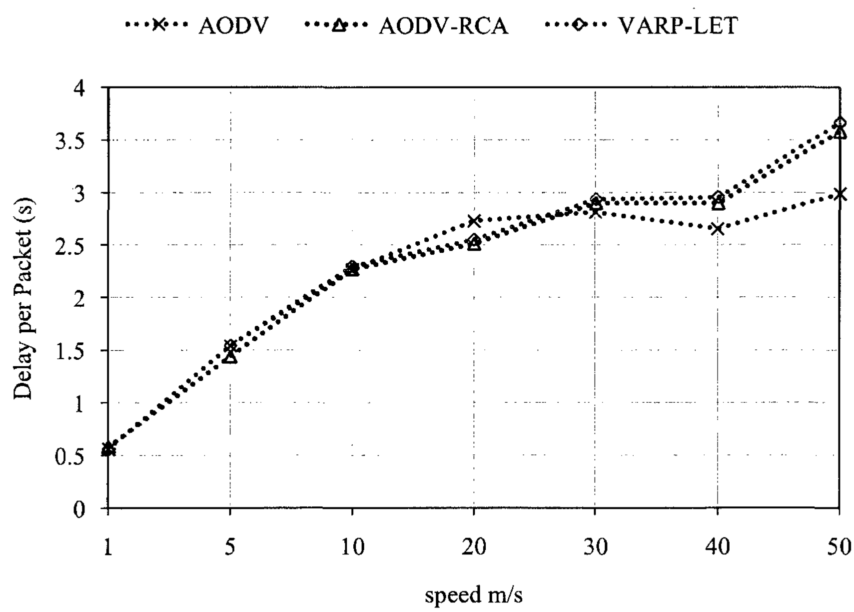

Figure 3.16: End-to-end delay vs. mobility (Manhattan Grid)

nodes in a route decreases. It causes larger number of hops between the source and the destination which nullifies any gains made in terms of lower broadcast overhead and a smaller number of nodes involved in the route formation.

3.10 Performance analysis (highway scenario)

In order to measure that how the proposed routing protocol behaves by varying distances between source and destination node. A simulation of 20 kilometer (km) long unidirectional highway scenario is created with parameters shown in Table 1.

Table 1: Unidirectional highway (20Km)

Cars speed slots	80 - 90 Km/h	90 - 100 km/h	100 - 110 km/h	110 - 120 km/h
meter / sec	22.22 - 25.00	25.00 - 27.77	27.77 - 30.55	30.55 - 33.33
Min & Mean speed	22.22 & 23.61	25 & 26.38	27.77 & 29.16	30.55 & 31.94
Speed update dist.	500 meter			
Standard deviation	1			
Speed Change Prob.	0.2			
Node Density	16 Nodes per km			
Distribution	Uniformly distributed			
Total nodes	160			

In this simulation, four speed slots of vehicles were chosen. The vehicles move within its allocated speed slot on the highway. Each vehicle changes its speed (within its own timeslot) with a probability of 20% by covering every 500 meter, defined as speed update distance. Vehicles whose speed is minimum increases its speed, vehicles whose speed is maximum decreases its speed in the next speed update. The participating nodes (vehicles) are uniformly distributed in the simulation distance and node density is set to 16 nodes per km. Each reading on the graph is an average of twenty runs. For each run same speed of source and destination is chosen but at different positions for each run. The distance between source and destination is taken in hop count; each hop is set to 250 meters.

The purpose of this simulation is to observe the behavior of the proposed protocol regarding a selection of a reliable link under dynamic environment and by varying a distance between source and destination nodes.

Figure 3.17 shows that the packet delivery ratio of AODV-RCA and VARP-LET is better than traditional AODV. It is also observed that after approximately nine hops the traditional AODV starts showing poor results. This was also highlighted in [9] that after approximately nine hop the routing path in the reactive routing protocols may disappear before the first packet is acknowledged. It is due to the same fact that as the route selection decision in the traditional AODV is based on a minimum hop routing only which may break even with a small increase in relative speeds of nodes. Thus, routes selected by AODV break quite frequently as relative speed of vehicles increase. In contrast to this, AODV-RCA and VARP-LET uses LET to select a route and also avoid those nodes that are unstable during route discovery phase. Hence, in this case a selected route will last longer which results in a higher packet delivery ratio. As observed earlier, VARP-LET gives better performance than that of AODV-RCA, as it uses an RBI signal for the link which is near-to-be-broken. This helps to avoid the loss of packet which were lost if the link breaks suddenly. Therefore, as shown in Figure 3.17 that at fourteen hops (distance between source and destination) the packet delivery ration is improved by 23% in AODV-RCA and by 30% in VARP-LET.

