Routing protocol for V2X communications for Urban VANETs

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ABSTRACT

Intelligent Transportation Systems (ITSs) have been attracting tremendous attention in both academia and industry due to emerging applications that pave the way towards safer enjoyable journeys and inclusive digital partnerships. Undoubtedly, these ITS applications will demand robust routing protocols that not only focus on Inter-Vehicle Communications but also on providing fast, reliable, and secure access to the infrastructure. This thesis aims mainly to introduce the challenges of data packets routing through urban environment using the help of infrastructure.

Broadcasting transmission is an essential operational technique that serves a broad range of applications which demand different restrictive QoS provisioning levels. Although broadcast communication has been investigated widely in highway vehicular networks, it is undoubtedly still a challenge in the urban environment due to the obstacles, such as high buildings. In this thesis, the Road-Topology based Broadcast Protocol (RTBP) is proposed, a distance and contention-based forwarding scheme suitable for both urban and highway vehicular environments. RTBP aims at assigning the highest forwarding priority to a vehicle, called a mobile repeater, having the greatest capability to send the packet in multiple directions. In this way, RTBP effectively reduces the number of competing vehicles and minimises the number of hops required to retransmit the broadcast packets around the intersections to cover the targeted area. By investigating the RTBP under realistic urban scenarios against well-known broadcast protocols, eMDR and TAF, that are dedicated to retransmitting the packets around intersections, the results showed the superiority of the RTBP in delivering the most critical warning information for 90% of vehicles with significantly lower delay of 58% and 70% compared to eMDR and TAF. The validation of this performance was clear when the increase in the number of vehicles.

Secondly, a Fast and Reliable Hybrid routing (FRHR) protocol is introduced for efficient infrastructure access which is capable of handling efficient vehicle to vehicle communications. Interface to infrastructure is provided by carefully placed RoadSide Units (RSUs) which broadcast beacons in a multi-hop fashion in constrained areas. This enables vehicles proactively to maintain fresh minimum-delay routes to other RSUs while reactively discovering routes to nearby vehicles. The proposed protocol utilizes RSUs connected to the wired backbone network to relay packets toward remote vehicles. A vehicle selects an RSU to register with according to the expected mean delay instead of the device's remoteness. The FRHR performance is evaluated against established infrastructure routing protocols, Trafroute, IGSR and RBVT-R that are dedicated to for urban environment, the results showed an improvement of 20% to 33% in terms of packet delivery ratio and lower latency particularly in sparse networks due to its rapid response to changes in network connectivity.

Thirdly, focusing on increasing FRHR's capability to provide more stable and durable routes to support the QoS requirements of expected wide-range ITS applications on the urban environment, a new route selection mechanism is introduced, aiming at selecting highly connected crossroads. The new protocol is called, Stable Infrastructure Routing Protocol (SIRP). Intensive simulation results showed that SIRP offers low end-to-end delay and high delivery ratio with varying traffic density, while resolving the problem of frequent link failures.

Dedication

To my father

To my lovely wife

To all my children, brothers, sisters, and friends

For their endless support, encouragement and love

Acknowledgement

First and foremost, I would like to dedicate this thesis to the memory of my beloved father who has always believed in my capacity to achieve such a great project in the academic arena. You are gone but your belief in me has made this journey possible.

I would like also to thank and dedicate this work to my mother for providing me with unfailing support and continuous encouragement throughout my years of study and through the process of researching and writing this thesis. This accomplishment would not have been possible without her support.

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- Al-Kubati, G., Al-Dubai, A., Mackenzie, L. and Pezaros, D. (2013) Fast and reliable hybrid routing for vehicular ad hoc networks. In: 13th International Conference on ITS Telecommunications (ITST), Tampere, Finland, 5-7 Nov 2013, pp. 20-25.
- Al-Kubati, G., Al-Dubai, A., Mackenzie, L. and Pezaros, D. (2014) Efficient road topology based broadcast protocol for VANETs. In: IEEE Wireless Communications and Networking Conference (IEEE WCNC), Istanbul, Turkey, 6-9 Apr 2014, pp. 2711-2716.
- Al-Kubati, G., Mackenzie, L. , Pezaros, D. P. and Al-Dubai, A. (2015) Stable Infrastructure-based Routing for Intelligent Transportation Systems. In: IEEE International Conference on Communications (ICC), London, UK, 8-12 June 2015, pp. 3394-3399. ISBN 9781467364324

List of Abbreviations

ABSRP	Based Service Resolution Protocol
A-STAR	Anchor-based Street and Traffic Aware Routing
ACAR	Adaptive Connectivity Aware Routing
AODV	Ad hoc On Demand Distance Vector
AP	Access Point
AR	Access Router
ASV	Advanced Safety Vehicle
BS	Base Station
CBF	Contention Based Forwarding protocol
CLA-S	Connection Less Approach on Street
CN	Correspondent Node
CoA	Care of Address
DDR	on-Demand Differentiated Reliable routing protocol
DSDV	Destination-Sequenced Distance-Vector routing protocol
DSR	Dynamic Source Routing protocol
DSRC	Dedicated Short Range Communications
DTN	Delay Tolerant Network
FA	Foreign Agent
FCC	Federal Communications Commission
GeOpps	Geographical Opportunistic Routing
GPS	Global Positioning Systems
GPSR	Greedy Perimeter Stateless Routing
GSR	Geographic Source Routing
GTLR	Geographic and Traffic Load Based Routing Protocol
HA	Home Agent
IDM	Intelligent Driver Model
IDM-IM	Intelligent Driver Model with Intersection Management
IDM-LC	Intelligent Driver Model with Lane Changing
ITS	Intelligent Transportation Systems
IP	Internet Protocol
LOS	Line Of Sight
LRQ	Location Request message
LRP	location reply
LRU	Location and Registration Update packet
LTE	Long Term Evolution
MAC	Multiple Access Control
MANET	Mobile Ad hoc Networks
MDDV	Mobility-Centric Data Dissemination Algorithm for Vehicular Networks
MIP	Mobile IP
MN	Mobile Node
MURU	Multi-hop Routing for Urban VANET
NLOS	Non Line Of Sight
NS	Network Simulation
OBU	On-Board Unit
OFDM	Orthogonal Frequency-Division Multiplexing
OLSR	Optimized Link State Routing protocol
PHY	Physical Layer
PROMPT	Routing Protocol [33]
RAR	Roadside-Aided Routing protocol
RBVT	Road Based using Vehicular Traffic routing protocol
RC	Route Correction Message
RI	Routing Information
RLSMP	Region-based Location Service Management Protocol
ROAMER	Routing Protocol [35]

RREP	Route Replay Packet
RREQ	Route Request Packet
RRP	RSU-assisted Routing Protocol
RRP-v1	RSU-assisted Routing Protocol version one
RSU	Roadside Unit
RU	Route update message
QoS	Quality of Service
SA	Service Announcement Message
SAF	Service Announcement Forwarder
SADV	Static Node Assisted Adaptive Routing
SI	Services Information
SINR	Signal to Interference plus Noise Ratio
SUMO	Simulation of Urban Mobility
TIGER	Topologically Integrated Geographic Encoding and Referencing
TrafRoute	Routing Protocol [32]
UMTS	Universal Mobile Telecommunication System
V2I	Vehicle To Infrastructure
V2R	Vehicle To Roadside Unit
V2V	Vehicle To Vehicle
V2X	Vehicle To Vehicle or/and To Infrastructure
VADD	Vehicle Assisted Data Delivery
VANET	Vehicular Ad Hoc Network
VanetMobiSim	VANET Mobility Simulator
VITP	Vehicular Information Transfer Protocol
VLBR	Load Balanced Routing protocol
VLS	Vehicle Location Service
VoIP	Voice over IP
WAVE	Wireless Access in Vehicular Environments
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WWAN	Wireless Wide Area Network
ZRP	Zone Routing Protocol

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CHAPTER 1 : INTRODUCTION

1.1 General Overview

The Vehicular Ad hoc Network (VANET) has emerged to offer solutions for Intelligent Transportation Systems (ITS) that aim at helping drivers on the roads by anticipating hazardous events or avoiding bad traffic areas, and it has received significant attention from industry, academia and national government agencies [1][2][3][4][5]. The Federal Communications Commission (FCC) allocated a 75 MHz band at the 5.9 GHz frequency (5.85–5.925 GHz) for the dedicated short range communications system (DSRC) in 1999, as a candidate for use in a VANET in North America. DSRC is defined as a short to medium range communications system that supports mainly safety applications in vehicle to vehicle (V2V) and vehicle to roadside (V2R) or vehicle to infrastructure (V2I) communication modes. Figure 1.1 depicts the overall components of a VANET.

In 2009, the Vehicle Safety Communication (VSC) project sponsored by the US DoT (Department of Transportation) determined that the 5.9 GHz DSRC wireless technology is potentially best able to support vehicular communications requirements [6]. In 2010, the IEEE 802.11 Working Group (WG) published the IEEE 802.11p wireless access in vehicular environments (WAVE) amendment standards that provides a protocol suite solution to support DSRC vehicular communications in this licensed frequency band at 5.9 GHz [7].

The primary motivation beyond the IEEE 802.11p amendment [7] is to establish lightweight rules for accessing the medium in a highly mobile vehicular environment of which the opportunity to communicate may be fleeting and lasting only a few seconds. The upper DSRC layers are defined by IEEE 1609.x standards [127-130]. These standards define how applications will function in the WAVE environment.

Two units are defined in the WAVE environment: the RoadSide Unit (RSU), and the OnBoard Unit (OBU) which are essentially stationary and mobile devices respectively. The

IEEE 802.11p MAC is based on the Enhanced Distributed Channel Access (EDCA) of IEEE 802.11e whereas the IEEE 802.11p PHY is based on the Orthogonal Frequency-Division Multiplexing (OFDM) technology of the IEEE 802.11a standard. It is expected that the DRSC devices will commonly use 6Mb/s data rate from a 10MHz bandwidth since it seems to provide a good compromise between channel load and signal-to-noise requirement [8].

VANET technology can be utilized for many other applications beyond collision avoidance applications. For example, it can be used to facilitate navigation, make electronic payments (e.g., tolls, parking, and fuel), improve fuel efficiency, draw traffic probes, and disseminate traffic updates. Furthermore, the trend of ubiquitous availability of IP networks has also made internet access and multimedia content delivery possible in the vehicular environment [9][10][11][12]. Such infotainment applications should provide entertainments to drivers and passengers during a trip. The passengers can use VANET Internet connectivity if the other known Internet access networks (Wi-Fi, cellular networks, etc.) aren’t accessible. Even with such networks, a vehicle linked to the Internet using these networks can provide other vehicles with Internet access through VANET [139], [140]. Peer-to-peer applications that can benefit VANETs, such as gaming, chatting, file sharing, and IPTV are good examples of these applications [133], [141]. However, these applications require a wide range of restricted QoS levels that result in some difficulties and challenges to build them on top of the direct communication between vehicles. Undoubtedly, the capability to satisfy these applications’ requirements will open up great value-added services and will be a critical factor to commercial success of vehicular networks deployment [1]. Most of these applications involve unicast communication to and from the infrastructure, on the other hand, other ambitious applications rely on efficient broadcasting services and advertisements offered by the infrastructure. For instance, companies can leverage the roadside infrastructure units (RSUs) to broadcast information about their products and services to potential customers in their zone . This can be particularly useful for businesses such as petrol fuel stations or roadside restaurants, as they can use this medium to declare their prices or announce their menus to passing passengers [134][135][143]. Furthermore, with the help of parking navigation applications, commuters can navigate unused vehicle spaces during peak times, thereby reducing traffic congestion and promoting efficient dissipation of vehicles [144]. These innovative approaches not only facilitate effective communication between businesses and potential customers but also contribute to the overall development of smarter and more sustainable transportation systems.

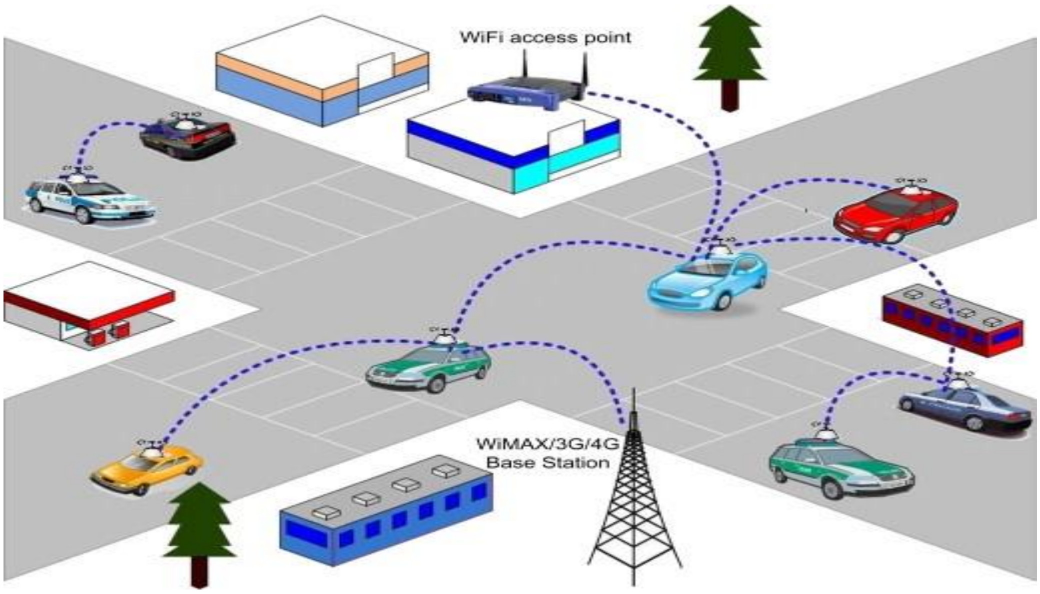


Figure 1.1: General model of the vehicular network

VANETs are usually operated in two typical communications environments. In highway traffic scenarios, the environment is quite simple and straightforward, while, in city conditions, it becomes much more complex. Although several attempts have been made to study data dissemination on VANETs, the urban environment has largely been considered as a subsidiary issue and simulation experiments typically either did not include the urban scenario or an unrealistic radio propagation model was used that does not reflect actual city conditions [10]

1.2 Background

1.2.1 VANET versus Other Wireless Networks on Roads

Recently, vehicular networks (VANETs) have attracted remarkable attention from the research community as a special kind of mobile ad hoc network (MANET) [18][19][20]. In fact, these studies have focused on discriminating the nodes mobility environment, i.e. nodes in VANETs are vehicles moving on roads with higher speeds than nodes in many MANETs, rather than the nature of required services. In other words, the main concern was to adapt generic MANET capabilities to face new constraints necessitated by fast vehicles moving in mainly one-dimensional space instead of the general two-dimensional field assumed in MANETs, for example, in order to improve ad hoc routing.

A MANET, as a kind of infrastructureless self-configured network, is a powerful means of communication when infrastructure is absent or has failed [21]. At the initial level to develop vehicular networks, the researchers mainly considered satisfying the ITS requirement to help in decreasing the number of collisions on roads. Vehicles should be enabled to establish communication links on the fly to avoid collisions, with communication latency less than 50ms. Maybe VANETs leverage MANET technology but may also be integrated with fixed infrastructure. In fact, other significant ITS applications on the roads necessitate some sort of central administration assistance and collaboration with vehicles, such as making electronic payments.

Vehicular networks can be distinguished from other kinds of ad hoc networks due to the nature of distinct communication environment and unusual wide services range as follows [22][23][24]:

1.2.1.1 VANET environment is characterised by:

- ***Highly dynamic topology:*** Due to high speed of movement between vehicles, the topology of VANETs is always changing.

- ***Frequently disconnected network:*** The connectivity of the VANETs could also be changed frequently. Especially when the vehicle density is low, it has higher probability that the network is disconnected.
- ***Mobility model and predication:*** Due to node movement, in most cases, on constrained one-dimensional streets, mobility model and predication may play an important role in network protocol design for VANETs.
- ***Various communications environments:*** VANETs are usually operated in two typical communications environments. In highway traffic scenarios, the environment is quite simple and straightforward, while in city conditions it becomes much more complex.

1.2.1.2 Expected wide range of services demands:

- ***Different kind of support:*** collision avoidance requires V2V ad hoc supporting scheme, whereas most other on-road services need also infrastructure supporting.
- ***Different QoS requirement:*** from high priority low delay for collision avoidance messages to wide range QoS levels of VoIP, multimedia streaming, text, etc.
- ***Different scope of spreading:*** for location-based service provisioning, announcing messages are geo-casted in a specific region of interest, while, for internet access, service request/reply messages are peer to peer transmission.
- ***Different security levels:*** some services require high level security guarantee while for others there is no need for that.
- ***Billing:*** some services are free, while others are not.

In generic MANETs, the infrastructure support is largely considered as a subsidiary issue to provide internet access, but the mission and services of the infrastructure in VANET goes beyond that to embrace critical issues, such as security and billing, and provisioning of essential services; therefore, the use of roadside infrastructure units (RSUs) has an absolutely crucial role in vehicular network deployment [25]. In conventional wireless local area networks (WLAN), several access points (APs) are distributed across most of the target area, using ad hoc mode only to extend the service in dead zones; in VANETs on the other hand, RSUs should be carefully deployed to guarantee the best trade-off between quantity and quality of services offered as well as cost of investment. Vehicles will typically use ad hoc mode to communicate outside the service area of RSUs. In summary, VANETs share almost all the functionalities of MANET and WLAN networks. Recently, several studies appeared that also discussed the usability of integrating VANETs with cellular networks aiming at providing broadband internet access. Table 1.1 compares the existence wireless networks in terms of services and coverage.

Table 1.1: Wireless Networks on Roads

	WLAN	MANET	Cellular Network	VANET
Infrastructure	Very high no. of APs	Very low no. of APs	Very low no. of BSs	Moderate no. of RSUs
Mobility Management	Handoff strategy	Routing Protocol	Handoff strategy, Clustering.	Routing Protocol & Handoff strategy
Cost	High	Low	Very high	Moderate
Main Applications/ Services	Internet access	Data collection	Voice communications, Internet access	Collision avoidance, Location-based services, Traffic Data collection, internet access.

1.2.2 Vehicular Communications in Cities

Recently, different attempts have been made to cope with the problem of message forwarding at intersections. In urban environments, obstacles such as high buildings hinder message propagation, and increase the shadowing and multipath effect on radio waves, making communication only possible when vehicles are in line-of-sight or few meters away from crossroads (i.e., near-line of sight [26]), as shown in Fig. 1.2. The reception probability of the packet P via vehicles A and E is high, whilst vehicle B and D may receive P with very low success ratio. Vehicle C will not receive P. Furthermore, in most capital cities, there are traffic lights at most crossroads and, when the number of vehicles increases at busy periods, long queues are formed, and data traffic congestion becomes higher. Consequently, intersections turn into bottlenecks in the network graph. In addition, at low vehicle population, the message forwarding at intersections introduces high latency. In fact, the existence of obstacles compounds the sparse network problem. This thesis mainly focuses on the urban VANETs since the highway environment is well considered by the research community.

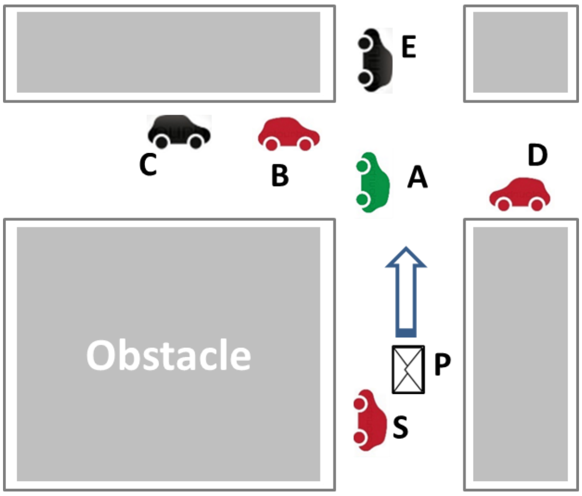


Figure 1.2: Obstacles and disconnections in an urban environment.

1.2.3 Broadcasting Strategies for Urban VANETs

Recently, attention has been drawn to providing many infotainment and commercial services which are expected to hasten the VANET market penetration rate, but fast message delivery is fundamental for many appealing applications [27]. To design an efficient reliable broadcast protocol, the following metrics should be taken into consideration: reliability, overhead, and speed of data dissemination. In safe-driving applications, critical information such as hazards and alarms have to be delivered to as many cars as possible in a certain area with the lowest possible delay [28][29]. Therefore, the broadcast protocol should ensure not only a high level of reliability but also speed of data dissemination. Such information will be useless if it arrives too late. On the contrary, infotainment and commercial applications relying on broadcast include sharing traffic, weather, and road data among vehicles, as well as delivering advertisements and announcements. These applications generate packets of various lengths at different rates. For example, advertisement bulletins for restaurants or hotels can be broadcast in long messages that carry pictures, directions, or even small videos. Transmission of such large-sized units may exacerbate the Broadcast Storm Problem (BSP) [30], and thus, the total amount of the incurred overhead. Furthermore, applications, such as emergency video dissemination and interactive gaming and social networks on roads demand high bandwidth and low delay. The key problem is how to optimise these metrics whilst conditions in vehicular networks are highly variable. The challenging problem is compounded in urban areas crowded with tall buildings which will absorb radio waves, making communication impossible when vehicles are not in line-of-sight.

Most of the protocols use distance-based relay selection techniques (DBRS) where the packet receiver decides to rebroadcast the packet according to its distance from the sender. These protocols mainly differ in the additional rules that differentiate a vehicle’s capability to efficiently reach hidden area upon urban environment due to the obstacles. For example, in UV-CAST [31] which uses the waiting timer concept, vehicles at intersections are given high priority. They wait less than other vehicles before transmission. Whilst the sender tends to select a neighbour at the intersection rather than the farthest neighbour in these protocols utilize the greedy forwarding (GF) concept such as ERD [32]. To improve the reliability, some of these approaches dedicated to broadcasting event-driven notification messages (EDNM) utilize the RTS/CTS/ACK handshaking concept to avoid the hidden terminal problem and to ensure the packet transmission progress while others rely on implicit acknowledge principle.

1.3 Motivation

Upon careful examination of the literature on VANET prospecting applications and their service requirements, it has become evident that an RSU is an essential service provider.

The RSU's service information is expected to be delivered via advertisement messages that are disseminated through vehicle-to-vehicle (V2V) communication within its designated service area. However, this raises a vital question of how to collect real-time routing information from these messages without dissipating network resources. Finding a solution to this issue is of utmost importance for ensuring the efficient and effective functioning of VANETs. There is no doubt that an well-designed broadcasting protocol that addresses these concerns is crucial.

Broadcasting transmission is an essential operational technique that serves a broad range of applications which demand different restrictive QoS provisioning levels. Although broadcast communication has been investigated widely in highway vehicular networks, it is undoubtedly still a challenge in the urban environment due to the obstacles such as high buildings [13][14]. I proposed the Road-Topology based Broadcast Protocol (RTBP): a distance and contention-based forwarding scheme suitable for both urban and highway vehicular environments.

The problem of finding a unicast route under different surrounding scenarios is still a difficult problem in VANETs [9]. Recently, several attempts have been proposed that explore the availability of RSUs to help in the unicast routing protocol from different points of view. After a comprehensive study of these infrastructure-assisted routing approaches highlighting the benefits behind RSUs' usage, a novel Fast and Reliable hybrid Routing (FRHR) protocol is proposed that exploits RSUs to deliver lightweight, robust, and reliable urban vehicular communications.

Towards providing smooth QoS-based services on VANETs, I have investigated the stability of the routes on the urban environment. Although there are novel routing algorithms attempt to provide stable routes between vehicles to enhance QoS[15][16][17], these routings are dedicated to working on highway scenario. Hence, Stable Hybrid Routing Protocol (SIRP) has been developed to provide stable routes that can satisfy a wide range of the QoS levels required by different potential applications on the road grid keeping into consideration the importance of the capability of the new stable routing protocol to operate fairly on both urban and highway scenarios.

1.4 Thesis Statement

The evolving applications paving the way to inclusive digital partnerships and safe and enjoyable journeys have attracted incredible attention in industry and academia through Intelligent Transportation Systems (ITS). However, applications associated with the ITS demand robust routing protocols able to centre on Inter-Vehicle Communications while offering secure, consistent, and fast I to infrastructure. Due to infrastructure concerns, the routing encounters issues with data packets, especially in an urban environment. Broadcast communication poses a challenge to the urban setting because of the hurdles mentioned earlier despite the extensive investigation, especially in highway vehicular networks. As a result, the following is affirmed:

T.1. Although existing broadcast routing protocols, it is worthy to investigate the capacity of vehicle residing on the intersections using the available road map. Due to its ability to distribute the packet in various directions in the urban topology, the contention-based forwarding (CBF) scheme may assign a vehicle at intersection the highest forwarding priority, a mobile repeater. However, in the daytime, when vehicles start forming large queues at intersections in cities, such CBF scheme may suffer from higher collision rate [37] due to increase the number of cars intending to transmit at the same time. Therefore, the density of the local vehicle can be utilized to controls the number of potential mobile repeaters at every intersection.

T.2. As long as RSUs are the main service providers and enable vehicles to communicate with distant peers, paths towards nearby RSUs are more frequently requested than those towards other vehicles. Therefor proposing the unicast routing protocol that utilizing this fact into consideration will reduce the total amount of losses. In other words, the protocol may allow the cars to proactively sustain new routes with minimum delays to various RSUs while exploring routes to adjacent vehicles.

T.3. Collecting real-time vehicular traffic information (i.e., location, and vehicle density) on the road grid may simplify the mission of optimizing the route selection and distributing the network load among RSUs. Hence it will be a more effective way to eliminate network bottlenecks, increase network throughput, and improve network flexibility than those approaches in literature where no global network information exists.

1.5 Contribution

Our intended research works aim at developing routing protocols for urban VANETs. To do so, I split the mission into three contribution steps that will pave the way towards achieving our vision as stated above in the thesis statement. The contributed development steps consist of:

C.1. The development of a CBF-based scheme enhances broadcast performance in urban settings, called road topology-based broadcast protocol (RTBP). Realistic experimental simulation environments have been used to test the protocol performance against well-known broadcast protocols. The results indicate that RTBP can reduce latency, increase reachability, and consequently save system resources.

C.2. A novel Fast and Reliable Hybrid Routing (FRHR) protocol is introduced that integrates both features of reactive and proactive routing schemes. FRHR maintains proactively routes towards RSUs while it reactively seeks for other nodes on the networks. Furthermore, FRHR is a position-based routing protocol, in which the route is a sequence of successive intersections' ids. The experimental results have shown the superiority of FRHR over the peer protocol, Trafroute, mainly in terms the end-to-end latency and the reliability of the routing protocol against RSUs failure.

C.3. A novel route selection policy is integrated to improve FRHR to build routes from highly stable connected intersections using a new intersection stability metric. The resultant protocol is called Stable Hybrid Routing Protocol (SIRP).

To sum up, this thesis successfully introduces an innovative collective routing paradigm that is both service-aware and highly efficient. The use of RSUs to disseminate service advertisements facilitates the proactive construction of routes to the most requested nodes in the network (i.e., RSUs). This approach has resulted in a fast communication setup, reduced total propagation delay, and self-healing routing, all while making the best use of available resources. With its outstanding solutions and benefits, this paradigm opens up new doors not only for internet access-based applications but also for efficient service advertisement-based applications, particularly in future smart cities. Its dissemination approach in urban scenarios, which is the cornerstone of its success, enables better communication and utilization of available resources.

1.6 Thesis Structure

The order and structure of this thesis comprise six chapters. The introduction chapter offers a background of the topic revealing that VANET technology is used for various applications that surpasses applications on collision avoidance. For instance, VANET enables electronic payments and facilitates navigation. The research problems have been broadly discussed on the motivation and research statement sections. The research outcomes are expressed on the contribution section. Chapter two was about the literature review to help evaluate the past studies on a similar topic and to help identify a knowledge gap. Chapter three presents the RTBP protocol in details showing its operation and its advantages above the rivals.

Chapter four focuses on the FRHR protocol, which is appropriate for fast infrastructure access and effective vehicle-to-vehicle communications as well. The chapter describes the FRHR's operational process and presents results analysis. Chapter five has thoroughly explored the SIRP protocol and its performance evaluation. The entire work is summarized in chapter six, *Conclusions*. Primarily, the chapter is made to emphasize the attainment of the research objectives and to ascertain limitations and recommendations for further studies. Future studies should consider developing a new route selection policy to offer a stable roué that satisfies the provision levels for QoS that different applications require for road grids.

CHAPTER 2 : LITERATURE REVIEW

2.1 Unicast Routing Protocols

In addition to the similarities to mobile ad hoc networks, such as short radio transmission range, self-organization and self-management, VANETs pose more critical and challenging issues that make most routing protocols proposed for conventional MANETs unsuitable for vehicular environment [38][39]. The connectivity of VANETs could change frequently due to the movement of vehicles at high speeds. Especially when the fluctuating vehicle density is low, there is a high probability that the network is frequently disconnected. Hence the topology of VANETs always changes every few hundred milliseconds. VANETs are usually operated in two typical space environments (i.e. Highway and city) where network protocols must fairly well function. In a highway traffic scenario, the vehicular environment is relatively straightforward (e.g. Constrained one-dimensional movement), while, at city conditions, it becomes particularly complex. However, the mobility model and predication can play a decisive role in routing protocol design for VANETs.

For the sake of facilitating communications within a vehicular network, a routing protocol must, therefore, find reliable and efficient routes between network elements. Then the routing should maintain or even proactively recover routes when a disconnection event occurs. Several MANET routing strategies have been adapted for VANETs. V2V routing protocols are thoroughly investigated in the literature [40][41]. Traditionally, ad hoc routing protocols have been classified as topology-based, or position-based. We aim in the following to clarify the basic terminology of these classes for use later.

