Location Management and Hybrid Geo-Routing for Urban Vehicular Networks

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Location Management and Hybrid Geo-Routing for Urban Vehicular Networks

AISLING O’DRISCOLL
Location Management and Hybrid Geo-Routing for Urban Vehicular Networks

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Department of Electronic Engineering.

Supervised by Dr. Dirk Pesch

A thesis submitted for the degree of
Doctor of Philosophy
Cork Institute of Technology,
January 2014
Declaration

I hereby declare that this submission is entirely my own work and that, to the best of my knowledge and belief it contains no material previously published or written by another person nor material which to a substantial extent has been accepted for the award of any other degree or diploma of the university of higher learning, except where due acknowledgement has been made in this text. I also declare that this work has not been submitted for an award at any other institution.

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Certified by: [Redacted]

Date: 27/10/14
Abstract

In recent years the motivation for comfort applications e.g. infotainment, file exchange and vehicle to vehicle (V2V) multiplayer gaming amongst others, has emerged as an active area of vehicular communications and network research. The success of such applications relies on the ability of a geo-routing protocol to deliver communication packets in a frequently disconnected communication environment. To do this, the location of the destination vehicle must first be determined and secondly, must reliably deliver the packet from source to destination.

To determine the location of a target vehicle towards which packets can be forwarded, geo-routing algorithms utilise a location service protocol. Such protocols often focus on providing a scalable location service protocol with minimal overhead but neglect the core underlying motivation, which is prioritising robust packet delivery in frequently disconnected vehicular networks with highly transient wireless links. Furthermore such protocols often exhibit drawbacks such as an inability to facilitate locality in communication between vehicles, describe poor location server placement strategies or do not avail of partial infrastructure to maximise their operation and accuracy. This thesis presents a location service protocol for unicast vehicular communications, namely the Urban Vehicular Location Service (UVLS) protocol, where the emphasis is on maximising packet delivery to ensure consistent retrieval of accurate destination vehicle location for the routing protocol. UVLS demonstrates improved query success rates with accurate location information and comparable overhead, thereby enabling the geo-routing protocol to make correct routing decisions.

Furthermore, current geo-routing solutions typically provide a completely distributed routing solution or a centralised only approach, while a hybrid approach that can avail of partial infrastructure has, so far, not been considered. Current infrastructure schemes dictate the placement and density of RSUs and assume a densely connected network. Partial Road-Side Unit (RSU) infrastructure is a more imminent reality. This thesis therefore proposes the Infrastructure Enhanced Geo-Routing Protocol (IEGRP), designed to deliver best practice multi-hop communications while utilising a dynamic
greedy and recovery routing scheme to exploit the use of partial road-side unit infrastructure, where available, on a per packet basis to maximise packet delivery. IEGRP is shown to deliver improved packet delivery rates with no increased delay and comparable path lengths.

Finally the performance of UVLS, IEGRP and comparable protocols are evaluated in a comprehensive and bespoke Inter-Vehicular Communication (IVC) simulation environment.
Acknowledgments

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Firstly, I would like to thank my supervisor Dr. Dirk Pesch, for his invaluable guidance, insights and advice throughout the course of this research. I would also like to thank my external examiners Professor John Murphy and Dr. Melanie Bouroche.

I am indebted to my extended family and friends, and in particular my parents, for their continuous and unconditional support and encouragement of all my undertakings, scholastic and otherwise. I would like to give particular thanks to Mary for being a constant source of sound advice, moral support and friendship throughout this process.

Finally, this thesis, or any of my achievements, would not be possible without Pat; his unwavering patience and quiet support, though sometimes unacknowledged, is deeply appreciated. I look forward to spending the rest of our lives together.
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<td>Adaptive Connectivity Aware Routing</td>
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<td>AIFS</td>
<td>Arbitrary Inter-Frame Spacing</td>
</tr>
<tr>
<td>ARIB</td>
<td>Association of Radio Industries and Businesses</td>
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<tr>
<td>ASTAR</td>
<td>Anchor-based Street and Traffic Aware Routing</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<tr>
<td>C2C-CC</td>
<td>Car-2-Car Communication Consortium</td>
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<tr>
<td>CALM</td>
<td>Communications Access for Land Mobiles</td>
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<td></td>
<td>Continuous Air-interface for Long and Medium Telecommunications</td>
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<td>CAR</td>
<td>Connectivity Aware Routing</td>
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<td>CBF</td>
<td>Contention Based Forwarding</td>
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<td>CCH</td>
<td>Control Channel</td>
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<td>CEN</td>
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<td>CORDIS</td>
<td>Community Research and Development Information Service</td>
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<td>CVIS</td>
<td>Co-operative Vehicular Information Systems</td>
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<td>DES</td>
<td>Discrete Event Simulator</td>
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<td>DHT</td>
<td>Distributed Hash Table</td>
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<td>DSRC</td>
<td>Dedicated Short Range Communications</td>
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<td>DTN</td>
<td>Delay Tolerant Network</td>
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<td>EC</td>
<td>European Commission</td>
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<td>ECDA</td>
<td>Enhanced Distributed Channel Access</td>
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<td>ESO</td>
<td>European Standards Organisations</td>
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<td>ETC</td>
<td>Electronic Toll Collection</td>
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<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
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<td>FCC</td>
<td>Federal Communications Commission</td>
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<td>FOT</td>
<td>Field Operational Test</td>
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<td>FP</td>
<td>Framework Programme (6/7)</td>
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<td>FSL</td>
<td>Free Space Loss</td>
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<td>FSM</td>
<td>Finite State Machine</td>
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<td>Description</td>
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<td>FTP</td>
<td>File Transfer Protocol</td>
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<td>GeoDTN+NAV</td>
<td>Geographical DTN Routing with Navigator Prediction</td>
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<td>GG</td>
<td>Gabriel Graph</td>
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<td>GHLS</td>
<td>Geographic Hashed Location Service</td>
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<td>GOSR</td>
<td>Geographical opportunistic Source Routing</td>
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<td>GPCR</td>
<td>Greedy Perimeter Coordinator Routing</td>
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<td>GPSR</td>
<td>Greedy Perimeter Stateless Routing</td>
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<td>GPUR</td>
<td>Greedy Perimeter Urban Routing</td>
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<td>GSR</td>
<td>Geographic Source Routing</td>
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<td>GyTAR</td>
<td>Greedy Traffic Aware Routing</td>
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<td>HLSRG</td>
<td>Hierarchical Location Service with Road-adapted Grids</td>
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<td>ICMP</td>
<td>Internet Control Message Protocol</td>
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<td>IEEE</td>
<td>Institute of Electrical and Electronic Engineers</td>
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<td>IEGRP</td>
<td>Infrastructure Enhanced Geographic Routing Protocol</td>
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<td>IETF</td>
<td>Internet Engineering Task Force</td>
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<td>ILS</td>
<td>Intersection Location Service</td>
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<td>IP</td>
<td>Internet Protocol</td>
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<td>ISO</td>
<td>International Organisation for Standardisation</td>
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<td>ITSA</td>
<td>Intelligent Transportation Society of America</td>
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<td>ITU-R</td>
<td>International Telecommunication Union Radio (ITU-R) communication sector</td>
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<td>ITS</td>
<td>Intelligent Transportation Systems</td>
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<td>IVC</td>
<td>Inter Vehicle Communication</td>
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<td>JOSM</td>
<td>Java Open Street Map</td>
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<tr>
<td>LOS</td>
<td>Line of Sight</td>
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<td>LOUVRE</td>
<td>Landmark Overlays for Urban Vehicular Routing Environments</td>
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<tr>
<td>MAC</td>
<td>Media Access Controller</td>
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<td>MANET</td>
<td>Mobile Ad Hoc Network</td>
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<td>MBLS</td>
<td>Map Based Location Service</td>
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<td>MoU</td>
<td>Memorandum of Understanding</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>NEMO</td>
<td>NEtwork MObility</td>
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<td>NLOS</td>
<td>Non Line of Sight</td>
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<td>OBU</td>
<td>On-Board Unit</td>
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<td>OPNET</td>
<td>Optimised Network Engineering Tools</td>
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<td>OSI</td>
<td>Open Systems Interconnect</td>
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<td>OSM</td>
<td>Open Street Map</td>
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<td>P2P</td>
<td>Peer-to-Peer</td>
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<td>PDR</td>
<td>Packet Delivery Rate</td>
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<td>PLR</td>
<td>Packet Loss Rate</td>
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<td>QLSP</td>
<td>Quorum-based Location Service Protocol</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>QSR</td>
<td>Query Success Rate</td>
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<td>RAR</td>
<td>Roadside-Aided Routing</td>
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<td>RBNT</td>
<td>Relay Based Node Tracking</td>
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<td>RBVT</td>
<td>Road Based using Vehicular Traffic information</td>
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<td>RDGR</td>
<td>Reliable Directional Greedy Routing</td>
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<td>RLSMP</td>
<td>Region-based Location Service Management Protocol</td>
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<td>RNG</td>
<td>Random Number Generator</td>
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<td>ROAMER</td>
<td>ROAdside units as MEssage Routers</td>
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<td>RSLS</td>
<td>Responsible Sections Location Service</td>
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<tr>
<td>RSU</td>
<td>Road-Side Unit</td>
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<tr>
<td>RTTT</td>
<td>Road Transport and Traffic Telematics</td>
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<tr>
<td>SADV</td>
<td>Static node-assisted Adaptive Dissemination in Vehicular Networks</td>
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<tr>
<td>SCH</td>
<td>Service Channel</td>
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<tr>
<td>SHA</td>
<td>Secure Hashing Algorithm</td>
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<td>SIFS</td>
<td>Short Inter-Frame Spacing</td>
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<tr>
<td>STD</td>
<td>State Transition Diagram</td>
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<td>SUMO</td>
<td>Simulation of Urban Mobility</td>
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<td>TCP</td>
<td>Transmission Control Protocol</td>
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<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
<td>TIGER</td>
<td>Topologically Integrated Geographic Encoding and Referencing</td>
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<td>TO-GO</td>
<td>TOpology assisted Geo-Opportunistic routing</td>
</tr>
<tr>
<td>TRG</td>
<td>Two-Ray Ground</td>
</tr>
<tr>
<td>UDP</td>
<td>User Datagram Protocol</td>
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<tr>
<td>UVLS</td>
<td>Urban Vehicular Location Service</td>
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<tr>
<td>V2I</td>
<td>Vehicle to Infrastructure</td>
</tr>
<tr>
<td>V2V</td>
<td>Vehicle to Vehicle</td>
</tr>
<tr>
<td>V2X</td>
<td>Vehicle to ‘X’ technology</td>
</tr>
<tr>
<td>VA</td>
<td>Vienna Agreement</td>
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<tr>
<td>VANET</td>
<td>Vehicular Ad Hoc Network</td>
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<tr>
<td>VLS</td>
<td>Vehicular Location Service</td>
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<tr>
<td>VNC</td>
<td>Vehicular Networking Conference</td>
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<tr>
<td>VTC</td>
<td>Vehicular Technology Conference</td>
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<tr>
<td>WAVE</td>
<td>Wireless Access in Vehicular Environments</td>
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<tr>
<td>WLAN</td>
<td>Wireless Local Area Network</td>
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<td>WPAN</td>
<td>Wireless Personal Area Network</td>
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Chapter 1: Introduction

1.1 Thesis Background and Motivation

In the last decade, leading car manufacturers have jointly collaborated with government agencies, standardisation bodies and academic institutions to develop Inter-Vehicular Communication (IVC) solutions. These solutions are aimed at assisting drivers by anticipating hazardous events or avoiding congested areas of traffic i.e. road safety and traffic management applications. This has resulted in the standardisation of Wireless Access for Vehicular Environments (WAVE) [1], which outlines a wireless standard for V2V and Vehicle-to-Infrastructure (V2I) communications. In V2V communications, vehicles, equipped with WAVE devices known as On-Board Units (OBUs), form a decentralised network via wireless multi-hop communication, known as a Vehicular Ad-hoc NETwork (VANET).

While the primary impetus behind vehicular applications has been towards safety services and traffic management applications, promising infotainment and location based applications for drivers and passengers are also envisaged via multi-hop vehicle communications. These include, but are not limited to, file sharing e.g. music or movie files or utilisation of location-based content such as travel related information, news items etc. Organisations such as the Car-2-Car Communication Consortium (C2C-CC) [2] and CALM3 [3], and projects such as CarTALK [4], Network on Wheels (NoW) [5], CarNet [6], FleetNet [7,8], amongst others, have contributed to this research field. In a recent survey by Accenture [9], it was found that 39% of 14,000 drivers surveyed in South America, Asia, Europe and the United States said that their primary consideration in choosing a new automobile is in-car technology, compared with 14% who said driving performance had the greatest influence on their choice. Thus, such systems, while meeting a vital safety need from a societal perspective to reduce injuries and mortalities, also potentially have an economic benefit in terms of stabilising the motor industry and answering a demand for next generation smart vehicular applications. Furthermore, the report found that Indonesian drivers have a high interest in real-time entertainment such as social media and gaming as well as services such as email and calendar content with
South Korean drivers expressing the highest interest in live traffic information. 30% of users think C2C communications for passenger applications are important.

While safety applications typically utilise local broadcast mechanisms for packet delivery, it is expected that such infotainment applications would benefit from unicast multi-hop communications. In V2X networks, unicast routing occurs using geo-routing protocols, also referred to as position or location based routing, the benefits of which are widely recognised over their topology based counterparts. However in order for a packet to be routed to the destination effectively, a geo-routing protocol must firstly determine the location of the destination vehicle. It is therefore reliant on a location service protocol, often referred to simply as a location service, to determine timely and accurate location information regarding the destination towards which it can route.

Since vehicles move at high speeds and with driver behaviour and traffic conditions resulting in multiple possible routes to a destination, the design of a robust and accurate location service protocol that can monitor the locations of vehicles and reliably answer location queries constitutes a significant challenge. Without such a location service protocol to ensure location server availability and query resolution, geo-routing ultimately fails. Furthermore, inaccurate location information will invalidate the operation of the geo-routing algorithm leading to incorrect forwarding decisions.

Additionally, even if an idealised location service is assumed, which is a common assumption in quantitative geo-routing evaluations, packet delivery is not guaranteed due to the frequently disconnected nature of VANETs. Therefore robustness of the geo-routing protocol, in order to maximise packet delivery, is also paramount.

It should be further noted that all too frequently either the location service protocols or the geo-routing protocols that use them, only consider fully distributed networks and are not equipped to avail of road-side infrastructure, if available, to maximise packet delivery. The alternative scenario is that they assume the existence of full infrastructure and ignore the consequences of frequent network disconnections. Few geo-routing or
location service protocols can adapt to operate in fully distributed, partially equipped or fully infrastructure based topologies. As a fully deployed RSU infrastructure may not be economically feasible in the short term, partial infrastructure in urban environments is a more imminent reality, particularly in the early years while vehicular networks are being adopted. Not only does the utilisation of RSUs in multi-hop routing facilitate wide area vehicular communications as it can be assumed that RSUs are connected via high bandwidth links, but it can also overcome holes in the network to improve the delivery rate for short distance communications. Commitment for such infrastructure has been made by car manufacturers, comprising the Car-2-Car Communication Consortium, who signed a Memorandum of Understanding (MoU) to make V2X technology available from 2015 [10]. Furthermore it motivates the need for interim routing and location management solutions over partial infrastructure.

1.2 Research Challenges

As previously stated, unicast geo-routing protocols are reliant on a robust location service protocol to successfully seek the destination vehicle’s location. Furthermore, successful V2X communication is reliant on the geo-routing protocol, if employed, to successfully deliver the packet. Geo-routing is the preferred method of routing in vehicular networks due to its stateless behaviour, scalability and suitability for high node mobility over traditional routing techniques [11,12]. In both cases successful packet delivery and robustness of the protocols is paramount, the failure of either renders communication useless.