Figure 3.18 shows that the frequency of route breakages is more in traditional AODV due to the same effect as explained earlier in the previous section. The important thing here is the number of RBI and RERR in VARP-LET. For clarity, they are shown separately here. The number of RERR generated in VARP-LET is very small. In fact it is replaced with number of RBI in VARP-LET and as explained earlier that the RBI may generated by more than one node if there are near-to-be-broken links exist between nodes. Even, though small, RERR signals were observed in VARP-LET. And as explained earlier that in case RBI signal is lost or missed RERR signal will be generated.

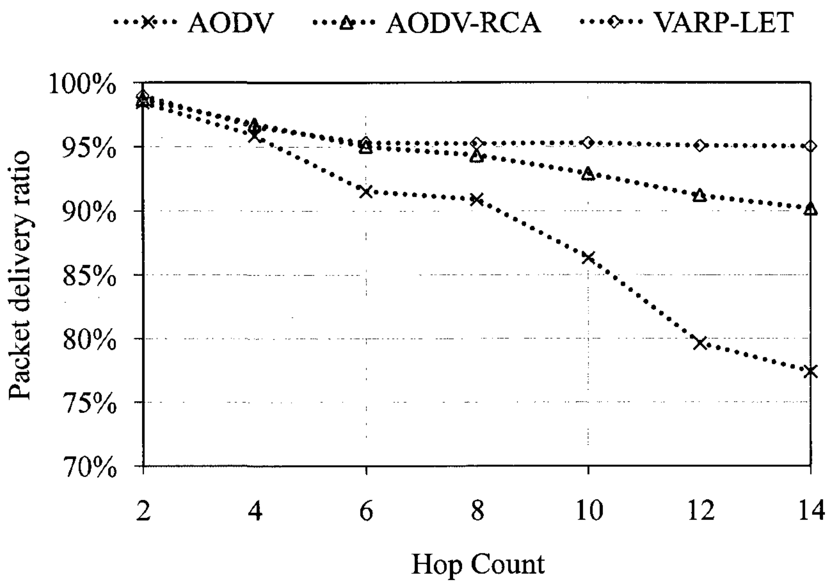

Figure 3.17: Packet deliver ratio vs. hop count (highway scenario)

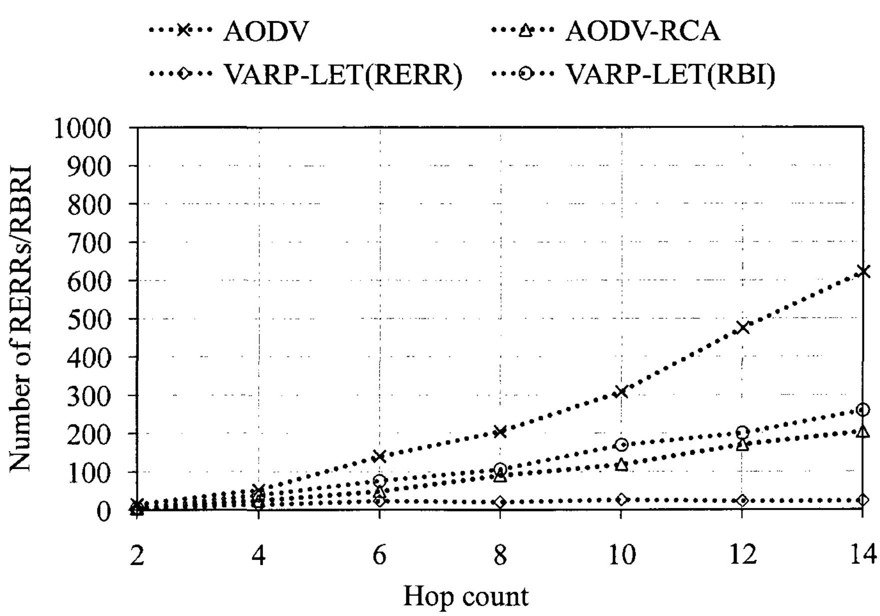

Figure 3.18: Number of RERRs vs. hop count (highway scenario)

Figure 3.19 shows that there is less routing overhead both in AODV-RCA and VARP-LET as they both restrict the broadcast area for nodes to take part in route selection process. Thus, there are fewer number of nodes taking part in route selection process which results lower number of broadcast.

End-to-end delay is better in both AODV-RCA and VARP-LET as compared to the traditional AODV protocol. It is due to the fact that route path is more stable and long live, in result there are controlled overhead in both AODV-RCA and VARP-LET as compared to traditional AODV.