Topology-based routing approaches rely on the collected link information in making routing decisions [42][43]. Based on the routing information update mechanism, they are categorized into proactive, reactive, and hybrid. Proactive approaches work on the basis of the shortest path algorithms. Routing tables are maintained by nodes, including routing information to all nodes of the network at all times, even if the paths are not currently being used. There is no route discovery. Whenever any change occurs in network, every node updates its routing information in the routing table. A route to the destination is always maintained in the background and is available upon lookup. Different strategies have been proposed in the aim of wisely and quickly sending the update information to decrease bandwidth utilization, memory usage and processing time; however, these developments typically cannot endure in face of a VANET's fast and frequently changing topology. The most cited instances of this category in the MANET domain are *Destination-Sequenced Distance-Vector* (DSDV) routing and *Optimized Link State Routing* protocol (OLSR) [44][45].

Reactive strategies have been proposed in order to minimize the network overhead thereby alleviating the burden on the network. These implement route determination on a demand or a need basis and maintain only the routes that are currently in use. The reactive (so-called *On-demand*) routing protocols may be further classified into two subclasses; Hop-by-Hop Routing and Source Routing. In hop-by-hop routing, the source node sends each data packet containing just the destination and the next-hop node IDs, whereas, in source routing protocols, the data packet will include the IDs of all intermediate nodes on the path towards the destination, i.e., a full source route. The *Ad hoc On demand Distance Vector* Protocol (AODV) and the *Dynamic Source Routing Protocol* (DSR)[46][47] are well known reactive unicast routing protocols for MANETs and have been adapted to VANETs, as well.

In general, there are two basic procedures in most on-demand routing protocols; Route Discovery and Route maintenance in which different control messages are exchanged. Route discovery in reactive routing can be done by broadcasting a RREQ (Route Request) message from a node when it requires a route to send the data to an unknown destination. Upon receiving a RREQ message, a node will check the destination ID in the RREQ. If it is itself the destination, it will response with RREP (Route Reply). Otherwise, it will either ignore or rebroadcast the RREQ according to some criteria. An intermediate node is allowed to response with RREP if it has a valid route to the destination in its routing table /cache. In addition to the destination ID, the RREP contains the next-hop node ID in AODV and the full source route in DSR. In maintenance procedures, if a link breakage event is detected while data is flowing, a Route Error (RERR) message is sent to the source of data. The source node, in turn, invalidates the route and reinitiates route discovery if necessary.

In AODV, nodes may collect and update neighbourhood information by receiving periodic Hello messages, whereas there is no requirement for such periodic broadcasting in DSR. AODV keeps at most a single entry for each destination in the routing table whereas DSR provides the capability of route caches. Upon receiving multiple RREPs, DSR nodes keep more than one route to the same destination provisioning the facility of routes caching. In case of route breaking, alternative routes are already available to the destination, and this saves the processing time, as well.

In VANETs, the mobility of vehicles at high-speed results in a highly dynamic network with rapid topological changes and frequent route failures [48]. Therefore, frequent exchange of routing network overhead also dramatically increases, thus wasting significant amount of precious network bandwidth and raising the packet transmission latency. The redundancy in route caches is also unreliable.

To tackle the deficiencies of reactive and proactive routing protocols, hybrid MANET routing protocols have been proposed that combine the features of suitable proactive and reactive routing protocols in order to provide reliable and scalable routing. Zone Routing Protocol (ZRP) [49] is a hybrid routing protocol in which each node proactively keeps routes to each destination inside its predefined zone, and reactively initiates a route discovery if the required destination is outside its zone. ZRP may minimize the network overhead that is caused by proactive routing and manages the delay in networks that use only reactive routing; however, like its predecessors; it does not perform well in vehicular environments.

In these topology-based routing approaches, routes are established over a fixed sequence of nodes (identified by IP addresses) which can lead to broken routes and high maintenance overhead to repair these routes. The peculiar conditions and requirements for vehicular communications, including frequent topology changes, short connectivity time and positioning systems have justified the development of dedicated routing solutions based on geographic positions where the routing decisions may depend upon the position information of the participating nodes (vehicles). These approaches, so-called *position-based routing* protocols are more suitable for VANETs environments where vehicles typically move on some specified paths or road lanes.

In fact, the use of geographic position information enables forwarding to be decoupled from a node's identity. The position of the destination node can be used rather than a route to it, and then data traffic flows via a set of neighbours. Thus, position-based routing provides a more scalable and efficient forwarding mechanism appropriate for highly volatile ad hoc networks like VANETs. Position based routing protocols may include following three main parts/patterns: Beaconing, Location Service, and Forwarding Strategies.

Beaconing is a single–hop periodic broadcasting (HELLO message) by which every node must send up-to-date mobility status information such as position, speed and direction to its neighbours. To deliver data packets successfully to the neighbourhood of the target destination, a source node must know with a reasonable accuracy the location of that destination. Therefore, a critical component of position-based routing is the location service strategy. Some location services paradigms may consist of location updates or location request components, depending on whether the update or request messages are flooded in the network. Some location service schemes, for instance, VLS [50], use a few nodes as location servers that receive location update messages from neighbouring nodes and then reply to request messages in order to reduce the amount of the incurred overhead.

After a source node recognizes the possible current location of the destination, position-based routing algorithms now differ by the methods utilized to forward the data packets towards the destination efficiently, in terms of reducing the number of hops, and how they attempt to escape from holes (local maxima) in the disconnected networks. The minimum number of hops is equivalent to the shortest connected path that guarantees reducing bandwidth usage and increasing packet delivery ratio, while the holes are the empty (and so uncrossable) regions between trusted nodes on the path towards the destination. For instance, Gr*eedy Perimeter Stateless Routing* (GPSR) [51] uses “greedy” forwarding in which the closest neighbour to the destination is chosen as a forwarder. GPSR attempts to escape from a hole through the perimeter forwarding mode in which neighbours around the hole are chosen on a path towards the destination. This type of algorithms considers the network to be fully- or semi-connected.

For sparse networks characterized by many of holes, the *Vehicle-Assisted Data Delivery*, VADD [52] protocol uses a carry-and-forward approach. A vehicle carries a packet in the hole till it finds the destination or a neighbouring vehicle that may forward the packet towards the destination. Such protocols are classified as *Delay Tolerant Network* (DTN) protocols because of the high incurred delay.

Other approaches use hybrid techniques such as GeoDTN+Nav [53]. GeoDTN+Nav utilizes a delay tolerant mode when greedy and perimeter modes fail. Exploiting the on-board navigator, the latency is improved in GeoDTN+Nav by passing vehicles’ Virtual Navigation Information (e.g., intended destination, direction, trace of the route covered so far, future route plan, etc.) to select the most appropriate vehicle for passing the packet to.

Moreover, several position-based protocols relax beacon message requirements to eliminate the associated overhead, such as the *Contention-Based Forwarding* (CBF) protocol [54]. CBF does not require periodic transmission of beacon messages; instead, data packets are broadcasted to all direct neighbours and the neighbours themselves decide if they should forward the packet based on a distributed timer-based contention process.

For urban scenarios, several protocols have been proposed to forward packets on logical links formed by anchor points (Landmarks) as RBVT [55]. *Road Based (using) Vehicular Traffic* (RBVT) routing presents two protocols; RBTV-R, and RBTV-P. RBTV-R is reactive and creates source routes of successive intersections that have a high probability of network connectivity among them. It is beaconless and has no need for location service as it otherwise it use an improved flooding technique to discover locations. RBTV-P is a proactive protocol. It randomly selects a subset of nodes to send multi-hop discovery control messages (called Connectivity Packets CPs) which will return to the originator carrying the real time road connectivity information. The originating nodes will build their routing tables of reachable intersections, and then broadcast these tables to the other nodes in the route update (RU) packets. This will enable the other nodes to build their routing tables, as well. RBTV-P assumes a source node can query a location service.

Most position-based routing algorithms consider the location service scheme as a prerequisite, ignoring the significant additional amount of incurred overhead in overall evaluation of the protocol performance. Moreover, routing protocol transactions are prime targets for impersonation attacks but, security and privacy issues are often left to the upper network layers, sometimes at the cost of involving unforgivable amount of authentication overhead and complexity. Recent approaches have suggested utilizing the idea of using pseudonyms instead of real IDs to prevent malicious VANET participants who may listen to others' transmissions, using the information thus scraped to building a movement profiles about selected individuals, which riskily jeopardizes their location privacy [56][57].

2.2 Infrastructure-Assisted Unicast Routing Protocol

As vehicular applications range from emergency operations (e.g. collision avoidance, natural disaster, terrorist attack, etc.) to e-mail and voice over IP, different types of assistance from the infrastructure (i.e., RSUs) will be requested. The basic idea behind utilizing RSUs is that they act like fixed reliable nodes. Fixed nodes may offer more robust communication with less administrative overhead compared to the case where both communicating parties are mobile[58]. In addition, RSUs could be connected by backbone links with high bandwidth, low delay, and low bit error rates. A few implementations have indicated the superiority of the RSU-assisted routing protocols in terms of their overall performance. In the following, we illustrate some of the proposed benefits of using RSUs in literature.

RSUs can be used as fixed location servers in hierarchical-based location service schemes. There is, therefore, no need for location tables' handover as in case of mobile location servers. Saleet et al. [58] have proposed the *Region-based Location Service Management Protocol* (RLSMP) in which a source vehicle sends queries to a local RSU covering a cell in the road grid. The query is forwarded in spiral cells represented by other RSUs around the local one until the location of the destination is found. After that, the data packet can be forwarded in the backbone network between the source and destination RSUs. This will reduce the bandwidth usage in a congested network and can go around a hole in a partitioned network instead of using a higher latency cost approach such as the "carry-and-forward" scheme.

Discovering and accessing services on the road is a crucial component in the architecture of future vehicular ad hoc networks, and for successful deployment of services. An RSU can act like a fixed service directory for neighbouring service providers, such as gas stations or restaurants. The infrastructure-based service discovery protocols show better performance in terms of the scalability than the infrastructure-less protocols [59]. In addition, most envisioned vehicular applications/services will in any case require support by a roadside infrastructure with robust Internet connectivity [60]. Furthermore, RSUs with a secure service architecture may present the best way to pave the road to fast and wide vehicular network deployment in future [61].

In fact, internet access will likely play a key role in the wider deployment of VANET technology in the future. In the last few years, several research efforts have been conducted to provide Internet connectivity to VANETs via gateways with main concern being gateway discovery schemes [62][63]. According to the mobility of the gateway, two gateway types have been suggested, stationary and mobile. A stationery gateway is part of the roadside infrastructure such as RSU-DSRC, AP-WiFi/WiMAX, and BS-UMTS/LTE, while a mobile gateway is a distinct vehicle (e.g., bus, taxicab) on the road which has a direct internet connection through the previous roadside infrastructure. However, regardless of a mobile gateway's usage effectiveness, it is not clear how realistic the situation is! It is also uncertain whether vehicles would be motivated to securely share their wireless Internet connections with others, when these connections are likely to be costly. In addition, the bandwidth of any mobile gateway's wireless WAN connection would need to be sufficient to support the total bandwidth demand of multiple client vehicles.

Two issues should be considered in the routing using RSUs: 1) the cost of the infrastructure deployment; and 2) coping with infrastructure breakdown. During initial years of VANET deployment, not all vehicles will be equipped with OBU interfaces. However, sufficient RSUs, intelligently distributed at roads, can be used to bridge network partitions in VANETs. These will also enhance market penetration by attracting the public attention towards the affordable services. Some algorithms have been proposed to position the RSUs in the most effective locations around the city, such as [64].

In case of the infrastructure network breakdown, the routing protocol must compensate for the loss of one or more RSUs by, for example, using mobile location servers instead in their service areas. In a complete infrastructure breakdown due to e.g. a natural disaster, a VANET should continue to run, by configuring itself and route information using the available resources, i.e. the routing layer should return to a fully V2V routing protocol.

Finally, roadside infrastructure units will not only provide secure access to a wide variety of services, but also help in offering more robust and effective communications in VANETs.

Several proposed routing strategies assisted by RSUs are now discussed, that take account of various vehicular network characteristics.

2.2.1 Roadside-Aided Routing (RAR) in Vehicular Networks

The authors in [65] propose a routing framework called RAR (*Roadside-Aided Routing*) which considers a one-dimensional road network topology and tries to alleviate the drawbacks pertaining to hierarchical routing approaches in hybrid MANETs. The road network is divided up into sectors bounded by RSUs. Each RSU broadcasts a one-hop agent advertisement with no attempt to extend the RSUs service area beyond this. A vehicle must affiliate to a sector when it passes the transmission range of any of the sector's surrounding RSUs. RSUs are connected via backbone links; hence the affiliation and route information is synchronized between all RSUs of this sector, and can be searched by other RSUs. A vehicle that has a packet to send broadcasts a route request. If the destination vehicle is in the same sector, it responds by route reply (with a direct ad hoc route) otherwise the route request broadcasting will continue till reaching the nearest RSU. The first RSU, upon receiving the route request, queries the other RSUs for the destination sector, and then forwards the route request to all RSUs serving this sector which all then broadcast the request. Upon receiving multiple requests, the destination replies with the best path (a route via RSUs). Hence, the best route is discovered in a single phase utilizing the backbone network as a shortcut without the route-maintaining overhead that is required in hierarchical ad hoc routing protocols. However, although RAR can significantly reduce communication overheads and latency; it relies on spreading a significant number of RSUs according to the road network topology.

2.2.2 Differentiated Reliable Routing in Hybrid Vehicular Ad-Hoc Networks

An on-demand *differentiated reliable routing* (DRR) protocol was developed by Rongxi et al [66] against wireless link failures in hybrid VANETs such that it discovers different numbers of link-disjoint paths between the source and destination for each application according to its reliability requirements. RSUs are used to act as fixed reliable nodes and functionally form a virtual equivalent node via connections to backbone links. This work mainly focuses on: firstly, providing differentiated services for each application in order to reduce the amount of overhead pertaining to route discovery and maintenance in traditional multipath routing schemes; and, secondly, utilizing RSUs in order to improve the successful rate of link-disjoint Paths discovery. However, it relies on the number of RSUs more than RAR, and is not scalable. The amount of the control overhead will incredibly increase as the vehicle density increases.

2.2.3 Reliable Routing for Roadside to Vehicle Communications in Rural Areas

In [67], authors propose a source routing protocol for internet access on rural roadways. A reasonable number of APs are deployed along the roadside that connect vehicles to the internet, and these play a key role in route discovery and maintenance. The protocol comprises a link lifetime prediction algorithm and two reliable routing strategies. The challenge of vehicular communication in the rural environment is the terrain factor. The problem of losing line-of-sight (LOS) is considered in predicting the link lifetime. APs utilize the expected lifetimes of the links between the vehicles on roads to construct weighted communication graphs. When an AP receives a route request from a source vehicle, that has data to send to the

Internet, it may select a stable route either with long lifetime or one with a short length (number of hops) then include the computed route in a route reply message and return it to the source vehicle. The weighted communication graph is updated by each AP based on the location and mobility information piggybacked in the received packets; hence, an AP can perform route maintenance by proactively replacing current unstable routes with new routes that have longer lifetimes.

2.2.4 Infrastructure-Assisted Geo-Routing for Cooperative Vehicular Networks

Borsetti et al [68] investigated the benefits of using RSUs in enhancing topology-aware geographic routing protocols. They proposed an infrastructure-based geo-routing approach based on a modified network graph representation of the road topology, where the RSUs connected by a reliable backbone network are merged into a unique graph node called the "backbone gate". The new approach is integrated into GSR (geographic source routing) [113], and for the sake of clarity, we will refer to this protocol as IGSR. Simulation experiments on urban scenarios showed improved performance of IGSR in terms of the packet delivery ratio; however, the performance is still sensitive to the vehicle density.

2.2.5 TrafRoute: A Different Approach to Routing in Vehicular Networks

In TrafRoute [69], the route is discovered on demand such that it includes successive virtual waypoints at intersections (called *Forwarding Points* or FPs) from the source to destination. Therefore, one can say that it is a mix of the three tradition routing schemes, reactive, proactive and geographic, but with the aid of RSUs. RSUs are deployed in the network; divide the area into Sectors each with a single RSU (called the *Central Relay Node* or CRN). As in RAR, when a vehicle enters a new sector, it registers with its CRN which maintains a shared Distributed Hash Table (DHT) indexing the vehicle associations with the other interconnected CRNs via the internet. The source broadcasts the route request (RREQ) through the whole originating Sector. The sector's CRN, upon receiving an RREQ, either discards the message if the destination in the same sector or relays the message to the destination's CRN which in turn will broadcast the RREQ into its sector. A source CRN can discover the destination's CRN using DHT index. When the destination has received a RREQ it replies using a Route Reply packet (RREP). The main contribution is the flooding mechanism. Only subsets of the vehicles located in the proximity of FPs are allowed to relay the message. FPs are strategically chosen to reduce the set of forwarding nodes. At all times the vehicles proactively perform a forwarder self-election procedure based on their distance from the FPs, the underlying road network and their neighbouring state information. Thus, each node periodically broadcasts a HELLO packet to help in maintaining this required information. In simple words, a node that is much closer to the centre of the intersection (or FP) and has mostly a direct LOS with neighbouring FPs will forward the messages. However, like source routing, when the destination moves away from the FPs included in the route, the path is disconnected, and no local recovery correction mechanism is introduced. Instead, the source node periodically issues a *Route Check* (RCHECK) small packet during an ongoing communication. If it does not receive a reply within a timeout period, the path is dropped, and a new route discovery is initiated. TrafRoute is sensitive to the road topology such that the FPs must be chosen carefully, and their locations and IDs should be downloaded in advance by each vehicle. TrafRoute performance is highly depended on the accuracy of the location discovery system. Each vehicle should precisely determine the distance between it and the centre of the closest FP to control the amount of overhead. Current GPS error, for reference, is typically within a 15m range [70]. TrafRoute seems to be suitable for even-distributed moderate vehicular density urban scenarios with a low number of RSUs.

2.2.6 PROMPT: A cross-layer position-based communication protocol for delay-aware vehicular access networks

Jaruban et al [71] designed the PROMPT cross-layer infrastructure-based routing protocol for urban scenario in VANETs. The principal aim of this work is to combine source routing and geographic routing strategies with the aid of MAC function using a relay node selection procedure. Infrastructure units called base stations (BS) are installed at fixed locations along roads acting as gateways. Beacon message are periodically broadcasted by each BS not only to advertise its services, but also to collect the data traffic statistics along travelled paths. Each vehicle, which may receive multiple beacons, maintains a path information table, and then it forwards a beacon, as a relay, updating it with its current location and local *data load information*. A path information table contains an entry for each path to the BS represented by a sequence of relay (location, mobility and load) information. The vehicle leverages this traffic load information and the predicted additional load, to estimate the end-to-end delay along a given path. Whenever a source vehicle has a packet to send to BS, it initiates the route selection process to obtain the best possible route in terms of total path delay. The selected source route consists of streets and directions (geographic routing) on a path on the roadmap from the source to the BS (source routing), which is attached to the data packet.

The MAC layer then selects the farthest relay nodes along the directions contained in packets during the contention process. A relay node is selected independent of the node address, so there is no need for a neighbour management mechanism. The authors also present a packet train mechanism to further reduce the average delay, such that relay nodes try to bundle different packets with the same path and send them in a single batch. Therefore, the channel is contended for only the first packet in the batch, reducing the average end-to-end delay. This protocol is limited to vehicular access networks where vehicles access a wired backbone network by means of a multi-hop data delivery service, utilizing the exchange of beacons to carry the data load information.

2.2.7 A Distributed Routing Protocol and Handover Schemes in Hybrid Vehicular Ad Hoc Networks

Vehicles on the road may move in or out the service areas of different RSUs. In [72], Sheu et al propose a distributed routing protocol that integrates handover schemes to extend the lifetime of the communication links between a source vehicle and a destination vehicle in VANETs.

The proposed scheme takes advantage of the hash function to combine the registration and location services. The road network digital map is divided into several regions each served by at least one RSU with a unique ID. Initially, each vehicle is assigned to a single home RSU. In the hash function, a vehicle ID is divided by the total number of all RSUs, and the remainder is the home RSU ID. When a vehicle receives a beacon from a RSU, it registers its ID and location information to this RSU which then becomes the so-called registered RSU of the vehicle. The registered RSU determines the home RSU of the vehicle by its ID and the hash function. After that the registered RSU sends its ID and the vehicle's ID to the vehicle's home RSU via the backbone network. The home RSU searches the vehicle ID in its table and updates the vehicle's registered RSU ID. Now, whenever a source vehicle needs the location information about a destination vehicle, it just broadcasts a route-request to the home RSU and to the registered RSU of the destination vehicle. When the destination's registered RSU receives the route request, it appends the expected destination location to the message and sends it to its neighbouring vehicles. After the destination receives the request, it sends a reply to the RSU via the reverse path of the request packet. This process has a lower cost in overhead than that produced by visiting all RSUs in the network.

Using the advance greedy forwarding mechanism, a source vehicle broadcasts its route request to the nearest RSU. A receiver that is much closer to this RSU has the highest privilege to rebroadcast the request using a back-off time controlling scheme.

Two kinds of handover are considered: intra-RSU handover and inter-RSU handover. The key concept here is to use intelligently the Received Signal Strength Indicators (RSSIs) of the periodic RSU beacons to choose the future next-hop the RSU of a vehicle before link failure occurs in order to prolong the link lifetime.

In general, this is an on-demand reactive routing protocol and more suitable for highway scenarios with a feasible number of RSUs and adequate number of vehicles. There is not any recovery mechanism when any intermediate node along the route changes its location. The RSU beacon is broadcasted only in one hop, and the vehicle registers only by overhearing the beacon. It is not mentioned, if either the vehicle should update its registration when it moves away from the region of the registered RSU, or the home RSU will inform the previous registered RSU about the change.

2.2.8 ROAMER: Roadside Units as message routers in VANETs

In contrast, ROAMER **[73]** is a new hop-by-hop routing approach that addresses the geographic forwarding problem in sparse density networks using the carry and forward scheme, and RSUs assist in routing packets between distant locations in VANETs. In ROAMER, each vehicle sends both HELLO and BEACON control messages (every 2 seconds in the simulation). HELLO message contains the mobility and location information of the source and its neighbouring vehicles in a bounded vicinity that may be adaptively extended and include some RSUs. The BEACON message is used to inform the RSU about vehicles in its vicinity that is bounded by its neighbouring RSUs.

Whenever the source vehicle has a packet to send, there is no need for a route request message. If the destination is in its vicinity, the source just estimates the location of destination and the number of hops, then unicasts the packet to the restricted set of neighbours heading towards the destination (redundancy transmission). In this case, the intermediate neighbour will usually have the destination in its neighbourhood table; hence it can repeat the same procedure till the packet reaches the destination. Actually, the destination may be a vehicle or a RSU. If the destination is not in the source vicinity, an RSU, upon receiving the packet from the source, undertakes the mission of packet delivery in a similar manner to the above, if the destination in its vicinity. Otherwise, it sends queries gradually to its first-level neighbouring RSUs (one hop distant RSU) then second-level neighbouring RSUs and so on, till it receives a reply from a RSU that can serve the destination. After that, the source's RSU sends a packet to the replying RSU.

ROAMER strongly relies on the neighbour management scheme. Taking advantage of the "carry and forward" approach proposed in the literature, when any node has a packet to send, it can carry the packet for a limited time until it finds proper neighbours or the destination. ROAMER also tries to address problems pertaining to the increasing distance between the source and destination. It tries to limit the expected geocasting area of the destination to a circle with a centre on the latter's geographic coordinates, at the instant of time that it could receive the packet, and a radius adaptively computed according to the road topology.

The unicasting nature of packet delivery necessitates using restricted redundancy of forwarding along the delivery path (possibly in different directions) to handle the possible destination movements and to help in decreasing the potential latency due to carrying the packets for a long time. In their simulation, authors showed the superiority of ROAMER over TrafRoute especially in sparse scenarios, due to buffering.

2.2.9 RSU-Assisted Geocast in Vehicular Ad Hoc Networks

Authors in [145] introduced a novel approach to find the optimal RSU aiming to deliver a message to a vehicle following a minimum cost path within a defined area. A quadtree model is used to represent the geographic area that is assumed to be divided into square partition on the basis of geographic position. After that, a tree trimming scheme is used to find the intersections between quadtree and the destination region. An election approach is proposed which is used to select optimal RSU to disseminate the message to the destination region. This new method is applied to support the geocast. Authors focused mainly in modelling the time complexity to find the proper RSU in case of the availability of many RSUs in the vehicle's vicinity. The new protocol is not evaluated in realistic urban scenarios.

Table 2.1: Infrastructure-aided routing protocols

			Routing Protocols			
			TrafRoute [69]	**Distributed Routing [72]**	**ROAMER [73]**	**Protocol in [74]**
Intra-sector communications		Routing Strategy	On demand + geographic based	On demand + geographic based	Position based + Carry and Forward	Position based
		Hello/Beaconing	One hop		One hop (Incremented)	One Hop
		Neighbourhood Maintaining	Yes		Yes (Vicinity Maintenance)	
		Route Discovery	Flooding (Sector-limited)	Flooding (CBF) (Sector-limited)		
		Greedy forwarding			Yes	Yes
		Routing Metric	No. of hops	No. of hops	Distance	Distance
		Route Recovery/ Maintenance	Yes (Passive)	Yes (Active)	Carry and Forward	
		Route Stability	No	No	Opportunistic	No
Inter-sector communications	RSU	Usage	Relay, Registrar	Relay, Registrar	Relay, Location Server	Relay, Location Server
		Beaconing	One hop	One hop	One hop (Incremented)	One Hop
		No. of RSUs	Moderate-High	Moderate-High	Low-Moderate	Low-Moderate
	Affiliation	Sector Dimensions	Fixed geographic coordinates	Bounded by RSUs	Fixed distance to sector's RSU	Fixed geographic Coordinates
		Type	Registration	Registration	Registration, Location Update	Registration, Location Update
		Registration triggering metric	Entering a new sector	Passing by a new RSU's transmission range	Distance to RSUs	Entering a new sector
		Location updating method			Vicinity Maintenance, Periodic location update packet to RSUs	Periodic location update packet to RSUs

2.2.10 Discussion and comparison

In proactive topology-based routing protocols, like DSDV, nodes build routing table and use the shortest path algorithm, i.e., Dijkstra, consequently the runtime complexity is exponential to the number of nodes (n), the control message overhead grows as $O(n^2)$. With Fibonacci or binary heap implementation, the Dijkstra algorithm has a complexity $O(|E| + |V| \log|V|)$ where the V and E is the number of nodes and edges respectively in the network graph $G(\mathrm{V}, \mathrm{E})$. This makes DSDV a suitable option for small populations of mobile nodes. On the other hand, reactive topology-based protocol like AODV aims to reduce control overhead and achieve scalability by building routes on demand.

For highly dynamic vehicular networks, city map aware topology-based routing protocols like GSR and IGSR are preferred. These protocols modify the network graph representation to include intersections and road segments as vertices and edges respectively, allowing for data packets to be forwarded through virtual addresses of fixed locations, decoupling the protocols from using fall source route of mobile nodes' addresses into using route of consecutive intersections' ids on the road grid. Any available vehicle at an intersection can forward the packet. However, the runtime complexity still depends on number of the intersections. Therefore, the idea of dividing the city map to small zones has attracted the attention of [146] to enhance the scalability.

As long as, position-based routing protocols require location service strategy to determine the destination location, researchers in [69][72][73][74] propose using RSUs as location servers or registrar on their extended service area or map sectors. These protocols, hence, maintain both location tables by forwarding beacon to RSUs and neighbourhood table by one-hop periodic broadcasting, which means more control overhead of $O(n^2)$. These protocols are highly dependent on the number of RSUs, that should be placed intelligently on the road grid, to control the amount of the total required overhead to ensure the correct operation and enhanced scalability.

Infrastructure-assisted routings can be classified into two categories [67][70]: protocols depending on internet access, i.e. finding the best route to infrastructure units; and those that just use unicast routing in the vehicular network itself. It is worth devising unicast routing algorithm that lets the vehicles always maintain routes to RSUs.

In two-phase routings, source node firstly searches for the destination node in the local area. If no response, the destination is believed to be in the wired network. In the second phase, packets are delivered to internet gateways to forward further. Two phases and the gap between them not only increase the overhead but also increase delay in routing discovery procedure. In one-phase routings, similar to[65][66][69][72][73] , RSUs, as location servers, serve joined bounded zones where each vehicle inside each zone has to firstly register and periodically update its location relative to its corresponding RSU. When the RSU receives a RREQ that intended to a destination outside its zone, it will directly send the request to other RSUs over fast and reliable backbone network. The destination's RSU will then reply with no need for waiting for a wide-network search, thus reducing both overhead and latency.

In [67], vehicles piggyback their mobility information on any packet travelling to an AP which, in turn, builds a "link lifetime"-weighted communication graph. If an AP receives a RREQ, it will compute the best route and then send a RREP. In PROMPT [71], on the other hand, a BS periodically broadcasts beacons which are propagated outside its communication range to a specific limit (lifetime or beacon hop limit). A vehicle which may receive the same beacon over multiple paths, determines whether to forward the received beacons, but before forwarding, the vehicle updates the beacon with mobility information and local data traffic statistics; therefore the receivers can obtain detailed knowledge about the path to the BS. Vehicle information is transferred upward to APs in each packet in [67] and downward from BSs to vehicles in PROMPT.

The frequency band at 5.9 GHz (5.85–5.925 GHz), specified for VANET, only allows Line of Sight (LoS) communications with a few obstacles in between. As a consequence, the graph restricted to vehicles at city intersections is almost as connected as a full graph including all the vehicles. In TrafRoute [69], a vehicle, close to the centre of an intersection, has mostly a direct LoS with neighbouring intersections and can forward messages accordingly; however, a vehicle should maintain a neighbourhood table to elect itself as a forwarder. The beaconless strategy relying on a distributed timer-based contention process is still an attractive solution to reduce the overhead, as in RBTV-R. Although RBTV-R [55] is a beaconless protocol that creates, on demand, routes of succession intersections that have a high probability of network connectivity among them, it floods the whole network to find a destination.