Location service protocols suffer from a number of challenges, including the maintenance of high and accurate query success rates while minimising overhead, inability to deal with frequent network voids and disconnections as well as the inability to accommodate locality of communication between nodes. For the most part, location services have traditionally focused on proposing and evaluating the asymptotic costs associated with location update and query mechanisms. They often assume a node exists in the range of a location to act as a distributed location server and disregard or do not adequately address the non-uniform disconnected nature of VANETs. However the success of a location
service protocol is only feasible if connectivity to the location server is provided. It will be unable to reliably facilitate V2X communication unless it is robust and ensures the high availability of location servers in order to maximise the receipt of location updates and accurate query resolution. Many existing schemes do not provide adequately robust algorithms, ignore the consequences of frequent disconnections, only consider ad-hoc networks and are not equipped to avail of road-side infrastructure to maximise delivery [12, 108, 111, 113-132]. In order to deliver a robust service, a location service protocol should be able to dynamically adapt across fully distributed, hybrid and infrastructure based vehicular network to facilitate query resolution. This remains an open challenge.

Also key to the provision of a reliable location service protocol is the ability to handle the "locality" problem, defined by the authors in [13] as a scenario where the requested location information is stored potentially far away from both the source and destination nodes even when they are in close proximity, causing high overhead on update and query operations. More importantly than the issue of high overhead is that the lack of locality awareness can impact the reliability of the scheme as updates and queries may need to travel long distances, particularly in flat location service protocols, increasing the likelihood of unsuccessful delivery. Existing hierarchical schemes tackle this problem by using a hierarchical distribution of location servers to enforce locality of operation but fail to consider non-uniform wide area queries and frequently disconnected communication paths. Thus, the challenge in the immediate future is the design of a location service protocol that is both locality aware and robust to maximise query resolution and successful receipt of updates and that can exploit the presence of infrastructure if available.

Once the location of the target node has been determined, reliable routing is required to deliver the packet to the destination. As previously noted, interim or partial infrastructure is likely in the near future and a routing protocol that can adapt its routing decisions to exploit infrastructure where available in order to improve packet delivery does not currently exist. Not only does the utilisation of RSUs in multi-hop routing facilitate wide area vehicular communications as it can be assumed that RSUs are connected via high
bandwidth links, but it can also overcome holes in the network to improve the delivery rate for short distance communications. This can facilitate wide area routing.

Thus, packet routing represents a significant challenge in VANETs due to the inherent vehicle mobility and lack of a connected route through the multi-hop network. To facilitate packet routing, the source vehicle should be able to firstly accurately locate the destination vehicle, and secondly reliably route, availing of infrastructure if available.

Therefore the goals of this thesis are two-fold:

- The proposal of a routing protocol that can be transition easily from infrastructureless to fully infrastructure based networks. This protocol should be able to modify its routing decisions, exploiting infrastructure where available, but should be able to adapt to the current environment and not dictate rigid constraints on RSU density or placement. Most importantly, it should prioritise successful packet delivery, making as much use of infrastructure as possible, particularly with low vehicular densities and without incurring increased delays. Such a routing protocol is necessary as there is currently no single approach that identifies itself as a general purpose geo-routing protocol that will dynamically adapt as infrastructure is slowly deployed.

- The proposal of a vehicular location service protocol that should maximise receipt of location update and query packets to provide reliable and accurate resolution of a target vehicle’s location. It should also account for the distance between a source and destination vehicle so that querying the location of the destination does not incur unnecessarily long path lengths, diminishing likelihood of packet delivery. Similar to the geo-routing protocol, such a location service protocol should exploit infrastructure where available and most importantly should scale as new infrastructure is introduced. If such a location service protocol is not made available in the transitory period between completely ad-hoc to infrastructure
based networks, poor location resolution and accuracy will limit the potential for successful geo-unicast applications.

1.3 Thesis Contributions

To address the afore-described shortcomings and fulfil the outlined goals, this thesis studies inter-vehicular communication in vehicular networks, as it relates to both challenges: vehicle location management and robust packet routing.

Overall, the main contributions of this thesis are as follows:

• A hybrid geo-routing scheme, the *Infrastructure Enhanced Geo-Routing Protocol (IEGRP)*, that exploits infrastructure where available to prioritise packet delivery and functions in completely distributed, partially connected and fully infrastructure based networks. Pre-defined RSU placement is not required.

• A locality aware and robust location service protocol entitled the *Urban Vehicular Location Service (UVLS)* that is designed to prioritise receipt of location updates and successful query resolution. Unlike previous location service schemes that are typically fully distributed or centralised only, UVLS functions over hybrid vehicular networks with its performance further optimised via location caching/opportunistic location resolution and passive updates.

• A comprehensive IVC simulation environment for the quantitative simulation of V2X communication, that requires the implementation of comparative geo-routing and location service protocols as well as accurate modelling of radio propagation, vehicle mobility and vehicular networking standards.

To support the primary contributions of this thesis, a large body of additional research was required and this can be considered as two secondary contributions including:

• A review of distributed and infrastructure based vehicular geo-routing and location service protocols.
Chapter 1: Introduction

- A thorough evaluation of the suitability of the protocols proposed in this thesis with comparative vehicular protocols and a discussion of their overall performance. Traditionally location service and geo-routing evaluations are often compared against MANET equivalents or previous iterations of the protocol under evaluation.

1.4 Thesis Outline

The outline of this thesis is as follows:

Chapter 2 presents the current state of the art in IVC systems with respect to the underlying technologies, international standardisation activities and research projects, as such standards are common to all proposed communications architectures. Particular attention is paid to international standardisation activities to provide clarity and context relating to the IVC concepts underpinning the proposed geographic routing and location service protocols. The concepts behind geographical routing are next discussed together with a categorisation and review of the most significant infrastructureless and infrastructure assisted protocols as well as a discussion of their limitations, thereby deriving the motivation for the geo-routing protocol proposed in this thesis. The concepts behind location management are next described with a categorisation and overview of infrastructureless and infrastructure-assisted location service protocols provided, highlighting the motivation of the proposed location service protocol. Finally a review of the quantitative simulation environment and parameters commonly considered by state of the art geo-routing and location protocols is described, highlighting the need for a comprehensive vehicular simulation environment, as described in Chapter 4.

Chapter 3 introduces a hybrid geo-routing protocol known as the Infrastructure Enhanced Geographic Routing Protocol (IEGRP) that exploits the existence of Road-Side Unit (RSU) infrastructure where available to provided significantly improved packet delivery rates. Secondly the Urban Vehicular Location Service (UVLS), a locality aware and robust location service protocol is provided. This chapter describes in detail the structure and operation of these proposed protocols.
Chapter 1: Introduction

Chapter 4 presents a comprehensive simulation environment for inter-vehicular communication systems and the evaluation of the proposed protocols. Making use of existing network and traffic platforms, the implementation of numerous simulator extensions are described providing a complete vehicular framework that accurately models all aspects of a realistic vehicular environment. Aspects such as mobility modelling, channel modelling, application modelling as well as the evaluation scenarios with respect to vehicular and infrastructure density, are specifically considered. This chapter also discusses Discrete Event Simulators (DES) network and traffic/mobility modelling simulation packages, outlining the reasons behind the packages of choice and provides a comparative analysis of the chosen simulation framework parameters and models against those of the most significant comparative protocols.

Chapter 5 presents simulation analysis to highlight the significance of the proposed IEGRP and UVLS protocols under a variety of network and traffic conditions. A subset of the routing and location management techniques discussed in Chapter 2 are further considered and used for comparative purposes in the simulation study. Simulation analysis highlights the benefits of the proposed protocols in terms of improved packet delivery and query success rates across realistic vehicular environments.

Finally, Chapter 6 summarises the main conclusions that can be drawn from this thesis, and indicates possible future directions for the presented research.
Chapter 2: Literature Review

2.1 Introduction

Wireless communications and networking is a key enabler for the next generation of Intelligent Transportation Systems (ITS) that rely on cooperative vehicular or IVC systems. Such systems are based on the wireless exchange of information between vehicles (V2V), as well as between vehicles and infrastructure such as RSUs, known as V2I. With commitment to bring V2X technology to market evidenced by the C2C-CC Memorandum of Understanding within the next 2 years [10], the eventual rollout of roadside infrastructure is clear. However experts predict deployment anywhere between 2015-2020 [14] and given that it is expected that sufficient built-in and retrofit smart vehicle penetration rates to support ITS V2V applications will not be available until 2025 [15], a hybrid approach that overcomes the inherent challenges of packet routing in vehicular environments with partial infrastructure is required. As a source vehicle needs to be able to accurately locate the destination node to enable packet routing, location management is also a vital area of study. This chapter is organised into 5 primary sections as follows:

Section 2.2 provides an overview of the proliferation of Intelligent Transportation System (ITS) standards, enabling technologies and international projects that are driving the development and adoption of IVC systems. This provides context while also summarising key concepts underpinning the IVC research presented in this thesis. Sub-section 2.2.1 provides a high level overview of standardisation activities specifically relating to routing and location management research.

Section 2.3 summarises the methodologies and generic operation of the routing techniques employed in multi-hop V2X communications. Sub-section 2.3.1 provides a categorisation and development timeline of current protocols, a survey of the literature in V2X routing and a summary of the drawbacks that exist in current approaches.
Similarly, Section 2.4 summarises location service protocol operation with sub-section 2.4.1 providing a categorisation and development timeline of techniques, a literature review and a summary of current protocol drawbacks.

Section 2.5 provides a concise survey of the quantitative evaluations provided by state of the art vehicular routing and location schemes, summarising their deficiencies in terms of the considered simulation environments and highlighting the need for a comprehensive cross-layer vehicular simulation environment, as presented in this thesis.

As a result of the discussions presented in Sections 2.4 to 2.6 inclusive, conclusions are presented in Section 2.6 highlighting the need for the protocols proposed in this thesis.

2.2 Cooperative Vehicular Systems: Technologies, Standards and Projects

Significant investment from industry, government and academia has led to the development of enabling technologies, with the standards and projects driving their development now outlined.

In 1999, following petition from the Intelligent Transportation Society of America (ITSA), the United States Federal Communications Commission (FCC), allocated 75 MHz of spectrum in the 5.850 - 5.925 GHz frequency band to be used for short to medium range wireless communication by ITS' known as Dedicated Short Range Communications (DSRC). Of the allocated 75 MHz spectrum, 5 MHz is reserved as a guard band and seven 10-MHz channels are defined, comprised of 1 control channel (CCH) and 6 service channels (SCHs). The CCH is reserved for high-priority safety and control data, while all other data is transmitted on the SCHs [16]. The use of the term DSRC was somewhat misleading as it had been in use since the 1980s in Europe and Japan for Electronic Toll Collection (ETC) [17]. In Europe, the European Committee for Standardisation (CEN), namely the Road Transport and Traffic Telematics (RTTT), had already allocated dedicated spectrum, used for ETC, in the 5.795-5.815 GHz band. Dedicated European frequency allocation for ITS applications occurred much later than in North America with the European Telecommunications Standards Institute (ETSI) [18]
allocating 30MHz (5.875 – 5.905 GHz band) in 2008. This is reserved exclusively for safety ITS applications, comprised of two SCHs and 1 CCH and was later extended for a further 20 MHz for non-safety applications (5.855 – 5.875 GHz band) i.e. two further SCHs. In Japan, the Association of Radio Industries and Businesses (ARIB) have allocated spectrum in the 5.770-5.850 GHz range. Unlike North America and Europe, Japan does not have separate control and service channels, instead allocating one CCH, as a result of historical ETC development. A wireless vehicular frequency allocation diagram was recently provided by Tsuobi [19], updated from the original provided in [20].

The standardisation of protocol frameworks for ITS' is still in progress and there is currently a proliferation of standards, particularly in Europe [21]. Numerous standardisation organisations and consortia are involved, with the leading bodies being the Institute of Electrical and Electronics Engineers (IEEE), the International Organisation for Standardisation (ISO) and ETSI. The ITS standards that they provide, in the form of IEEE WAVE, ISO CALM and ETSI ITS, are now described and are illustrated in Figures 2.1, 2.2 and 2.4 with respect to the commonly referenced 7 layer Open System Interconnect (OSI) communication model.

Following the DSRC spectrum allocation in North America, the American Society for Testing and Materials (ASTM) specified a simple three layer standard for high speed vehicular environments [22] based on IEEE 802.11. This was approved in 2003, after which further DSRC development in North America was overseen by two IEEE working groups (WGs):

- The 802.11p WG, formed in 2004, was responsible for the specification of access technology at the MAC and PHY layers, ultimately resulting in the standardisation of 802.11p [23]. This is an amendment to the IEEE 802.11a standard [24], in 2010. When compared to IEEE 802.11a, 802.11p utilises a channel bandwidth of 10MHz to better cope with high speed vehicular channel conditions.
Chapter 2: Literature Review

- The P1609 WG (releases 2006/2007) is responsible for developing standards for the LLC sub-layer and higher network layer. In order to do this, the 1609 family of standards was developed i.e. a protocol suite, for V2X communications called Wireless Access in Vehicular Environments (WAVE) [1] specifying services and interfaces for V2V and V2I wireless communications. There are six standards in this suite 1609.1-6.

The Society for Automotive Engineers (SAE) is working towards developing a minimum set of performance requirements for safety applications [25] along with a set of messages [26] for WAVE in North America. The WAVE architecture is illustrated in Figure 2.1. Within European ITS standardisation, two standardisation organisations are of particular interest: the ISO (ISO 204) and ETSI (ETSI TC ITS), with significant co-operation from the C2C-CC. The ISO Technical Committee 204 was formed in 1993 to cover ITS activities as the second standardisation body after CEN TC 278 (DSRC), with both regulated under the Vienna Agreement (VA) to ensure alignment. The ISO TC 204 is formed of 16 working groups, with the general ITS communications systems covered in WG16 (ISO TC204 WG16) [27].

![Figure 2.1: ITS Communication Architectures: IEEE WAVE](image_url)
This working group is dedicated to the development of a protocol suite architecture for Communications Access for Land Mobiles (CALM) [28], formerly known as Continuous Air-interface for Long and Medium range telecommunications. The CALM protocol suite is shown in Figure 2.2 and validated as a reference architecture in European ITS projects, CVIS (Co-operative Vehicular Information Systems) and SAFESPOT. The functionality of the architecture is defined in a series of ISO standards. The CALM Communication Interface (CI) [29] is equivalent to the OSI physical and data link layers describing access technologies. Unlike WAVE, it makes use of heterogeneous mature technologies such as satellite, 2G/2.5G/GPRS [30], 3G [31], Infra-Red [32], CALM M5 (addresses 802.11p and WiFi [33]) and WiMax, in addition to many sensing technologies. The CALM Network layer is equivalent to the OSI network and transport layers, comprised of IP and non-IP standards. The CALM IP networking standard [34] makes use of IETF (Internet Engineering Task Force) NEMO (NEtwork MObility) [35], based on Mobile IPv6 [36], which specifies a protocol for network mobility support i.e. maintaining IP connectivity and auto address configuration (as opposed to host mobility in Mobile IPv6). The CALM non-IP networking standard specifies CALM FAST for ad-hoc V2V routing, analogous to IEEE WSMP [37]. CALM defines a management layer [38] comprising 3 modules: A CALM interface manager, network manager and application manager.