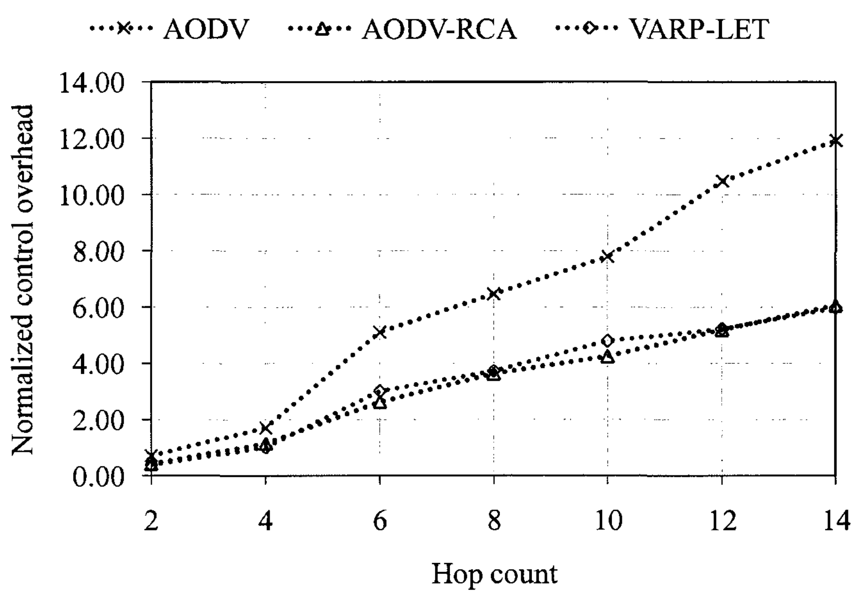

Figure 3.19: Normalized control overhead vs. hop count (highway scenario)

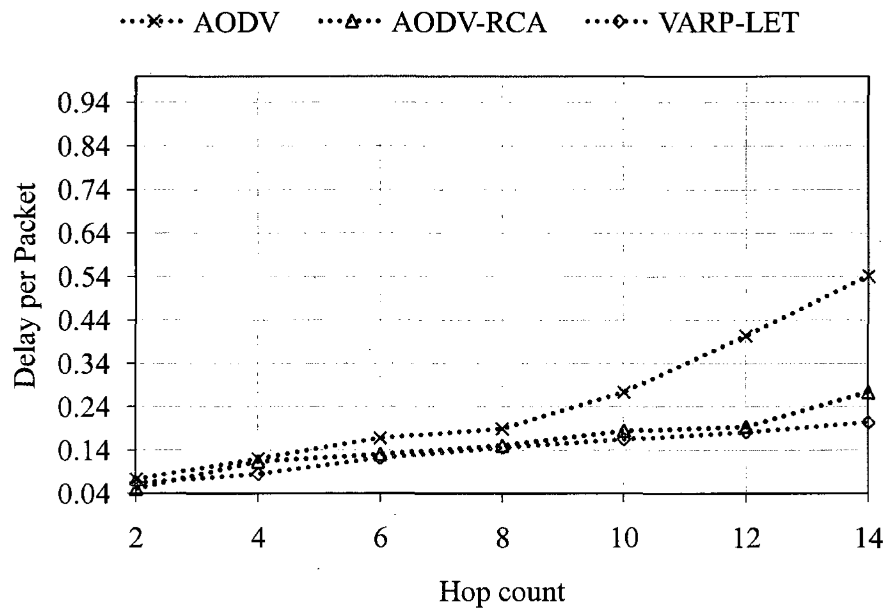

Figure 3.20: End-to-end delay vs. hop count (highway scenario)

3.11 Conclusions

In this chapter two new routing protocols were presented to improve the routing efficiency in highly mobile networks like vehicular ad hoc networks (VANETs). The first protocol AODV-RCA is based on a new routing metric called RCA-LET. In this metric route broadcast area is restricted to only those nodes that are selected as reliable. This metric works in route discovery phase and it tries to select long lasting route with as few hops as possible. The second protocol VARP-LET uses the same RCA-LET metric in its route selection process with the addition of RBI in route discovery. The VARP-LET protocol is capable of detecting a near-to-be-broken link and informing the precursor node about the link breakage ahead of time.

Simulation studies show that VARP-LET and AODV-RCA improves network performances by increasing network throughput, reducing routing overhead and the frequency of route breakages. VARP-LET and AODV-RCA is not only ensuring long lasting routes, but also able to minimize the number of hops between the source and the destination as much as possible within a specified reliable coverage area. Thus, though, the number of hops in AODV-RCA and VARP-LET is slightly higher than for traditional AODV, yet it has a comparable average end-to-end delay performance with respect to traditional AODV in city section mobility model and better in highway scenario. It is due to the fact that the AODV-RCA and VARP-LET has lower broadcast overhead and lower number of route breakages.