Table 2.1 introduces a thorough comparison of the main routing protocols [69][72][73][74] that are assisted by RSUs to work as location servers/registrars (i.e., so-called Infrastructure-assisted routing protocols). The table specifies the operations components of the protocols for Intra-sector and inter-sector communications and the required control overhead (the overhead complexity). The intra-sector represents the communications in the RSU extended service area. Trafroute and [72] flood the sector with the route request during the route discovery process while ROAMER and [74] use greedy geographic forwarding. All broadcast Hello periodically except [72], however, each vehicle in ROAMER uses them to build a location table for all vehicles inside its vicinity. Each vehicle adds its table on the hello packets. ROAMER is tailored to work in sparse networks. The DSRC standard requirement of sending periodic hello packets to support collision avoidance applications justifies the usage of this inevitable overhead.

In contrast, the protocols use RSUs to transmit the data packet to faraway destinations. In order to facilitate this, vehicles must register at the nearest RSU. A vehicle sends a registration request packet once it enters a new sector. In TrafRoute and [72], the map is assumingly divided into fixed sectors that vehicles, whereas ROAMER and [74] determine the RSUs locations from the map and select the registrar RSU according to the distance. Hence, an RSU will determine if the data packet needs to be transferred out its sector to other RSUs. Furthermore, vehicles in ROAMER and [74] need to update their location in RSUs using the periodic location update beacons which means more overhead. Nonetheless, it may be acceptable to trade off high location update costs against the fast communication setup time of proactive geographic routing. In sum, the amount of incurring overhead (and in return the scalability of the network) may be defined according to the size of sectors and the maximum expected number of vehicles that can be hosted in them.

2.3 Broadcasting in Urban VANETs.

The Vehicular Ad hoc Network (VANET) has emerged as a technology primarily to offer solutions for Intelligent Transportation Systems (ITS) that aim at helping drivers on the roads, by anticipating hazardous events or avoiding bad traffic areas [75][76]. Recently, attention has been drawn to providing many infotainment and commercial services which are expected to hasten the VANET market penetration rate, but fast message delivery is indispensable for many appealing applications [27]. As a result of such a broad range of expected applications, researchers have made a considerable effort to classify these applications according to the required communication mode and the level of the quality of service (QoS). Broadcasting is the one of the most important communication modes that play an important role in most appealing applications particularly safe-driving and traffic management applications [77][78][79]. To design an efficient broadcast protocol, the following metrics should be taken into consideration: reliability, overhead, and speed of data dissemination. In safe-driving applications, critical information such as hazards and alarms must be delivered to as many cars as possible in a certain area with the lowest possible delay. Therefore, the broadcast protocol should ensure not only a high level of reliability but also speed of data dissemination. Such information will be useless if it arrives too late. Infotainment and commercial applications relying on broadcast include sharing traffic, weather, and road data among vehicles, as well as delivering advertisements and announcements. These applications generate packets of various lengths at different rates. For example, advertisement bulletins for restaurants or hotels can be broadcast in long messages that carry pictures, directions, or even short videos. Transmission of such large-sized units may exacerbate the Broadcast Storm Problem (BSP) [30], and thus, the total amount of incurred overhead. Furthermore, applications, such as video dissemination and interactive gaming and social networks on roads demand high bandwidth and low delay. The key problem is how to optimise these metrics whilst conditions in vehicular networks are highly variable.

The challenging problem is compounded in urban areas crowded with tall buildings which will absorb radio waves, making communication impossible when vehicles are not in line-of-sight. Packets then only move through the crossroads. Most contributions in the literature have focused on the broadcasting safety-related messages using the default lowest transmission rate. This attempts to cope with the complexity of the vehicular communication environment and, at the same time, to widen the coverage area. However, it is worthwhile to study the use of higher data rates principally for broadcasting large but low priority non-safety-related packets. In fact, the possibility of using higher date rates in the urban environment still need to be investigated [76][77][78].

The goal is to balance demand to enhance both reliability and throughput. This may be achieved by exploiting the nature of the city grid which is generally composed of many intersections that are relatively close together: the average distance between any two adjacent intersections is typically less than 120meters. A Packet may traverse many adjacent intersections utilizing high data rates during its journey to cover an urban zone of interest. While there are many mechanisms intended to work in urban scenarios [80][81][82], we mainly focus on developing a contention based forwarding scheme that utilizes a wait timer which relies on the intersections' location information.

Most of the protocols use distance-based relay selection techniques (DBRS) where the packet receiver decides to rebroadcast the packet according to its distance from the sender.

These protocols mainly differ in the additional rules that differentiate the vehicle's ability to efficiently reach hidden area due to the obstacles. For example, in UV-CAST [31] which uses the waiting timer concept, vehicles at intersections are given high priority. They wait less than other vehicles before transmission. Whilst the sender tends to choose a neighbour at the intersection rather than the farthest neighbour, these protocols employ a greedy forwarding (GF) concept such as ERD [32]. To improve the reliability, some of these approaches dedicated to broadcasting event-driven notification messages (DENM) utilize the RTS/CTS/ACK handshaking concept to avoid the hidden terminal problem and to ensure packet transmission progress, while others rely on an implicit acknowledge principle.

UV-CAST [31] combines the store-carry-forward (SCF) mechanism and multihop broadcasting. It selects a relay node using distance-based waiting time in dense networks and assigns the SCF task to those vehicles that have a high probability of finding new target vehicles. In UV-CAST, more than one vehicle is selected to be a SCF agent in order to disseminate the message in many directions. These vehicles also keep rebroadcasting the message in the region of interest (RoI) when encountering uninformed vehicles. Vehicles inform each other about their formerly received messages in Hello packets to reduce the message redundancy (implicit acknowledge). The size of a Hello packet increases as the number of broadcast messages increases. It is undesirable to have large-sized periodic beacons that may overwhelming the network, even though it helps reliability. In waiting time computation, vehicles at an intersection are given the preference; however, there is a predefined maximum waiting time, which is reasonably high (i.e. 500ms). This approach exhibits high latency in dense networks.

In eMDR [34], an incoming warning message is rebroadcast to the surrounding vehicles only once when the distance between sender and receiver is higher than a set threshold, or the receiver is either at an intersection or in a different street than the sender. Therefore, warnings can be rebroadcast to vehicles which are traveling on other streets, overcoming the radio signal interference due to the presence of buildings. So, rather than using store-carry-forward mechanism, a warning is periodically broadcasted by the event source. The eMDR scheme is especially suitable in situations where there are few vehicles able to forward messages. In a dense network, the number of collisions will increase as the number of allowable vehicles at intersections on beyond the distance threshold increase.

To hasten message broadcast, POCA lets a sender select one neighbour to rebroadcast the message. If its neighbours do not receive the re-broadcast message, they initiate the waiting timer to re-broadcast the message again. The neighbour that is close to the failed selected next hop relay node will rebroadcast the message [83]. Like UV-CAST, POCA integrates SCF scheme. Beacons includes message IDs to recognize uninformed vehicles.

Authors in [84] considered a more realistic urban environment. They have proposed Bi-Zone Broadcast (BZB) which combines the advantages of both random and distance-based contention-based forwarding (CBF) and further adjusts the contention timer to provide a higher chance for relays (RSUs, buses, trams, trucks, etc.) with good dissemination properties (e.g antenna height) to be a relay.

Mapcast is also a waiting-timer based CBF that classifies the broadcast messages at the transmitter node depending on the forwarding policy: only forward, only backward, forward & backward, reserved. It uses the implicit ACK concept [35]. Authors handle the problem of concurrent message broadcasting using Multi Queue-Mapcast (MQ-Mapcast) which separately applies the Mapcast algorithm to each packet being broadcasted. This is achieved by introducing multiple MAC-layer queues within every vehicle, so that a node can temporarily store the received packets for which it is a candidate forwarder and handle them independently of each other. Furthermore, based on the positions of the sending nodes, Salvo et al [37] propose three different geometrical rules to be applied with a waiting-timer based CBF. The aim is to allow the data to cross road intersections and to propagate in multiple directions. However, in the daytime, when vehicles start forming large queues at intersections in cities, distance based CBF schemes suffer from a higher collision rate due to the increase in the number of cars trying to transmit at the same time.

The Road Topology based Broadcast Protocol (RTBP) is introduced as a CBF-based scheme suitable for both high-density urban and highway scenarios [85]. RTBP aims to assign the highest forwarding priority to cars which have the greatest capability to send the broadcast packet in multiple directions. These cars are called mobile repeaters (MRs). The number of potential MRs at each intersection is controlled, on the fly, by the local vehicle density and hence, the number of retransmitting vehicles and the collision rate are reduced. Consequently, the average latency is seen to decrease.

Another trend uses the greedy forwarding concept (GF), for example in Streetcast [33]. The packet sender selects one of neighbouring vehicles at the intersection as a forwarder without knowing its forwarding capability (unless the network is exchanging high-cost, up-to-date, 2-hop neighbourhood information). These schemes rely on an additional technique, similar to RTS/CTS handshaking, to ensure successful reception of the propagated packet by target receivers, but this may lead to an undesirable delay.

ERD is a road-based directional broadcast protocol for VANETs in urban environments [32]. To increase the chance of propagating data toward all directions at an intersection, the protocol classifies vehicles into groups based on road, and selects a relay node with the best line-of-sight for each group. Only the farthest node in each group is selected. The sender attaches the node ID list of selected vehicles to the message. ERD does not provide any technique to ensure reliability or to avoid collisions or hidden terminal. Otherwise, Multi-vehicle Select Broadcast (MSB) utilizes a backoff counter to avoid the collision from a simultaneous rebroadcast between selected vehicles [36].

Protocols, such as Urban Multi-hop Broadcast (UMB) [28] and Efficient Direction-based Broadcast (EDB) [86], utilize extra fixed devices called repeaters. These repeaters rebroadcast the packet immediately to the different connecting road segments after receiving the packet. However, these protocols induce high deployment cost.

The CBF scheme outperforms the GF scheme in the terms of packet delay, collisions, and overhead, and is therefore more suited to provide multimedia data dissemination services over vehicular networks, particularly in highway scenario. However, the disadvantage of this method is the contention delay and the possible packet forwarding redundancy. In case the packet is broadcast at high bit rate, the estimated communication range for successful reception is lower than the maximum radio range under the default basic rate. Therefore, vehicles that receive that packet correctly may delay the packet forwarding for much longer time. Table 2.2 presents a comparison of broadcast protocols that are designed to operate effectively in urban areas.

Table 2.2: Broadcast strategies on urban VANETs

Protocol	**BSP mitigation**		**Hidden Terminal**	**Reliability**	**Required Info.**	
	Category	Propagation limitation	RTS/CTS	ACK	Beacon/Neighbours' info.	Road Layout/ Map
UV-CAST [31]	DBRS, SCF	ZoI	No	Implicit	Yes	Yes
Streatcast [33]	Greedy Forwarding	TTL	MRTS/ CTS	Yes	Yes	Yes
eMDR [34]	DBRS	Not mentioned	No	No	No	Yes
Mapcast/QM-Mapcast [35]	DBSR	ZoI	No	implicit	No	Yes
MSB [36]	Greedy Forwarding	ZoI	No	Implicit	Yes	Yes
ERD [32]	Greedy Forwarding	ZoI	No	No	Yes	Yes
TAF [37]	DBRS	ZoI	No	No	No	No
RTBP	DBRS	ZoI	No	Implicit	Yes	Yes

CHAPTER 3 : ROAD TOPOLOGY BASED BROADCAST PROTOCOL (RTBP) FOR URBAN VANETS

In this Chapter, the Road Topology based Broadcast Protocol (RTBP) is proposed as a CBF-based scheme suitable for urban scenarios. RTBP aims at assigning the highest forwarding priority to vehicles, which have the greatest capability to send the broadcast packet in multiple directions. These vehicles are called mobile repeaters (MRs). MRs will repeat the contention process until broadcasting the packet in all directions at the intersection. RTBP controls the number of potential MRs at each intersection by exploiting the capacity of gathering up-to-date local vehicle density information, and hence, the number of retransmitting vehicles and the collision rate are reduced. Thus, the average latency is minimised.

3.1 The State-of-Art

Recently, different attempts have been made to cope with the problem of message dissemination at intersections. In urban environments, obstacles such as high buildings hinder message propagation, and increase the shadowing and multipath effect on radio waves, making communication only possible when vehicles are in line-of-sight or few meters away from crossroads (i.e., near-line of sight), as shown in Fig. 3.1. These obstacles can also exacerbate the hidden terminal problem at intersections. Furthermore, in most major cities, there are traffic lights at most crossroads and, when the number of vehicles increases at busy periods, long queues are formed, and data traffic congestion becomes higher. Consequently, intersections turn into bottlenecks in the network graph.

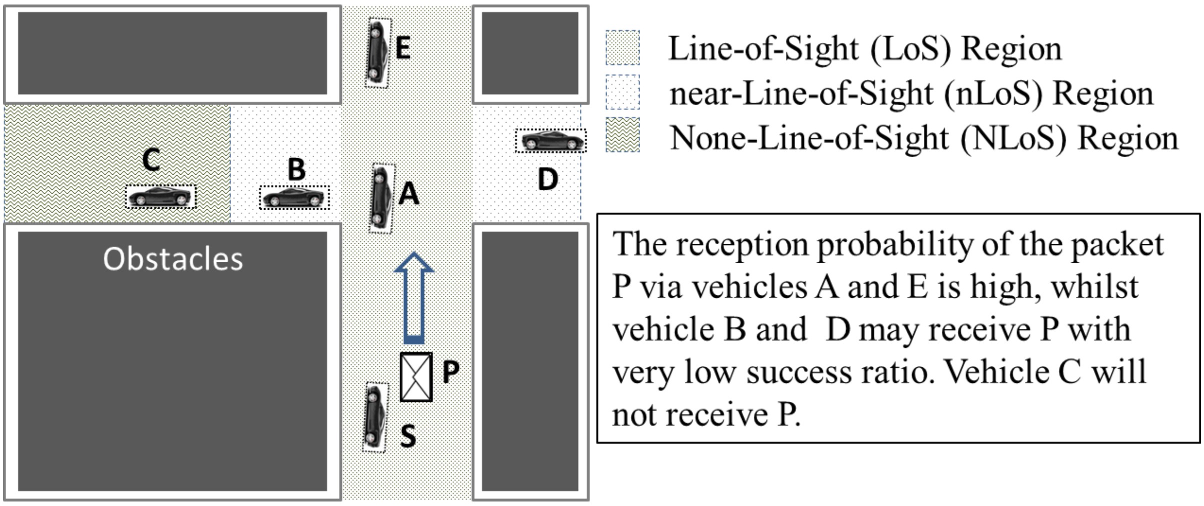


Figure 3.1: Obstacles and disconnections in an urban environment

Many broadcasting protocols have recently been proposed for urban vehicular networks [33][35][87]. Some of the earlier solutions use extra fixed infrastructure called repeaters, at least at main intersections [28][86]. Repeaters forward packets immediately to the different road segments after receiving them. The important conclusion that can be derived when dealing with these approaches is that selecting a stable forwarder at intersection leads to high reachability, and low redundancy on urban VANETs. However, reliance on fixed repeaters induces high deployment cost. To get rid of these fixed repeaters via using vehicles instead, two challenges need to be confronted: 1) How to select a vehicle to act as a repeater at an intersection; and 2) How to mitigate the hidden terminal problem which can occur when the selected forwarders for each direction at the intersection rebroadcast the packet simultaneously.

Various solutions to the first challenge have been proposed. ERD [32] is a GF-based protocol that always selects the furthest node (i.e., a vehicle) as a target forwarder unless the sender finds some nodes located at an intersection. It gives these nodes high priority, picking up one of them randomly as a target node. Nodes inform others about their existence at intersection using beacons. However, a sender receiving such beacons from nodes at intersections cannot conclude that these nodes are able to receive the broadcast packets since they experience different levels of interference. Therefore, this approach remains suboptimal in urban vehicular environments. Intuitively, the GF-based techniques reduce the number of potential contending forwarders at an intersection, but they require additional supplementary methods to ensure successful reception at any target node. Those techniques, similar to RTS/CTS handshaking, may cause additional delay. Thus, the receiver-centric algorithms may be more desirable if the redundancy level (and consequently the collision rate) is reduced carefully without compromising reliability.

eMDR [34] is a distance-based broadcast protocol aimed mainly at propagating warning messages. In eMDR, an incoming warning message is rebroadcast to the surrounding vehicles only once when either the distance between sender and receiver is higher than a distance threshold, or the receiver is close to an intersection or in a different street than the sender. eMDR is particularly suitable for situations where there are few vehicles able to forward messages. In a dense network, the number of collisions will grow as the number of rebroadcasting vehicles near intersections increases. The authors in [87] propose a novel technique to adapt the distance threshold according to the statistical spatial distribution and local vehicle density. The problem is that all waiting vehicles at intersections have virtually the same opportunity to retransmit broadcast messages so the collision levels remain high.

By contrast, in Contention-Based Forwarding (CBF) techniques [31][37][86][88], there is no such distance threshold. The broadcast message is buffered for a waiting time inversely proportional to distance from the message sender. The authors in [37] propose three different algorithms to allow the data to cross an intersection and to propagate towards multiple directions, applying simple geometric rules based on the positions of the sending nodes, During the waiting time, if a vehicle receives the same packet from two different neighbouring vehicles, it is able to measure the triangle formed by the three involved vehicles as vertices. After the timer expiration, the vehicle rebroadcasts the packet only if an additional geometric condition on the triangle's inside angles is satisfied. This helps the continuous propagation of message through crossroads, but the amount of the redundancy still depends on the number of nodes. Furthermore, the problem of redundancy is compound at intersections where vehicles are very close to each other or even have the same distance to the sender. Therefore, these vehicles wait for similar time before sending the packet to the MAC layer where there is not any rebroadcast suppression mechanism.

With respect to the second challenge, if A, in Fig. 1, sends a packet greedily to D and C, these nodes will rebroadcast the packet immediately resulting in a collision at the intersection. In this case, the sender or other nearby vehicles will send the packet again. To confront this problem, UMB selects one direction each time resulting in wasted bandwidth and increased latency [30]. Another approach utilizing the multiple-relay selection concept is adopted by Streetcast [33] . This is a MAC-layer solution which sends *Multicast Request to Send* (MRTS) packets to select forwarders in each direction simultaneously, which, in turn, reply with CTS. The sender and surrounding vehicles at the intersection, upon receiving ACK packets, avoid sending the same packet again. In fact, distance-based CBF can limit this situation to a great extent without the need for the handshaking procedure if the maximum waiting time is chosen carefully.

With respect to the existing literature, we aim to introduce the Road Topology based Broadcast Protocol (RTBP) as a fast multimedia message dissemination solution. It is a modification of CBF-based schemes to improve their performance in urban environments, exploiting available road map information. RTBP gives vehicles at intersections higher priority to rebroadcast the message: these are called *Mobile Repeaters* (MRs). The existence of multiple MRs will increase the propagation reliability in this difficult communication environment. To reduce the collision rate, RTBP controls the number of MRs at each intersection according to the vehicle density at the intersections. In addition, the priority of the repeater increases as its capability to spread packets in multiple directions increases. In ancient cities, the average street length is small enough (e.g., in Rome, it is about 46 meters [34]) to allow messages to propagate across multiple inline crossroads in one hop. According to the position of the sender from the nearest crossroad, the near-line-of-sight area may extend to include crossroads in other directions as well [26]. Thus, the MRs at different intersections contend to rebroadcast a packet according to their distance from the sender.

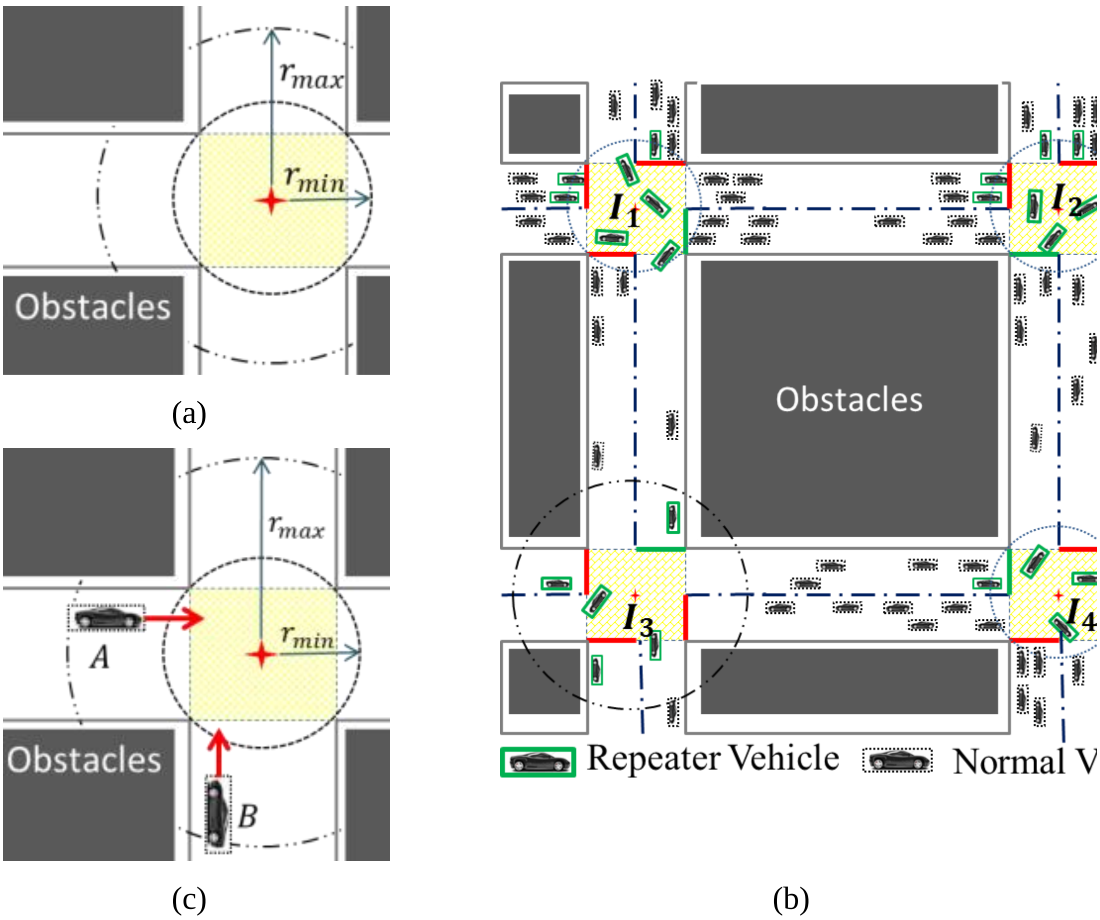


Figure 3.2: Repeaters and intersections in an urban scenario

3.2 The RTBP Operation

3.2.1 Mobile Repeater self-election process

In an urban scenario, most of the intersections (with/without traffic lights) are within radio range of each other as it is highly likely that the intersections are less than 250m apart. A vehicle at the centre of a given intersection typically has a line-of-sight path (LoS) to vehicles at neighbouring intersections. Furthermore, vehicles tend to create dense clusters at traffic lights at peak hours. Thus, RTBP limits the vehicles that act as MRs to the ones which are very close to the centre of each intersection. The aim is to control the number of forwarding nodes whilst maintaining the overall connectivity of the network. We assume that each vehicle knows in advance attributes of all intersections in the road network. Intersection attributes include ID, geographic coordinate, IDs of neighbouring intersections, and the width of all road lanes joined to this junction. This information could be contained on a preloaded digital map [32].

Inspired by TrafRoute [69], vehicles continuously and proactively run a self-election procedure to determine which subset of them will perform the forwarding process. To do this, each vehicle maintains a fresh neighbour table using mandatory broadcast beacon messages, called Cooperative Awareness Messages (CAMs). RTBP complies with European standards (ETSI [88][90][96]); CAM messages include all required information (e.g., vehicle ID, geographic coordinates, velocity, direction, etc.). According to the closest intersection's attributes, and the current (N) and average $(\overline{\mathrm{N}})$ number of neighbours, each vehicle then independently computes the reference distance, d_{ref}:

$$d_{ref} = r_{min}\left(1 + (N-1)^{-\frac{\overline{N}}{50}}\right) \qquad (3.1)$$

Where $\mathrm{r}_{\mathrm{min}}$ is the minimal forwarding radius, representing the radius of a circular area covering the centre of the intersection, as shown in Fig. 3.2(a). If a vehicle finds that its distance to the closest intersection's centre is less than d_{ref}, It elects itself as a MR. According to equation (3.1), the d_{ref} value depends on the vehicle density. Hence, when the vehicle density increases, d_{ref} decreases and consequently, the number of MRs is reduced. On the contrary, when the opposite is true, the area is expanded to include the potential MRs that at least have neighbouring vehicles in their near-Line-of-Sight (nLOS) zone which may receive the packet successfully as shown in Fig. 3.2(b). In addition, each repeater computes its own Penetration Index (PI), the number of distinct directions that a vehicle may cover (i.e., it has at least one reliable vehicle on the street that connects the current and neighbouring intersections in its neighbour table). A vehicle considers all vehicles on the LoS region as reliable vehicles. For vehicles on the nLoS region, as shown in Fig. 3.2(c), the transmitting vehicle *A* considers vehicle *B* a reliable vehicle because they are moving towards the same intersection, and their distance from the centre are less than r_{max}. In our experiments, we set $r_{max} = 2\, r_{min}$ however, in reality, this value may increase or decrease; therefore, the minimum acceptable number of received CAM messages per second can be used instead. For example, vehicle *A* in Fig. 3.3 has one reliable vehicle (*C*), therefore, its PI is 1. On the contrary, vehicle *B* may have vehicles *C*, *D*, and *E* in its neighbour table, thus its PI is 3. The Penetration Index value will determine the priority of the MR to rebroadcast the packets as described below.

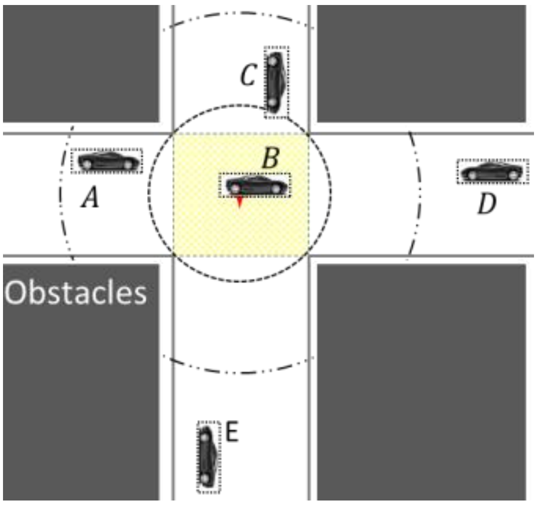


Figure 3.3: Example of a reliable vehicle

3.2.2 Contention-based forwarding process

RTBP aims at assigning the highest forwarding priority to a car which is most capable of sending the broadcast packet in multiple directions, taking into account the importance of the fast packet dissemination in the zone of interest on both the urban and highway environments. To do this, cars' forwarding priorities are determined by assigning different waiting times between reception and subsequent forwarding of messages. Upon receiving a new packet, the vehicle randomly chooses a waiting time (*T*) from (0, CW], CW being a *contention window* value determined by:

$$CW = \left\lceil \left(\frac{d_{max}-d}{d_{max}}\right)^{\alpha} \times (CW_{max} - CW_{min}) \right\rceil + CW_{min} \tag{3.2}$$

$$,\alpha = \begin{cases} (1 + PI) & if \quad MR == True \\ 1 & Otherwise \end{cases} \tag{3.3}$$

Where d is the Euclidean distance from the sender, and d_{max} is the estimated maximum transmission range for an acceptable error rate. In order to reflect the vehicle's capability to spread the packet in multiple directions, the variable α is equal to the vehicle's Penetration Index plus one if a vehicle is a self-elected mobile repeater. As shown in Fig. 3.4, the waiting coefficient $((d_{max} - d)/d_{max})^{\alpha}$ depends on the distance and the vehicle's status. In old cities a single broadcast transmission may cover multiple inline intersections. MRs at different intersections set different waiting times according to their distance from the sender. MRs at those intersections will repeat the contention process to send the packet until it covers all directions. In this way, RBPT takes into account the importance of fast data dissemination on both the urban and highway environments.

3.2.3 Data Dissemination

In RTBP, each broadcast packet includes two parts, a fixed and a variable. The fixed part contains the originating node location, a unique sequence number, a radius of the targeted Zone of Interest (ZoI), generation time, and datum timeout. The variable part includes both the current and previous senders' locations. In this way, vehicles, which are not acting as MRs, check if they are in a street traversed by the packet before they rebroadcast it. The main concern is how to broadcast the packet at an intersection. MRs keep the packet until the packet is transmitted to all directions (i.e., streets). To do so, RTBP uses a digital map and navigation system: a vehicle can determine at which streets it and the neighbouring vehicles are moving on and IDs of all streets connected to all intersections. Therefore, a MR at an intersection can record the street ID of each direction it has received the same packet from and, therefore, decide which directions the packet should now be broadcasted to. The process is summarised as follows:

1. When an MR receives a packet *P* for the first time, it determines which streets *P* came from and what streets it should be sent to. Then, it sets the timer to a value *T* according to its distance from the packet sender and its PI.
2. During *T*, if it receives the same copy again, it stops the timer and checks which street the packet came from, and then deletes this street from the street list. Then, it sets the timer again but with a new distance to the sender and a PI equal to the number of streets which have not been traversed yet.
3. If the timer expires, the MR broadcasts the packet once.
4. All MRs at the same intersection stop rebroadcasting *P* if any of them has already sent *P*.