<table>
<thead>
<tr>
<th>OSI Model</th>
<th>ISO CALM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>CALM FAST</td>
</tr>
<tr>
<td>Presentation</td>
<td>CALM IP</td>
</tr>
<tr>
<td>Session</td>
<td>Non-CALM</td>
</tr>
<tr>
<td>Transport</td>
<td>CALM Service Layer</td>
</tr>
<tr>
<td>Network</td>
<td>Network Layer</td>
</tr>
<tr>
<td>Data Link</td>
<td>Network Layer</td>
</tr>
<tr>
<td>Physical</td>
<td>TCP/UDP</td>
</tr>
<tr>
<td>CME</td>
<td>FAST</td>
</tr>
<tr>
<td>NME</td>
<td>Geo-Routing</td>
</tr>
<tr>
<td>IME</td>
<td>Other</td>
</tr>
</tbody>
</table>

Figure 2.2: ITS Communication Architectures: ISO CALM
The C2C-CC has also contributed towards the development of a common ITS protocol architecture (part of the ETSI TC ITS standardisation efforts discussed later in this section) and has been involved in V2X validation trials since 2001 [39]. The C2C-CC is a not-for-profit organisation comprised of European automotive manufacturers, partners and research institutions, whose goal it is to ensure a common European standard for vehicular communications, (safety applications) thereby safeguarding inter-vehicle operability. To this end, in 2007, the C2C-CC proposed the C2C architecture as part of its manifesto [40] as shown in Figure 2.3, detailing specific protocols. The left side specifies C2CNet, a geographic routing and addressing protocol with a C2C transport layer and 802.11p as an access layer. This primarily supports safety and traffic efficiency applications. The right column uses IPv6 network with mobility supported via NEMO to support Internet interaction. Pre-existing transport protocols TCP and UDP, are used. The middle column is designed to use both C2CNet and IPv6 simultaneously and has been specified via the FP7 GeoNet project, discussed later in this section and marked in blue in Figure 2.3.

Figure 2.3: ITS Communication Architectures: C2C-CC Architecture
Separately, in 2007, the ETSI TC ITS was established, comprising 5 WGs and responsible for developing standards for a complete protocol stack, following a similar approach to CALM [41]. ETSI TC ITS must also develop mitigation techniques to avoid interference with the ETC systems [42]. ETSI is different to ISO and CEN as it is a private institution (comprised of paying members). Similarly to the ISO approach, ETSI also considers multiple access technologies.

As a result of this proliferation of technologies, in May 2008 and October 2009, the European Commission released the ITS Action Plan [43] and an ITS mandate to the European Standards Organisations (ESO) [44] respectively, specifying the need for increased collaboration to realise cooperative ITS solutions. CEN TC 278 and ETSI TC ITS have jointly worked to satisfy this mandate of common ITS standards with CEN working with their international equivalent, the ISO TC 204. This resulted in the joint ISO/ETSI ITS Reference Architecture [45,46] released in 2010 and shown in Figure 2.4.

![Figure 2.4: ITS Communication Architectures: ETSI/ISO ITS Reference Model](image-url)
This architecture also includes work from major European projects such as COMeSafety, and GeoNet amongst other projects as well as the C2C-CC [47]. The access block is equivalent to OSI layers 1&2, the Networking & Transport layer is equivalent to OSI layers 3 and 4 and the Facilities block corresponds to layers 5, 6 and 7. On the networking side, ETSI supports CALM IPv6, CALM FAST (non IP) and a Geo-Networking Protocol for VANET communications, focused on geo unicast and geo-broadcast multi-hop solutions [48]. Multiple radio access technologies are considered.

ITS technology development is not just driven by standardisation. Academic research teams and profit/not-for-profit partners also play a large part in the development of ITS technologies with the European Commission (EC) funding a number of large ITS research projects via the EU Framework Programmes. Table 2.1 provides an overview of key projects detailing their duration, partners, funding programmes, budgets and reference URLs. This information has largely been sourced from the Community Research and Development Information Service (CORDIS) and the respective project websites. The most significant FP6 projects include Prevent, CVIS, SafeSpot and Coopers. The most heavily funded FP7 projects include HAVE-IT, teleFOT and euroFOT. Many of the most recent European ITS projects are dedicated to the consolidation of results from previous Proof of Concept (PoC) projects in order to bring ITS technology to the market:

The PRESERVE project, an FP7 funded project dedicated to providing security and privacy in V2X communications and whose results will be available for further Field Operational Tests (FOTs), combines results from preceding EU funded projects including SeVeCom (FP6), Preciosa, Evita and Oversee (FP7). Similarly, COMeSafety2 (FP7), another recently funded consolidation project, is focused on international ITS interoperability and further standardisation at ETSI and CEN. It builds on the first iteration of COMeSafety (FP6), the goal of which was to form an ITS communication architecture by amalgamating the findings of previous ITS projects including CVIS, GeoNet, Prevent, C2C-CC findings, SafeSpot and NoW amongst others. The consolidation from the first iteration of this project led to the standardisation of the
ETSI/ISO ITS Reference Station architecture shown in Figure 2.4. Similarly, DRIVE-C2X (FP7) leverages projects such as CVIS, SAFESPOT, COOPERS and PRE-DRIVE-C2X that provided proof of concepts for the feasibility of V2X safety and traffic management applications, with the goal of undertaking large-scale realistic field trials at multiple European test sites.

Similar ITS projects have been run in the USA (Vehicle and Infrastructure Integration (VII) [49], CICAS [50], SAFETRIP21 [51], PATH [52], VSC-A [53] (successor of VSC)) as well those undertaken in Japan (VICS [54], Smartway, ASV and ITS-Safety 2010). A more comprehensive overview of the ITS projects, architectures and standards undertaken in Europe, North America and Japan is provided in [27] as well as on their respective websites. An overview of the standardisation bodies, projects and regulatory bodies contributing towards ITS harmonisation is provided in Figure 2.5.

<table>
<thead>
<tr>
<th>Project</th>
<th>Years</th>
<th>Partners</th>
<th>Coordinator</th>
<th>Total Funding</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIDE [56]</td>
<td>2004-08</td>
<td>28 partners. Coordinator: Volvo</td>
<td>FP6, €12.6 million</td>
<td></td>
</tr>
<tr>
<td>PreVent [57]</td>
<td>2004-08</td>
<td>60 partners, 15 countries. Coordinator: Daimler AG</td>
<td>FP6, €54.1 million</td>
<td></td>
</tr>
<tr>
<td>HIDENETS [58]</td>
<td>2006-08</td>
<td>9 partners. Coordinator: Aalborg University</td>
<td>FP6, €3.6 million</td>
<td></td>
</tr>
<tr>
<td>COM2REACT [59]</td>
<td>2006-08</td>
<td>12 partners, 5 countries, Coordinator: Motorola Israel</td>
<td>FP6, €5.6 million</td>
<td></td>
</tr>
<tr>
<td>ATESST [60]</td>
<td>2006-08</td>
<td>10 partners, 4 countries, Coordinator: Volvo</td>
<td>FP6, €3.9 million</td>
<td></td>
</tr>
<tr>
<td>CyberCars-2 [61]</td>
<td>2006-08</td>
<td>12 partners, 6 countries, Coordinator: INRIA</td>
<td>FP6, €4 million</td>
<td></td>
</tr>
<tr>
<td>CVIS [62]</td>
<td>2006-10</td>
<td>61 partners, 12 countries, Coordinator: ERTICO</td>
<td>FP6, €41 million</td>
<td></td>
</tr>
<tr>
<td>SAFESPOT [63]</td>
<td>2006-10</td>
<td>51 partners, 12 countries, Coordinator: Fiat</td>
<td>FP6, €38 million</td>
<td></td>
</tr>
<tr>
<td>COOPERS [64]</td>
<td>2006-10</td>
<td>37 partners, 14 countries, Coordinator: Austria Tech</td>
<td>FP6, €16.8 million</td>
<td></td>
</tr>
<tr>
<td>SeVeCom [65]</td>
<td>2006-10</td>
<td>7 partners, 5 countries, Coordinator: Trialog</td>
<td>FP6, €4.5 million</td>
<td></td>
</tr>
<tr>
<td>GeoNET [66]</td>
<td>2008-10</td>
<td>7 partners, 5 countries, Coordinator: INRIA</td>
<td>FP7, €3 million</td>
<td></td>
</tr>
<tr>
<td>PRE-DRIVE C2X [67]</td>
<td>2008-10</td>
<td>23 partners, 9 countries, Coordinator: Daimler AG</td>
<td>FP7, €8.5 million</td>
<td></td>
</tr>
<tr>
<td>ROSATTE [68]</td>
<td>2008-10</td>
<td>18 partners, 11 countries, Coordinator: ERTICO</td>
<td>FP7, €4.7 million</td>
<td></td>
</tr>
<tr>
<td>PRECIOISA [69]</td>
<td>2008-10</td>
<td>4 partners, 2 countries, Coordinator: TRIALOG</td>
<td>FP7, €2.5 million</td>
<td></td>
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<tr>
<td>IETRIS [70]</td>
<td>2008-10</td>
<td>9 partners, 5 countries, Coordinator: Thales Communications</td>
<td>FP7, €4.5 million</td>
<td></td>
</tr>
<tr>
<td>FOT-NET [71]</td>
<td>2008-10</td>
<td>9 partners, 7 countries, Coordinator: ERTICO</td>
<td>FP7, €1.2 million</td>
<td></td>
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<tr>
<td>HAVEit [72]</td>
<td>2008-11</td>
<td>18 partners, 8 countries, Coordinator: Continental Automotive</td>
<td>FP7, €27.8 million</td>
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<tr>
<td>EuroFOT [73]</td>
<td>2008-11</td>
<td>28 partners, Coordinator: Ford</td>
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<td>E-FRAME [74]</td>
<td>2008-11</td>
<td>7 partners, Coordinator: Peter Jesty Consulting Ltd</td>
<td>FP7, €1.6 million</td>
<td></td>
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<tr>
<td>EVITA [75]</td>
<td>2008-11</td>
<td>12 partners, 5 countries, Coordinator: Fraunhofer</td>
<td>FP7, €6 million</td>
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<tr>
<td>TeleFOT [76]</td>
<td>2008-12</td>
<td>24 partners, 10 countries, Coordinator: VTT</td>
<td>FP7, €14.4 million</td>
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<tr>
<td>OVERSEE [77]</td>
<td>2010-12</td>
<td>8 partners, 4 countries, Coordinator: Escapei GmbH</td>
<td>FP7, €3.9 million</td>
<td></td>
</tr>
<tr>
<td>COMeSafety2 [78]</td>
<td>2011-13</td>
<td>11 partners, Coordinator: BMW</td>
<td>FP7, €2.9 million</td>
<td></td>
</tr>
<tr>
<td>DRIVE-C2X [79]</td>
<td>2011-13</td>
<td>34 partners, 13 support partners, Coordinator: Daimler</td>
<td>FP7, €18.6 million</td>
<td></td>
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<tr>
<td>FOTNET2 See [71]</td>
<td>2011-13</td>
<td>14 partners, Coordinator: ERTICO</td>
<td>FP7, €1.8 million</td>
<td></td>
</tr>
<tr>
<td>PRESERVE [80]</td>
<td>2011-14</td>
<td>6 partners, 2 support partners, Coordinator: University of Twente</td>
<td>FP7, €5.4 million</td>
<td></td>
</tr>
<tr>
<td>FOTsis [81]</td>
<td>2011-14</td>
<td>22 partners, Coordinator: Iridium</td>
<td>FP7, €13.8 million</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: European ITS Projects
To prepare policy decision for the safe deployment of cooperative vehicle systems, a lengthy process involving research projects (development and PoC), followed by field tests and then pilots must occur. As previously stated the focus of ITS projects at European level has largely migrated from PoC to FOTs. As evidenced with the funding of a number of FOT dedicated EU research projects e.g. EuroFOT, teleFOT, FOTNet, FOTNET2, FOTsis and DRIVE-C2X amongst others. A number of smaller national scale projects were also funded in past years and continue to be funded e.g. NoW and FleetNet.

This Section provides the context behind the standardisation activities, projects and, most importantly, technologies, underpinning ITS'. The next sub-section discusses the standardisation activities and technologies specifically relating to the geo-routing and location management contributions of this thesis.
2.2.1 Routing and Location Management

A particularly influential European vehicular project, of direct relevance to this thesis in terms of its geo-routing and location management capabilities, as well as its specification as part of the ETSI/ISO ITS reference architecture shown in Figure 2.4, is now discussed.

The EU funded GeoNet project was funded in 2008 and was tasked with producing a reference IPv6 geo-networking specification to push into standardisation organisations i.e. ISO and ETSI. It devised an architecture, set of scenarios, and protocols based on previously specified geo-routing protocol capabilities which directly contributed to the C2C-CC architecture (highlighted in blue in Figure 2.3) and the IPv6 capabilities specified as part of the ISO 21210 i.e. the CALM IP Networking standard [82]. Figure 2.6 illustrates the main functional components of the GeoNet communication architecture.

![Figure 2.6: Components of the specified GeoNet Communication Architecture, sourced from [82]]
The modules specified as part of the C2CNet layer shown in Figure 2.6 also drove the specification of the GeoNetworking layer outlined in the ETSI/ISO ITS reference architecture and highlighted in blue in Figure 2.4. Thus most of the GeoNetworking capabilities specified by the GeoNet project have since been taken over by ETSI TC ITS and are specified in [83,84]. The EU FP7 funded project CarGeo6 [85] is tasked with producing an open source implementation of IPv6 geonetworking as specified by the GeoNet project. As part of the Networking and Transport Layer in the ISO/ETSI Reference architecture, Geo-Routing is specified as the module tasked with geographic addressing and forwarding functions, i.e. routing a packet to destination node(s) located in a given geographic area. ITS architectures must also support Internet based communications in the form of IPv6. It is composed of the following three modules [86]:

1. **Geo-Position Calculation:**
   This module is tasked with node localisation.

2. **Geo-Routing:**
   This module is in charge of routing packets from a source node to a destination based on location. The geo-routing function is based on the GPSR (Greedy Perimeter Stateless Routing) routing algorithm. Numerous types of communication are specified in sub-modules a-e with a-c generally referred to as geocasting:
   a. **Geo-Unicast:** Routes data from a single source node to a single destination node for which the exact geographical location is known.
   b. **Geo-Broadcast:** Routes data from a single source node to all vehicles located in a specific geographical area.
   c. **Geo-Anycast:** Routes data from a single source node to any vehicle located within a specific geographical area.
   d. **Topology Broadcast:** Routes data from a single source node to all vehicles located at a certain distance in terms of hops.
   e. **Store and Forward:** Buffers the packet for a defined time period when greedy packet forwarding is not possible.

3. **Location Management:**
Manages location information amongst communicating nodes. Three sub-modules are specified:

a. **Beaconing**: Periodic transmission of packets to advertise presence to vehicles in the vicinity (contains the C2C-CC header with a positional vector).

b. **Location Table**: Local record of location information relating to neighbours and other potential destination nodes.

c. **Location Service**: Resolves the location of a destination node when no entry exists in the location table.

Thus the contributions in this thesis relating to geo-routing and location management, described in the next Chapter, directly add to identified functionality that is required as part of international ITS standardisation activities for OBUs and RSUs, highlighted in red in Figure 2.6. The next section details vehicular routing techniques, provides a categorisation of geo-routing protocols and summarises the nuances of individual geo-routing protocols.

### 2.3 Vehicular Routing Overview

Considerable research efforts have been focused on efficient routing techniques for V2X communications over the last decade. As V2X routing often involves multi-hop communications and Vehicular Ad-Hoc Networks (VANETs) share many common principles with Mobile Ad-Hoc Networks (MANETs), distributed MANET routing and location principals have been the focus of significant attention. However while vehicular networks are often seen as a specialised MANET, they have a number of highly specific characteristics, which provide unique routing and location service challenges, distinct from generic MANETs:

- **Highly Dynamic Network Environment** – The high speed of vehicles, potentially in opposite directions, can lead to highly transient wireless connections of a very short duration.

- **Frequently Disconnected Network** – Vehicle speed also contributes to high volatility in the connectivity of the network; an issue exacerbated further in sparse
networks. Thus a routing path through the network may not always exist. Connectivity is often explicitly assumed in the MANET routing solutions, an assumption that is not valid for vehicular environments.

- **Restricted Node Mobility** – Vehicles do not move randomly as is often assumed in MANETs. They follow a geographically constrained topology defined by the road layout/infrastructure with the behaviour of an individual driver impacted by the vehicles surrounding it.

- **Potential Infrastructure Support** – Unlike MANETs where the possibility of infrastructure is rarely considered, infrastructure in the form of Road-Side Units, attached to existing transportation infrastructure such as traffic lights, can be considered although the density of this infrastructure is uncertain due to cost and deployment issues.