Chapter 4: Conclusions and Future work

4.1 Summary of contributions

The main objective of this thesis is to design a routing protocol that works under highly dynamic networks such as vehicular ad hoc networks (VANETs). The proposed protocol considers both the reliable coverage area and link expiration time information (RCA-LET) for a stable and reliable route selection. Hence, the protocol obtains route that last longer with as few hops as possible. The protocol is capable of detecting an early route breakage by using the mobility parameters to avoid any loss of packets due to link failure. In Chapter 2, it has been shown that the generic minimum hop metric used in reactive routing protocols like Ad Hoc On-demand Distance Vector (AODV) routing protocol and Dynamic Source Routing (DSR) is not a feasible choice under high mobility environment. The mobility makes the network highly dynamic which makes routing decision very challenging. The mobility has been shown to bring about different problems that affect the overall performance of the network. Some of the problems are: (1) frequent link breakages, (2) increased network overhead, (3) inefficient use of bandwidth. Frequent link breakages lead to packet loss and reduce the system throughput. For the same reason, the network overhead is largely increased by frequent link breakages, which increase number of broadcast packets for reinitiating a route discovery mechanism. Ad hoc networks are bandwidth constrained networks; thus, increasing routing overhead leads to inefficient use of system bandwidth.

In Chapter 3, two new protocols were introduced. One is based on the new proposed routing metric RCA-LET during the route discovery phase and is named as AODV-RCA. The other is a modified version of the AODV-RCA and uses RBI signal during route maintenance phase to detect near-to-be-broken link. The protocol is named as vehicular ad hoc routing protocol with link expiration time information (VARP-LET). VARP-LET has two phases, the route discovery phase and the route maintenance phase. VARP-LET does not need to maintain the global network topology like that of AODV protocol. It uses the locally available information at each node for route selection process. It classifies nodes as reliable nodes and unreliable nodes. VARP-LET restricts the broadcast area for only those nodes that are considered reliable nodes. Since only reliable nodes are allowed to take part in route selection process this increases the chances of selection of a reliable and stable routes during route selection process. And as number of participating nodes is lower in VARP-LET which helps reducing the network broadcast overhead. In addition, VARP-LET uses the real-time value of LET to determine the near-to-be-broken link. This detection of an early breakage of a route leads to avoid the loss of packets which could result from a sudden link failure. Simulation results showed that there was significant performance improvement over AODV when VARP-LET and AODV-RCA was used.

In first experiment, the performance of AODV-RCA was compared with an optimized AODV (O-AODV) and traditional AODV protocol by using random way point (RWP) mobility model. Simulation results showed that AODV-RCA had better performance than O-AODV and AODV protocol, though O-AODV protocol showed performance improvement over the AODV.

Then the performance of both VARP-LET and AODV-RCA was tested and compared with traditional AODV protocol by using Manhattan Grid mobility model and high way scenario. Simulation results showed that VARP-LET outperforms both AODV-RCA and AODV protocol and AODV-RCA showed better performance over AODV protocol.

The simulation results presented in this thesis have shown that the objective of this thesis, which is to design a vehicle protocol that performs better in VANETs and to select routes that are more stable and reliable, has been achieved.

4.2 Future work

In this thesis, the proposed protocol has been simulated using NS-2 network simulator. In all the simulation carried out, network nodes have the same transmission radius. That means, shadowing effects have not been taken into consideration. Hence, the protocol can be extended and tested using dynamic node's radius.

The shadowing effects do add additional complexity, which directly relates with the received power signal strength. The propagation loss factor increases because of the shadowing effect and the effect of this change in the routing decision needs to be investigated and adjustments need to be made to the algorithm.

The proposed protocol VARP-LET relies on a single path selection like that of AODV protocol during route selection phase. After the failure of this route, the VARP-LET needs to initiate a route discovery phase again. The multipath scheme keeps the redundant route in the route cache that could be utilized on failure of the route can be implemented.

VARP-LET is specifically designed for vehicular networks which is not an energy constraints network. Hence, the performance of VARP-LET in terms of energy efficiency has not been investigated in this thesis. In order to implement VARP-LET in wireless sensor nodes that are highly energy constrained, the treatment of energy efficiency needs to be investigated and a modification of the protocol for energy optimization can be done.

The performance of the protocol has been tested only on simulation environment. Implementing VARP-LET in real vehicles on a road will be interesting. This can help to compare the results taken by simulated environment with that of real scenarios.

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Appendix A : List of publication

[C1]I. Ahmed, K. E. Tepe, and B. K. Singh, “Reliable Coverage Area Based Link Expiration Time (LET) Routing Metric for Mobile Ad Hoc Networks,” First International Conference on Ad Hoc Networks, Niagara, Ontario, Canada, ADHOCNETS 2009, Sep. 23-25, 2009.

VITA AUCTORIS

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