In this way, even if the packet has been received two or more times, it will be rebroadcast if there are vehicles on other streets that have not received it. The vehicle with highest PI will get the channel early. Rather than using explicit acknowledgements, RTBP depends on data packets reception (i.e., a passive acknowledgment). Therefore, only a subset of nodes that are "d_{max}" meters apart from the sender can participate in the contention to rebroadcast the packet. The distance "d_{max}" is determined as the threshold for which there is a high reception probability in urban environments (e.g., 90%). This estimation is required to let the passive acknowledgement mechanism operate as described in [35].

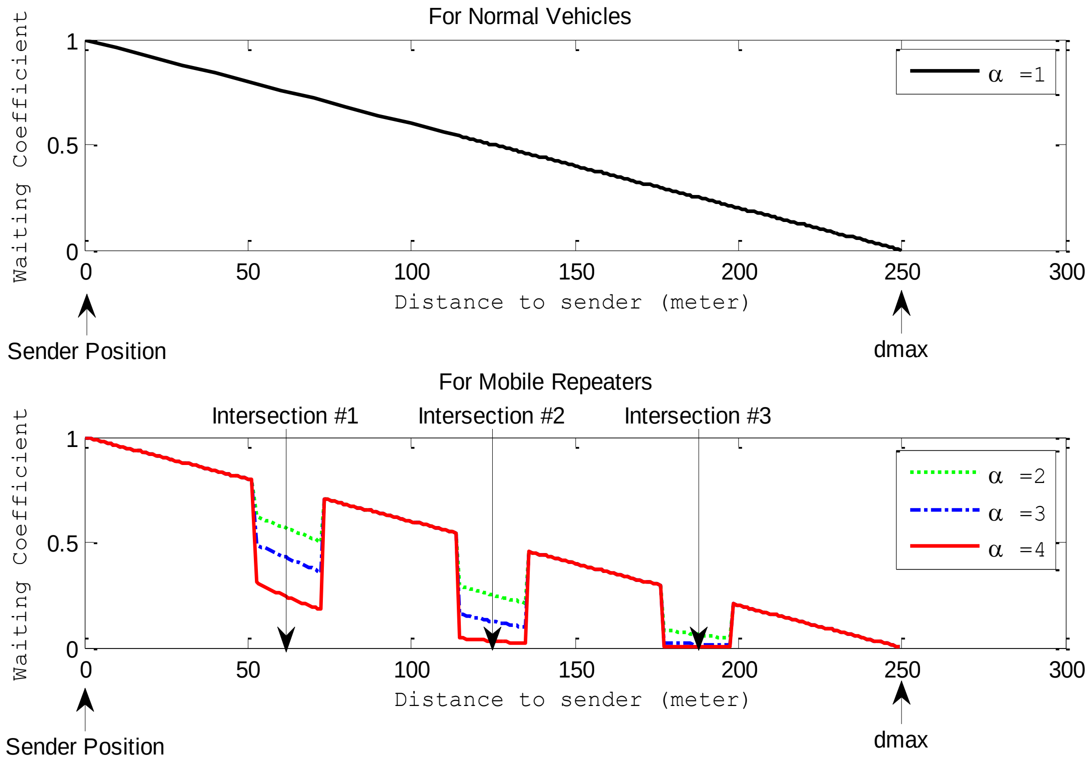


Figure 3.4: Waiting coefficient versus distance for different α values assuming three inline intersections.

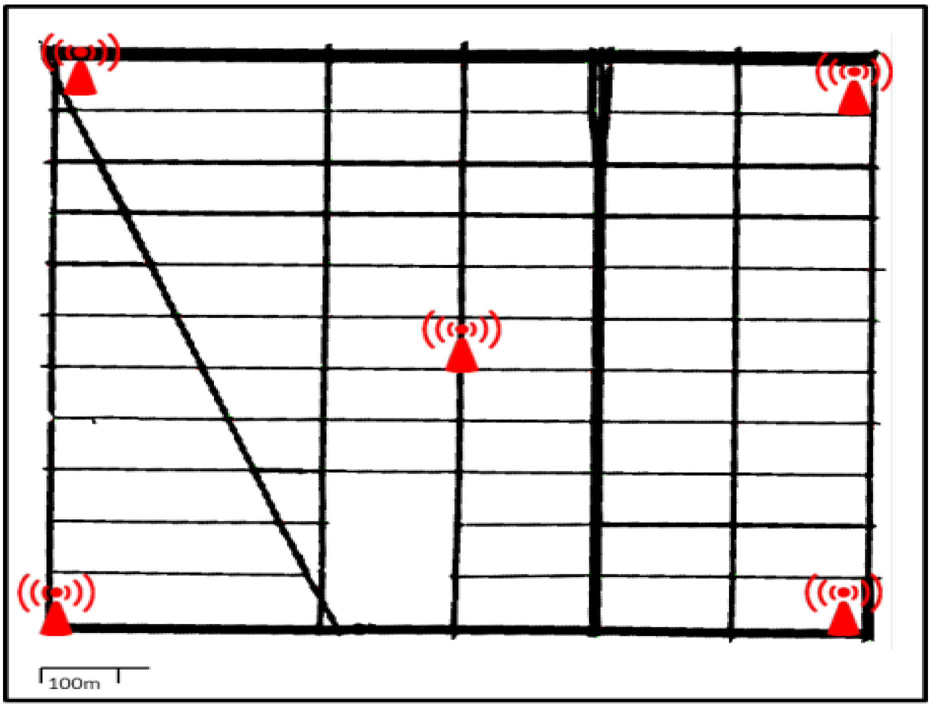


Figure 3.5: Roads Network from the South Part of Manhattan Island, Centred on $(40.7377^o, -73.9882^o)$ with Size Area $\approx 1\ km^2$

Table 3.1: Simulation Setup

Number of RSUs	5
Number of vehicles	100 ~ 900
Maximum vehicle speed	15 m/s
Data rata	6Mbps
Transmission Power	20dBm
Receiver sensitivity	-86dBm
CAM Interval	0.5 s, 1s
Tmax for TAF	10ms
Dth for eMDR	200m

3.3 Performance Evaluation

This section presents the evaluation of RTBP against the eMDR [34], TAF [37], and Simple-CBF approaches. It is worth indicating that eMDR represents the distance-based broadcast protocols whilst TAF represents distance-based CBF. Simple-CBF is a version of RTBP without MRs. Simulation experiments are performed taking real vehicular communications conditions into account. VanetMobiSim is used as a mobility generator to build a real urban scenario from the south part of Manhattan Island centred on (40.7377^o,-73.9882^o), with an area $\approx 1\ \mathrm{km}^2$, as shown in Fig.3.5. The average street length is circa $120\mathrm{m}$ and there are traffic lights at all intersections. Then the resultant realistic vehicular mobility traces are used as an input for a ns2 network simulator. There are five Road Side Units (RSUs): one at the centre and the others at corners. We conduct our experiments with different numbers of vehicles (that reflect the realistic vehicle populations in the city on peak to off-peak hours [84]) , repeating each at least 30 times and calculating average values.

The propagation model parameters are similar to that of WINNER B1 model for the urban environment [91]. Although the WINNER B1 model considers the log normal shadowing and LOS/NLOS visibility between vehicles, we add the previous condition (in Section 3.2.1) to ensure the reliable packet reception. In addition, IEEE 802.11p is used as MAC/PHY layer with the default values according to ETSI standards [27], as shown in Table 3.1. According to [126], The data rate of 6Mbps is the optimal choice for various safety message sizes. The transmission power of 20dbm along with receiver sensitivity of -68dbm were used to ensure that the packet transmission range is 400m in urban environments [91].

3.4 Results Analysis

3.4.1 Scenario 1:

In first scenario, there are four randomly chosen stopped vehicles sending high priority warning message of 512 bytes each, every two seconds, to all vehicles inside a ZoI with $r = \max(300, d_{RSU})$. Note that d_{RSU} is the distance to the nearest RSU. In this way, all interested vehicles will be informed about the event, and this radius is large enough to also notify the authorities via RSUs. RSUs broadcast low priority messages of 2048 bytes. These messages are used to inform vehicles about current traffic, news, advertisements, etc. The transmission rate for each RSUs is 0.1 ± 0.05 message/second and the radius of their extended service area is 600m. The packet time-out is 100ms for high priority warning messages and 500 ms for low priority messages.

The first metric used to evaluate the RTBP performance is *reachability*. This is the average ratio of vehicles inside the originating vehicle's ZoI that received the packet successfully to the total number of vehicles. As shown in Fig. 3.6, as the number of vehicles grows, the network connectivity improves allowing most nodes in the ZoI to receive a copy of the broadcast packets.

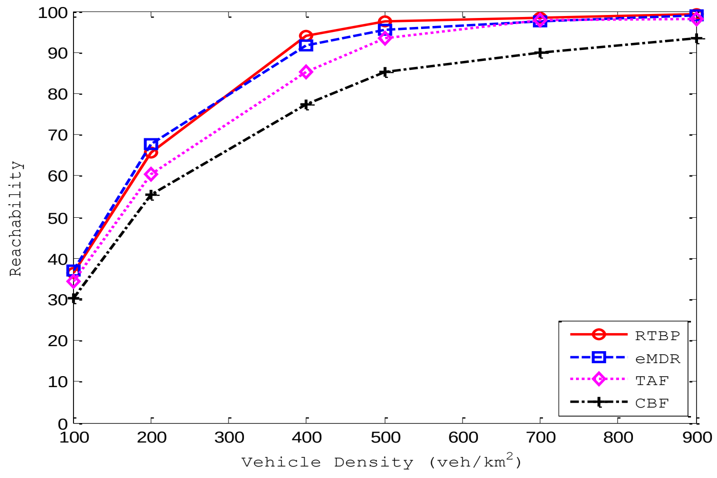


Figure 3.6: Reachability vs Vehicle Density.

Both RTBP and eMDR show similar results, while TAF performance develops slowly. In TAF, a vehicle rebroadcasts the packet only if it receives the packet for the first time, or the following geometric rule is satisfied: the inside angles of the triangle formed by the positions of the senders and the receiver are greater than a threshold value (60^o). As long as most packet transfers are performed by vehicles within the LoS region, TAF has lower capability than both RTBP and eMDR. This problem is compounded in CBF.

The second metric is the broadcast redundancy which is the average ratio of the number of retransmitting vehicles to the total number of current vehicles inside each ZoI.

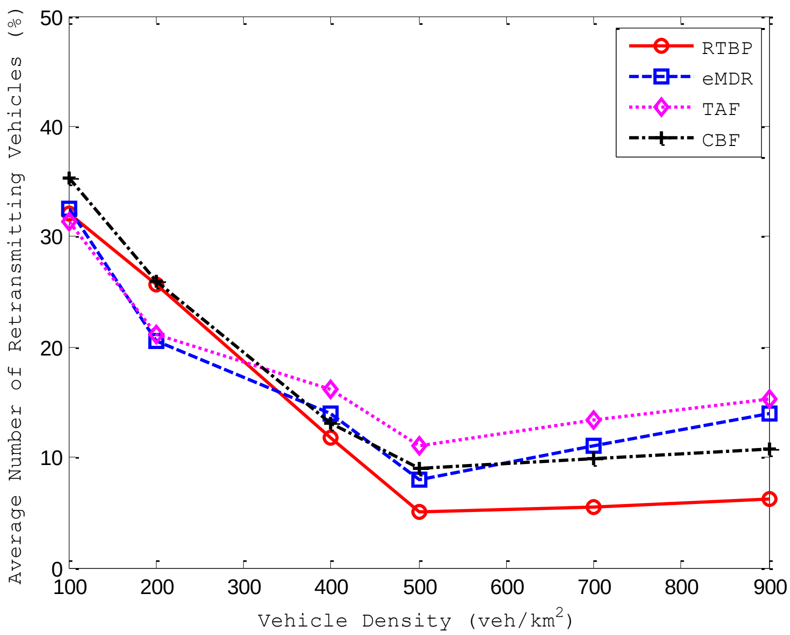
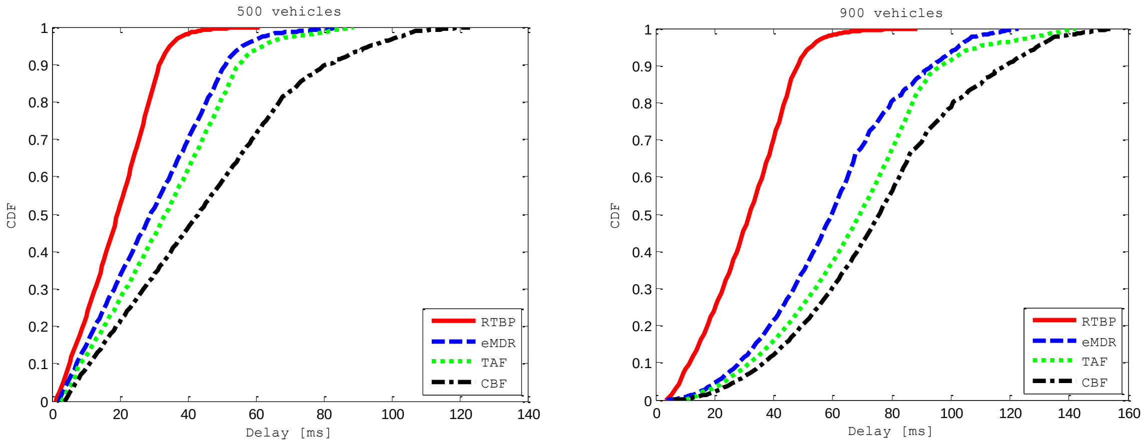


Figure 3.7: Average number of retransmitting vehicles versus vehicle density.

In Fig 3.7, When the number of vehicles is 500, RTBP uses the lowest number of retransmitting vehicles for two reasons. First, vehicles close to intersections have the highest privilege to rebroadcast the packet and their priority increases as their capacity to send in multiple directions rises; hence, the total number of hops required to scan the ZoI reduces. And second, as the vehicle density at an intersection increase, only a small number of vehicles will participate in the channel contention. Consequently, this reduces the number of collisions and results in fewer retransmissions. As illustrated in Fig. 3.7, eMDR and TAF behave similarly in dense networks due to the increased number of contending vehicles at intersections. Pertaining to CBF, a lower value of retransmitting vehicles does not, unfortunately, mean that it works well since the reachability values for higher number of vehicles are already low. The poor performance of CBF necessitates adding further rules to manage the broadcasting problem in real urban VANETs such as that in RBTP and TAF.

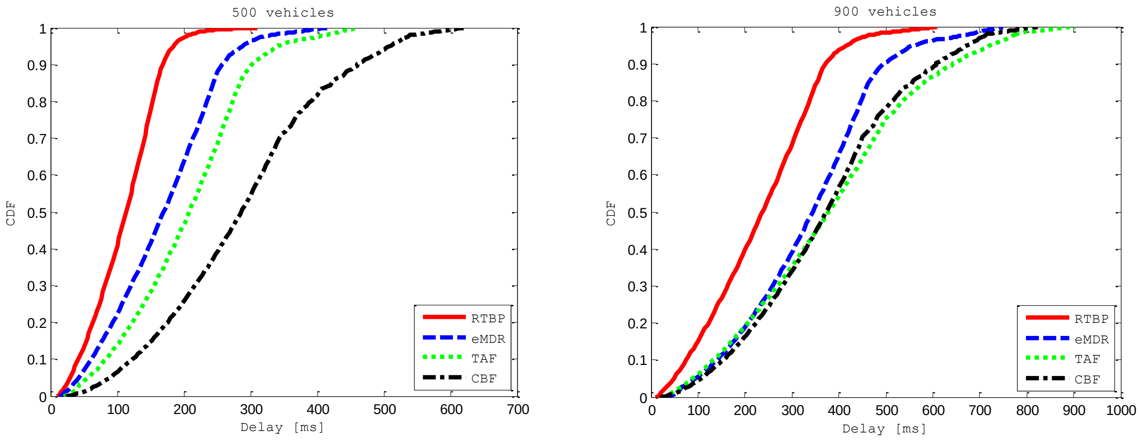
In emergency situations, an immobilised vehicle sends high-priority warning packets periodically but the information carried becomes worthless after a certain time (time-out). Hence, we are interested in the percentage of vehicles inside the ZoI that received the packet before timeout expiration. To study the effect of the traffic load and potential collision rate due to the hidden terminal problem, we take two vehicle density scenarios: i) 500 vehicles where the network has an optimal connectivity; and ii) 900 vehicles where the network is really congested. Fig 3.8 plots the Cumulative Distribution Function (CDF) of the reception delay for warning messages.



(a) 500 vehicles ***(b) 900 vehicles***

Figure 3.8: Cumulative Distribution Function (CDF) of the reception delay for warning messages.

It is clear that RTBP exploits MRs to reduce the number of hops needed to cover the targeted area while also reducing the number of contending vehicles. In Fig. 3.8(a), for 90% receiving vehicles, RTBP shows 58% and 70% lower delay than eMDR and TAF, respectively. When the number of vehicles is increased to 900 in Fig. 3.8(b), RTBP shows better resistance with a delay increase of less than 17ms (51%), contrasting favourably with eMDR and TAF, both of which exhibit a delay increase of more than 40ms (75%). CBF presents the worst performance here with only ≈80% of vehicles receiving the messages before the deadline. This phenomenon is repeated for normal messages' broadcast in Figure 3.9. Using RTBP, it takes 169ms before 90% of targeted receivers successfully receive the first normal message in the case of the medium vehicle density, whereas eMDR and TAF show 54% and 81% delay increase, respectively. The curves become very slow in dense networks but even here RTBP exhibits faster dissemination latency, some 33% and 62% less than eMDR and TAF, respectively.



(a) 500 vehicles ***(b) 900 vehicles***

Figure 3.9: Cumulative Distribution Function (CDF) of the reception delay for normal messages.

4.4.2 Scenario 2:

Additional load is injected in the network to measure the capacity of the protocols to efficiently disseminate the messages. Ten vehicles generate additional low priority 1 KB traffic packet every 0.1 ± 0.5 seconds to be propagated in service areas of 600m radius. Fig 3.10 shows the reachability that obviously shows the negative effect of the packet traffic congestion particularly exaggerating on dense networks. Comparing to Fig 3.6, RTBP, however, shows more resilience, the degradation is almost %3. RTBP shrinks the contention area among transmitting vehicles when the vehicle density increases, which means limited number of collisions even though the number of packets, being transmitted, increases. eMDR performance is still better than TAF however they show almost %7 difference comparing to the previous lighter load scenario. The main reason is the need of eMDR and TAF for retransmitting the packets due to high level of packet collisions, as indicated on Fig 3.11, as well as high incurred reception delay shown on Fig 3.12 and Fig 3.13.

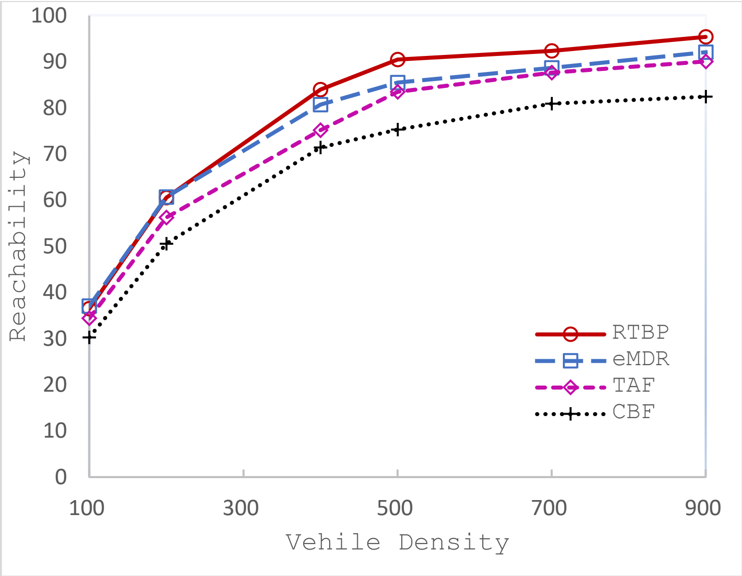


Figure 3.10: Reachability vs Vehicle Density.

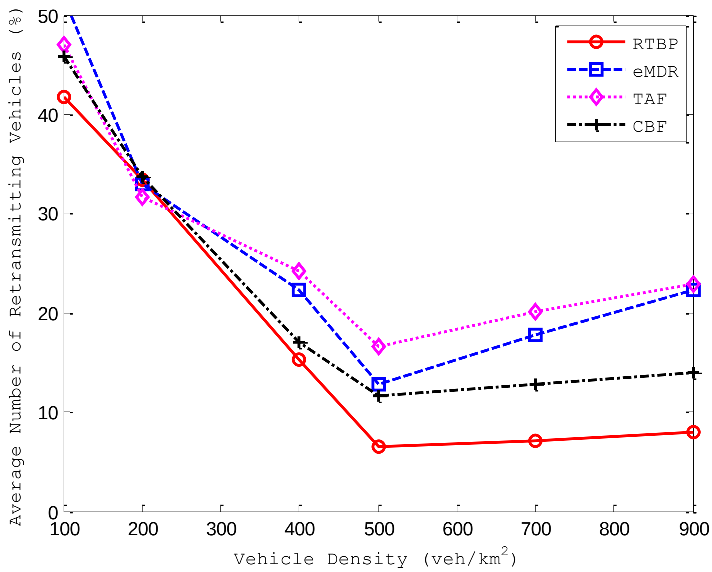
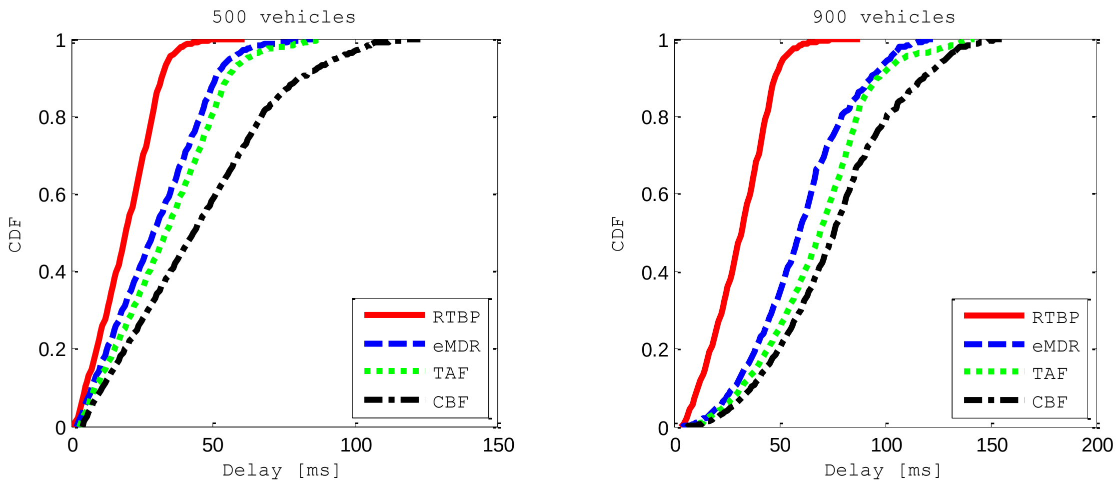
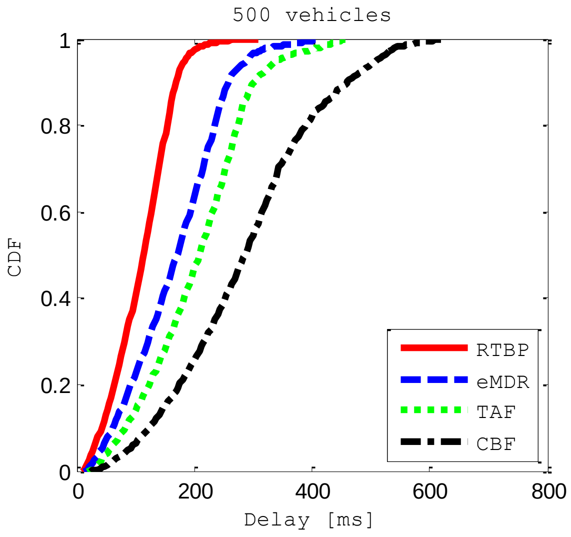


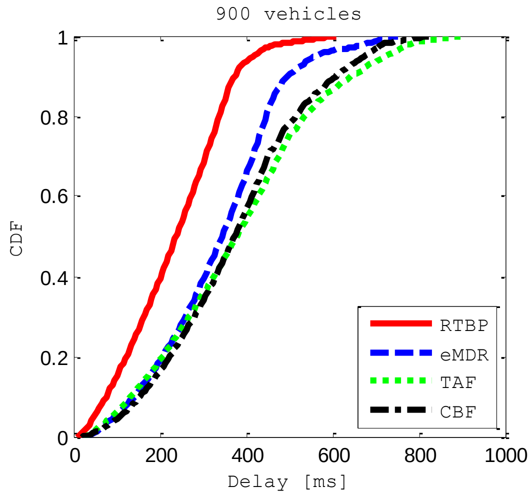
Figure 3.11: Average number of retransmitting vehicles versus vehicle density.



(a) 500 vehicles *(b) 900 vehicles*

Figure 3.12: Cumulative Distribution Function (CDF) of the reception delay for warning messages.





(a) 500 vehicles *(b) 900 vehicles*

Figure 3.13: Cumulative Distribution Function (CDF) of the reception delay for normal messages.

3.5 Conclusion

In this Chapter, we introduced RTBP, a Road Topology based Broadcast Protocol as a fast multimedia message dissemination solution. RTBP is a CBF-based scheme that improves broadcast performance in urban environments by exploiting available road map information. A small number of vehicles at intersections are selected on-the-fly to act as mobile repeaters, and to ensure rapid dissemination of messages in all directions. We have used realistic simulation environments to test the protocol performance against well-known broadcast protocols. The results indicate that RTBP outperforms its counterparts and can reduce latency, increase reachability, and save system resources.

CHAPTER 4 : FAST AND RELIABLE HYBRID ROUTING (FRHR) PROTOCOL FOR URBAN VANETS

In this Chapter, a novel Fast and Reliable Hybrid Routing (FRHR) protocol is introduced that integrates both features of reactive and proactive routing schemes. FRHR maintains proactive routes towards RSUs while it reactively seeks for other nearby nodes on the network. As long as RSUs are the main service providers and enable vehicles to communicate with distant peers, paths towards nearby RSUs are more frequently requested than those towards other vehicles. Reducing the need for reactive routes, in favour of proactively connecting vehicles to nearby RSUs will reduce the total amount of control overhead and speed up the routes building and maintenance where most of data traffic will be concentrated. Additionally, it should improve the system immunity to RSU failure.

4.1 State-of-The-art

As vehicular network applications range from emergency operations (e.g., collision avoidance, natural disaster, terrorist attack, etc.) to e-mail and voice over IP, different types of assistance from the infrastructure (i.e., RSUs) will be requested. In a vehicular environment, the communication-based automotive applications span both the V2V and V2I communication modes.

The basic idea behind utilizing RSUs is that they act as fixed reliable nodes. Fixed nodes allow for more robust communication with less administrative overhead compared to the case where both communicating ends are mobile. In addition, RSUs could be connected through high bandwidth, low delay, and low bit-error rate backbone links in order to relay packets to distant vehicles. A number of studies indicate the superiority of the RSU-assisted routing protocols upon the others in terms of their overall performance of [68][69][72][73][95].

Borsetti et al [68] investigated the benefits of using RSUs to enhance topology-aware geographic routing protocols. The authors proposed an infrastructure-based geo-routing approach utilising a modified network graph representation of the road topology, where RSUs, connected to a reliable backbone network, are merged into a unique graph node called a “backbone gate”. In [69][72][73][95], the city-wide road network is divided into smaller areas called sectors. Each sector may be served by one or more RSUs with which a vehicle may register when it passes the border of a new sector. Intra-sector communications will be performed in multi-hop fashion, and inter-sector communications will be relayed through the backward infrastructure network. These protocols differ slightly in terms of the registration process and inter-sector communications, but significantly in intra-sector communications. Note that the main goal of road network sectoring is to reduce either the space of a route discovery process - for instance in [69][72][95] - or the zone of the proactive neighbourhood location table maintenance in ROAMER [73]. In infrastructure-based routing, the vehicle chooses the nearest RSU to register or update its location regardless of the actual real-time traffic conditions on the road grid or even the capacity of this RSU to handle its demand. Furthermore, the performance of these routing protocols depends primarily on the number of the deployed RSUs, which determines the size of the corresponding sectors. Consequently, the amount of incurred overhead and latency depends on the sector size. However, deploying a large number of RSUs is undesirable mainly as a result of maintenance issues. In addition, if a sector’s RSU fails to respond (due to breakdown, congestion, or an empty RSU service area), any packet that should be relayed by this RSU will suffer from high latency unless it is dropped.

TrafRoute [69] is a reactive loose ‘‘source routing’’ protocol characterised by two key features. First, it builds a path to the intended destination only when there is a demand to route traffic to it. Secondly, it uses an efficient flooding technique where only a sub-set of vehicles close to a pre-defined set of landmarks called forwarding points (FPs) is allowed to forward packets. At each FP, vehicles continuously (in a proactive manner) run a self-election procedure to determine which sub-set of them will actually perform the forwarding process. In

TrafRoute, like others [72][73][95], if the destination is outside the source vehicle's sector, RSUs are responsible for relaying the packets. Therefore, if the destination enters a new sector, it becomes unreachable until it re-registers to the new corresponding RSU. Otherwise, it will be not able to receive a packet from a distant vehicle. From the above observations, there is a need for a more service-aware unicast routing that suits both V2V and V2I communications [92][93][94]. In this chapter, we present FRHR in which, firstly, each vehicle on the road proactively maintains a routing table that includes fresh routes towards the nearest RSUs, whilst searching for target nearby vehicles using a controlled flooding mechanism. Secondly, a vehicle re-registers in a new sector if it finds that it connected with a lower delay route to the new sector's RSU. These features make FRHR more robust, fast, and reliable in the face of real-time traffic conditions and RSU failures.

4.2 The proposed Protocol FRHR

The FRHR routing protocol exploits the fact that most unicast data traffic will pass through the RSUs. Since, in general, vehicles demand connections to RSUs at higher recurrence rates than directly to other vehicles, maintaining fresh routes to nearby RSUs is more important. FRHR, therefore, aims to enable vehicles proactively to build and maintain routing table entries for RSUs while searching for other vehicles only on-demand.