- **Challenging wireless communications environment** – Vehicular environments, particular urban areas, present unique wireless challenges that can impact packet delivery. Diminished wireless links from trees, buildings and other motorists along with Non Line-Of-Sight (NLOS) communications must be carefully considered when evaluating communication protocols as opposed to the simplistic deterministic channel models assumed in many MANET evaluations.

Other distinct VANET characteristics include ample energy and storage, high application Quality of Service (QoS) criteria (particularly in terms of safety applications) and significant interaction with on-board sensors.

As a result of these unique criteria, MANET routing solutions may not generalise well to a vehicular environment. Traditionally, MANET routing protocols use topology driven approaches in the form of proactive, reactive or hybrid schemes. However such techniques have been shown to perform poorly in high speed, frequently disconnected vehicular environments (discussed further in the next section) [87]. Thus there is a common consensus that geo-routing protocols are the de facto routing technique employed and as such geo-routing forms the prevalent basis for most vehicular routing protocols.
When employing geo-routing, a node needs to be aware of three pieces of information in order to make a routing decision:

- Its own position via GPS or some form of self-configuring localisation system.
- The destination location, typically obtained via some location service protocol.
- The position of local one hop neighbours via periodic beaconing. These beacons can simply include the vehicle’s ID and its position or can be extended to include position and motion vectors.

Therefore the node’s own location, the target device’s position and its one hop neighbour location are typically the minimum requirements needed to make a next hop routing decision although some routing protocols make use of additional information such as the road topology and traffic densities to make their next hop routing decision, as discussed later in the chapter. There is general consensus that every hop should enable the packet to make forward progress towards the destination i.e. decreasing the geographic distance between the source and destination. This is often referred to as greedy routing. In the case where greedy routing is not possible i.e. there is a temporary network disconnection often known as a “void” or the “local maximum”, a recovery scheme should be employed. Therefore a geo-routing protocol needs to operate in two modes:

- A forward routing mode e.g. greedy forwarding or advanced greedy derivative, which routes the packet geographically closer to the destination.
- A recovery mode that overcomes temporary network disconnections.

2.3.1 Routing Protocol Categorisation and Summary

Vehicular routing protocols can be categorised according to their communication paradigm: broadcast, multicast, geocast or unicast. This is in alignment with the communication types specified by the Geo-Routing module of the GeoNet project. A classification of VANET routing protocols, for all paradigms, is provided in [88]. Of these, unicast routing protocols are the most challenging to find a stable route between source and destination vehicles. As this thesis addresses vehicular unicast
communications only, a review of existing unicast vehicular routing protocols will be provided. Vehicular unicast routing algorithms for ad-hoc networks have been addressed by many researchers with a proliferation of survey papers existing in this space: (2001: [89], 2007: [90], 2008: [91, 92, 93], 2009: [94], 2010: [95, 96, 39], 2011: [97, 98, 99, 27], 2012: [100, 101, 102], 2013: [103]). However current taxonomies vary greatly, a common categorisation does not exist and as existing taxonomies do not include infrastructure assisted vehicular routing protocols, either in the form of partially or fully equipped geo-routing schemes, a new categorisation has been specified in Figure 2.7. It should be noted that a new category has been included, entitled “Infrastructure Hybrid” and highlighted in blue in Figure 2.7. The geo-routing protocol proposed in this thesis is designed to operate in this new category as it can transition between distributed and infrastructure based routing.

Figure 2.7: Categorisation of V2X Unicast Routing Protocols
Chapter 2: Literature Review

Unicast routing protocols can be categorised into distributed or infrastructure-based depending on the existence of static RSUs to aid in routing packets using a backbone network. The author of this thesis has also included a new category for hybrid schemes such as the proposed routing scheme which will be outlined in the next chapter.

In distributed approaches, a node must utilise multi-hop wireless links between nodes within radio range of each other to deliver packets. Distributed routing protocols can be further classified as topological, beacon based or contention based.

The first category, topology based protocols can be further classified into proactive, reactive and hybrid schemes. In proactive schemes, each node periodically transmits control packets to maintain links between nodes and keep an up to date routing table. In reactive schemes, a node only discovers a route to a destination 'on demand' i.e. when there is a requirement to transmit a data packet. Hybrid schemes also exist that combine both techniques i.e. typically a global network reactive approach and a local network proactive approach. Topology based proactive (routing table based), reactive (on demand) and hybrid (combination of the aforementioned approaches) routing protocols do not perform well in highly dynamic wireless ad-hoc networks as they require high overhead to maintain convergence and to establish a path through the network.

The second category refers to beacon based routing which can be further sub-divided into position based and trajectory based routing. Beacon based schemes rely on the periodic transmission of short beacon packets so that nodes can build a ‘neighbour’ table of devices within their radio range. Entries in the neighbour table are time, with entries phased out according to a beacon interval to prevent stale entries. Packet routing decisions are made based on their neighbour table. Position based routing refers to forwarding decisions made based on the physical location i.e. geographical coordinates of the source and destination vehicles. Trajectory based routing combines aspects of source based routing with greedy forwarding. Source based routing allows the source node to specify a routing path of forwarding nodes through which the packet will traverse to the destination. This approach is not viable in mobile networks due to constantly changing
routing topology as a result of node mobility. However in a vehicular network, a forwarding path can be specified based on the geographical route that should be taken which is stable due to physical characteristics of the road network. This geographical route, referred to as a trajectory (as opposed to forwarding nodes) is included in the packet header. Within position based or trajectory based forwarding, routing schemes can be opportunistic (also known as delay tolerant) or non-delay tolerant. *Opportunistic routing* represents another category of protocol. As connectivity between the source and destination cannot be guaranteed at all times, particularly in sparse and partitioned vehicular networks with low penetration rates, opportunistic schemes opt for a store and forward strategy rather than an explicit recovery strategy. The main premise is exploit the mobility of vehicles to deliver packets such that if no suitable forwarding vehicle is available, the node stores the packet, carries it for a period of time and forwards the packet when another more suitable node is in its radio range. Beacon-based routing protocols can be further categorised as overlay based schemes or non-overlay approaches. *Non-Overlay* approaches treat all nodes equally in the routing process. The alternative to this is an *Overlay* approach where certain nodes have extra responsibilities or a more important role in the routing process. Importantly, this term is borrowed from Peer-to-Peer (P2P) and Distributed Hash Table (DHT) research which uses a similar term with relation to super-peers. Coincidently some of the routing schemes that will be outlined in the next section and part of the geo-routing protocol proposed in this thesis employ an actual overlay (using the P2P meaning of the term).

*Contention based* schemes, also often referred to as receiver based forwarding, do not require periodic beacon transmissions, with source vehicles instead broadcasting a packet with each node determining whether it should forward the packet based on a distributed contention process.

*Infrastructure based* schemes, rely on a fully deployed high speed backbone infrastructure to route packets and do not have capabilities to deal with partial availability.
Finally, as previously stated, a new category, *Infrastructure Hybrid*, has been specified for the geo-routing protocol proposed in this thesis that is designed to modify its routing decisions depending on whether infrastructure is available and whether it is operating in distributed or infrastructure mode will maximise packet delivery.

In literature, many geo-routing protocols have been proposed for MANETs and sensor network environment as well as vehicular specific schemes. These do not perform well in a highly dynamic vehicular environment, as already outlined and thus the operation of these protocols is not considered in the subsequent section. However it should be noted that many vehicular schemes have been proposed based on modification to MANET schemes. Therefore certain key schemes that form the basis for a vehicular routing protocol or those that act as a comparative basis of many vehicular simulation evaluations are described.

Specific vehicular geo-routing protocols are now considered with a timeline depicting their chronological development shown in Figure 2.8. The authors in [104] also chronically classify protocols (though not as comprehensively) but with the express purpose of identifying the potential influence between schemes over time. In Figure 2.8, vehicular specific distributed routing protocols are highlighted in orange, vehicular specific infrastructure assisted routing protocols are highlighted in green and the MANET routing protocol from which many vehicular equivalents are derived is highlighted in blue. While the operation of vehicular routing protocols is now considered chronologically, their relevant categorisation according to Figure 2.7 is also discussed.
2.3.1.1 Distributed Vehicular Routing Protocol Overview

Individual distributed routing protocols are now described as well as their categorisation and their performance drawbacks. The collective drawbacks of distributed schemes (and sub-categories) is then summarised in Section 2.3.1.1.1. As previously stated, current vehicular routing schemes are typically either completely distributed or are reliant on a fully deployed infrastructure located at prescribed locations.

The GPSR (Greedy Perimeter Stateless Routing) protocol [105] is the only MANET based solution discussed in this review and is a position based non Delay Tolerant Network (DTN) routing protocol. GPSR is the earliest geo-routing protocol specified for generic ad-hoc networks and is often used as a baseline comparative geo-routing protocol. When a packet needs to be transmitted and assuming the location of the destination is provided from a location service protocol, a node forwards the packet to whichever of its one hop neighbour is geographically closest to the destination node i.e. basic greedy forwarding. In order to circumvent temporary holes in the network, GPSR introduces the concept of the ‘perimeter routing’ recovery scheme, utilising the right-hand graph traversal rule. This recovery scheme specifies that when a node first enters
into recovery mode, its next forwarding hop is selected sequentially counter-clockwise to the virtual edge formed by itself and the destination. Subsequently, the next hop is chosen counter-clockwise to the edge formed by the current forwarding node and the previous forwarding node. The algorithm exits perimeter mode when a node is encountered that can greedily route to the destination. The right-hand rule requires that all edges are non-crossing, proposing either the Relative Neighbourhood Graph (RNG) or the Gabriel Graph (GG) [106,107] to get a planar network graph with no crossing edges. The primary drawback of GPSR relates to its recovery scheme. Perimeter mode routing is based on the assumption of a planar graph however this is susceptible to routing loops as nodes are mobile. This leads to long path lengths and possible unsuccessful packet delivery. Furthermore the basic greedy routing scheme does not account for the direction the forwarding node is travelling in.

The **GSR (Geographic Source Routing)** algorithm [108] was the first algorithm to combine greedy geo-routing with topological street map information and is a trajectory based, non DTN protocol. GSR constructs a shortest path route (based on Dijkstra’s algorithm) through the road network to the destination i.e. a graph of connected intersections, with packets routed greedily between intersections. This path of connected intersections (known as Anchor Points) is included in the packet header. The Reactive Location Service (RLS) [109], a MANET based location service, is used to determine the current location of the destination. This has been shown to suffer from scalability and delay issues when applied in a vehicular environment [110]. Importantly, GSR assumes a densely connected network to provide a multi-hop path and the situation where there are not enough nodes to forward the packet is ignored. GSR also makes uses of a flooding based location service protocol to identify the location of the destination and thus the overhead does not scale well as distance between the source and destination vehicle increases. GSR does not discuss how to maintain the path through the network as vehicles move nor handling the mobility of the source or destination vehicle. Thus the process of forming an anchor path needs to be performed for every transmitted packet. In its evaluation GSR assumes a high 500m radio range and the IEEE 802.11b MAC with a 2Mbps bandwidth.
The ASTAR (Anchor based Street and Traffic Aware Routing) algorithm [12], specified by Seet et. al, creates a path of anchor points, formed of intersections (similar to GSR) through which a packet must travel en-route to the destination and is a trajectory based, non DTN routing protocol. However ASTAR also considers traffic density via what they call either a “statically or dynamically rated” map. Using the statically rated map, ASTAR uses pre-configured information on city bus routes, which is assumed to imply a relatively stable high vehicle density and build a Dijkstra shortest path graph based on weighted edges. The number of bus routes on an edge dictates its weighting, with more routes representing less weight. A dynamically rated map is not pre-configured but is based on real-time traffic monitoring by RSUs. Between anchors, packets are routed by the default greedy algorithm. If a local maximum is encountered, ASTAR specifies a recovery method such that a new anchor path is computed. Furthermore to prevent the same occurrence of the local maximum repeating itself with subsequent packets, the street is temporarily marked as “out of service”, with this information disseminated throughout the network, preventing this street being used as part of an anchor path. When compared to GPSR and GSR routing protocols, ASTAR exhibits improved delivery rates because it selects paths with higher connectivity for packet delivery but at the cost of marginally increased delays due to possibly longer, but higher connectivity paths. A drawback associated with ASTAR is that it does not make decisions on a per packet stateless basis. It builds an anchor path through the network but this can potentially be built on static bus routes connectivity on a particular street cannot be guaranteed. Furthermore as packets will be primarily routed via vehicles on primary streets, bandwidth consumption on those streets will be high and could potentially lead to congestion. ASTAR is not equipped to be easily transitioned to an infrastructure based approach and in its evaluation assumes a high radio range of 350m.

The CBF (Contention Based Forwarding) scheme [111] is a greedy routing algorithm that does not require periodic beacon transmission and is a contention based routing scheme. When a source vehicle is transmitting a packet, it broadcasts to all neighbours in its radio range, with those nodes determining if they should forward the packet. This decision is based on a distributed contention process where a timer, $t$ is calculated based
on the forward progress this vehicle can make towards the destination i.e. the greater the forward progress, the shorter the timer. A vehicle thus forward the packet after $t$ seconds unless it overhears the transmission of a packet with the same ID by some other node. In this case, the timer is cancelled. Additionally, each node keeps track of the IDs of the forwarded packets to avoid sending duplicates. As it is possible that a vehicle may not hear another vehicle’s transmission of the packet, an area based suppression strategy is used to avoid packet duplication. CBF is partial to packet duplication. When quantitatively compared to the Position Based Routing (PBR) protocol [112], CBF incurs marginally improved delivery rates and much improved overhead. CBF, as a contention based broadcasting approach is not easily compatible with being modified to avail of infrastructure. Furthermore it is limited in its scalability due to its broadcast based approach and in its evaluation CBF assumes IEEE 802.11b MAC with a 2Mbps bandwidth.

Lochert et. al, the same authors as GSR, next proposed the **GPCR (Greedy Perimeter Coordinator Routing)** algorithm [113]. Similar to GPSR, it does not assume the use of a digital map or known road topology. Routing decisions are only made at junctions, with greedy routing employed between junctions with the express purpose of forwarding the packet to a node on the junction where a routing decision can be made. As a static road map is not available, nodes must infer if they are located at a junction in which case they assume the role of a ‘coordinator’, broadcasting their role i.e. ability to make routing decisions. This occurs in two ways: A vehicle has two neighbours that are with radio range of each other but do not list each other as neighbours and a correlation coefficient that shows when there is no linear relationship between neighbours (indicating location at a junction). At a junction, a coordinator vehicle makes a path forwarding decision i.e. an exit road from the intersection, it should route towards, based on default greedy behaviour. If a local maximum is reached, packets are greedily routed backwards to the nearest junction where the right hand rule is used, but using the street topology as the planar graph. A drawback of such an approach is that packets must always stop at a junction node for a routing decision to be made as it is not possible to bypass a junction, resulting in longer path lengths and inefficient routing. Furthermore, the right hand rule
has been shown to be prone to routing loops in highly mobile networks and there is costly overhead associated with the junction detection algorithm. In its evaluation GPCR assumes a high 500m radio range with the IEEE 802.11b MAC and a 2Mbps bandwidth. This scheme is only feasible for highly dense networks and to operate over sparse networks would need a high proliferation of RSUs located at intersections with the routing algorithm modified to route over a backbone network.