The FRHR protocol includes the following functional procedures: *Forwarder Self-election; Registration and Localization; Route Discovery and Maintenance*. An adequate number of RSUs are distributed in the road topology network, starting from the periphery of a city towards the centre. Each RSU has a unique ID (R_k), and all are fully connected by a wired/wireless network. Each RSU in FRHR is responsible for sending a periodic beacon called a *service advertisement message* which is multi-hop broadcast, gathering routing information on each hop. Upon receiving these advertisements, vehicles determine fresh routes to RSUs, helping them continuously find the best candidate, called the *corresponding RSU*, to register with. In addition, vehicles also update their locations, if they find a new robust route to their corresponding RSU; hence RSUs also determine fresh routes towards their registered vehicles. Vehicles do not only build tables of routes to nearest RSUs, but also RSUs maintain lists of their currently registered vehicles including the entire route towards them. For the sake of sending packets to remote vehicles, the RSUs maintain, via the backbone network, a shared Distributed Hash Table (DHT) indexing the vehicle associations as discussed in [69]. Therefore, each packet that is relayed via the infrastructure will be re-routed to the RSU to which the destination is currently registered, i.e. the destination's corresponding RSU. The prevalence of the beacons on the road topology will determine the actual RSUs' extended service areas rather than using fixed sectors. Using such beacons will help in improving the overall system performance in terms of the average latency where, for a big portion of data packets generated in the network, the routes already exist and are generally more reliable and stable because of RSUs since one of the endpoints is a fixed node.

In contrast, a vehicle builds routes towards adjacent vehicles using a reactive route discovery process. When a vehicle has a packet to send to the internet or its corresponding RSU, it just picks up a fresh path from the routing table and start unicasting the packet towards its corresponding RSU. If no route exists in the table, the source vehicle initiates the routing discovery process by broadcasting a route request packet (RREQ) across the corresponding RSU's service area. If the destination vehicle receives the RREQ packet, it will reply with a route reply packet (RREP); otherwise, the corresponding RSU, upon receiving the RREQ, determines the destination vehicle's location and its corresponding target RSU via a DHT index. The corresponding RSU of the source, therefore, sends the RREQ to that of the target. If the target RSU has a fresh route towards the destination, it will reply with RREP directly; otherwise, it re-broadcasts the RREQ packet on its service area.

Although FRHR tries to consume system bandwidth wisely, taking into account the nature of potential applications and the vehicular environment, broadcasting such control messages may lead to a broadcast storm scenario. To avoid this, FRHR follows the efficient forwarder self-election process used in RTBP, as discussed in section 3.2.1. It limits the set of vehicles that act as forwarders to ones located in the proximity of a predefined set of locations called *forwarding points* (FPs). For this purpose, at all times, vehicles proactively perform a self-election procedure based on their distance to FPs. We assume a small set of FPs is strategically chosen mainly at the road intersections and the resulting route built by FRHR is a sequence of FP IDs that need to be traversed in order to reach the destination. Thus, each vehicle on an FRHR network has a unique ID (V_m) and is equipped with both a positioning system (GPS) to determine its distance from the nearest FPs and a digital map which includes certain FPs attributes.

Whenever the source vehicle receives an RREP packet, the route discovery phase is over and the route maintenance phase begins. FRHR checks the validity of the route during ongoing data transfer. If the source vehicle recognizes that the path is no longer valid, it drops it and initiates a new route discovery process. This exploits current traffic conditions effectively and provides a more robust path. In the next section, we will explain in depth the FRHR's functional processes.

4.3 The operations of FRHR

The main difference between FRHR and other infrastructure-based routing protocols is that FRHR enables vehicles to track paths towards RSUs proactively and so they can send packets to RSUs quickly. Similarly, it enables RSUs to maintain routes to their registered vehicles. Hence, the data transfer between vehicles and RSUs are performed in a proactive fashion. The registration and localization procedures, however, are completely new and the route discovery scheme is modified to reap the benefits of maintaining proactive routing tables. In what follows, we describe the FRHR in detail.

4.3.1 Forwarder self-election process

In an urban scenario, most of the road intersections/junctions (with/without traffic lights) are within radio range of each other as it is highly likely that the intersections are less than 300m apart. A vehicle at the centre of a given intersection typically has a Line of Sight (LoS) to vehicles at neighbouring intersections. Furthermore, it is known that vehicles tend to create dense clusters at traffic lights. FRHR therefore limits the vehicles that act as forwarders to ones which are very close to the centre of each road junction, to control the number of forwarding nodes whilst maintaining the overall connectivity of the network. In a highway or suburban scenario, a road may need several hops to traverse, thus requiring the placement of additional FPs. Each vehicle, therefore, must know in advance attributes of all FPs in the road network at any given time. These attributes include ID, geographic coordinate, IDs of neighbouring FPs, and the width of all road lanes joined to this FP. The FP attributes could be contained in the preloaded digital map. For more details, reader can refer to section 3.2.1.

4.3.2 Registration and Localization Processes

The assumption of dividing the city-wide network into fixed sectors (RSUs' extended service areas) is relaxed. In [69][72][73][95], the road map is divided into fixed sectors, each sector is served by single RSU. if the sector's RSU fails (due to breakdown, congestion, or an empty RSU coverage area) or even if there is no suitable path, a vehicle that enters the service area of the failed RSU will not be able to re-register or receive packets intended for it until the problem is resolved. A vehicle, therefore, does not re-register when it enters a new sector. Instead, each vehicle is allowed to select a proper RSU according to the real situation on the road. It is enabled to keep eavesdropping on periodic multi-hop broadcast beacons from RSUs in its vicinity, and then selects one as a corresponding RSU to which it has a relatively reliable, stable, and minimum delay route. This will not only help vehicles to remain connected in a sparse network, or even in the event of corresponding RSU breakdown, but will also improve congestion and the balanced distribution of vehicles among neighbouring RSUs in dense networks. Hence, a service advertisement mechanism is adopted in the registration and localization processes.

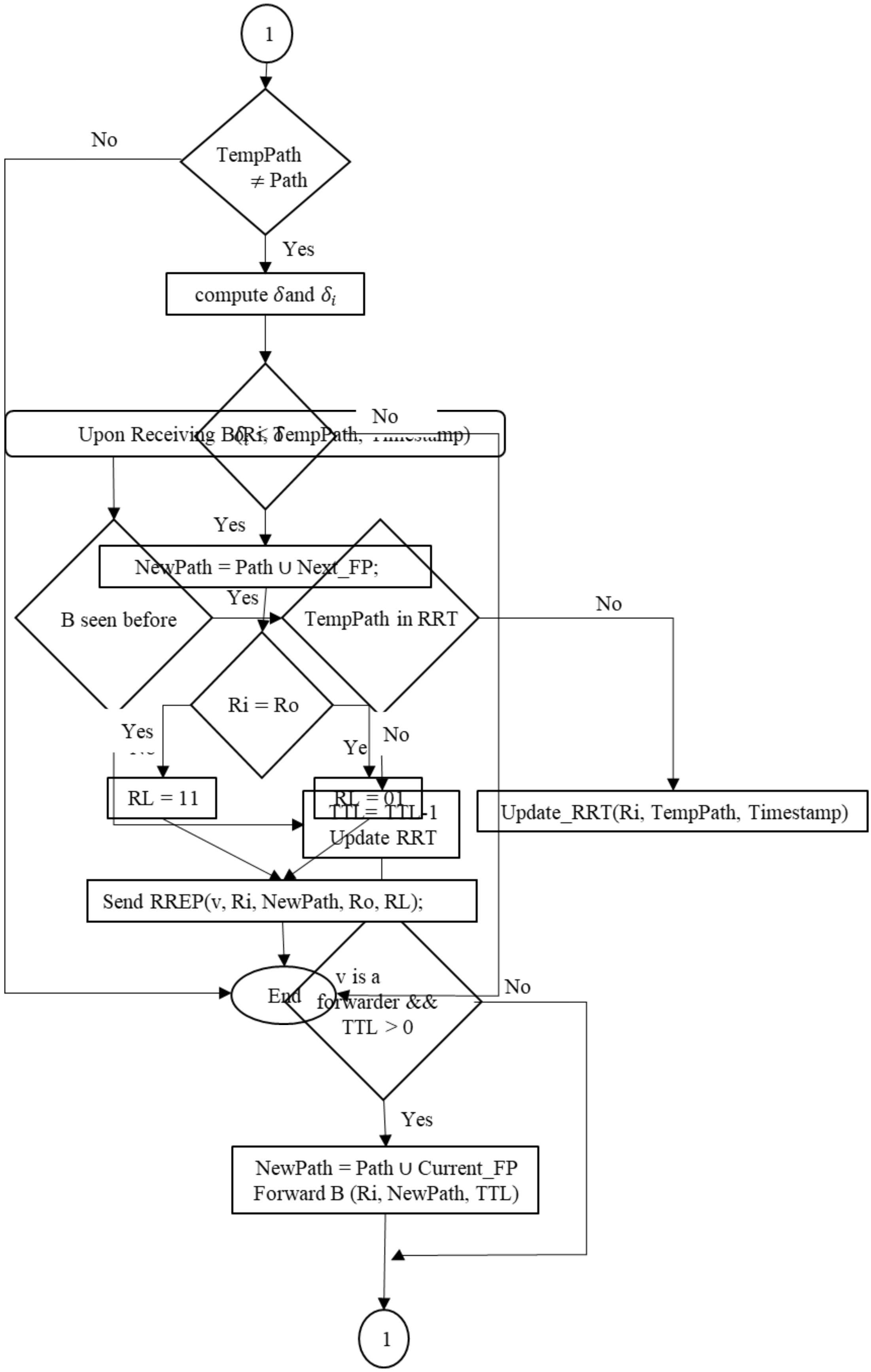
Each RSU advertises its services by broadcasting a beacon message every T_b seconds. Each such beacon includes the RSU's ID, sequence number, SEQ, time to live, TTL, timestamp, T_s, and $PATH$. The TTL field indicates the beacon's hop limit. $PATH$ is the sequence of IDs of the FPs along the beacon propagation path. Only self-elected forwarders are allowed to rebroadcast beacons and then only once. The beacon forwarder will add the FP's ID to PATH and decrease the TTL. T_s indicates the time when the beacon is transmitted. Upon receiving beacons from distinct RSUs, each vehicle proactively maintains fresh routes towards these RSUs along with their delay, T_d, where $T_d = \ Current\ Time - T_s$. If a vehicle finds that it has a lower delay route to a new RSU than to an old one, it re-registers with the former and starts updating its location. To avoid the Ping-Pong effect, a vehicle does not immediately re-register with a new RSU. Instead, each vehicle, upon receiving few distinct beacons from different RSUs, calculates the delay changing rate δ_i of the routes towards each RSU_i over a specific period of time T_r:

$$\delta_i = \frac{\sum_{n=1}^{K} T_d^n}{K},\ given\ that\ \ K \geq \left\lceil 0.5\,\frac{T_r}{T_b} \right\rceil \tag{4.1}$$

Where K indicates the number of received beacons during T_r. T_d^n refers to the time delay upon received beacon from RSU_n. If a vehicle finds that an RSU has δ_i less than the previous one and receives at least $\lceil 0.5\, T_r/T_b \rceil$ distinct beacons during T_r, it re-registers with the new RSU using a modified RREP packet.

Table 4.1: Registration and localization processes pseudocode in FRHR

Phase 1: Registration and localization process in FRHR at vehicle v
Notation:
v: ID of the current vehicle.
Ro, Ri: IDs of the corresponding RSU and the RSU source of the beacon packet.
B: Beacon packet.
RREP: Route Reply packet
RU: Route Update packet to inform old RSU about the new Ro
RRT, VRT: RSUs route table and vehicles route table
Path: the path to the corresponding RSU.
TempPath: path in the received beacon B.
RL: two bits field in RREP (00: Regular, 01: Register, 11: Update)
δ, δ_i: Delay changing rate of Path and the i^{th} route in RRT.
Upon Receiving B(Ri, TempPath, Timestamp)
if (B seen before) **Then**
  if (TempPath not in RRT)
  Update_RRT(Ri, TempPath, Timestamp);
  end if
else
  Update RRT;
  TTL= TTL-1;
  if (v is a forwarder && TTL > 0) **Then**
  NewPath= Path ∪ Current_FP;
  Forward B(Ri, NewPath, TTL);
  end if
  if (TempPath != Path) **Then**
  compute $\delta$and δ_i
  if (δ_i < δ) **Then**
  NewPath= Path ∪ Next_FP;
  if (Ri != Ro) **Then** RL = 01; **else** RL = 11; **end if**
  Send RREP(v, Ri, NewPath, Ro, RL);
  end if
end if
Routine Update _RRT(Ri, TempPath, Timestamp)
$T_d = Current\ Time - Timestamp$;
if (TempPath not in RRT) **Then**
  Store(Ri, TempPath, { $T_d, Timestamp$ })
else // TempPath exists
  Store_tuple {$T_d, Timestamp$};
  Delete_tuple {$T_d, Timestamp$};
// If $Curren\ Time - Timestamp_n > T_r$
end if
Upon Receiving RREP(v, Ri, NewPath, Ro, RL) at RSU Ri
if (RL == 11) **Then**
  Update VRT (v, NewPath)
else if (RL ==01)
  Update VRT(v, NewPath)
  Send RU(old_Ro, Ro, v) // to inform the old Ro
end if


1
TempPath ≠ Path
No
Yes
compute δ and δ_i
Upon Receiving B(Ri, TempPath, Timestamp)
No
Yes
NewPath = Path ∪ Next_FP;
B seen before
Yes
TempPath in RRT
No
Ri = Ro
Yes
No
RL = 11
RL = 01
TTL = TTL-1
Update RRT
Update_RRT(Ri, TempPath, Timestamp)
Send RREP(v, Ri, NewPath, Ro, RL);
End
v is a forwarder && TTL > 0
No
Yes
NewPath = Path ∪ Current_FP
Forward B (Ri, NewPath, TTL)
1

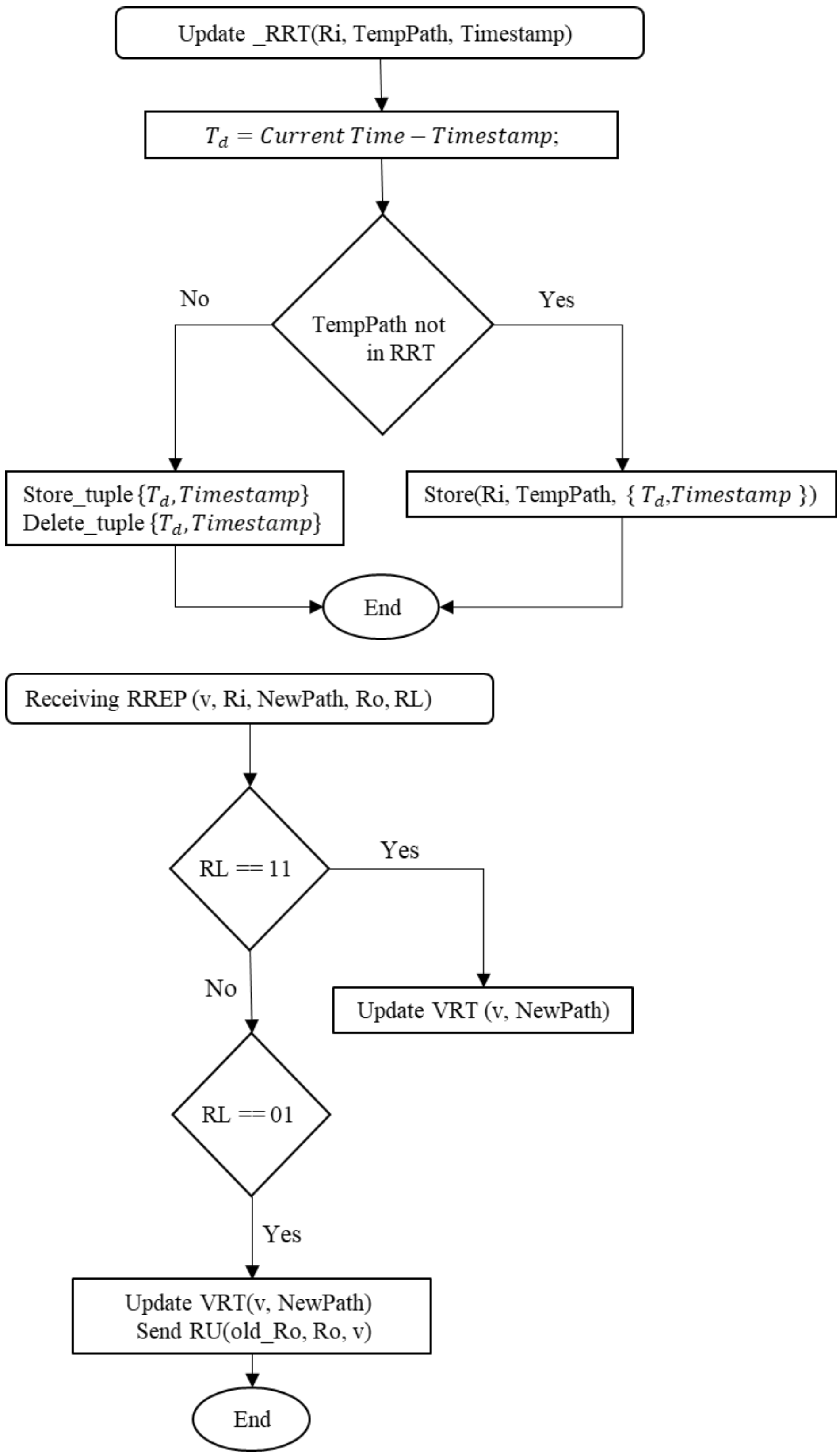


Figure 4.1: Registration and localization process program flow chart in FRHR

To update its location, when a vehicle either finds a new robust minimum delay route to its corresponding RSU or has no forwarder in its neighbourhood table for the last FP in the previous route (i.e. it is no longer connected to this FP), it waits for a new beacon from its registered RSU and then unicasts the modified RREP packet. It is important to note that the destination is required to add the next intended FP to the route in its RREP packet as well. This process does not produce significant overhead because it is adaptive to the level of vehicle mobility on the road, whilst it speeds up the connection to the infrastructure. RSUs maintain a list of registered vehicles with the entire route towards them, implying that a vehicle has a virtual location between the last two FPs in the route, or at least it is still reachable through one of the last two FPs in the route.

In other words, a vehicle location here refers to its own reachable FPs instead of its own geographic coordinate. The difference between registration and localization is that the new RSU will inform the old RSU about the registration request in the registration process, where the registration request packet includes the old RSU's ID. Therefore, the old RSU, in turn, can delete a vehicle from its location table. The Registration and localization processes detailed in table 4.1 and figure 4.1.

Referring to section 2.2.10, The runtime and overhead complexities of the Registration and localization processes is highly dependent on the number of intersections which is constrained by the RSU extended service. The size of an RSU extended service is controlled by the beacon's hop limit, i.e., TTL. Although TTL value is set to a fixed value, it is worthy to find a technique to adapt its value according to the real situation on the city. This is applicable to the beacon interval, T_b, as well. As long as, CAM interval is fixed by the standard, using large T_b value will reduce the total overhead. But this may lead to frequent route breakage due to low real-time information accuracy.

4.3.3 Route Discovery

As the registration and localization processes guarantee that all vehicles register and update their locations (entire routes) in RSUs, the route discovery process is modified to reap the benefits of maintaining proactive routing. Vehicles keep and maintain fresh routes towards RSUs using beacons, whereas RSUs record entire continuously updated routes towards registered vehicles. Indeed, reducing reactivity, in favour of proactivity, will improve performance as long as most of data traffic passes through RSUs. When a vehicle has a packet to send, there are two scenarios 1) the destination is on the internet or its corresponding RSU, 2) the destination is a vehicle. In the first scenario, the vehicle picks up a fresh route from the RSU list and starts to unicast the packet to the RSU. It is possible that a source vehicle will receive new beacons from an RSU during the on-going session. In that case, the source may utilize a new route if the new route has lower latency or the current one is broken. This scenario also applies if the source is an RSU that includes the registered vehicle destination.

In the second scenario, a source vehicle computes a maximum delay $\mathrm{T_d^{max}}$ towards the corresponding RSU. $\mathrm{T_d^{max}}$ is the maximum beacon delay during each $\mathrm{T_r}$. Afterwards it broadcasts a RREQ message with a time-to-live outside $\mathrm{TTL_O}$, where $\mathrm{TTL_O} = \mathrm{T_d^{max}} + \mathrm{T_d^{margin}}$. An RREQ message is modified to include a time-to-live outside ($\mathrm{TTL_O}$) the RSU's extended service area. When the RREQ packet reaches an FP, vehicles are allowed to forward the packet, only if they are self-elected forwarders and they have not sent the same RREQ before. Further, if the forwarders are registered with the same RSU, they just re-broadcast the RREQ. On the other hand, if the forwarders belong to another RSU, they are allowed to re-broadcast the RREQ if $\mathrm{TTL_O} \leq \mathrm{Current\ Time} - \mathrm{T_s}$. This approach ensures that vehicles registered with a neighbouring RSU, which is much closer to the source vehicle than the existing correspondent, can receive a copy of the RREQ packet via an entirely ad hoc multi-hop communication pattern along with a mixed communication mode. Afterwards, the destination vehicle can select the minimum-delay route coming on the first received RREQ. Perhaps T_d^{margin} is adaptively selected according to a prior knowledge about the destination location; however, for the sake of simplicity, we put $T_d^{margin} = 0.5\ T_d^{max}$ ($TTL_O = 1.5\ T_d^{max}$). If the source's RSU receives the RREQ and recognizes that the destination belongs to another RSU, it will forward the packet to the destination RSU; otherwise, the source's RSU discards the packet. If the destination RSU has a fresh route towards the destination, it will reply with RREP directly; otherwise, it re-broadcasts the RREQ packet on its service area. Once the destination vehicle receives an RREQ, it computes the next intended FP according to its own current trajectory and velocity vector. It then also appends this next intended FP to the inverse FP sequence in the RREQ, if the next intended FP is not included. Afterwards it issues the RREP packet and it sends the packet back to the source vehicle using unicast. If the source vehicle does not receive the RREP packet after a timeout period, a new route discovery is initiated. Upon receiving RREP, the source starts sending the data packets after adding a small header containing the reverse FP sequence contained in RREP to each one. At each unicast packet forwarding step, the self-elected forwarder on the next FP with highest penetration index is selected as a next hop forwarder. During an on-going session, FRHR, like TrafRoute, checks the validity of the route. The source vehicle periodically issues a Route Check (RCHECK) packet along the path. Then, the destination vehicle will reply with a RCHECK reply packet. Adding the next FP to a FP sequence is also applied to the RRCHEK packet and its reply packet. This should keep the control overhead as low as possible and reduce data packet loss rate.

4.4 Performance Evaluation

4.4.1 Experiments Setup

This section presents the evaluation of FRHR against the TrafRoute (as a representative infrastructure-based routing protocol) under simulated urban conditions. We mainly focus on the FRHR capacity to relay packets among vehicles. The simulations were conducted using ns2 software (version 2.34 with the IEEE 802.11p and Nakagami propagation model). A 1.2 km^2 street grid layout is used to generate the node movement file via the VanetMobiSim mobility simulator. We use the default wireless configuration settings in nominal standards where the wireless bandwidth and the communication range of vehicles and RSUs were set to 6 Mbps and 400 m respectively [96][97]. We randomly select a source vehicle and a destination vehicle from the input vehicles and each vehicle generates a message every 60 seconds. The destination is selected randomly and it could be at any location on the map.. The main aim is to investigate the benefit of using the localization and registration processes as well as the RSUs as trusted relayers that most data are forwarded through them, low vehicle density scenarios are preferred and used in each experiment. According to ETSI standards, the retransmission interval for the CAM beacon is set to 0.5 seconds. Due to the low average speed of vehicles in cities and the low expected number of hops in routing paths, we have set the advertisement beacon interval to 2 seconds and the re-registration interval to 10 seconds. It would be beneficial to examine and optimize these values based on the actual situation on the road network. The other parameters were adopted from [69] as shown in table 4.2.

Table 4.2: Simulation Setup

Simulation area	1200m × 1200m
Simulation time	1000s
Number of RSUs	3 , 5
Number of vehicles	30 ~ 180
Vehicle speed	10 ~ 20 m/s
Transmission Range	400m
CBR rate	1 Pkt/m

Data packet size	512 bytes
CAM Interval	0.5 s
Beacon Interval T_b	2 s
Re-registration interval T_r	10 s

The performance metrics are:

a) **Packet Delivery Ratio (PDR):** is the number of data packets that were successfully delivered at destinations divided number of data packets that were sent by the source vehicle.

b) **Average End-to-End delay**: which is the delay elapsed between packet generation at the source and successful reception at the destination, and

c) **Routing overhead ratio**: is the total number of control bytes sent for each data byte that is successfully delivered.

4.4.2 The effect of the registration and Localization process

Packet Delivery Ratio: Fig. 4.2 shows that FRHR outperforms TrafRoute particularly in sparse networks. This result is due to the more rapid response of vehicles to changes in network connectivity. A vehicle re-registers with an RSU to which it has a connected path rather than maintaining its association to a disconnected RSU. Therefore, it is expected that increasing the number of vehicles and /or RSUs results in promoting the overall network connectivity, while reducing the effect of the registration process. As seen in Fig 4.2, the performance of FRHR converges to that of the TrafRoute in the dense network when five RSUs are deployed.

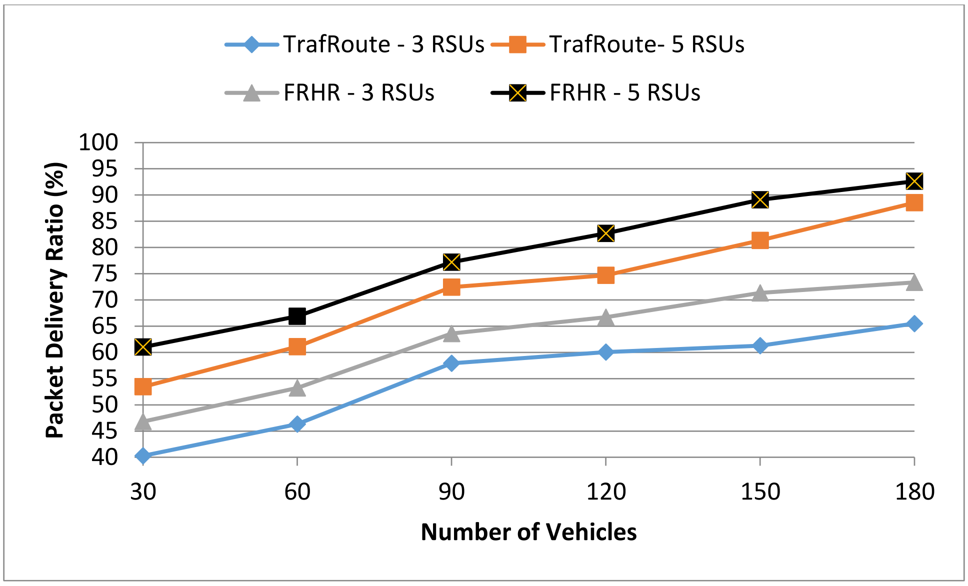


Figure 4.2: Packet Delivery Ratio versus Number of Vehicles using 3 and 5 RSUs.

Average E2E delay: Fig 4.3 shows that FRHR performs better than the TrafRoute protocol. As long as each source-destination pair is composed of vehicles at random distances from each other, enough data traffic will pass through RSUs towards these vehicles. The destination RSU can send packets intended for a registered destination directly, where paths among vehicles and RSUs are built in proactive fashion. Consequently, the route setup time is apparently reduced. The performance of FRHR when deploying three RSUs is improved, i.e., it approaches the performance of TrafRoute using five RSUs. This implies that if two RSUs fail the system is still capable of providing fast unicast connectivity.

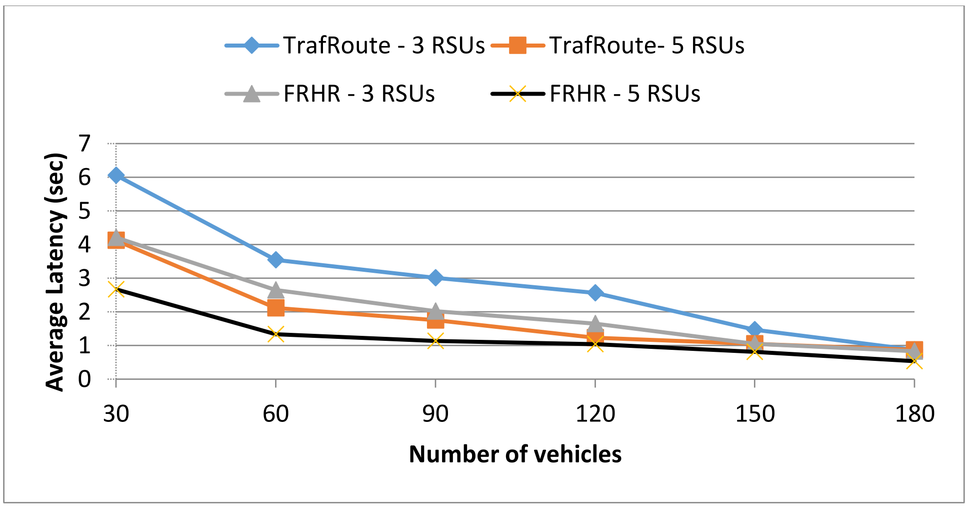


Figure 4.3: End-to-End Latency versus Number of Vehicles using 3 and 5 RSUs.