The VADD (Vehicle Assisted Data Delivery) [114] is a delay tolerant routing algorithm based on predictive vehicle mobility. A vehicle attempting to forward a packet, makes a routing decision in one of three modes (Intersection, StraightWay and Destination), depending on its current location. If a vehicle is located at an intersection, the exiting path from the intersection with the lowest packet delivery delay is chosen, with this path determined by parameters such as vehicle density, road distance and average vehicle speed. Once the forwarding path is chosen, the next hop vehicle is chosen according to one of the four variations of forwarding scheme specified by VADD. Location First Probe VADD (L-VADD) selects the vehicle located closest to the identified forwarding path, regardless of the direction in which the vehicle is travelling i.e. default greedy behaviour. Direction First Probe VADD (D-VADD) however chooses the vehicle that is greedily closest but also travelling in the direction of the identified forwarding path (may not be the closest overall). Multi-Path Direction First Probe VADD (MD-VADD) selects multiple vehicles travelling towards the forwarding path, analogous to multicast D-VADD. Finally Hybrid VADD (H-VADD) combines L-VADD and D-VADD so that L-VADD offsets the long D-VADD packet delays and D-VADD counteracts the L-VADD routing loops [96]. A drawback of VADD is that it assumes that a vehicle is aware of the vehicular density on the street on which it is travelling and that every node is aware of the average velocity of all other vehicles. The use of statistical traffic information is not real-time and does not account for unexpected changes in vehicular dynamics. Additional control overhead is incurred established a path and a second return path also needs to be formed. It should also be noted that in its evaluation that VADD assumes vehicles exchange beacons every 500ms. The beacon interval can have a notable impact on validity of stored one-hop neighbour location information. As greedy schemes are
designed to choose a forwarding node that makes the greatest forward progress they inevitably will choose a forwarding node as close to the periphery of their radio range as possible. If there is a large beacon interval there is a possibility that the one hop neighbour has moved out of range. The beacon interval of 500ms is not in line with the WAVE standard of 100ms.

The GeOpps (Geographical Opportunistic) routing algorithm [115] is a delay tolerant position based greedy algorithm where forwarding vehicles are chosen based on their suggested routes i.e. estimated destination, based on its likelihood to move the packet closer to the its final destination. The packet is opportunistically offloaded to any vehicle that has a shorter estimated arrival time to the packet destination, based on its pre-programmed route. Importantly, to correctly function, GeOpps assume that each vehicle has a pre-programmed route and destination available that is disseminated to other vehicles. When compared with GSR and the MoVe algorithm [116], GeOpps exhibits improved delivery rates and decreased overhead. The major drawback of GeOpps is its reliance on a pre-programmed route and furthermore the necessity for this pre-programmed route to be shared with other vehicles in the network which represents a privacy concern. Furthermore, GeOpps was evaluated with an IEEE 802.11b MAC and a beaconing interval of 5 seconds. As noted with VADD, a high beacon interval has the potential for choosing one hop forwarding vehicles that are no longer in range. A beacon interval of 5s is significant and assuming a vehicle is travelling at 50kph or ~13.8m/s, it could have travelled 69m out of radio range.

The CAR (Connectivity Aware Routing), proposed by Naumov et. al [117], is a non delay-tolerant greedy algorithm that does not require a location service protocol, as destination position discovery is integrated with the routing protocol. CAR specifies methods for destination location and path discovery, data forwarding and path maintenance [103]. In order to locate the destination and the path to it, the authors utilise an algorithm that they previously specified, entitled the Preferred Group Broadcast PGB, in [118], which is an amendment to the AODV route discovery process to minimise broadcast traffic. Once the path to the destination has been established, data packets are
greedily forwarded via the anchor points used in the Advanced Greedy Forwarding (AGF) algorithm (also specified in [118]). CAR uses the concept of a ‘guard’ to maintain a path given node mobility. Quantitative simulation highlights that CAR outperforms GPSR in terms of delay, overhead and delivery rate. As CAR is a Non-DTN approach it may be susceptible to failed packet delivery in a frequently disconnected network. Importantly, once a path is formed to the destination, it cannot adjust to a different path when the environment changes due to vehicle dynamics. Also increased overhead is incurred through the use of guard and anchor control packets and the forming the anchor path incurs additional delay. Furthermore CAR uses a tightly coupled location discovery approach based around the AODV path discovery using a limited broadcast.

Lee et. al specified the GPSRJ+ (Greedy Perimeter Stateless Routing) algorithm [119] which is an enhancement of GPCR. The same authors subsequently proposed GeoDTN + NAV and Louvre in 2008 and TO-GO in 2009, with one of the co-authors contributing to TrafRoute and ROAMER, infrastructure assisted methods described in Section 2.3.1.2. GPSRJ+ enhances GPCR by allowing forwarding nodes that are one hop neighbours of the junction nodes to predict the junction node’s routing decision i.e. exiting route. This is possible via two hop beaconing and allows packets to bypass stops at junction nodes. Dense network connectivity is assumed and GPSRJ+ is susceptible to the same drawbacks as GPCR, but with the benefit of shorter path lengths. GPSRJ+ is evaluated in a grid network only with a high vehicle transmission range of 371m and an IEEE 802.11b 2Mbps MAC.

The GyTAR (GreedY Traffic Aware Routing) algorithm [120], is similar in approach to algorithms such as GSR, ASTAR and GPCR in that it creates a path of intersections through which a packet must traverse to reach the destination. However rather than creating a static path through the network, similar to GSR and ASTAR, GyTAR chooses intersections dynamically. Intersections are chosen based on distance to the destination vehicle and traffic density, indicating connectivity. GyTAR is not delay tolerant, cannot avoid void areas of the network and thus does not perform well in a sparse network. Furthermore, similar to VADD, it operates on the assumption that a vehicle is aware of
the vehicular density of the street on which it is travelling from road sensors. This limits
the schemes applicability. Finally GyTAR uses the IEEE 802.11b MAC in its evaluation.

The GeoDTN+Nav (Geographical DTN Routing with Navigator Prediction) routing
algorithm [121] incorporates default greedy routing, the perimeter mode recovery scheme
proposed in GPSR (non DTN) with store and forward buffering (DTN) and so is a
position based hybrid algorithm. A vehicle can dynamically switch between a DTN and
Non-DTN recovery scheme depending on the connectivity of the network which it
estimates based on the number of hops the packets has traversed at that point in time, the
neighbour direction in relation to the destination location and the neighbours delivery
quality. The delivery quality is estimated through the Virtual Navigation Interface (VNI)
based on information gathered from the hardware. GeoDTN is limited in its basic greedy
approach, not considering advanced characteristics such as vehicle speed and density.
Furthermore it is susceptible to the same drawbacks as GPSR when it employs perimeter
mode routing i.e. routing loops. Vehicles have a high 350m transmission range and
packets are destined for fixed destinations only. An 802.11 MAC is assumed with a
2Mbps data rate.

Louvre (Landmark Overlays for Urban Vehicular Routing Environments) [122], a
scheme proposed by the authors of GPSRJ+, GeoDTN+NAV and TO-GO, is an overlay
based geo-routing scheme with intersections forming the DHT overlay nodes, known as
landmarks. These landmarks only join the overlay network if the traffic density of the
underlying network guarantees multi-hop vehicular routing between the overlay nodes.
This is based on a distributed traffic density estimation scheme used to determine the
existence of an overlay link. To route a packet to the destination, a vehicle forwards the
packet along a path of landmarks i.e. a path of intersections, to the destination. A vehicle
broadcasts the IDs of all its neighbours and the density of all the roads it has encountered.
Two recovery schemes are employed. For time sensitive traffic, packets can backtrack to
the second most preferred road or for delay tolerant traffic buffering can occur. While
Louvre overcomes the shortcomings of schemes such as VADD that uses statistical
density information by utilising real-time traffic density information, the broadcasting

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mechanism used to proactively obtain this density map leads to considerably increased overhead. When Louvre is evaluated nodes are assumed with 20% and 50% of them mobile at a given time and the rest assumed to be static and located at intersections for connectivity.

The ACAR (Adaptive Connectivity Aware Routing) protocol [123] proposes a routing algorithm that makes forwarding decisions based on the density of the routes. The decision is initially made on statistical route density but as the packet is forwarded, density data is collected in real-time and a new route can be determined. Thus this solution provides a hybrid solution of sorts to VADD and Louvre and is susceptible to the same drawbacks. ACAR is evaluated with a high vehicle transmission range of 400m and an IEEE 802.11b MAC.

Lee et. al, authors of Louvre, GPSRJ+ and GeoDTN+NAV, also propose the TO-GO (Topology-assisted Geo-Opportunistic Routing) protocol [124] which builds on their previous work in GPSRJ+ that bypasses junction nodes but also incorporates opportunistic forwarding, using similar time based contention methods as described in CBF (but requiring beacons). TO-GO, as a contention based broadcasting approach is not easily compatible with being modified to avail of infrastructure and inherits the shortcomings of GPSRJ+. TO-GO is evaluated using an IEEE 802.11b 2Mbps MAC.

The GOSR (Geographical Opportunistic Source Routing) protocol [125] is a trajectory based scheme where a list of junctions is computed based on Dijkstra’s algorithm and inserted into the packet header. The packet is initially routed on this premise but opportunistic routing is also used to choose a better route to the destination. As GOSR is another source based routing scheme that pre-determines a path through the network, its design is not compatible with transitioning between ad-hoc to infrastructure routing on a per packet basis. The transmission range of vehicles is undefined in the evaluation.
The RBVT (Road Based using Vehicular Traffic information) trajectory routing algorithms are presented in [126] with a reactive version (RBVT-R) and a proactive version (RBVT-P) proposed based on real-time traffic information. RBVT-R builds an on demand route, similar to AODV, by flooding a route request that appends the junctions to the path until it reaches the destination. The route reply will routed back to the source vehicle through this path of intersections, building a high quality path based on number of lanes, traffic flow etc. RBVT-R does not implement a delay tolerant buffering approach but rather when the local maximum is reached, the vehicle currently storing the packet will report the error to the source which will retransmit after a time period has elapsed. RBVT outlines a proactive alternative. Importantly, in a sparse network, such a timeout may lead to a high number of retransmissions and hence bandwidth congestion. Furthermore RBVT schemes do consider the changing vehicular dynamics when routing packets between a source and destination and the flooding based route discovery approach incurs high overhead. RBVT is evaluated with a high vehicle transmission range of 400m and an IEEE 802.11b MAC.

The PP (Position Prediction) position based routing algorithms [127] propose a series of improvements to the default distance based greedy forwarding algorithm. These include choosing a forwarding vehicles based on its predicted distance to the destination since the its last beacon (PP Strategy), choosing a forwarding vehicles based on predicted position including direction (PP Hybrid) and a combination of both (PP Greedy). PP algorithms are not designed to modify their routing decision to favour infrastructure if available and are evaluated with an IEEE 802.11b MAC assumed.

The RDGR (Reliable Directional Greedy Routing) position based protocol [128] uses a forwarding algorithm that instead of routing based on the greatest forward progress i.e. distance, calculates a score for each possible forwarding vehicles based on distance, speed, direction and link stability to ultimately choose the most suitable forwarding vehicle. The authors also propose the EBGR (Edge node Based Greedy Routing) protocol [129] which modifies this routing algorithm slightly by logically partitioning the radio range into bands and calculating the scores only for neighbours falling in the
outermost band. If no neighbours exist in this band, the scores for neighbours in the next band are considered and so on, moving closer to the source vehicle with each iteration. If no suitable forwarding vehicle exists, the packet is buffered. Both RDGR and EGBR are evaluated in 120s simulations, with the presence of an idealised location service assumed. An IEEE 802.11b MAC is assumed. Such schemes are not designed to avail of infrastructure if available and modify their routing decisions accordingly.

The GPUR (Greedy Perimeter Urban Routing) protocol [130] operates similarly to the GPCR protocol, previously described, in that a forwarding node is chosen at a junction based on particular road characteristics. However GPUR modifies this approach to consider 2 hop neighbours. GPCR does not consider vehicular specific topologies such as dead ends and thus cannot over the local maximum in such cases. It inherits the same drawbacks as GPCR and its performance is evaluated in 180s simulations with an IEEE 802.11b MAC assumed. The same authors next presented the RIPR (Reliability Improving Position-based Routing) algorithm [131] to reduce the possibility of reaching the local maximum. It was evaluated using the same simulation environment as previously outlined against GPSR and GPCR with improved results for the PDR noted. Most recently the authors have presented the GPGR (Grid-based Predictive Geographical Routing) protocol [132] which reduces the probability of the local maximum compared with GPUR by predicting the position of vehicles and selecting a forwarding node using a grid map based on the road topology. GPGR is evaluated using a IEEE 802.11b MAC and a vehicle radio range of 125m.

2.3.1.1 Distributed Vehicular Routing Summary

Setting aside scheme-specific drawbacks, distributed vehicular routing protocols are not designed to exploit infrastructure if available. Thus the forwarding routing algorithm will treat a RSU the same as any other vehicle in its neighbour table. It will choose a RSU as the forwarding node only if it is the node that makes the greatest greedy progress towards the destination. Furthermore these algorithms are not optimised to prioritise the transmission of packets over a high speed backbone network, rather than via the VANET, if available. These drawbacks present the motivation for a hybrid routing protocol that
can adapt its routing decisions in the presence of infrastructure with the routing protocol proposed in this thesis designed to overcome the drawbacks just outlined.

Very importantly it should be noted that despite these drawbacks, distributed geo-routing is the defacto routing technique specified in current ITS standards with the GPSR scheme specified as part of the GeoNet project and greedy routing with store and forward buffering specified as part of the ETSI TC ITS framework. For this reason and given that this thesis explicitly considers partial infrastructure, where there is still significant reliance on ad-hoc multi-hop communication, distributed schemes are evaluated as described in Chapter 5.

Importantly, it should be noted that many quantitative evaluations of distributed routing protocol performance presented in the previous section either do not specify or do not consider realistic simulation conditions with respect to MAC layer, channel models, transmission range and location service protocols amongst other parameters. This is discussed further in Section 2.5 and motivates the need for a comprehensive vehicular simulation environment.

### 2.3.1.2 Infrastructure-Assisted Vehicular Routing Protocol Overview

As previously stated, current routing approaches often provide a completely distributed routing solution. Very recently, the benefits of utilising fixed infrastructure as a routing complement to the vehicular ad-hoc network in order to improve reliable end to end multi-hop communications has been recognised. Individual schemes are now discussed along with their performance drawbacks with a summary provided in Section 2.3.1.2.1.

**Borsetti et al** [133] propose a routing improvement for the trajectory based GSR routing protocol (described in Section 2.3.1.1) by forming a path via RSU assisted anchor points and employing greedy forwarding along a pre-selected shortest path, assuming high vehicular density. This protocol, which is labelled as topology aware GSR, exhibits improved packet delivery rates over uniformly distributed density conditions when compared with CBF and GPSR. In non-uniform traffic density, the scheme is marginally
outperformed in terms of packet delivery by CBF (at cost of additional overhead) for non-optimal RSU deployments as the non-uniform RSU deployment diminishes their usage probability. However when RSUs are deployed in high density road segments, the scheme outperforms all others in the case of higher RSU deployments by increasing utilisation of RSUS between the source and destination. This is not the case with lower RSU deployments in non-uniform conditions. A pre-determined route to the destination is assumed, following the GSR scheme along with the assumption of a connected network. This approach neglects the case where there are not enough vehicles to forward packets when the traffic density is low.

**RAR (Roadside Aided Routing) [134]** proposes an approach that relies on widely deployed RSU coverage with communication mostly following a V2I2V paradigm. The road topology is divided into sectors, with a sector representing a road segment enclosed by RSUs. When entering a sector, vehicles are required to register their location with the closest RSU. The authors assume that a RSU is located at the entrance/exit points of each sector. RAR works on a route request/reply basis, similar to some traditional ad-hoc routing approaches. When a vehicle wishes to route, it broadcasts a route request within its sector. If the destination vehicle exists in the sector it replies, thereby establishing a route. However if the RSU receives the route request and the destination is not located in the sector it queries a central database and forwards the route discovery packet to all RSUs serving that sector. The RSU with the strongest wireless link to the destination will reply and the packet will be routed V2I2V. Quantitative simulation highlights that RAR outperforms k-hop routing [135] (k=6) in terms of overhead and delivery rate.

Notably, RAR assumes dense RSU deployment with the RSUs dictating the start and end of sectors and with multiple RSUs managing each sector. It does not outline a recovery scheme for partitioned networks or specify whether buffering is used, as it is based on the assumption of widespread infrastructure deployment. It implements its own proprietary route discovery mechanisms to identify the location of the destination and to establish the route, representing a tightly coupled routing and location service solution. Packets follow
this pre-determined route towards the destination. The authors evaluated RAR using 802.11 DCF with 2 Mbps bandwidth.

**SADV (Static Node Assisted Adaptive Data Dissemination in Vehicular Networks)** [136] employs a delay tolerant store and forward mechanism at RSUs so that rather than using the default store and forward approach that could perhaps cause a buffering vehicle to move a packet further away from its chosen destination, the vehicle can instead offload the packet to the RSU until a more suitable buffering vehicle comes into the radio range of the RSU or an optimal path is available. It relies on the assumption that a RSU is available at every intersection but that RSUs are not interconnected. This method is known as Static Node Assisted Routing (SNAR). The RSUs make a decision based on the best (most densely populated) forwarding link based on the Link Delay Update (LDU) transmitted between RSUs in order to make a real-time decision on traffic density in conjunction with statistical density information. The authors further propose using multi-path routing to improve the reliability of data delivery, entitled Multi-Path Data Delivery (MPDD). When compared with VADD and epidemic flooding, all SADV schemes exhibit less delay than VADD but more than flooding. The SNAR + LDU scheme incurs less overhead than VADD though this is not the case for SNAR + LDU + MPDD as a consequence of multi-path routing.

SADV also exhibits some drawbacks: It requires a RSU to be located at every intersection and in the case of partial deployment that they are located uniformly. It does not consider that static RSUs may be connected over a high speed backbone or via the Internet. When in radio range of the RSU, the vehicle carrying the packet queries the RSU for the optimal route to the destination (based on the minimum expected delay path) with the packet then greedily forwarded to another vehicle which makes the greatest forward progress in the correct direction towards this route, forwarded greedily to the static node or offloaded to the static node for buffering if a better forwarding node does not exist. Thus a basic greedy/buffering algorithm is assumed with no method for finding a preferred or alternative forwarding mechanism using the infrastructure network. SADV does not specify how it determines the destination node's location.
Similarly TrafRoute [137] also determines a pre-selected route with its partitioning scheme requiring an RSU to exist in each sector and does not require a location service protocol. It favours source routing over stateless greedy routing. The authors of TrafRoute state that while it proposes a sector based scheme, similar to RAR, TrafRoute has just one RSU per sector to facilitate inter-sector communications (unlike RAR that requires a high density of RSUs), with intra-sector communications facilitated via multi-hop V2V routing (in contrast to a V2I2V approach in RAR). When the route discovery features are compared to AODV, a decrease in delay and overhead is noted, however the evaluation is limited in its scope. In TrafRoute, the route is established before packet transmission and does not change. In TrafRoute, intra-sector communications is facilitated via multi-hop V2V routing with inter sector routing via the RSU network. As a path of Forwarding Points (FPs) i.e. intersections is established in advance, vehicles simply route greedily and when determining forwarding vehicles located within range of the FP, choose the vehicle with the highest Penetration Index (PI) i.e. the number of FPs the potential forwarding vehicle can reach. Thus a densely connect ad-hoc network is assumed and alternative routing techniques to overcome the shortcoming of standard buffering or the default greedy algorithm are not considered. TrafRoute requires a fixed number of RSUs (although not as many as RAR), distributed uniformly with one RSU per sector, although the sector partitioning scheme is not described. It is evaluated with vehicles using a 802.11b MAC.

Mershad et. al propose ROAMER (ROAdside units as MEssage Routers in VANETs) [138] which is similar in operation to TrafRoute but is designed to function in a sparsely connected as well as a densely connected network. ROAMER accomplishes this by making per hop routing decisions rather than determining a fixed route to the destination. ROAMER, like TrafRoute, does not require a location service protocol. It operates as follows: Vehicles exchange HELLO messages containing their current location, speed, direction and current timestamp which are rebroadcast within a vehicle vicinity threshold (set to twice the transmission range). This results in vehicle knowledge of two hop neighbours. Vehicles periodically register their location with their closest RSU, who must acknowledge this registration. The RSU vicinity is set to three times the radio range

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and this beacon information is then used by the RSU to deliver the packet (similar to a location service update). When a vehicle $s$ is sending a packet to a destination vehicle, it firstly checks its location table. If there’s an entry in the location table, it broadcasts the packet with a TTL set to $h + h$ where $h$ is calculated as the distance between the source and destination divided by the maximum radio range. The second $h$ is for reliability purposes. If there’s no entry in the location table, the packet is forwarded to the closest RSU. If the vehicle is in range of the RSU, the packet is sent as a unicast. However when multi-hop routing through the VANET, in order to reach the RSU, a source vehicle specifies a road path between its location and the receiver. When the vehicle wishes to offload a packet to its neighbours who are located greedily closer to the target destination, it multicasts for redundancy so that it sends to $k$ neighbours (multiple directions). This happens at every hop until the RSU is reached. Once the RSU receives the packet, if it has a location for the destination (meaning the destination vehicle is in its vicinity) it sends packet to the destination directly. However if no record exists, it uses a DHT (algorithm unspecified) to contact the RSU that is aware of the RSU responsible for the destination vehicle. This is possible as every time a vehicle joins a new RSU, the RSU must update the RSU in DHT is responsible for it. Once a RSU estimates a destination’s current position, it calculates $A$ (the area within which it should broadcast at the end). If the destination vehicle is on a straight road then $A$ is the circle with the destination’s estimated position at the centre and the radius is the estimated error. However in the more complex scenario, a destination vehicle could have deviated onto different roads if it encountered an intersection. Based on a map, the RSU will know the intersection where it may have deviated course. That intersection forms the centre of $A$ with the radius calculated according to an amended estimated error. When a vehicle receives the packet and is within $A$ it broadcasts. Once the destination vehicle is reached, it is expected to send an ACK back to the RSU, otherwise the RSU will retransmit the packet.

A quantitative evaluation where five uniformly distributed RSUs are considered, demonstrates improved delivery rates, reduced delay and comparable overhead when compared to RBVT-R over varying source destination distance ranges. In [139], Mershad et. al evaluated the same performance metrics but specifically considered varied distance
ranges between the source vehicle and its closest RSU (as opposed to V2V in the previous paper) as well as varied vehicle density (veh/m). In [140], the same authors present an extended analysis, jointly published with an author from TrafRoute. Unlike previous evaluations, in addition to RBVT-R, the authors compare ROAMERs performance against TrafRoute and SADV. Finally, in [141] Mershad et. al rename ROAMER to CAN DELIVER (Carry and forward mechaNisms for Dependable mEssage delivery in VanEnets using Rsus). Pseudocode for the algorithms is provided and a similar evaluation is presented. This work differs slightly in that the evaluation considers varied traffic jam densities, shown along with an evaluation of the results pertaining to the link between the source vehicle and RSU (the uplink connection), the RSU and the destination vehicle (the downlink) as well as the vehicle density (veh/m).

ROAMER is similar in operation to TrafRoute but is designed to function in a sparsely connected as well as densely connected network by making per hop routing decisions rather than determining a fixed route to the destination. However ROAMER also requires a high proliferation of RSUs with high coverage with most communication following the V2I2V paradigm given the networks size and RSU radio range considered in their evaluation. Furthermore the authors do not consider any QoS routing characteristics in ad-hoc multi-hop routing decisions. It does not implement a greedy unicast algorithm but rather utilises multicast for redundancy when utilising ad-hoc V2I or I2V routing, as well as bounded geo-casts when in range of the destination node, which incurs increased overhead. The multicast messages are based on a basic greedy default algorithm. Connectivity via high density is assumed as is widespread RSU deployment in prescribed locations as prerequisite to the correct operation of the protocol.

More recently, Kuo et. al presented RBNT (Relay-Based Node Tracking) [142] a node management scheme for R2V unicast transmissions. RSUs build a virtual backbone of relay vehicles. A high density of vehicles is assumed and maintenance between relay nodes is required. RBNT demonstrates improved round trip latencies when compared to AODV due to delays incurred during the AODV route discovery process. It also out performs GPSR as most packets are exchanged between adjacent RSUs.
2.3.1.2.1 Infrastructure-Assisted Routing Summary

Infrastructure-based schemes typically require dense RSU deployment in prescribed positions as a prerequisite to the correct operation of the routing scheme. This was noted for RAR (start and end of sector), TrafRoute (uniformly distributed with one RSU per sector), ROAMER (widespread deployment) and SADV (every intersection and in the case of partial deployment that they are located uniformly, no backbone connectivity). Such schemes are thus limited in their generic applicability across a wide range of road topologies that may have restrictions in terms of where RSUs can be deployed e.g. using existing infrastructure or may not lend themselves to uniform deployments. Thus a routing protocol that utilises infrastructure should not dictate a prescribed RSU deployment as this does not generalise well.

As described, routing protocols such as RAR, TrafRoute and ROAMER implement their own proprietary route discovery mechanisms to identify the location of the destination and to establish the route. Their solutions present tightly coupled routing and location service solutions. Packets must follow this pre-determined route towards the destination which it is statically determined and does not change, is reassessed at every intersection or the details of how it is determined are unspecified. This motivates the need for a vehicular routing scheme that works with any location service protocol that identifies the location of the destination with routing decisions made on a stateless per packet basis, rather than following a pre-determined route.

Importantly, current infrastructure based protocols do not typically specify a recovery mechanism i.e. when a route cannot be found in the ad-hoc network before reaching infrastructure or when a RSU does not exist where it is supposed to be located. RAR assume V2I2V with the widespread existence of infrastructure for each sector and outlining no multi-hop recovery scheme. SADV assumes an RSU are located at every intersection (though unconnected via a backbone), TrafRoute and Borsetti et. al do not specify a recovery scheme for multi-hop ad-hoc connections and ROAMER utilises multicast for redundancy when utilising ad-hoc V2I or I2V routing, as well as bounded
geo-casts when in range of the destination node, which incurs high overhead. Vehicular connectivity and widespread RSU coverage is assumed.

Similar to the discussion in Section 2.3.1.1.1, it is important to note that many quantitative evaluations of infrastructure-assisted routing protocol performance either do not specify or do not consider realistic simulation conditions as outlined further in Section 2.5. Specifically, in all of the afore-described state of the art infrastructure-based schemes, high vehicular density is assumed as is widespread RSU coverage to resolve the location of the destination. All of the afore-described schemes are designed to work well for particular network configurations e.g. specific vehicle or RSU density, but do not generalise well. Thus a routing scheme that can seamlessly transition between ad-hoc and infrastructure based behaviour and will not fail outright if certain conditions are not met, is required.

The described drawbacks of the current start of the art infrastructure based routing protocols presents the motivation for a routing protocol that can dynamically adapt its routing decisions between distributed and infrastructure based conditions, depending on the network topology under consideration at the time, in order to fulfil the most fundamental of routing objectives - packet delivery. Such a scheme should not dictate the network topology e.g. specific vehicle or RSU densities as this does not generalise well and limits its implementation. Such methods are not considered by current routing schemes.

The hybrid routing protocol presented in this thesis and described in Chapter 3 overcomes these drawbacks to meet the research challenges as outlined Section 1.2. It is important to note that fully infrastructure based schemes are not quantitatively evaluated in this thesis as the proposed scheme is designed to work over partial as well as full infrastructure and more importantly does not dictate prescribed RSU placement. Indeed the real-world road topology considered in Chapter 5 would not lend itself to uniform or prescribed RSU placements and thus a comparable evaluation would not be achievable. This would only be guaranteed by a grid based network.
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2.4 Vehicular Location Service Protocol Overview

As previously stated, when enabling V2X or 12X routing, the benefits of geo-routing, over its topology based counterparts, are widely recognised. However a geo-routing protocol is reliant on a location service protocol as a fundamental prerequisite for greedy routing. A source node uses a location service protocol, before the packet can be transmitted, to determine the position of the destination which is then included in the packet's header. Unavailability of the location service, either in terms of location server unavailability or lack of a stored destination location, results in failure for the routing protocol. Furthermore, it is vital that the location service provide timely and accurate location information for a requested destination node, as each node makes its routing decision based on destination position reported by the location service as well as the positions of its one hop neighbours. Inaccurate location information will lead to incorrect forwarding decisions in the operation of the geo-routing algorithm.

As outlined in the previous section, particular classes of geo-routing protocol do not employ a location service protocol. Instead they employ a route discovery mechanism similar to topological reactive protocols. However in such cases, this restricted flooding in the form of a route discovery phase is equivalent to the MANET location service protocol entitled the Reactive Location Service (RLS) [108]. This is susceptible to high bandwidth consumption due its flooding based approach that exhibits high overhead and low scalability.

A location service protocol is generally comprised of four parts, of all of which are necessary for it to function correctly:

1. **Location Server Election** - how to recruit and maintain nodes that will store vehicle locations.

2. **An Update mechanism** - the frequency with which location updates should be transmitted, identifying the location of the appropriate location server and how the updated location information should be disseminated.
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3. A Query mechanism - how to determine the location servers of a destination node and the query packet should be disseminated.

4. Location Server Maintenance - how location servers, if mobile, can be reliably located by vehicles and how location information can be exchanged between location servers.

Therefore a location service protocol will operate by electing location servers, using whatever location server election process is specified. Vehicles will register their current position with the location server either periodically, opportunistically or on demand. When a source vehicle wishes to transmit a packet and assuming the location of the destination is not already in the vehicle’s location table, it contacts the location server and requests that information i.e. a query. Once a reply is received from the location server, this information is inserted into the packet header and passed to the routing protocol for forwarding. Ultimately the goal of any location service protocol is to maximise the success rate of finding the accurate location of the queried destination while minimising the overhead associated with the location service maintenance process i.e. updates and queries. A large proportion of the location service proposed to date focus on reducing the overhead incurred – while this is a valid objective, it overlooks the primary and most important characteristic of a location service which is to maximise the delivery of accurate replies.

A plethora of location service protocols have been proposed to date and classified based on their strategies for selecting location servers, update and query schemes along with the number of nodes that act as location servers i.e. one or many. Many of these protocols are designed for a MANET environment and do not perform well when directly applied in a vehicular context. The high dynamism of vehicles and distributed location servers, restricted mobility patterns in accordance with the road topology, along with intersections, urban obstacles and wide area mobility are not compatible with the nuances of their update and query schemes and has a detrimental impact on performance. Vehicular equivalents have been proposed, often tweaked from a previously specified
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MANET location service protocol. In the next section location service protocols are categorised and individual schemes described.

2.4.1 Vehicular Location Service Categorisation and Summary

Location service protocols can be classified as either distributed or centralised (infrastructure based) in nature. While a classification has been provided in [143], it has been slightly redefined in Figure 2.9 to make reference to hash based approaches which is the more common term.

Distributed location service protocols can be further categorised as flooding based or rendezvous-based. Flooding-based techniques typically involve all or a large subset of the nodes in the network, for both location update and query. Such location services can be further divided into proactive and reactive schemes. In proactive schemes, each node periodically updates its location by flooding the network and if flooding is restricted within an area, queries will be directed to those areas. In reactive schemes, a node querying a location will flood the network using currently a recorded location or mobility information to target the scope of flooding. In rendezvous-based approaches, each vehicle’s ID is mapped to a rendezvous point, known as a location server, which is responsible for storing each vehicle’s location information either on periodic or reactive basis and responding to location queries. Rendezvous based location service protocols can be further categorised into quorum-based or hashed-based depending on the location server mapping used. In quorum-based approaches, a node issues a location update to a subset of available nodes known as the update quorum with a location query sent to a different subset of nodes known as a query quorum. The performance and scalability of the location service protocol relies on how well the update and query quorums intersect as well as their width and height, while ensuring the smallest overhead cost. In contrast to flooding, quorum approaches incur less communication overhead as no network-wide flooding is used.
A quorum-based location service protocol can be further classified as flat or hierarchical. In *hashed-based* location service protocols, a common hashing function is available on all nodes, which, given the ID of the target node, returns the position or geographic area of the location server. Location updates are sent proactively to the nodes located in or closest to that location. Hash-based location service protocols can be further classified as *hierarchical* with multiple location servers employed to reduce the cost of a location query, increase locality awareness, and robustness or *flat* approaches where a single location server exists.