Routing Overhead: To study the amount of incurred overhead, it is worth indicating that the beacon interval strongly depends on road layout and vehicle traffic properties. For the sake of simplicity, we set the beacon interval and its TTL to 2 Hz and 8 Hz, respectively which demonstrate a good performance in all scenarios. We choose a map containing relatively long streets with average length of 120 m and arranged mostly in a Manhattan-grid style. In Fig. 4.4, we can observe that the overhead ratio is almost settled in the case of using TrafRoute in dense networks. This result is due to the fact that even if the vehicle density is increased only a subset of vehicles in the proximity of FPs is allowed to forward packets. In other words, the number of forwarded packets depends on the number of FPs in the road grid layout rather than the number of vehicles. Although beacons are periodically propagated in the RSUs' vicinity, these do not produce a lot of overhead because of the adopted efficient flooding mechanism. In addition, a vehicle uses a unicast connection to re-register or update its location when it finds a new route to an RSU. In general, FRHR produces slightly more overhead, but showing good improvement in term of higher Packet delivery ration and lower latency

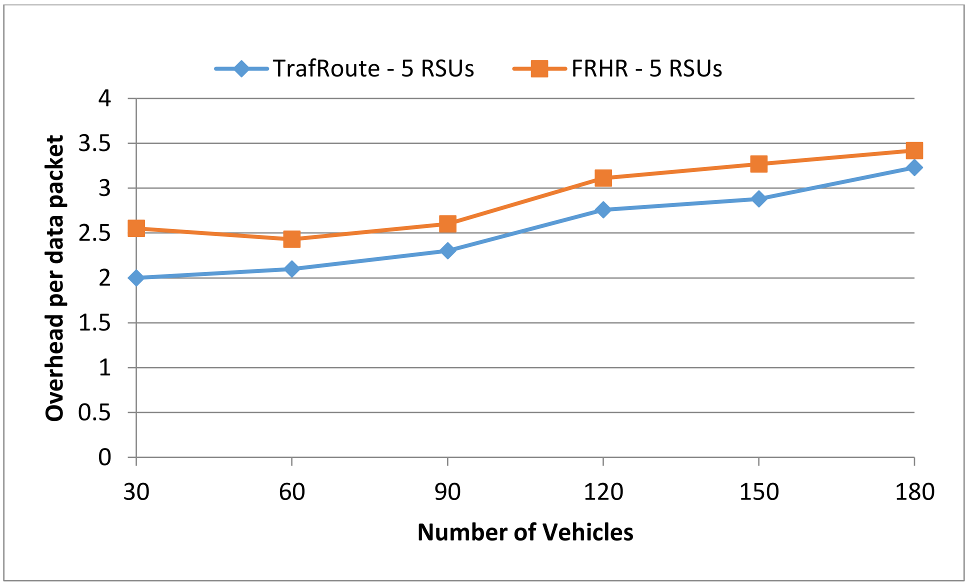


Figure 4.4: Overhead versus Number of Vehicles using 3 and 5 RSUs.

4.4.3 The Routing Protocols Comparison

Addition to the TrafRoute, two other representative routing protocols are selected to compare their performance against FRHR. First protocol is *Road Based (using) Vehicular Traffic* RBVT-R [55] which is a reactive routing protocol designed for VANET urban scenarios. RBVT-R combines geographic forwarding and route discovery. It reactively creates source routes of successive intersections that have a high probability of network connectivity among them. It is beaconless and has no need for location service. It, otherwise, floods the whole network to find a destination.

The second protocol is Infrastructure-assisted geographic routing protocol IGSR [68] which utilizes a new graph representation, referred as network graph. Road map graph is represented by a network graph which contains of anchor points and a backbone gate connected by weighted edges. Since RSUs are interconnected by high wireline network is considered single node called a backbone gate while anchor points represent intersections and edges represent streets. The route is computed by calculating the Dijkstra shortest path between the source and the destination using traditional GSR routing protocol [113].

Packet Delivery Ratio: Fig. 4.5 shows that FRHR outperforms the other routing protocols particularly in sparse networks. This result is due to the more rapid response of vehicles to changes in network connectivity. A vehicle re-registers with an RSU to which it has a connected path rather than maintaining its association to a disconnected RSU. Therefore, it is expected that increasing the number of vehicles and /or RSUs results in promoting the overall network connectivity, while reducing the effect of the registration process.

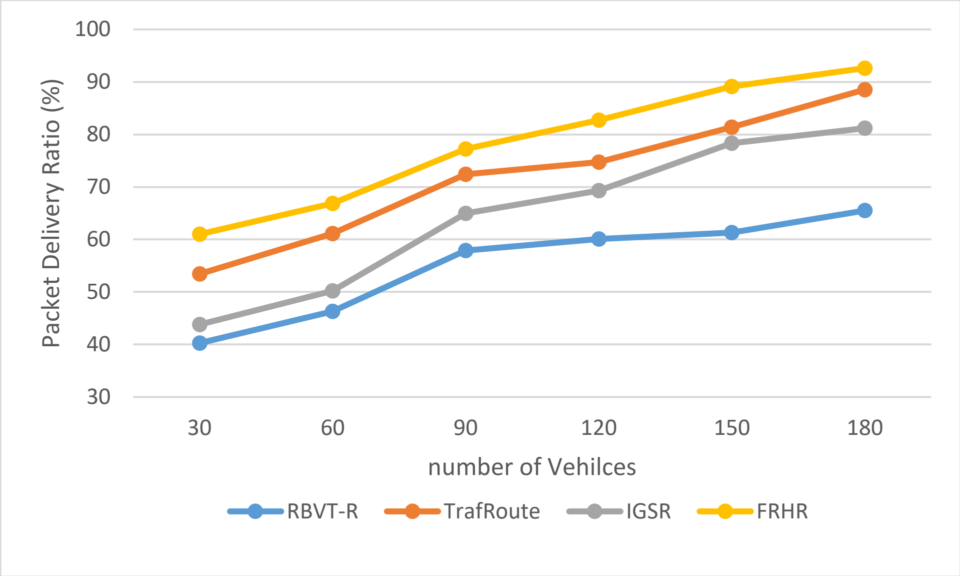


Figure 4.5: Packet Delivery Ratio comparison amongst FRHR, TrafRoute, IGSR, and RBVT-R.

Average E2E delay: Fig 4.6 shows that FRHR performs better than the other protocols. As long as each src-dist pair is composed of vehicles at random distances from each other, enough data traffic will pass through RSUs towards these vehicles. The destination' RSU can send packets intended for a registered destination directly, where paths among vehicles and RSUs are built in proactive fashion. Consequently, the route setup time is apparently reduced.

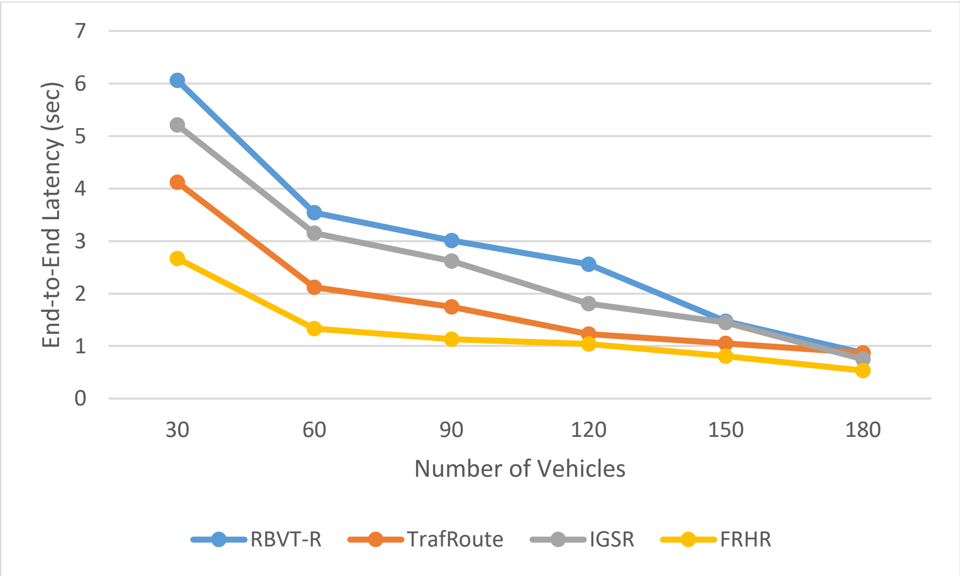


Figure 4.6: End-to-End Latency comparison amongst FRHR, TrafRoute, IGSR, and RBVT-R.

Routing Overhead: As before, we set the beacon interval and its TTL to 2 Hz and 8, respectively which demonstrate a good performance in all scenarios. Again we choose a map containing relatively long streets with average length of 120 m and arranged mostly in a Manhattan-grid style. In Fig. 4.7, we can observe that the overhead ratio is almost settled in the case of using TrafRoute in dense networks. This result is due to the fact that even if the vehicle density is increased only a subset of vehicles in the proximity of FPs is allowed to forward packets. In other words, the number of forwarded packets depends on the number of FPs in the road grid layout rather than the number of nodes. Although beacons are periodically propagated in the RSUs' vicinity, these do not produce a lot of overhead because of the adopted efficient flooding mechanism. In addition, a vehicle uses a unicast connection to re-register or update its location when it finds a new route to RSU. Although FRHR produces slightly more overhead, it presents apparent improvement in terms of the latency and the packet delivery ratio.

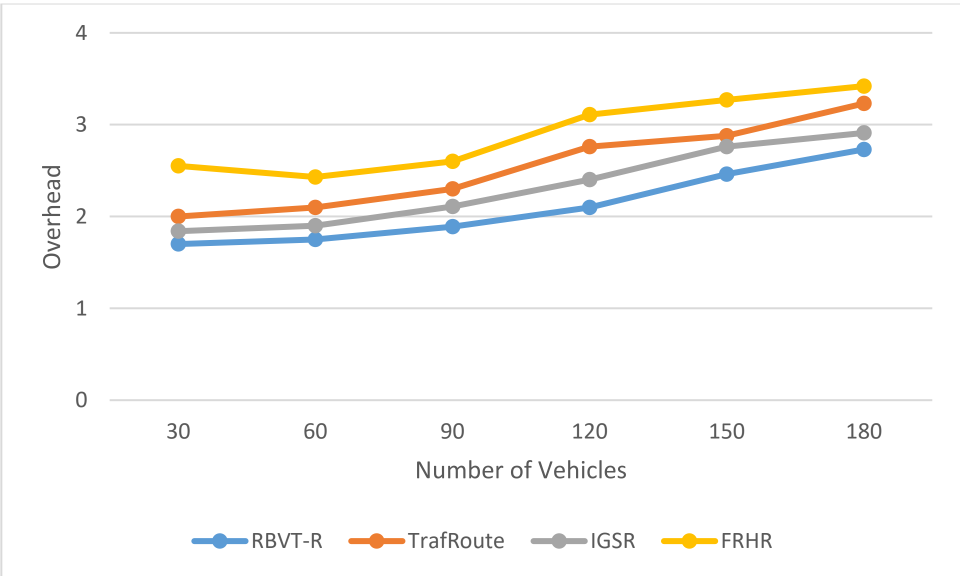


Figure 4.7: Overhead versus Number of Vehicles comparison amongst FRHR, TrafRoute, IGSR, and RBVT-R.

4.5 Conclusion

In this chapter, FRHR has been introduced as a routing protocol for fast infrastructure access that is also suited for efficient V2V communications. FRHR utilizes RSUs, connected through the wired backbone network, to act as registration servers for vehicles. In FRHR, RSUs periodically transmit beacons that are rebroadcast by vehicles after appending routing information into beacons. Upon receiving beacons, vehicles proactively maintain routing tables including routes towards nearby RSUs. Thus, a vehicle can select an RSU to register with, according to the expected delay rather than its remoteness. The route discovery process is hastened and there is no need to discover the routes from or to RSUs. The results confirm that FRHR improves end-to-end latency and enhances the reliability of the routing protocol against RSUs failure.

CHAPTER 5 : STABLE HYBRID ROUTING PROTOCOL FOR VANETS

In this chapter, the stability of the routes is discussed. A novel route selection policy is introduced to enhance the FRHR to be a stable infrastructure-based routing protocol for urban VANETs. It builds routes from highly stable connected intersections using a selection policy which uses a new intersection stability metric.

5.1 Introduction

The main difference between conventional MANETs and VANETs is that nodes in VANETs are vehicles that tend to move at higher speed levels while passing through different surroundings, leading to intermittent connectivity and consequently unstable routes. Hence, different approaches [99][100][101][102][103][104] have been introduced that aim at selecting the best intermediate nodes that prolong the route lifetime by integrating the motion prediction scheme [106][107]. For example, movement prediction routing (MOPR)[99] employs a mechanism to predict a vehicle's movement in order to create more stable connections that will reduce the number of path recovery processes needed to handle broken connections due to the topology changes. To do so, MOPR calculates the link stability metric based on the prediction of the vehicle's movements. The authors extended the AODV protocol to incorporate this feature. In a second work [107], MOPR was integrated into GPSR protocol, and thus, features a greedy geographic unicast strategy that uses the link stability concept. This is one of the first works to use the link stability idea in order to choose the best relay for unicast communications. However, MOPR, among other approaches, does not consider the urban environment where the stability problem takes us into another dimension. The vehicle's speed is the main concern in the link lifetime calculation on the highway and in rural scenarios, whereas, in urban conditions, vehicles tend to move with low to moderate speed levels. The route disconnection here is mainly due to tall buildings which restrict message propagation to crossroads. In this chapter, we discuss route stability mainly in the urban environment trying to propose new policies that may solve the problem of the frequent route disconnections.

5.2 The State-of-Art

Several attempts have focused on designing a unicast routing protocol for VANETs in order to support the QoS requirements of expected wide-range ITS applications on roads. Some of these applications, such as on-demand video downloading and shared resource accessing, can tolerate high latency, whilst real-time applications, likes emergency video streaming, imposes a restrictive delay requirement. The advantage of VANETs is that each vehicle will be equipped with positioning and navigation systems along with a wireless network interface so a routing protocol intended for VANETs can benefit from location and road layout information in building more robust routes.

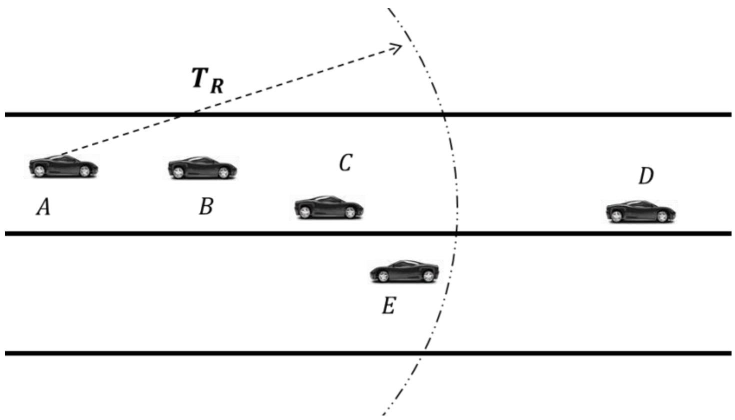


Figure 5.1: Route Stability on a highway scenario (T_R is the radio communication range).

The route stability issue has been much addressed in the literature but researchers, have largely focussed on the highway environment and the effect of the velocities of both ends of any communication links on its lifetime. Here vehicles typically move with high speed on long streets, as shown Fig. 5.1. In the diagram, Vehicle A has three choices (i.e., vehicles B, C and E) for a next hop node to send a packet to vehicle D. The question is how to choose the next forwarding vehicle to extend the link lifetime and hence reduce the packet drop ratio without requiring an excessive total number of hops. Furthermore, due to the single-direction propagation model, it is an easier to integrate the store-carry-forward mechanism for delay-tolerant applications.

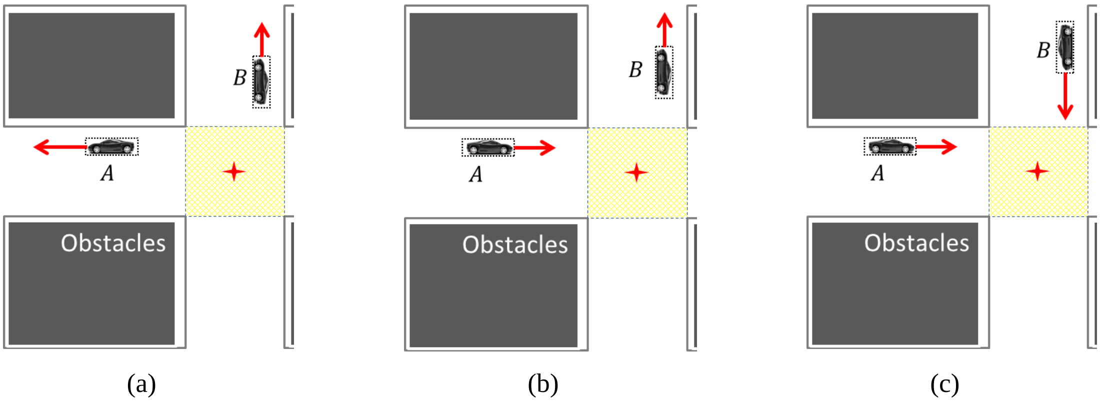


Figure 5.2: The problem of the link stability around the intersections in MAR.

In contrast, vehicles tend to slow down in the urban environment due to the shorter average roads length, the existence of traffic lights and the imposition of speed limits. The end-to-end paths may include short roads connected by crossroads with or without traffic lights. Although the city network presents more routing options, the complexity of choosing one end-to-end stable route increases. While a short straight road may be traversed using one or two hops in cities, the existence of high buildings represents the main challenge since these will limit the packet propagation only through road intersections due to the line-of-sight phenomenon. Few solutions have addressed the stability of routes on cities from different point of views. Some solutions can be classified as single-link solutions such as MOPR. The Multi-Adaptive routing protocol MAR extends the MOPR rules to include the multi-directional propagation through intersections, and the new policy has been integrated on AODV [100]. However, due the lack of the global knowledge and frequent traffic topology changing, MAR may not be considered the best option for an end-to-end stable routing. In Fig. 5.2, the red arrows show the directions of vehicles' motion. Whilst the link between vehicle A and vehicle B in (a) should be avoided due to the expected fast link failure (i.e., the obstacle will block the signals soon), the links in (b) and (c) are more stable, but the preference depends on the position of the next-hop towards the destination.

Another trend considers the stability in terms of the single-road connectivity likes Gytar[105], E-Gytar [115] and TOBOCBF[104] , the possibility of reaching neighbouring intersections is examined in a real-time manner. Although these position-based routing approaches may alleviate the local maxima problem [114], this improvement is only in terms of a single road not the entire path towards the destination as shown in Fig. 5.3. In addition, both Gytar and TOBOCBF assume the availability of an accurate destination location beforehand which means additional implied overhead. Ayaida et al [108] incorporates the movement prediction mechanism to reduce the amount of incurred overhead due to frequent location requests.

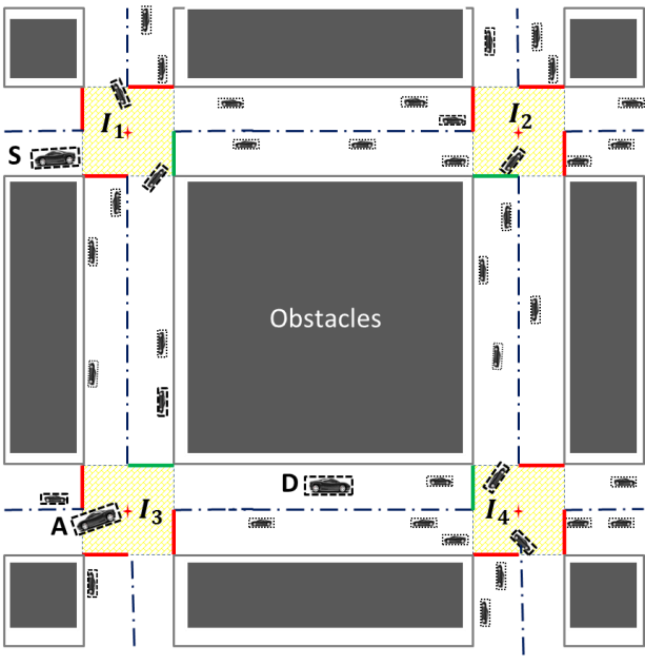


Figure 5.3: The road connectivity around the intersections.

Referring to Fig 5.3, suppose vehicle S wishes to send a message to vehicle D, Both Gytar and TOBOCBF will choose the path including $\{\boldsymbol{I_1}, \boldsymbol{I_3}\}$ intersections where $\boldsymbol{I_3}$ is closer than $\boldsymbol{I_2}$ to D. The path $\{\boldsymbol{I_1}, \boldsymbol{I_2}, \boldsymbol{I_4}\}$, however, is more connected than $\{\boldsymbol{I_1}, \boldsymbol{I_3}\}$ because the vehicle densities around both $\boldsymbol{I_2}$ and $\boldsymbol{I_4}$ are greater than that around $\boldsymbol{I_3}$ intersection.

In fact, the location discovery process utilizes the same concept of route discovery process. A location request packet is broadcast seeking the destination or a location server which in turns will respond with the destination geographic coordinate in a location reply packet. Another trend takes into account the connectivity of the entire path. RBVT-R [55] is CBF-based routing protocol that reformats the location discovery process to find the best route in terms of successive connected roads on the urban grid rather than the destination location. RBVT-R considers that the road is connected if there is a vehicle that can forward the packet to the next road using a contention-based forwarding mechanism. RBVT-R may benefit from the global knowledge about the vehicle traffic towards the destination; however, this approach, was not examined under a realistic radio propagation model that restricts the possibility of successive packet reception to vehicles that are very close to an intersection and mostly have a line of sight. Consequently, the delay and the packet drop ratio may increase at intersections as the result of choosing an inadequate next-hop neighbouring vehicle.

In Fig. 5.4, for example, the vehicles A, B and C are in the line of sight with the packet sender S, but only vehicles A and B on the predetermined route can contend to forward the packet towards the destination D. If A is chosen, the probability of reception the packet by E is low and it decreases as A moves away from the intersection, unless it, in turn, relies on B to re-forward the packet to E

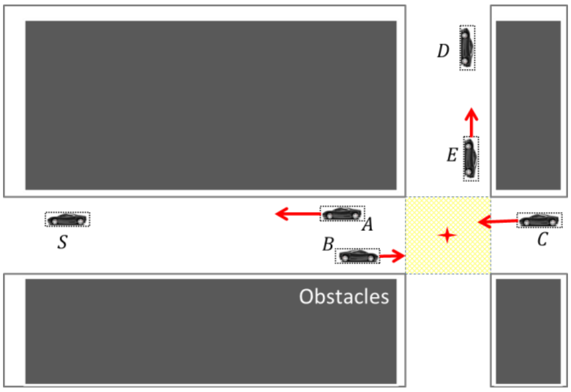


Figure 5.4: The problem of the relay selection at an intersection on RBVT-R routing protocol.

In contrast, TrafRoute searches for connected intersections rather than connected roads. It is assumed that the road length is less the maximum radio transmission range, and each intersection is in the line of sight of its neighbouring intersection. If there is at least one vehicle at two neighbouring intersections, these intersections are considered connected. TrafRoute uses a sender-centric forwarding concept where the sender is responsible for selecting one of its neighbours at the next intersection on the route, as a next-hop forwarder. In case of an temporarily low vehicle population at any intersection along the path, TrafRoute tends to reinitiate the route discovery process resulting in more delay and overhead even if there are vehicles between the intersections that could ensure the packet progress with acceptable latency.

Furthermore, when the number of vehicles increases at busy periods, long queues at intersections with traffic lights are formed. In this situation, the connectivity of these intersections increases, but data traffic congestion would get higher, and the total end-to-end latency would consequently increase. Hence, from the previous observations, we conclude that there is still a need for a stable unicast routing protocol that adapts well to continuously changing network conditions in the urban environment. When the network is sparse, it should take the road and intersection connectivity into account to maximize the chance of packet reception for delay tolerant application. On the other hand, in dense networks, the routing protocol should select a route with minimum delay among the well-connected routes without compromising the route stability. At the same time, the routing protocol should work efficiently on the highway.

The main goal here is to improve FRHR to be a QoS-aware stable routing protocol and the new derived protocol will be called *Stable Infrastructure-based Routing Protocol* (SIRP). A new route selection policy is introduced that takes into account both route stability and the required QoS, while other protocol's processes are adapted versions to that of FRHR.

5.3 The proposed protocol SIRP

SIRP aims to build routes of successive intersection IDs that need to be traversed in order to reach the destination, and it weighs each intersection's capability to forward packets using an intersection stability metric. As position-based routing, SIRP requires that each participating vehicle is equipped with both a positioning system (GPS) and a navigation system with a digital map from which it knows in advance attributes of all roads and intersections in the local road network at any given time. Intersection attributes include ID, geographic coordinates, IDs of neighbouring intersections, and the number with the width of all joined road lanes. Additionally, vehicles can localise neighbouring vehicles on road layouts.

SIRP includes two functional procedures: *Registration and Localization process* and *Route Discovery and Maintenance*. It assumes that, an adequate number of RSUs are distributed in the road topology network, over any area of interest (e.g. a city). Each RSU has a unique ID (R_k) and is fully connected by a wired/wireless network. Each is responsible for sending a periodic beacon called a *Service Advertisement* (SA) *message* which is a multi-hop broadcast after gathering routing information on each hop. Upon receiving these advertisements, each vehicle determines its *corresponding RSU*, to register with and also update its location. In this way, the size of RSU's service area is adapted according to the state of network, rather than using the fixed areas. To facilitate sending packets to remote vehicles, the RSUs maintain, via the backbone network, a shared Distributed Hash Table (DHT) indexing the vehicle associations. Therefore, each packet that is relayed via the infrastructure will be re-routed to the RSU to which the destination is currently registered. In contrast, a vehicle builds routes towards adjacent vehicles using a reactive route discovery process. In the next subsections, we explain in depth the operations of SIRP.

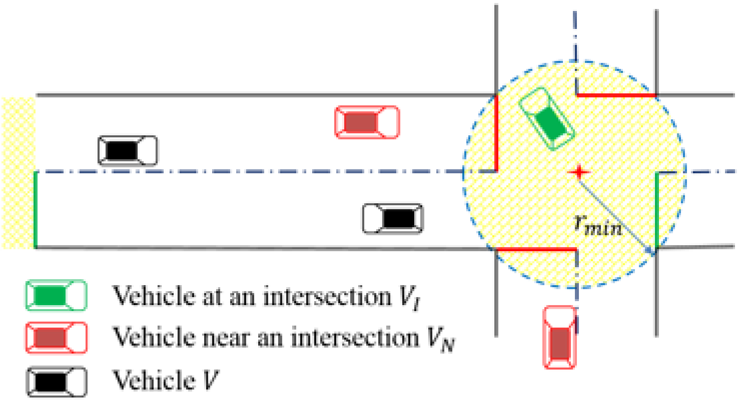


Figure 5.5: Vehicles classification in an urban scenario

5.3.1 Vehicle Classification

SIRP classifies vehicles around an intersection according to their position and moving direction to the intersection. As discussed on section 3.2.1, SIRP follows RTBP and FRHR and gives vehicles at any intersection (denoted by V_I) *the highest priority to act as packet forwarders*. At the same time, it limits the number of V_I vehicles to those close to the centre of each junction to control the number of forwarding vehicles whilst maintaining overall network connectivity. As shown in Fig. 5.5, If a vehicle finds that its distance to the closest intersection centre is less than d_{ref}, from eq 3.1, it elects itself as a member of V_I. In this way, the more vehicles around the intersection, the smaller the number of vehicles that join V_I. Note that a long or curved road may need several hops to traverse, thus requiring the placement of additional virtual intersections along its length.

If a vehicle moving towards an intersection receives CAM beacons from either vehicles already at that intersection or vehicles that are heading towards it from other streets not-inline, it considers itself as a member of the set of *near-intersection* vehicles, V_N. Vehicles not in V_N or V_I are in a third set, V. Each vehicle uses a *Status Flag* (SF), an extra two-bit field, in its own CAM packet, to inform neighbours of its current membership state: V_I, V_N, or V. Each vehicle can determine the intersection a CAM transmitting vehicle belongs to using the location and direction of velocity vector. In addition, a 3-bit field, denoted by *Penetration Index (PI)*, is appended to the CAM. With respect to a V_I vehicle, *PI* equals the number of distinct neighbouring intersections that the vehicle's transmission can reach: it has at least one V_I or V_N vehicle belonging to those intersections in its neighbours table. On the other hand, for a V_N vehicle, *PI* equals the number of intersection legs that V_N vehicle's transmission can reach: it has at least one V_N vehicle at those legs.

5.3.2 Route Selection Policy

SIRP uses a novel metric called Intersection Stability (IS) to measure the stability of source routes of successive intersections in urban scenarios. Following the example shown in Fig.5.6, we are going to describe the intersection stability concept. When V_N^B receives a CAM message from V_N^C or V_I, it declares its status and generates a new CAM message. As mentioned above, SIRP considers only vehicles that are moving towards the intersection as near-intersection vehicles in order to increase the confidence that a selected vehicle will be able to retransmit the packet through the intersection in all directions. At the same time, it will refer to the expected number of vehicles that will be in V_I in the near future. Therefore, SIRP makes near-intersection vehicles compute the size of V_I and V_N, and once inside the intersection area, they compute $m(t)$, the sum of the sizes of V_I and V_N: *this value will determine the capacity of the intersection to carry stable connections at the current time.*

Definition: *The stability, $s^i(t)$, of the multi-hop connectivity of the i^{th} intersection approximately equals the number of vehicles (V_I's and V_N's), $m^i(t)$, that can provide expected high stable connections through the intersection;*

$$s^i(t) \cong m^i(t) \quad (5.1)$$

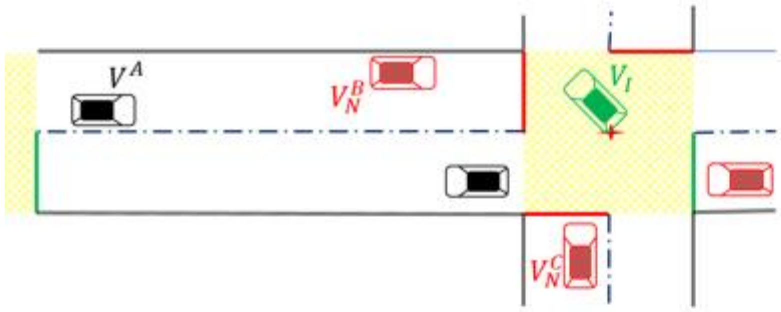


Figure 5.6: Intersection stability Example

At the time of the decision-making, $t_0 + t$, the stability, s^i, can be determined approximately as follows:

$$s^i(t_0 + t) \approx M_0^i + \int_{t_0}^{t} \frac{\partial m^i}{\partial t}\, dt \quad (5.2)$$

where M_0^i is the initial number of vehicles V_I and V_N at the generation time, t_0, of the RREQ packet. s^i can be approximated further using:

$$s^i \approx M_0^i + \rho^i\, t \quad (5.3)$$

where ρ refers to the average expected value of M changing rate which takes into account the short-term variation in M incurred by changes in status of neighbouring vehicles around the intersection area.