In literature, many location service protocols have been proposed for MANETs and sensor network environment as well as vehicular specific schemes. Specific location service protocols are now considered with a timeline depicting their chronological development shown in Figure 2.10. This is worth noting as many of the vehicular schemes that have been proposed are based on modification of previously specified schemes. Vehicular specific location service schemes are highlighted in orange in Figure 2.10 with MANET location service protocols highlighted in blue. Thus, the operation of
vehicular location service protocols is now considered chronologically, with their relevant categorisation also highlighted.

![Location Service Protocol Development Timeline]

Figure 2.10: Location Service Protocol Development Timeline

Location Service protocols designed for generic MANET scenarios are not described unless their design explicitly forms the foundation of a vehicular equivalent scheme. The exception to this is the **Geographic Hashed Location Service (GHLS)** [144] as it is one of the comparative location service schemes simulated in Chapter 5. This MANET scheme is considered as it acts as a baseline comparison in numerous vehicular location service protocol performance evaluations. MANET designed location services include periodic flooding solutions such as SLS [145], DLS (location service for DREAM) [146] and SFLS [147] as well as on demand flooding protocols such as RLS [108] and HLLS [148]. MANET quorum based location services include XYLS [149], SEEKER [150], DQS [151], LLS [152] and DFLS [153]. Hashed location service protocols include hierarchical MANET solutions such as GLS [154], DLM [155], HLS [156], HIGH-GRADe [157], SLALoM [158], ADLS [159], HALS [160], MLS [161], VHLs [162], FHLS [163] along with flat approaches such as GHLS, SLURP [164], VPDS[165], GrLS and LBLS [166].
Individual vehicular location service protocols are discussed in the next section.

2.4.1.1 Distributed Vehicular Location Service Protocols

The Geographic Hash Location Service (GHLS) [144] is a flat location service designed for mobile ad-hoc networks. It is the only MANET based solution discussed in this review as it is often used as a baseline comparative location service protocol. Its main design objective is to reduce location management overhead (when compared to hierarchical and quorum based location services) and improve the packet delivery rate. A node/vehicle has only one location server in the network. This is chosen by hashing the vehicles unique ID to a randomly chosen set of co-ordinates anywhere within the network boundary, with the node currently closest to this location assuming the role of location server. Updates are transmitted towards the hashed server coordinates when a distance based update threshold $d$ has been exceeded. To facilitate the phasing out of stale update entries by a location server, each update packet has a timeout window specifying the validity of the packet. This timeout window varies per update packet and is calculated based on $d$ and the current speed of the vehicle at the time the update is issued. If the timeout window has expired by the time the update reaches the location server, the server simply discards the update. To query a vehicles location, a source vehicle will hash the queried destination vehicles unique ID using the same hashing function and will route towards the resulting location server co-ordinates. A reply will be routed directly from the location server to the source vehicle. In order to address locality GHLS specifies a mechanism whereby the generated hashed location server coordinates can restricted to a central part of the network specified by the product of the side length of the map and a configured alpha factor, $\alpha$. A thorough quantitative evaluation of GHLS with GLS and XYLS presents reduced overhead as a consequence of the flat nature of the scheme and improved delivery rates over GLS for increasing map sizes (comparable to XYLS). The flat nature of GHLS does not take vehicle locality into account with query packets potentially travelling large distances despite close proximity between the communicating vehicle pairs. While GHLS proposes an $\alpha$ factor to minimise this, as it is a MANET scheme this does not consider the restricted road topology. This can potentially impact
the delivery of update and query packets, decreasing the query success rate of the location service.

The **Intersection Location Service (ILS)** [167] is a flat location service and one of the few that attempts to address robustness rather than overhead optimisations by using an overlay network of vehicles at intersections. The proposed robustness exists in the unique characteristics of the DHT Chord algorithm [168] that exhibit resilience to empty areas of the network. Therefore unlike other location services, updates and queries will not continue to be transmitted to empty areas of the network. Using ILS as a location service, a node/vehicle has a single location server in the network i.e. intersection towards which it updates its location, though this information may be distributed amongst many vehicles to act as servers. This server is chosen by hashing the vehicles unique ID. The “Chord node” i.e. intersection, with the closest ID higher than or equal to this hashed vehicle ID will be responsible for assuming the role of location server. All vehicles within a given radius act as the location servers and are representative of a single virtual “Chord node”. It is assumed that all vehicles store the same location information by sharing the received location information via beacons packets. Updates are transmitted towards the closest intersection when a distance based update threshold \( d \) has been exceeded. Importantly, ILS update packets do not specify a timeout period for entries, thus a validity time is not indicated to the location server. Therefore the location information is never phased out and is simply updated if a newer update is received. The location server will return the most recent location information available when queried. To query a vehicles location, a source vehicle will transmit the query towards the closet intersection. The vehicle acting as a location server for the closest intersection hashes the queried destination vehicles unique ID using the same hashing function as above and routes towards the Chord node i.e. intersection with the ID closest to or equal to the hashed queried ID. A reply will be routed directly from the responsible location server to the source vehicle. As all vehicles within a given range of an intersection act as servers, explicit handover is not necessary if the vehicle moves out of range of the intersection. If a vehicle moves out of range it deletes its stored location information. However ILS does not address how to form the overlay, determine successor pointers, build the finger tables or address locality.
awareness. Furthermore it is not feasible to maintain the consistency of the overlay ring in a vehicular network with overlay inconsistency having a detrimental impact on performance. The quantitative evaluation considers a perfectly formed overlay and demonstrates significantly improved query success rates over GLS and HLS as a result of the dynamic overlay healing scheme. The Responsible Sections Location Service (RSLS) [169] presents a similar overlay approach to ILS making use of a distributed hash table and is susceptible to the same drawbacks as described with ILS. It also presents an improvement in query success rate over GLS and HLS. Both ILS and RSLS are evaluated using an IEEE 802.11b 11Mbps MAC and use GPSR with perimeter mode routing as the recovery mechanism to transmit location service packets. This suffers from drawbacks in a disconnected network. However the most notable drawbacks of these schemes is that they do not address how to maintain the consistency of the overlay network i.e. correct successor and predecessor points. These are necessary in order for the query to be routed to the correct location server. Maintaining the consistency of an overlay network is a challenge in a mobile environment and could potentially be impacted greatly if connectivity between overlay nodes i.e. intersections is not provided. Thus these schemes are based on the assumption of dense multi-hop connectivity.

The Map Based Location Service (MBLS) [170] provides a hierarchical hashed vehicular location service that closely resembles the Grid Location Service (GLS), a frequently compared hierarchical MANET location service, in its operation. MBLS partitions the entire area hierarchically into recursively smaller order squares where four order-i squares comprise an order-i+1 square and so on. A location server is elected by mapping the vehicle's unique ID to an intersection (referred to as a waypoint) at each hierarchy level. A vehicle updates its order-1 server which acts as a proxy for its higher order servers i.e. the order 1 server is then responsible for updating the order 2 server and so on. MBLS vehicles update their location servers after crossing every intersection and the validity time on the update is calculated based on the sum of the radio range divided by the current speed of the vehicle and the distance between intersections. To query a location, a vehicle a will start searching in its level 1 square by hashing the queried node's ID e.g. b to the closest intersection ID. If a location record for b is stored at the
node closest this point, a reply is returned directly to $a$. If not, the query will be forwarded to the closest intersection ID in the next higher level square and so on. Therefore a query can be resolved in a maximum of $i$ “hierarchical” hops. When a vehicle crosses a boundary in the hierarchy it must select new servers in its lowest order square and vehicle acting as the location server for that intersection will proxy it to the higher order server who in turn acts as a proxy node. Handover of location information occurs when a vehicle chosen as a mobile location server moves a distance more than half the transmission range from the intended intersection. MBLS differs from GLS in that it does not expect vehicles to move randomly, assumes that vehicles make use of a digital map, uses intersections as the basis for selecting location servers and makes use of a static hierarchy height of 3 with a single server at each hierarchy level (not one in each sibling square). MBLS does not consider robustness as it uses a static hashing algorithm that does not consider the situation where an intersection is empty in a particular order square. As with GHLS, MBLS does not deal with the situation where an intersection is empty in a particular order square as it uses a static hashing algorithm. The hierarchical update and query schemes rely on a chain of servers such that if any one of the servers fails, all subsequently higher order servers will also fail to receive the update or query packet.

The authors of MBLS subsequently proposed derivatives called **Density MBLS (DMBLS)** [171] and **Efficient MBLS (EMBLS)** [172]. DMBLS refines the original location server selection strategy by assuming vehicles have knowledge of network density information in order to select location servers at intersections with a high density of vehicles. EMBLS presents an adaptive updating technique and a localised query strategy. The authors compare EMBLS and DMBLS to each other but do not benchmark the performance against other vehicular location services.

All of the afore-described MBLS schemes are hierarchical which supports locality awareness. However they employ a chain of location servers with the network partitioned hierarchically. Thus if any one of the servers fail to receive an update, all subsequently higher servers in the hierarchy will also fail to receive the update. The scheme does discuss a recovery approach if a lower order square does not contain an intersection.
Furthermore MBLS’ update mechanism could potentially cause location inaccuracy in the presence of long roads and low speeds as vehicles update their location once they cross an intersection as opposed to on a distance basis as is commonly the case. Finally a drawback of hierarchical schemes and in applicable to this scheme is the potential for high overhead caused by frequent cross of boundaries in the portioned network.

The authors of the **Vehicular Location Service (VLS)** [173] propose a scheme that partitions the network into grids. A vehicle’s ID is hashed to a location server located in every grid so a vehicle has multiple locations servers. Vehicles update location servers in their local zone (area with side length three times that of the radio range) more frequently than location servers outside of this range. Queries are directed to the closest location server for that node from the querying vehicle with subsequent servers checked if a location does not exist (order of this method is not made explicit). When quantitatively compared to GHLS and GLS, VLS incurs improved query success rates as a result of its location server selection scheme, reduced delays as the location servers are not as susceptible to mobility and outperforms GHLS in larger networks as a result of its adaptive update policy. VLS will incur higher overhead than other schemes by maintaining a location server in every grid in the network. Furthermore such a partitioning method does not provide a solution that will generalise well with all road topologies. By delaying updates to remote grids, this can potentially lead to inaccurate location information on a remote location server. Furthermore the order in which alternative location servers are search if a query is not resolved at the nearest location server is not made explicit. An IEEE 802.11b MAC is assumed in the VLS evaluation.

The **ETSI TC ITS** standard defines a simple location service is proposed as part of the ETSI GeoNet project [83]. It adopts a restricted flooding approach with a location query rebroadcast amongst nodes with a maximum hop count of five from the source vehicle. This scheme thus only considers local queries within a five hop range, does not exploit the availability of infrastructure to cover greater distances to facilitate wide area queries and employs broadcast mechanism. It is not quantitatively evaluated.
QLSP [174] is a recent approach that uses a flat quorum technique where vehicles residing in the radio range of an intersection assume the role of a location server. Query packets are sent to intersection(s) that the destination vehicle's ID hashes to. When quantitatively compared against Self Organising Location Servers (SOLS) [175], ILS and Terminode [176], a marginal improvement in success rates are noted over SOLS and ILS. The scheme is not designed to exploit infrastructure to reduce path lengths and will be impacted by non-uniform traffic patterns. Furthermore location service locality is not considered. 300s simulations evaluate QLSP with an IEEE 802.11b MAC and a small 100m radio range.

2.4.1.2 Infrastructure-Assisted Vehicular Location Service Protocols

The afore-mentioned schemes discuss distributed location management protocols only. Vehicular location service protocols that utilise infrastructure have also been proposed and are now described.

The authors of a Region-based Location Service Management Protocol (RLSMP) [177] propose a hierarchical quorum vehicular location service, with a focus on overhead minimisation and locality awareness. RLSMP was the first vehicular location service to consider packet aggregation techniques. The network is partitioned into sections known as clusters with each cluster partitioned into cells and cells subsequently partitioned into cell elements. Every cell has a location server(s) known as a Cell Leader (CL) comprised of all the vehicles located in the central element of the cell. The CL is responsible for storing the location information of the vehicles in the cell and aggregating this information for forwarding to the Location Service Cell (LSC) which is defined as the central cell of a cluster, containing a fixed static location server. Thus RLSMP is a hybrid location service protocol combining distributed and infrastructure based techniques. LSCs are responsible for answering location queries with inter-cluster queries resolved using a spiral search pattern of LSCs until the required location is resolved. To optimise overhead, both update and query packets are aggregated and delayed. Accuracy of the location information stored at location servers is not evaluated, locality awareness is not considered between cells, requiring updates and queries to travel to the centre of the
cluster and a route is always assumed. When evaluated against SLURP, XYLS and HLS (MANET schemes) it exhibits the least packet loss and delay. Robustness of RLSMP is not considered as a route is always assumed. This is reflected in the authors evaluation with a constant density of vehicles enforced, a trait that is not always realisable given the disconnected nature of VANETs. Locality awareness is not considered between cells requiring updates and queries to travel to the centre of the cluster. The partitioning mechanism does not consider the underlying road topology. Furthermore the CL aggregates update packets and delays sending them to the LSC which could lead to inaccurate information stored at the LSC. Finally an unachievable radio range of 750m is assumed and the authors do not consider the phenomenon of “empty home regions” where nodes do not exist within a cell to assume the location server role.

The Hierarchical Location Service with Road-adapted Grids (HLSRG) [178] operates very closely to that of RLSMP and thus inherits its drawbacks, with the difference being that it employs a road-adapted method for partitioning the network into a grid accounting for the underlying topology and decreasing the number of location updates. Quantitative evaluation of HLSRG indicates lower location update and query overhead, improved query success rates and decreased query delays when compared with RLSMP which the authors attribute to the proposed partitioning scheme and the storage capabilities at RSUs. HLSRG assumes existence of RSUs in pre-defined locations. An IEEE 802.11b MAC is assumed with a 250m transmission range. While HLSRG compares against and improves RLSMP it does not provide a thorough evaluation or description of the environment.

The past authors of the MANET Group-based Location Service (GrLS) protocol [179], propose another vehicular quorum based location service entitled the Mobile Group based Location Service Management (MG-LSM) protocol [180] which also operates very similarly to RLSMP. It partitions the network (called regions instead of RLSMP clusters) placing a fixed node in each region (namely Region Heads (RHs) instead of LSCs) and elects a number of mobile location servers within the region that aggregate updates and communicate with the region head (known as Group Leaders (GLs) instead
of Cell Leaders (CLs)). A key differentiating factor is that it proposes a dynamic scheme whereby local location servers are elected based on the dynamics of group mobility (a single GL) rather than a fixed partitioning scheme of cells (all vehicles in the central cell element of a cell acting as CLs). Methods for dynamic group management i.e. joining, disbanding and merging vehicular groups are described. This improves location service overhead particularly in dense networks but inherits all the same drawbacks as previously identified with RLSMP which are not addressed in the quantitative evaluation. The performance of MG-LSM is quantitatively compared against RLSMP and a scheme which the authors entitle FRLSMP. FRLSMP can be considered to be analogous to MRLSMP (a scheme which is later described) except that FRLSMP assumes fixed nodes or RSUs. The analysis presents results solely focusing on the location management overhead and while it incurs a considerable improvement over MRLSMP, it indicates comparable or slightly worse location update overhead than FRLSMP. It is notable that the analysis presents results solely focusing on the location management with a 250m transmission range employed (channel model and MAC layer unspecified) and does not evaluate the protocol with respect to delivery rate and location accuracy. More recently the authors of MG-LSM present a Location Service using Vehicle Trajectory (LSVT) [181]. No notable differences in the location service algorithms can be observed so it is thus assumed MG-LSM was retitled and exhibits the same characteristics as previously described. An evaluation of only the overhead is again provided with an increased 300m radio range. This improves location service overhead particularly in dense networks but inherits the same robustness issues as previously identified with RLSMP which are not addressed in the quantitative evaluation.