By using the Round-Trip Time (RTT), the destination determines approximately the expected s^i at the time of reception at the i^{th} intersection, $s^i \approx M_0^i + \rho^i\, RTT^j$. This value will refer to the expected intersection stability. As long as $s^i > 0$, the intersection will be still able to forward transmitted packets. To select the most stable route, a naïve approach is to select the route with the maximum value of the minimum intersection stability along the route. When a vehicle has a packet to send to another vehicle, it initiates the route discovery process by broadcasting a RREQ message. Upon reception of a RREQ, each intermediate vehicle checks its status. If it is a V_I vehicle, it will append M_0^i and ρ^i for the out-going intersection 'i' along the route. The stability of route 'j' denoted by S^j , can be computed as follows:

$$S^j = \min_{\forall\, intersection\, i \in route\, j} s^i \qquad (5.4)$$

Upon reception of multiple RREQs, the destination may select a best candidate route 'k' from the candidate route set "U" according to:

$$route\ k = \max_{\forall\, route\, j \in U} S^j \qquad (5.5)$$

Using the aforementioned policy leads to two issues: (a) in a dense network, the highest stability route will be the route with the maximum congestion level; and (b), during the validation experiments, we found that the probability of the route breaking increases with the number of unstable intersections along the route. Consequently, the route set is divided into two subsets: U^1 includes highly stable routes; and U^2 containing the other routes sorted according to the existence of multiple unstable intersections. Therefore, we improve route selection policy as follows:

$$route\ k = \begin{cases} \min_{route\, j \in U^1} TT^j, & U^1 \neq \emptyset \\ \min_{route\, j \in U^2} UI^j, & otherwise \end{cases} \qquad (5.6)$$

Where TT is the packet trip time, which is the duration time between the generation time of the RREQ packet and the reception time of the RREQ at the destination, and UI is the number of the unstable intersections in the route. By receiving multiple RREQs, the destination will employ this route selection policy to select the proper route according to the real-time network situation: either the minimum-delay and lowest-congested route in a dense network, or the most stable route in a sparse network. Even if the stability of the intersection is zero at the RREP reception time, the intersection may be still able to forward the packets by vehicles that for instance, have just left the intersection area.

5.3.3 Registration and Localization Processes

In SIRP, each vehicle is allowed to select a suitable RSU according to the actual situation on the road. The assumption of dividing the city-wide network into *fixed* sectors (RSUs' extended service areas) is relaxed. In [7][8][9], if a sector's RSU fails (due to breakdown, congestion, or an empty RSU coverage area) or even if there is no suitable path, a vehicle that enters the service area of the failed RSU will not be able to re-register or receive packets intended for it until the problem is resolved. In SIRP, a vehicle is able to keep eavesdropping on periodic multi-hop broadcast beacons from RSUs in its vicinity, and can then select one as a corresponding RSU to which it has a relatively reliable, stable, and minimum-delay route. This will not only help vehicles to remain connected in a sparse network, but will also mitigate congestion and balance the vehicle distribution among neighbouring RSUs in dense networks. Hence, a service advertisement mechanism is adopted in the registration and localization processes.

Each RSU advertises its services by broadcasting a SA beacon message every T_b seconds. Each such beacon includes the RSU's ID, sequence number, time to live (TTL), timestamp (T_s), and $PATH$. The TTL field indicates the beacon's hop limit. T_s indicates the time at which the SA beacon is generated. $PATH$ is the sequence of $< i, M_0^i, \rho^i >$ tuples of each intersection i along the beacon propagation path. Each beacon forwarder will add its intersection's tuple to PATH and decrease the TTL. Note that, only V_I vehicles are allowed to broadcast the SA beacon to limit the amount of overhead while selecting more stable routes.

Upon receiving beacons from distinct RSUs, each vehicle, after selecting the most stable route to each RSU, proactively maintains a fresh route towards each RSU along with the beacon trip time delay, T_d, where $T_d = Current\,Time - T_s$. If a vehicle finds that it has a lower-delay stable route to a new RSU than to an old one, it considers re-registering with the latter and updating its location. To avoid a ping-pong effect, however, it does not do this immediately: instead, upon receiving few distinct beacons from different RSUs, it calculates the delay changing rate δ_i of the routes towards each RSU_i over a specific period of time T_r:

$$\delta_i = \frac{\sum_{n=1}^{K} T_d^n}{K},\ given\ that\ \ K \geq \left\lceil 0.5\,\frac{T_r}{T_b} \right\rceil \tag{5.7}$$

where K indicates the number of received beacons during T_r. If it finds that a new candidate RSU has δ_i less than the current one and receives at least $\lceil 0.5\,T_r/T_b \rceil$ distinct beacons during T_r, it re-registers with the new RSU using a modified RREP packet.

To update its location, when a vehicle either finds a new robust minimum delay route to its corresponding RSU after T_r or has no candidate forwarder in its neighbours table towards the last intersection in the previous route (i.e., it is no longer connected to this intersection), it waits for a new SA beacon from its registered RSU and then unicasts the modified RREP packet. It is worth noting that the destination is required to add the next intended intersection to the route in its RREP packet as well. This process does not produce significant overhead because it is adaptive to the level of vehicle mobility on the road, while it speeds up the connection to the infrastructure. RSUs maintain a list of registered vehicles with the entire route towards them, implying that a vehicle has a virtual location between the last two intersections in the route, or at least it is still reachable through one of the last two intersections in the route. In other words, a vehicle location here refers to its own reachable intersections instead of its own geographic coordinates. The difference between registration and localization is that the new RSU will inform the old RSU about the registration request in the registration process, where the registration request packet includes the old RSU’s ID. Therefore, the old RSU can in turn delete a vehicle from its location table. Note that, as long as a vehicle finds a proper route of successive intersections towards an RSU, this implies that other vehicles along this path will choose the same RSU for registration. In this way, the RSU's extended service area is constructed by all vehicles which registered with that RSU, and this area is adaptive to the current network conditions. The registration and localization process flow chart is depicted in Fig. 4.1.

The difference between Registration and localization processes in SIRP and FRHR is the usage of different route selection metric otherwise they show similar runtime and overhead complexities as mentioned on section 4.3.2.

5.3.4 Route Discovery

Since the registration and localization processes guarantee that all vehicles register and update their locations (entire routes) with RSUs, the route discovery process is modified to reap the benefits of maintaining proactive routing. Vehicles keep and maintain fresh routes towards RSUs using beacons, whereas RSUs record complete continuously updated routes towards registered vehicles. Indeed, reducing reactivity in favour of proactivity will improve performance as long as most data traffic passes through RSUs. When a vehicle has a packet to send, there are two scenarios: 1) the destination is on the Internet or its corresponding RSU; 2) the destination is a vehicle. In the first scenario, the vehicle picks up a fresh route from the RSU list and starts to unicast packets to the RSU. It is possible that a source vehicle will receive new beacons from a RSU during the on-going session. In that case, the source may use a new route if the new route is more appropriate or the current one is impaired. This scenario also applies if the source is a RSU that includes the registered vehicle destination.

In the second scenario, a source vehicle computes the maximum delay $\mathrm{T_d^{max}}$ towards the corresponding RSU. $\mathrm{T_d^{max}}$ is the maximum beacon delay during each $\mathrm{T_r}$. Afterwards it broadcasts a RREQ message with a time-to-live outside $\mathrm{TTL_O}$;

$$\mathrm{TTL_O} = \mathrm{T_d^{max}} + \mathrm{T_d^{margin}}. \quad (5.8)$$

After the source vehicle broadcasts the RREQ packet, a vehicle is allowed to forward the packet only if it is in V_I and the packet has not been passed through the same intersection before. Furthermore, if the vehicle in V_I is registered with the same RSU as the source, it will simply re-broadcast the RREQs. On the other hand, if it is registered with another RSU, it should re-broadcast the RREQ only if $\mathrm{TTL_O} \leq \mathrm{Current\ Time} - \mathrm{T_s}$. To facilitate this process, RREQ packets always include the requesting vehicle's corresponding RSU ID. Also, each RREQ forwarder appends the $< i, M_0^i, \rho^i >$ tuple of the current intersection. This approach ensures that vehicles registered with a neighbouring RSU, which is much closer to the source vehicle than the existing correspondent, can receive a copy of the RREQ packet via an entirely ad hoc multi-hop communication pattern along with a mixed communication mode. $\mathrm{T_d^{margin}}$ can be adaptively selected according to prior knowledge of the destination location; however, for the sake of simplicity, here we set $\mathrm{T_d^{margin}} = 0.5\ \mathrm{T_d^{max}}$ ($\mathrm{TTL_O} = 1.5\ \mathrm{T_d^{max}}$).

If the source's RSU receives the RREQ and recognizes that the destination belongs to another RSU, it will forward the packet to the destination RSU; otherwise the source's RSU discards the packet. If the destination's RSU has a fresh route towards the destination, it will reply with RREP directly; otherwise it re-broadcasts the RREQ packet in its service area.

Once the destination vehicle receives multiple RREQs, it determines the most appropriate route selected by the aforementioned route selection policy. It subsequently computes the next intended intersection according to its own current trajectory and velocity vector and appends this next intended intersection to the inverse intersection sequence of the selected path if the next intended intersection is not included. It then issues the RREP packet and it sends the packet back to the source vehicle. If the source vehicle does not receive the RREP packet after a timeout period, a new route discovery is initiated.

5.3.5 Data Forwarding and Route Maintenance

Upon receiving RREP, the source starts sending the data packets, after adding a small header containing the reverse intersection sequence contained in RREP. At each unicast packet forwarding step, if the vehicle forwarding the packet has a number of V_I vehicles at the next intersection on the path, it selects the one with the highest penetration index (PI) as a next hop forwarder. If it has none, it selects the V_N vehicle with the biggest PI; otherwise, it chooses the farthest vehicle along the path. If the vehicle carrying the packet has no candidate forwarder along the path, it sends the route error (RERR) packet back to the source. However, it is likely that RERR packet cannot reach the source vehicle due to the route impairment. Therefore, during an on-going session, SIRP, checks the validity of the route by periodically issuing a Route Check (RCHECK) packet along the path. Then, the destination vehicle will reply with a RCHECK reply packet. Also, the next intersection to the route is also added to the RRCHEK packet and its reply packet. This should keep the control overhead as low as possible and reduce data packet loss rate.

5.4 Performance Evaluation

This section presents the evaluation of SIRP under simulated urban conditions. Simulation experiments are again performed using ns-2 with the VanetMobiSim mobility generator to build a real urban scenario from the south part of Manhattan island centered on $(40.7377^o, -73.9882^o)$, with an area $\approx 1.2\ \text{km}^2$, as shown in Fig. 4.5. The average street length is circa 120m and there are traffic lights at all intersections. The propagation model parameters are similar to that of the WINNER B1 model which takes into account the log-normal shadowing and LOS/NLOS visibility between vehicles on the urban environment [34].

In addition, IEEE 802.11p is used as MAC/PHY layer with the default values according to ETSI standards [27][88][90][96]. The main objective is to assess the effectiveness of the implemented route selection process. Therefore, we are inclined towards testing it in scenarios with moderate to high levels of vehicular traffic.

We randomly select a source and a destination from the input vehicles, and the destination is selected randomly and it could be at any location on the map. Each experiment is conducted 30 times and calculating the average values. Two scenarios are applied to study the possibility of using different transmission ranges (400m, and 250m). The simulation parameters are summarized in Table 5.I. While the CAM beacon retransmission time interval, T_{CAM}, is put 0.5 seconds according to ETSI standards, we set the advertisement beacon time interval, T_b, as 2 seconds and re-registration time interval, T_r, as 10 seconds due to low average vehicle speed in cities and the low expected number of the hops in the routing paths. However, it is worthy to investigate and optimize their values according to the real situation on the road grid.

Table 5.1: Simulation Setup

Simulation area	1200m × 1200m
Simulation time	800s
Number of RSUs, vehicles	3, 200 ~ 800
Vehicle speed	10 ~ 20 m/s
Transmission Range	400m
Data Transmission rate	6Mbs
Number of CBR sources	20
CBR rate	2 Pkt/s
Data packet size	512 bytes
T_{CAM}	0.5sec ,
T_b	2sec
T_r	10sec

5.4.1 First Scenario: 23dbm 400m

SIRP is evaluated against RBVT-R [55], TrafRoute [69], and FRHR [36] routing protocols. RBVT-R is one of the earliet suggested routing protocols for urban VANETs that builds source routes of successive connected roads. However, it does not consider that the main cause of the route failures is empty intersections. If a vehicle forwarding an RREQ has already left an intersection, the data packets may not find suitable forwarders through that intersection. Thus, the scheme builds low stability routes that are highly breakable as clearly shown in Fig. 5.7, and it tends to reinitiate the route discovery frequently, as shown in Fig. 5.8. TrafRoute constructs routes from intersections and outperforms RBVT-R, as shown in Fig. 5.7 and Fig. 5.8. It uses a superior forwarding technique that obviously reduces the broadcast redundancy in urban scenarios. TrafRoute prefers minimum-delay routes with fewer intersections even though there may not be enough vehicles around these intersections to extend the route lifetime. FRHR follows the same concepts as TrafRoute, except that FRHR utilizes *the registration and location procedure* by which it maintains *proactivity* routes between vehicles and RSUs; using these, leads to a lower number of broken routes and fewer RREQ packet broadcastings if there are some source-destination pairs belonging to different RSUs. *In this case, vehicles can update their routes towards RSUs on-the-fly, and vice versa.* When the number of required interfaces to the infrastructure or to distant vehicles increases, the advantage of proactive route maintenance towards RSUs becomes more and more apparent. Furthermore, with a higher number of vehicles in the network, the number of broadcast RREQs grows in RBVT-R. It is worth indicating that the other protocols are more scalable because they limit the packet forwarding to vehicles residing near the intersections. TrafRoute and FRHR prefer minimum-delay routes with fewer intersections, whereas SIRP uses a more flexible route selection policy that takes into consideration the importance of weighing the intersection capability for multi-hop connectivity: this increases route stability in low and medium-density vehicle networks while avoiding selecting highly congested intersections in dense networks.

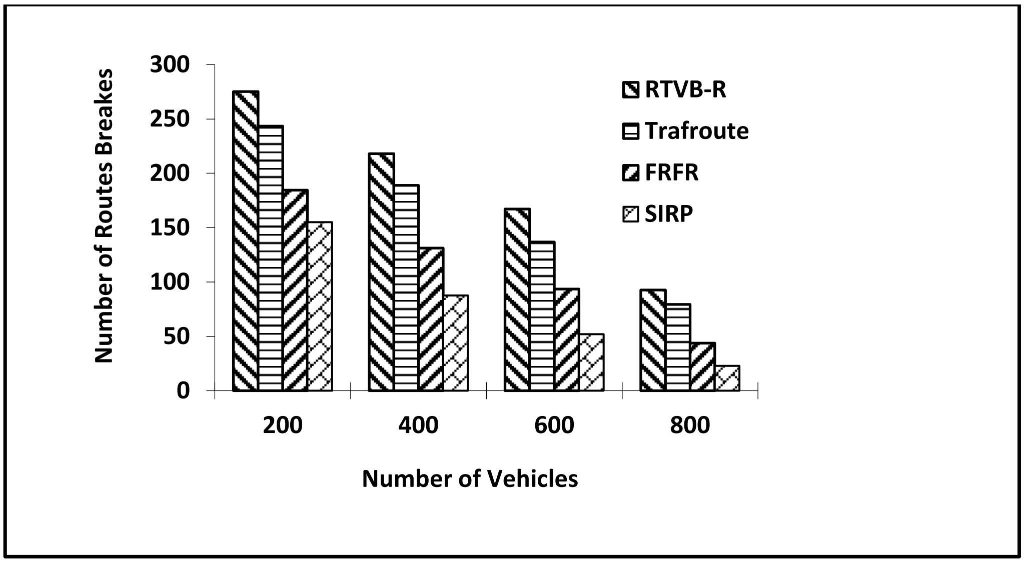


Figure 5.7: Number of routes breaks versus Number of Vehicles when the transmission range = 400m

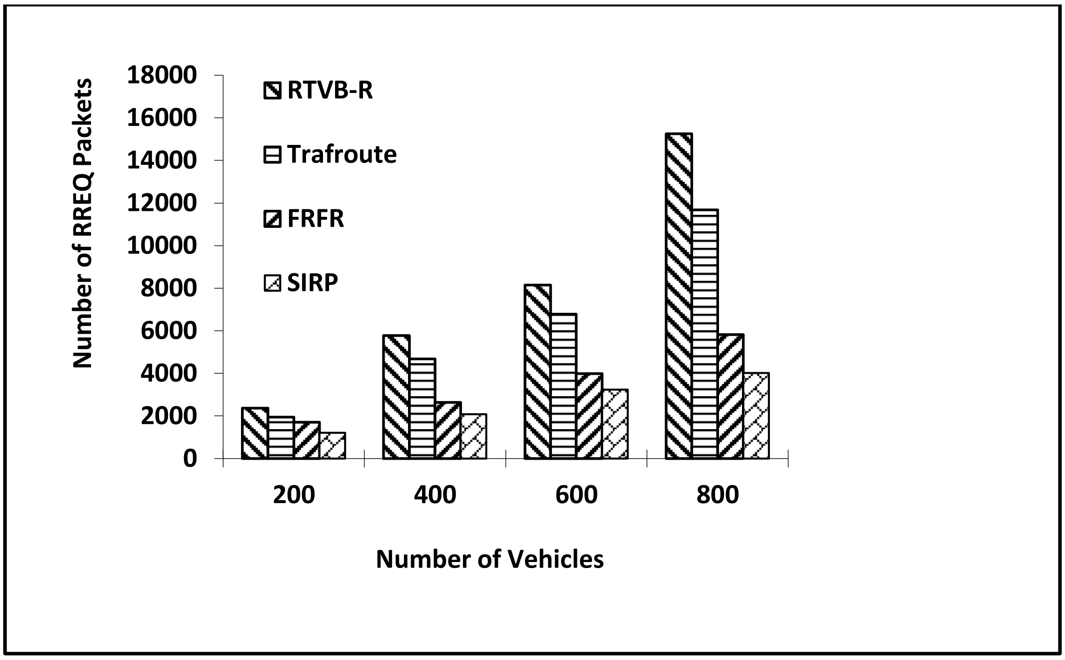


Figure 5.8: Number of produced RREQ Packets versus Number of Vehicles when the transmission range = 400m

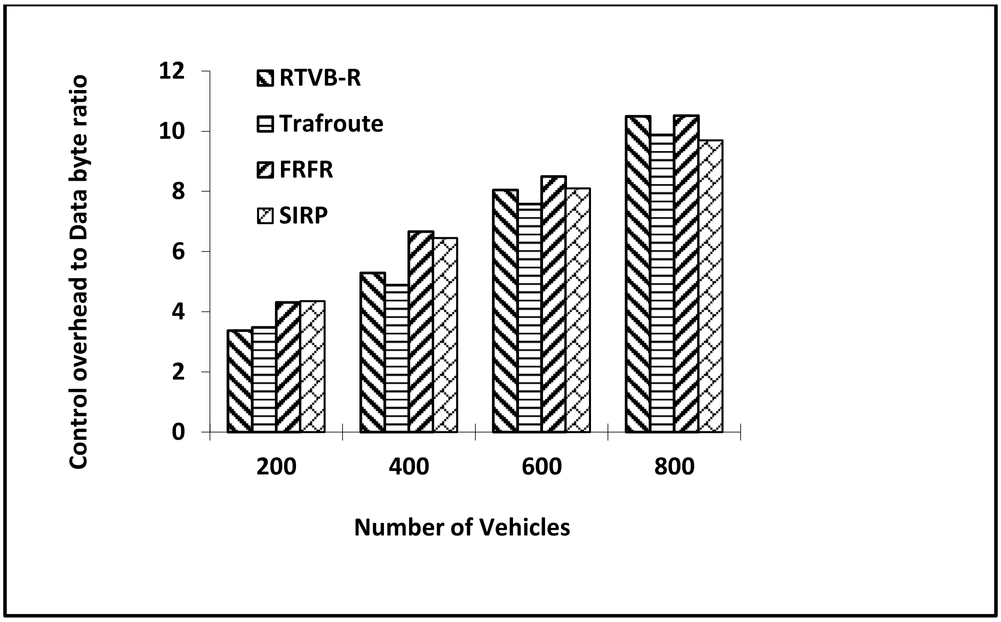


Figure 5.9: Overhead versus Number of Vehicles when the transmission range =400m.

Fig. 5.9 shows the total control overhead to received data byte ratio. Generally, the ascending trend of the overhead ratio is attributed to the increased number of CAM messages produced while the number of CBR sources is fixed. Although RBVT-R is beaconless, CAM broadcasting in VANETs is essential and irreplaceable. Other protocols modify the CAM packets adding few extra bits. FRHR and SIRP use additional control packets in the registration and localization procedure; however, the increased demand for routes through RSUs and improved route stability outweighs the influence of this additional overhead.

Fig. 5.10 shows the data packet delivery ratio. SIRP and FRHR outperform TrafRoute and RBVT-R, particularly in sparse networks. This result is due to the more rapid response of vehicles to changes in network connectivity. A vehicle re-registers with a RSU to which it has a connected path rather than maintaining its association to a disconnected RSU in TrafRoute and RBVT-R. As depicted in Fig 5.10, the performance of TrafRoute and RBVT-R gradually converge to that of FRHR as the network gets denser. However, that is still achieved by involving multiple routes requests which causes increased end-to-end delay, as shown in Fig. 5.11. If each source-destination pair is composed of vehicles at random distances from each other, enough data traffic will pass through RSUs between these vehicles. In FRHR and SIRP, the destination RSU can send packets intended for a registered destination directly, whereas paths among vehicles and RSUs are built in a proactive manner. Consequently, the route setup time is substantially reduced as well. Furthermore, SIRP avoids selecting intersections with low vehicle-populations, if possible, so as to build highly stable routes which, in turn, enhance performance in low-to-medium populated networks. SIRP prefers long-distance, long-lasting routes over shorter but more transient alternatives that would re-initiate the route discovery much sooner. In dense networks, SIRP selects the lowest congested route, taking into account that the route should be sustainable. Overall, SIRP has displayed superiority over its counterparts, and it adapts well to the continuously changing network status characteristics of the urban environment.

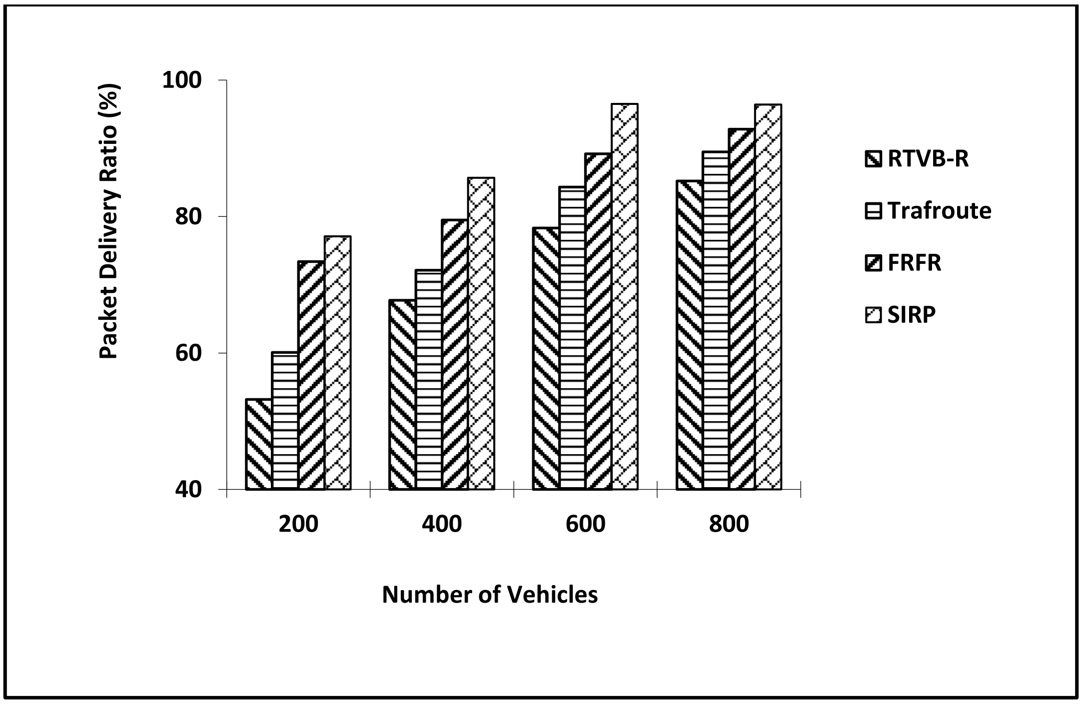


Figure 5.10: Packet Delivery Ratio versus Number of Vehicles when the transmission range =400m.

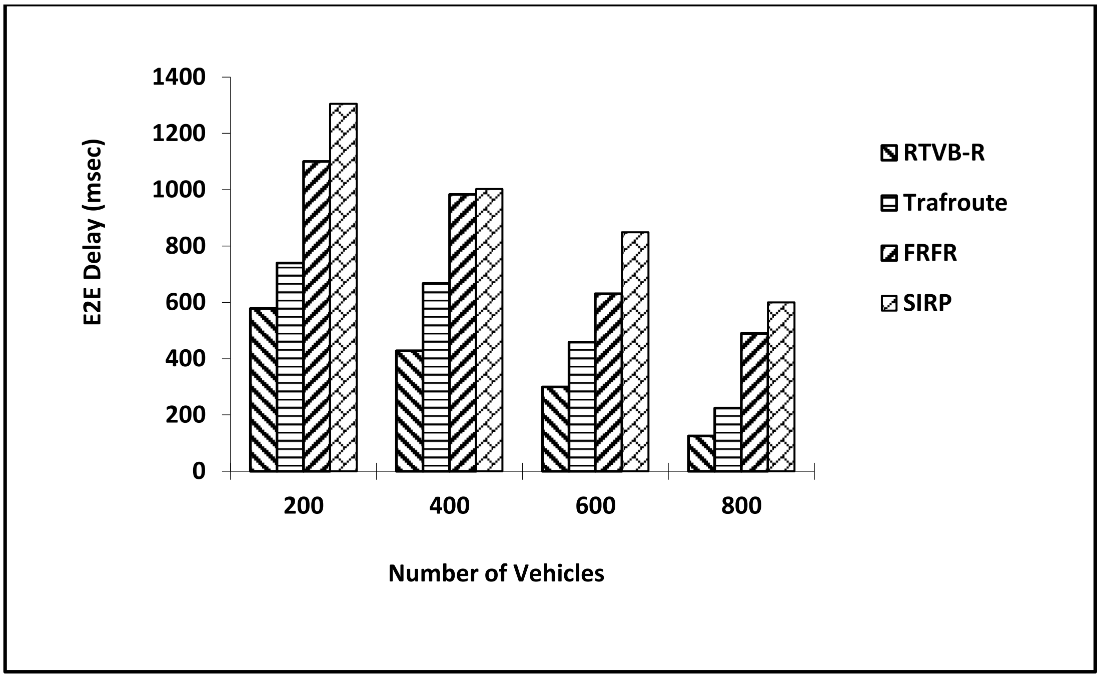


Figure 5.11: End-to-End Latency versus Number of Vehicles when the transmission range =400m.

5.4.2 Second Scenario: 16 dbm 250m

Using smaller transmission range affects the ability of the routing protocols to build stable routes. As shown in figure 5.12, the number of route breaks has increased in general; however SIRP shows resistance to this situation compared to the other protocols. That is reflected in the lower number of RREQ packets used and in the total overhead transmitted, as shown in Fig 5.13. and Fig 5.14.

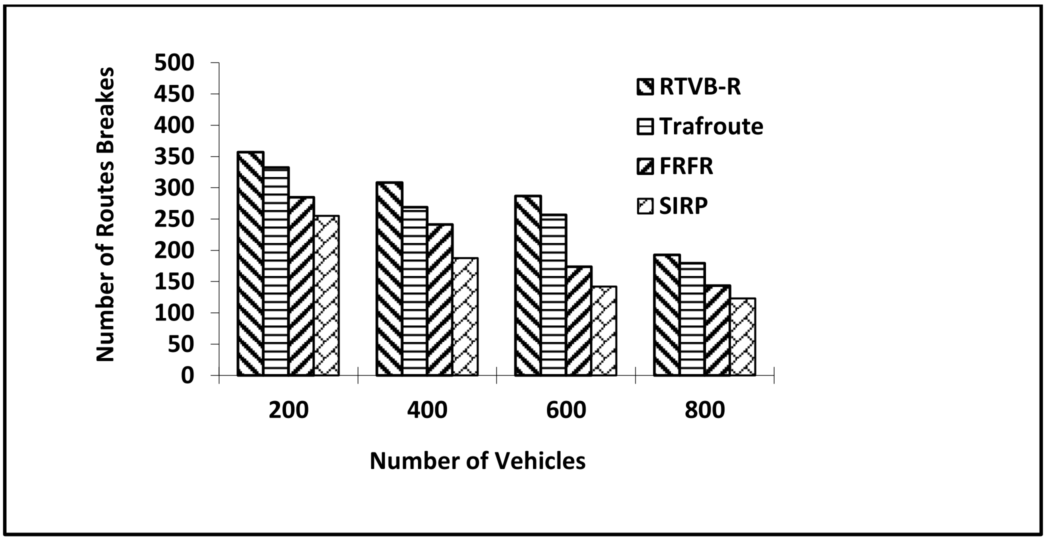


Figure 5.12: Number of routes breaks versus Number of Vehicles when the transmission range = 250m.

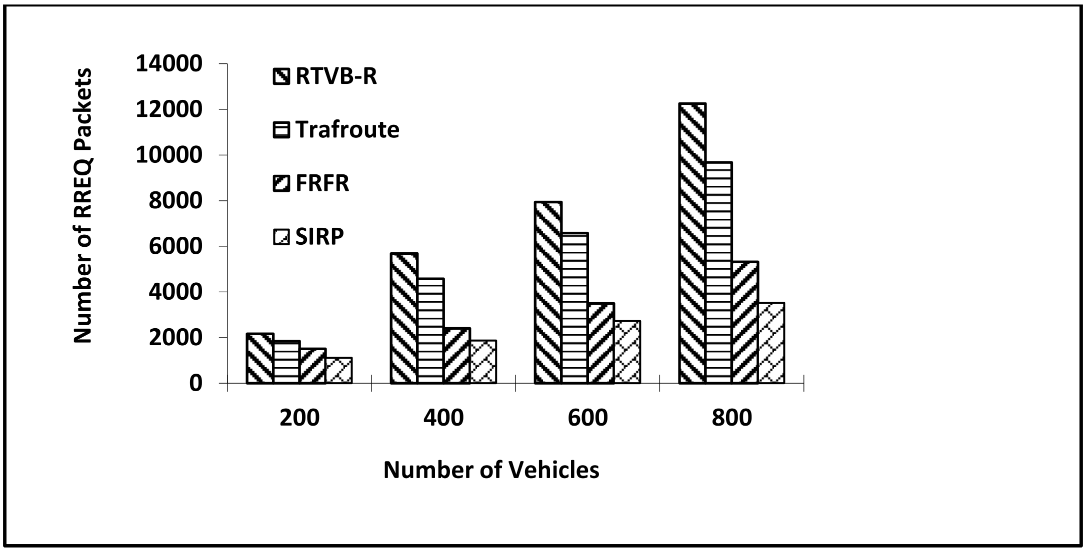


Figure 5.13: Number of produced RREQ Packets versus Number of Vehicles when the transmission range = 2500m

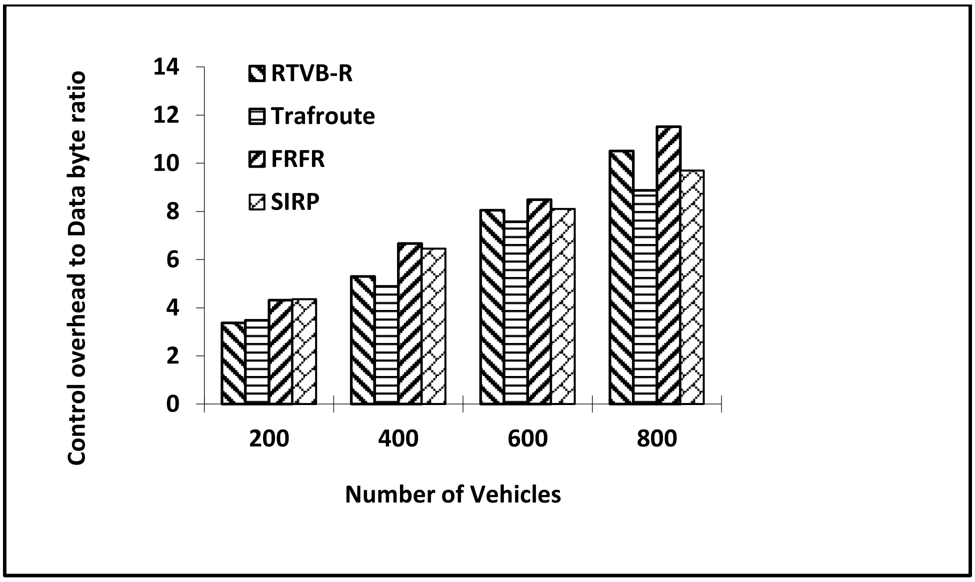


Figure 5.14: Overhead versus Number of Vehicles when the transmission range =250m.

In figure 5.15, the performance of the RTVB-R approaches that of TrafRoute in dense networks but it deteriorates as the number of vehicles decreases. It still the lengths of streets are less the transmission range. As can be seen, SIRP and FRHR outperform TrafRoute and RBVT-R, particularly in sparse networks. This result is due to the more rapid response of vehicles to changes in network connectivity. A vehicle re-registers with a RSU to which it has a connected path rather than maintaining its association to a disconnected RSU in TrafRoute and RBVT-R. As depicted in Fig 5.15, the performance of TrafRoute and RBVT-R gradually converges to that of FRHR as the network gets denser. However, that is achieved by using multiple routes requests which cause increased end-to-end delay, as shown in Fig. 5.16. As long as each source-destination pair is composed of vehicles at random distances from each other, enough data traffic will pass through RSUs towards these vehicles. In FRHR and SIRP, the destination RSU can send packets intended for a registered destination directly, whereas paths among vehicles and RSUs are built in a proactive manner. Consequently, the route setup time is substantially reduced as well. Furthermore, SIRP avoids selecting intersections with low vehicle populations if possible so as to build highly stable routes which, in turn, enhance its performance in low-to-medium populated networks. It prefers long-distance, long-lasting routes over shorter but more transient alternatives that would re-initiate the route discovery much sooner. In dense networks, SIRP selects the lowest congested route, taking into account that the route should be sustainable. Overall, SIRP has displayed superiority over its counterparts, and it adapts well to the continuously changing network status characteristics of the urban environment.

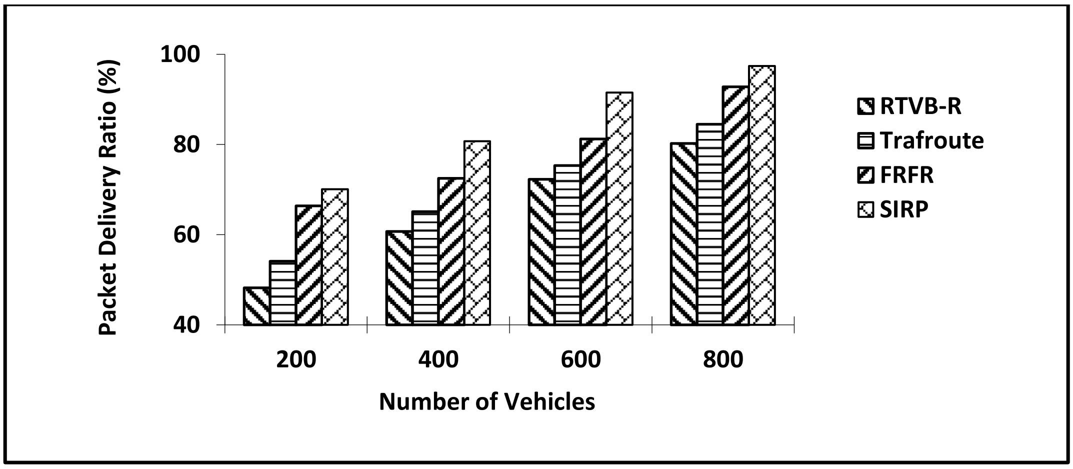


Figure 5.15: Packet Delivery Ratio versus Number of Vehicles when the transmission range =250m.

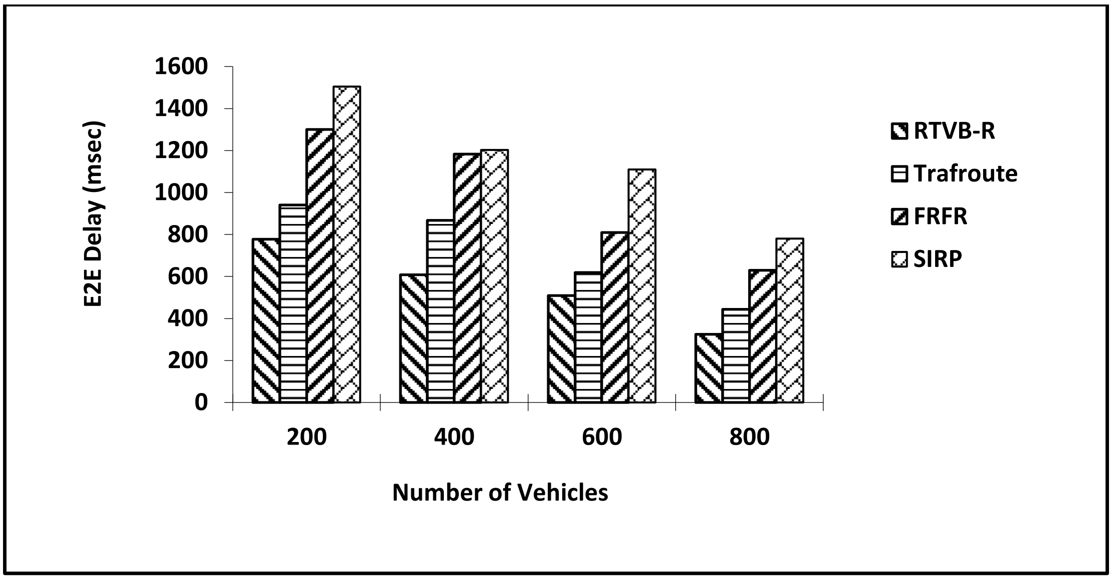


Figure 5.16: End-to-End Latency versus Number of Vehicles when the transmission range =250m.

5.5 Conclusion

This chapter proposes a routing protocol, SIRP, for fast infrastructure access and efficient V2V communications. SIRP uses the RSUs, connected through the wired backbone network, to act as registration servers for vehicles. SIRP proactively builds routes through successive intersections between vehicles and RSUs, and reactively among vehicles. This returns a fast connection set-up time with the most important nodes in the network, namely the RSUs. Moreover, SIRP takes route stability into account to resolve the problem of frequent breaks in urban VANETs as clearly seen in the simulation experiments. It exhibits the lowest end-to-end latency and the highest delivery ratio with varying vehicular traffic.

CHAPTER 6 : CONCLUSION

The consistent mobility coupled with increasing vehicles on major roads and the essentiality of infrastructure-less communication technology for ITS have made VANETS a vital research area for vehicular and wireless technologies. Recent advances in ITS have tried to provide mobile broadcast of information to enhance on-road communications while increasing vehicle awareness regarding their surroundings with the aim of promoting safety, traffic congestion control, fuel consumption and toxic emission, as well as many futuristic applications. Thus, VANET is considered a significant solution to assist drivers to effectively navigate roads and even in facilitating electronic payments. Furthermore, with the pervasive availability of IP networks, internet access plus the delivery of multimedia content have been made possible within the vehicular environment. Nonetheless, such applications need to achieve multi-dimensional QoS levels, leading to several challenges and ensuring direct communication between various vehicles and service providers.

While VANETS can operate in two communications settings, the highway traffic scenario provides a simple and upfront setting, but the city conditions are increasingly multifaceted. While researchers have tried solving data dissemination amongst VANETs, the city environment has not received decisive attention with simulation experiments not including city scenarios or deploying unfeasible radio propagation models that are not sufficiently informed regarding the urban conditions. The main goal of this thesis is to address the harsh communication environment problem in urban VANETs and to promote solutions to route data packets on city roads.

After extensively exploring literature, receiver-centric broadcast techniques such as that based on contention-based forwarding (CBF) show efficient performance in such a harsh vehicular communication environment. However, during daytime, when vehicles start forming large queues at intersections in cities, distance-based CBF schemes suffer from higher collision rates due to the increasing number of vehicles that intend to transmit at the same time. Motivated by the above observations, the Road Topology based Broadcast Protocol (RTBP) is introduced as a CBF-based scheme utilizing a powerful mobile repeater self-election process. It has been a challenge to find a unicast route under various surrounding setups for urban VANETs. Contemporarily, attempts have been made to examine the availability of a Road-Side Unit (RSU) to assist in unicast routing protocol from various points of view. This study undertook an extensive exploration of these infrastructure-based routing techniques to present the advantages of deploying RSU in a new Fast and Reliable Hybrid Routing (FRHR) protocol to offer reliable, and robust urban vehicular communications. To realize smooth multimedia services within VANETs, the study investigated the stability of routes in the city environment and presented a novel stable infrastructure-based routing (SIRP) Protocol. The subsequent sections summarize the main findings regarding RTBP broadcasting, FRHR, and SIRP which are proposed and evaluated in this study.

6.1 Broadcast RTBP

Broadcasting transmission is an increasingly pivotal method serving an array of applications that require various restrictive QoS provisioning extents. Broadcasting facilitates safe driving and traffic management. Even though broadcasting has received considerable attention in highway vehicular networks, it remains a challenge in the city environment attributable to difficulties like high structures. The majority of broadcasting protocols employ distance-based relay selection approaches where the receivers of the packets will decide to rebroadcast packets based on the distance from the senders. Such protocols are not effective in reaching hidden areas in city environments where tall buildings and crowding can obstruct a direct point of view. To develop an effective broadcasting protocol, the research adhered to several metrics: speed of disseminating data, reliability, and overhead. The objective was to balance demand while enhancing throughput and reliability.

The researcher proposed the use of Road-Topology Broadcast Protocol (RTBP) which is founded on the distance-based contention-based forwarding (CBF) model that can be employed successfully for highway vehicular settings. To elevate its capacity in urban scenario, RTBP assigns the highest forwarding priority to vehicles with the greatest capability to transmit broadcast packets in several directions (MRs). The use of several MRs will enhance propagation reliability, but to minimize collision rate, RTBP regulates the quantity of MRs at every intersection based on the density of cars. CBF-centered models were found to outperform greedy forwarding schemes when examining the overhead, packet delay, and collisions and hence proposed in offering multimedia data dissemination services. CBF employs accurate location-based information and eliminates beacon overhead.

RTBP was found to grant cars at intersections a higher priority for rebroadcasting messages. Cars will continually and proactively run a self-selection algorithm to establish that subset that undertakes forwarding processes. To achieve this, all cars maintain a fresh neighbour table by employing a Cooperative Awareness Message (CAM) packet, mandated by the ETSI standards. The performance of RTBP was evaluated against other procedures, including Simple-CBT, eMDR, and TAF schemes using simulation experiments undertaken by employing ns-2 where real city scenarios were developed on Manhattan Island.

Reachability was employed to evaluate the performance of RTBP and the findings revealed that eMDR and RTBP had similar results while TAF performed developed slowly. For TAF, vehicles will only rebroadcast packets only when they receive the packets for the first time. TAF was found to have a lower capability of reachability than eMDR and RTBP with simple-CBF showing even worse outcomes.

Also, the impact of traffic load plus collision rates because of the hidden terminal challenges were investigated by examining two-vehicle densities: 500 cars (network with optimal connectivity) and 900 cars (network is congested). From the findings, it was evident that RTBP takes advantage of MRs to minimize the number of hops required to cover the entire targeted area, while minimizing the number of cars competing. RTBP demonstrated outstanding resistance with the delay increasing by less than 17ms compared to TAF and eMDR which exhibited a delay increase of at least 40ms. Meanwhile, simple-CBF still recorded the worst performance in handling traffic load and reducing collision rates. It only takes 169ms before 90 percent of the targeted receivers obtain a first normal message depicting medium vehicle density for RTBP whereas TAF and eMDR experience delay increase of 81 percent and 54 percent delays respectively. Therefore, RTBP outclasses its counterparts and minimizes latency, while saving systems resources and augmenting reachability.

6.2 Fast and Reliable Hybrid Routing (FRHR)

The study examined the effectiveness and feasibility of a novel FRHR protocol incorporating proactive and reactive features of routing schemes. FRHR has the capability of maintaining proactive routes towards RSUs, while still it can reactively try and find other close nodes within the network. When RSUs act as the primary service providers and allows cars to communicate with their distant peers, the paths towards close RSUs will be recurrently be requested compared to those located far away. The minimization of the need for reactive routes while favouring proactive connections of vehicles adjacent to RSUs leads to a reduction of the total amount of control overhead while speeding up routes building and maintenance where most of the data traffic is concentrated. Also, this enhances system immunity to RSUs failures. The fundamental aspect behind the use of RSUs is that they act as fixed reliable nodes that ensure robust communications with minimal administrative overhead than when both communications nodes are moving. Besides, RSUs can effectively be connected via high bandwidth, low bit-error, and low delay backbone connection to transmit packets to distant cars.

The proposed FRHR routing protocol takes advantage of the fact that most of the unicast data traffic will go through the RSUs. FRHR involves several functional procedures: localization, registration, and self-election processes plus discovering the route and maintaining it. The protocol ensures a sufficient number of RSUs will be distributed throughout the road topology networking beginning with the periphery of an urban area towards the centre. Every RSU within the FRHR will periodically relay a beacon as a multi-hop broadcast gathering information within every hop. After receiving the beacon, cars will establish fresh routes to RSUs and assist them to continually find the ideal candidate or corresponding RSU. Besides, cars will be able to update their geographical locations after finding a novel robust route to their corresponding RSU. Vehicles will build route tables of their nearest RSUs and even maintain a list of the currently registered vehicles. The use of beacons enhances the overall performance of the system regarding its average latency, stability, and reliability due to fixed endpoints of RSUs.

Using simulated city conditions, a performance evaluation was undertaken on FRHR in comparison with TrafRoute (which represents an infrastructure-based routing protocol). The evaluations primarily focused on the capacity of FRHR to convey packets between cars and were undertaken within ns2 software. Other performance metrics assessed include average end-to-end delay, packet delivery ratio, and routing overhead ratio. FRHR outperformed TrafRoute protocol in sparse networks since it leads to the quick response of cars to changes in network connectivity. The increase in the quantity of vehicles and RSUs promotes the overall network connectivity while minimizing the effects of the registration process. Additionally, FRHR performed better in terms of average end-to-end delay compared to the TrafRoute protocol. Accordingly, when every src-dist pair consists of vehicles at a random distance from one another, sufficient data traffic will go through RSUs to reach the vehicles. The destination RSU effectively sends packets that should reach the registered destination directly where the paths of vehicles and RSUs are developed proactively. As a result, the route setup period is considerably reduced.

The exploring of routing overhead of FRHR against TrafRoute, including the amount of overhead incurred revealed that the overhead ratio when TrafRoute is used in a dense network is almost settled since even though the vehicle density is augmented only by a subset of cars within the proximity of forwarding points is enabled to forward the packets. Whereas beacons are periodically conveyed in the vicinity of RSUs, this will not generate significant overhead since an efficient flooding mechanism has been adopted. Generally, FRHR generates slightly more overhead.

When the packet delivery ratio was examined, FRHR outperformed other routing protocols, especially in sparse networks because of its rapid response of vehicles to changes in connectivity. Also, we studied the average end-to-end delay and still FRHR performed better than the TrafRoute protocol. Therefore, the results obtained reveal that FRHR enhances end-to-end latency and is expected to improve the reliability of routing protocol even if RSU fails.

6.3 Stable Hybrid Routing Protocol for VANETs

Additionally, the study proposed a stable hybrid SIRP routing protocol be deployed in urban VANETS to facilitate connections demanded by vehicles to RSUs at higher recurrence and maintain fresh routes to close RSUs. SIRP will enable cars to proactively create and sustain routing table entries for RSUs while looking for other vehicles only on-demand. This is achieved by building routes of successive intersections to forward a packet through the intersection stability metric. SIRP requires every participating car to have navigation comprising a digital map and positioning system (GPS) to be aware of advances about all road features and intersections within road networks at a specific time. The intersection attributes under consideration include IDs, the number with the width of all enjoined road lanes, and IDS of the bordering intersections.

SIRP has two functional processes: registration and localization procedures and Route Discovery and maintenance processes. SIRP employs a new metric (Intersection Stability [IS]) to compute the stability of source routes of successive intersections of city scenarios. To enhance confidence that vehicles will retransmit packets via the intersections in all directions, SIRP will consider only cars that are moving towards intersections as the near-intersection cars. Every vehicle in SIRP is allowed to choose the ideal RSU based on the actual situation within a road. The vehicle will keep eavesdropping on periodic multi-hop broadcast beacons from the RSU within its vicinity and choose one as the corresponding RSU with a relatively stable, minimum-delay, and reliable route. This will ensure vehicles are connected in a sparse network and mitigate congestion challenges while balancing the distribution of cars amongst adjacent RSUs within a dense network.

The performance evaluation of SIRP was conducted through simulating urban city conditions and the simulations experiments used ns-2 software comprising VanetMobiSim mobility generator to assist in building real urban scenarios from the south region of Manhattan. The simulation parameters include area (1200m x 1200m), vehicle speed of 10 ~ 20 m/s, simulation time 800s, transmission range 400m, number of RSUs (3, 200 ~ 800), CBR rate (2 Pkt/s), and 20 sources of CBR. The first simulation scenario involved 23dbm 400m where SIRP was assessed against RBVT-R, FRHR, and TrafRoute routing protocols. RBVT-R's major weaknesses involve not considering the primary cause of route failures including the empty intersections leading to low stability routes. Meanwhile, TrafRoute can develop routes from intersections and outperforms RBVT-R and it employs a superior forwarding approach that minimizes broadcast redundancy within urban areas.

Examination of FRHR showed that it followed a similar concept as TrafRoute but FRHR employs location and registration procedures to ensure proactivity routes between RSUs and vehicles. As a result, FRHR experiences lower broken routes as well as few RREQ packet broadcastings. Evaluations of data packet delivery ratio revealed that FRHR and SIRP outperformed RBVT-R and TrafRoute especially in sparse networks attributable to the more rapid response of vehicles to changing network connectivity. The destination RSU for SIRP and FRHR can relay packets to the registered destination directly while the paths among RSUs and cars are created proactively. As a result, the time spent on setting up routes will be reduced considerably.

In the second scenario, a smaller transmission range was used involving 16dbm 250m and this affected the capability of the routing protocols to create stable routes. The performance of RTVB-R was found to approach that of TrafRoute for the dense network but deteriorated with the decline of vehicle quantity. Also, FRHR and SIRP outperformed RBVT-R and TrafRoute in the second scenario in the sparse networks. Moreover, SIRP was found to avoid the selection of low-vehicle inhabited intersections in creating stable routes and this improves SIRP's performance within low-to-medium populous networks. SIRP chooses the lowest congested routes while considering the most sustainable route. As a result, SIRP displayed outstanding superiority over its counterparts and it adapts effectively to the consistently changing network status which is a major feature of the urban environment. Thus, SIRP was the ideal candidate for providing a stable routing protocol for VANETs.

6.4 Future Studies

The major weakness found with the routing algorithm is that it delivers stable routes for a vehicle for a highway environment. Therefore, in future, it is vital to create a novel route selection policy that provides stable routes to satisfy broader QoS provisioning levels needed by various applications for road grids. The study should take into account the significance of the capability of a novel stable routing protocol to operate effectively for both highway and urban scenarios. Additionally, will FRHR routing protocol was examined in this study, it is important to assess its effectiveness in harsher city scenarios where there is high occurrence traffic congestion and collision incidences have been reported.

Moreover, the security framework of VANETs is an increasingly neglected aspect. With several sensors and Internet of Things (IoT) devices linked into a single network, it is increasingly critical to study and implement security defense systems as well as privacy protection mechanisms [109][110]. Security is a multi-layered aspect closely associated with regulations and compliance. There is a need for robust safeguards for each connected device in VANETs devices including the use of user authentication, data encryption, and access control among other security safeguards [111]. The development of internet of vehicle (IoT) solutions that can withstand intrusion and data breaches require extensive investigation, including simulations before such solutions are deployed. Specifically, future studies need to focus on security challenges facing VANETs and performance parameters and standards of security to propose adequate measures.

Besides, as smart vehicles become pervasive, the existing network technological resources are unlikely to handle traffic loads. It is anticipated that 6G communication systems could fulfill the requirements of VANETs [112]. This area has not received sufficient attention and future studies should focus on the applicable routing protocols for 6G communication networks and the security requirements that need to be fulfilled. Another issue that needs to be examined involves the protracted product lifecycles for connected vehicles. Recent studies have shown that building connected devices can take months but for connected vehicles, it takes several years. On the other hand, the consumers anticipate leveraging futuristic technologies while buying new vehicles. Research should focus on how this can be achieved by delivering such technology by investigating how to accomplish seamless scalability as well as integration.

Future studies need to focus on big data pre-processing. The conveyance of massive data, especially videos via the Internet of Vehicle (IoV) is a major challenge. Additional research is required regarding the enhancement of information preparation to facilitate upgrades of execution of IoV innovations. It is predicted that at least one-fifth of cars on the streets will be web-based and the global vehicular traffic to surpass 300,000 Exabyte by the year 2032. The explosion of information requires to be processed by being transmitted via the systems. Failure to pre-process information will result in a steep crash of IoV innovations. Pre-processing of big data is considered to be ideal while the other data analysis processes such as data dissemination coupled with data transport with minimal latency are centred on pre-processing the data. To actualize data pre-processing activities, extensive research is required using a big number of datasets based on the interests of the scholars. Additionally, because of the security issues, it is challenging to obtain actual data deployed in the vehicular cloud. Hence, equivalent experimental setups can be undertaken to examine the effectiveness of the suggested solutions. Such experiments will assist users to make informed decisions and benefit the transportation sectors in various ways such as optimizing traffic cybersecurity, weather forecasting, and intelligence.

Furthermore, no fixed standards exist for tackling various aspects like programming and equipment, conventions, interoperability, and the corresponding innovations. Some of the standards that exist are fundamentally for IoT deployment whereas no standards have been developed for IoV. Standardization across the landscape of IoV will minimize the challenges of interoperability. Thus, future works should focus on the development of standards regarding IoV's networks, protocols, data semantics ad physical communications systems.

Given the highly dynamic and heterogeneous characteristics of Vehicular networks, traditional routing protocols face a significant problem of the location information accuracy of the navigation systems [116, 117]. Furthermore, Scalability is one of the main challenges; the network performance must be reliable in sparse and dense networks. Using G4/5G/6G cellular networks are considered a prospective solution for scalability issues in the VANET network [118,119]. As long as, in such infrastructure-based protocols, BS/LTE/RSUs can collect data from current vehicles within the area they cover, such global information may facilitate and speed up VANETs deployment by alleviating the other challenges as well, such as network resources utilisation and unbalanced traffic flow, when it is integrated with intelligent controlling paradigm. Therefore, researchers have recently considered using software-defined network (SDN) centralized control, adapted mainly for data centres, to analyse the information and make future decisions [116, 120, 121]. The potential of flexibility, programmability, and centralized knowledge in SDN makes it an appealing solution to VANETs [125]. The separation of the data plane and the control plane simplifies network management problems when the number of vehicles increases.The proposed architecture considers various heterogeneous characteristics such as physical medium, mobility, topology, and capability; Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications. Furthermore, connecting vehicles through infrastructure to cloud data centres will extend their ability to send and retrieve vast amounts of data and utilise cloud computing storage and computation facilities. However, the constantly changing conditions of vehicular environments necessitate a computing paradigm that operates in close proximity to the vehicles for time-sensitive applications with tight latency requirements and to guarantee uninterrupted services. Therefore, the researchers have proposed new VANETS architecture based on Fog computing to support highly demanded QoS services. Fog computing is a Cloud computing paradigm in which data, processing and services are concentrated at the edge of the network instead of entirely far away in the cloud. Fog Computing offers various benefits such as low latency, location awareness and mobility support and turns conventional data centres into distributed, heterogeneous platforms.

Additionally, the emergence of the connected autonomous vehicles and the Internet of Vehicles has introduced a new challenge of a huge quantity of data produced by a large number of embedded sensors. These sensors, ranging from standard sensors such as GPS and ultrasonic sensors to more specialized camcorders and LiDAR sensors, will improve the vision and make decisions before entering dangerous areas alike to adaptive cruise control systems and reroute assistance. In a dense driving situation, these sensing systems generate a massive amount data that should be collected, processed, and delivered to autonomous vehicles in very low latency which necessitates powerful computation resources and high data rates. In fact, smart vehicles are enhanced with a substantial amount of storage and computing capabilities, and therefore researchers consider them as a form of edge computing and introduce a new approach based on the integration of cloud-fog-edge computing in Software-Defined Vehicular Ad hoc Networks (SDN-VANETs)[122]. Moreover, this new paradigm will pave the way to apply artificial intelligence (AI) algorithms in the VANET application domain which will be reflected in more enhancement in the network performance and the data reliability. According to [123], artificial intelligence (AI) algorithms have remarkable problem-solving capabilities and a high ability to enhance conventional data-driven methods and, therefore, they can provide autonomous vehicles with promising models for environment awareness and sufficient decision-making for smooth navigation. Due to insufficient vehicles and RSUs resources to implement AI models within minimum latency, the augmenting of fog and edge computing can lessen the computation burden of AI-based solutions by distributing the computations between vehicles and external computation systems and storage servers founded at the edge, fog, or cloud [124].

Although progress has been made, a few issues need to be addressed regarding the current architecture. Specifically, the localization and performance measurement of edge cloud nodes have not been thoroughly examined in real-time environments. Additionally, the high mobility of vehicles can cause delays as they move out of range of the edge cloud. Latencies will build up as the connectivity adds extra network hops to reach the in-use cloud server. Further research is needed to accurately measure the impact of vehicle mobility on edge computing node performance. Choosing the right edge cloud that is both reliable and high performing can be challenging. This is especially true when migrating applications across multiple edge clouds during a road trip. It is vital to ensure seamless performance and communication reliability throughout the journey.

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