 Saleet et. al, the authors of RLSMP, also specified a scheme entitled the Modified Region-based Location Service Management Protocol (MRLSMP) [182]. Unlike RLSMP, MRLSMP is an infrastructure based location service where every Cell Leader is designed to be a fixed RSU reducing the overhead associated with mobile Cell Leaders. When compared to SLURP, HLS and XYLS location service protocols, MRLSMP exhibits less update overhead by employing message aggregation. The analysis further shows reduced query overhead in contrast to compared schemes, by
incorporating locality awareness by forwarding query packets to RSUs in the vehicle’s vicinity. However a wired backbone network is not considered. Furthermore, MRLSMP is only evaluated with respect to overhead with no evaluation of packet delivery rate or location accuracy shown. Aggregation and delay techniques could impact location accuracy at the location server, in turn impacting routing packet delivery rates.

The authors in [183] consider a hybrid centralised approach using fixed RSUs and nodes with WiMaX interfaces. More recently Li et. al [184] propose a scheme similar to RLSMP with RSUs forming an overlay network that also makes use of historical data. When quantitatively compared to RLSMP, it exhibits improved latencies in query response and close to comparable communication overhead over a variety of map sizes. Importantly, the scheme demonstrates significantly improve success rates by utilising historical location data. Finally, Katsaros et. al [185] propose two cloud based location service architectures, one that utilises 802.11p as the access network and another that utilises a cellular network.

### 2.4.1.3 Summary and Discussion of Vehicular Location Service Protocols

In this thesis, a quantitative evaluation is conducted against the C2CNET (a restricted vehicular flooding approach), GHLS (a flat MANET hashing technique), MBLS (a hierarchical VANET hashing technique) and ILS (a flat VANET overlay technique).

Many of the vehicular location service protocols, described Sections 2.4.1.1 and 2.4.1.2, both distributed and infrastructure-based, have focused on proposing and evaluating the asymptotic costs associated with update and query mechanisms [173,177,178,180,182], assuming a node exists in range of a location to act as a distributed server and disregard or do not adequately address the non-uniform disconnected nature of VANETs [144,167,170,171,172,177,178,180,182,184,185]. However the success of V2X applications is only feasible if connectivity can be provided, which is dependent on either high vehicular density to sustain multi-hop communications or on the sufficient availability of fixed infrastructure in the form of RSUs. Thus a location service will be unable to reliably facilitate V2X communication unless it is robust in order to maximise
query resolution. This motivates the need for a location service that prioritises location service packet delivery and accurate location resolution.

Utilising infrastructure for connectivity and to act as a static location server can intuitively aid in improving location query resolution and accuracy. Many location service protocols only consider infrastructureless ad-hoc networks [144,167,169,170,171,172,173,174,83] and are not equipped to avail of road-side infrastructure if available to maximise delivery of location server packets but also to act as static location servers. Furthermore the location server placement strategies and the inter-server communication mechanisms employed by these protocols are not always compatible or fully exploit infrastructure. Of those schemes that are designed explicitly for infrastructure, many assume the existence of uniformly distributed density of fixed RSUs, located in prescribed locations. Furthermore it is expected that such RSUs will be located centrally within a partitioned topology that may not comply with the underlying network map [177,178,180,181,182,184].

A subset of the current state of the art location service protocols now propose aggregated schemes (often hierarchical for locality awareness) to reduce location update and query overhead [172,177,178,180,181]. This is further in line with the goal of many location services, as already described, to reduce cost of the overhead incurred. Vehicle updates, and in some case query packets, are delayed and aggregated and therefore may experience delay which can lead to reported location inaccuracies. Furthermore all of the afore-described schemes suffer from "service disruption time" (a phrase used in the evaluation of LSVT [181]) i.e. if a vehicle changes cell or group while a LSC/RH update is occurring, incorrect location information will be returned to a querying location. Finally these schemes consider very high LSC/RH and CL/GL update intervals as well as CL/GL advertisement intervals. Such high intervals will lead to the dissemination of stale and inaccurate location information. While the update mechanisms just described are associated specifically with aggregated hierarchical schemes, the update mechanism i.e. frequency with which updates are issues and identifying the appropriate location server has significant impact on the ability to resolve queries in the first instance and secondly

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the accuracy of the returned location information. This motivates the requirements for a location service protocols that employs an update and query mechanism to maximise delivery of packet (facilitated by proximity to location server) and accuracy of the subsequent reply.

Key to the provision of an ideal location service is the ability to handle the "locality" problem, defined by the authors in [186] as a scenario where the corresponding location information is stored potentially far away from both the source and destination nodes even when the source and destination nodes are in close proximity, causing high overhead on update and query operations. Not only is the issue of high overhead a drawback as the authors indicated but more importantly such lack of locality awareness could affect the reliability of the scheme as updates and queries may need to travel long distances, increasing the likelihood of unsuccessful delivery. This is even more applicable in vehicular networks because as discussed and characterised in [187,188,189] it is expected that many vehicular non-broadcast based application traffic will be bounded within a specified geographic area. Many existing schemes handle locality by implementing a hierarchical scheme. Flat location service schemes exhibit a drawback in that the location server can potentially be located far away from both source and destination nodes. This can lead to high update and query path costs and an increase in failed update and query packets as a result of long distance multi-hop communications. The benefit of hierarchical location services is that when the source and destination node are located in close proximity, long query paths are avoided improving the scalability of the location service. They incur higher overhead than flat schemes however. To tackle locality awareness, existing hierarchical vehicular protocols tackle this problem by using a hierarchical distribution of location servers to enforce locality of operation but fail in their lack of consideration of non-uniform wide area queries and frequently disconnected communication paths.

Lastly a simple technique that would further disseminate vehicle location information is for forwarding vehicles to store 'overheard' location information from packets that it routes. This is currently only considered by one distributed location service protocol,
RSLS [169]. Furthermore if a vehicle receives a query packet destined for a location server and notes that it is the vehicle whose location is being queries it should respond itself directly to the source vehicle. This is not opportunistic location resolution is not considered in most location service protocols with the exception of restricted broadcast based approaches such as the ETSI TC ITS LS [83].

The described drawbacks of the current start of the art location service protocols presents the motivation for a location service protocol that can fulfil the most fundamental of location service objectives – location query resolution. The challenge in the immediate future and addressed in this thesis is the design of a location service that is both locality aware and robust to maximise query resolution and successful receipt of updates and that can exploit the presence of infrastructure if available but that can also overcome its slow introduction by providing efficient multi-hop communications. In order to deliver a robust service, a location service protocols should be able to adapt across fully distributed, hybrid and infrastructure based vehicular network to facilitate local and wide area query resolution. This remains an open challenge. Such a scheme should not dictate RSU placement as this does not generalise well and limits its generic applicability across different road topologies. Such methods are not considered by current location service schemes. The hybrid vehicular location service protocol presented in this thesis and described in Chapter 3 overcomes these drawbacks to meet the research challenges as outlined Section 1.2.

Importantly, as with vehicular routing protocols, it should also be noted from this section that many quantitative evaluations of location service protocol performance either do not specify or do not consider realistic simulation conditions with respect to MAC layer, channel models, transmission range amongst other parameters. This is discussed further in next section and further motivates the need for a comprehensive vehicular simulation environment.
2.5 Survey of V2X Quantitative Performance Evaluations

Simulation of vehicular networks is especially complex as realistic vehicular conditions and traffic modelling must be provided as well as advanced communication protocols and wireless radio conditions. As further discussed in Chapter 4, a number of hybrid vehicular simulators have been devised but largely neglect to implement the required level of detail. As a result, IVC environments are typically developed using separate but inter dependent network and traffic simulators and require significant customisation.

Very importantly, the literature detailing the simulation environments used in existing vehicular routing and location service protocol evaluations is poorly defined or demonstrates the use of inappropriate parameters that can have a significantly biased impact on the presented results. Recently, Joerer et. al [190] conducted a review of the credibility of simulation studies in the field of IVC protocols and applications based on 116 papers submitted to ACM VANET (Workshop on Vehicular inter-NETworking), the IEEE Vehicular Networking Conference (VNC) and the IEEE Vehicular Technology Conference (VTC). The authors noted not only the need to better indicate simulation parameters in order to improve the reproducibility and comparability of presented IVC results but also noted the need for a realistic scenario and platform for the quantitative assessment of new IVC protocols. These findings are in accordance with that noted by the author of this thesis during a review of the literature in this space as well as during the development and implementation of a realistic and thorough IVC simulation environment as described further in Chapter 4. To this end, a review of the simulation parameters employed in the quantitative evaluation of the previously discussed routing protocols and location services are listed chronologically in Tables 2.2 and 2.3.

It can be noted in Table 2.2 that many schemes are evaluated based on unrealistic or unspecified simulation parameters. 17 out of 24 reviewed protocols do not specify their channel model, a quantitative model that has considerable impact on packet delivery. Similarly 5 do not specify their MAC and of those that do, WAVE specific MAC/PHY conditions are rarely modelled, opting instead for the 802.11b standard or equivalent in 17 cases. It can be further noted that 4 do not specify their application modelling and of
those that do, many omit important details such as the number of communicating source-destination pairs, packet size etc. Furthermore, simulation studies typically do not specify the simulation duration or utilise short durations where it is likely results are highly correlated and not statistically significant. On a positive note, most consider real maps with only a few marked as “Grid” or “Topology Unspecified”. It was also noted in the literature that very importantly, many routing schemes for vehicular networks are based on geo-routing protocols such as VADD, GOSR, MDDV, ASTAR, ACAR and GPCR that assume a perfect or idealised location service while others such as GPSR, RBVT-P, GSR and GyTAR utilise MANET-developed location services. However location services developed for MANETS suffer from scalability and accuracy issues when applied to vehicular scenarios and do not consider road topology when configuring location server placement. Importantly, they also suffer from robustness and availability issues over the high dynamism of vehicular networks.

Similar observations can be made for Table 2.3 when reviewing the quantitative evaluation of location services, with channels and application models largely unspecified and under-utilisation of the 802.11p MAC observed. Importantly, when considering location service performance, the routing protocol is often unspecified. While the results of the published location service protocol and comparative scheme is relative and therefore any improvements most likely still stand, the routing protocol can have a profound impact on the obtained results obtained with the location service as it will determine whether location queries or replies can be determined. Therefore it is vital that this be specified. Furthermore some routing protocols are evaluated over GPSR which has known drawbacks relating to its perimeter mode recovery scheme in vehicular networks, which can lead to routing loops. Furthermore, it can be noted that location service evaluation often focuses on the Query Success Rate (QSR) i.e. the ability to get back an answer re location but rarely examines the accuracy of the returned location by examining the distance the vehicle has travelled from the returned location i.e. the location accuracy. This motivates the need for a comprehensive vehicular specific simulation environment as described in Chapter 4.
<table>
<thead>
<tr>
<th>Scheme</th>
<th>Map Size</th>
<th>Max RR</th>
<th>Channel Model</th>
<th>Vehicle Density</th>
<th>Sim Dur.</th>
<th>MAC</th>
<th>Results</th>
<th>Comparative Schemes</th>
<th>App Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEGRP</td>
<td>2500m x 2500m Cork city map</td>
<td>210m</td>
<td>TRG, Shadowing, Obstacle + Nakagami</td>
<td>~5-9 v/km</td>
<td>1000s</td>
<td>802.11p (6 Mbps)</td>
<td>PDR, ETE, HC</td>
<td>GPSR, ISO/ETSI GeoUnicast</td>
<td>10 random pairs 20 pps, 100B payload</td>
</tr>
<tr>
<td>GSR</td>
<td>6250m X 3450m Berlin map</td>
<td>500m</td>
<td>N/S</td>
<td>955</td>
<td>N/S</td>
<td>802.11b (2Mbps)</td>
<td>PDR, ETE, HC</td>
<td>AODV, DSR</td>
<td>“several” random pairs 4 pps</td>
</tr>
<tr>
<td>A-STAR</td>
<td>2800m X 2400m</td>
<td>350m</td>
<td>N/S</td>
<td>200-500 (+50)</td>
<td>500s</td>
<td>802.11b</td>
<td>PDR/ETE</td>
<td>GPSR, GSR</td>
<td>CBR, 4pps, 64B</td>
</tr>
<tr>
<td>CBF</td>
<td>10000m Highway</td>
<td>250m</td>
<td>TRG</td>
<td>N/S</td>
<td>N/S</td>
<td>802.11b (2Mbps)</td>
<td>PDR, PH</td>
<td>GPSR</td>
<td>10 random pairs, 4pps, 64B</td>
</tr>
<tr>
<td>GPCR</td>
<td>6250m X 3450m</td>
<td>500m</td>
<td>N/S</td>
<td>955</td>
<td>N/S</td>
<td>802.11b (2Mbps)</td>
<td>PDR, ETE</td>
<td>GPSR</td>
<td>“several” random pairs 4 pps</td>
</tr>
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<td>VADD</td>
<td>4000m X 3200m topology unspecified</td>
<td>200m</td>
<td>N/S</td>
<td>150,210</td>
<td>N/S</td>
<td>N/S</td>
<td>PDR, ETE, OH</td>
<td>DSR, GPSR</td>
<td>15 random pairs, CBR, 0.1-1 pps, 128B</td>
</tr>
<tr>
<td>GeOpps</td>
<td>15000m²</td>
<td>250m</td>
<td>N/S</td>
<td>Peak 21500, mean: 2000</td>
<td>N/S</td>
<td>802.11b</td>
<td>PDR, ETE, HC</td>
<td>MoVe</td>
<td>1000 sources, 1 destination, 1 packet, 5s BI</td>
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<td>CAR</td>
<td>Topology unspecified</td>
<td>400m</td>
<td>Shadowing</td>
<td>15 v/km, 30-40 v/km 50+ v/km</td>
<td>300s</td>
<td>N/S</td>
<td>PDR, ETE, OH</td>
<td>GPSR</td>
<td>20 random pairs, CBR, 4 pps</td>
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<td>GPSRJ+</td>
<td>1500m² Grid (topology unspecified)</td>
<td>371m</td>
<td>N/S</td>
<td>75-175 (+25)</td>
<td>N/S</td>
<td>802.11b (2Mbps)</td>
<td>PDR, ETE, HC</td>
<td>GPSR, GPCR</td>
<td>5 random pairs, CBR</td>
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<td>GyTeAR</td>
<td>2500m²</td>
<td>~266m</td>
<td>N/S</td>
<td>100-300</td>
<td>200s</td>
<td>802.11b</td>
<td>PDR, OH</td>
<td>DSR, LAR</td>
<td>CBR, 5 pps, 128B</td>
</tr>
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<td>GeoDTN + NAV</td>
<td>1500m X 4000m Oakland</td>
<td>350m</td>
<td>N/S</td>
<td>50</td>
<td>N/S</td>
<td>802.11b (2Mbps)</td>
<td>PDR, ETE, HC</td>
<td>GPSR, GPCR</td>
<td>Fixed destinations</td>
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<td>1000m² Washington</td>
<td>N/S</td>
<td>Restricted LOS</td>
<td>100 (50%-80% static)</td>
<td>300s</td>
<td>N/S</td>
<td>PDR, ETE, HC</td>
<td>GPSR, GPCR</td>
<td>1pps, 1460B</td>
</tr>
<tr>
<td>ACAR</td>
<td>1500m² L.A.</td>
<td>400m</td>
<td>N/S</td>
<td>150, 250, 350</td>
<td>2000s</td>
<td>802.11b</td>
<td>PDR, ETE</td>
<td>GPSR, GSR, CAR</td>
<td>N/S</td>
</tr>
<tr>
<td>TO-GO</td>
<td>1800m X 300m Grid</td>
<td>250m</td>
<td>FSL with inter road radio blocking</td>
<td>75-150</td>
<td>180s</td>
<td>802.11 (2Mbps)</td>
<td>PDR, ETE, HC</td>
<td>GPSR, GPCR, GPSRJ+</td>
<td>1 random pair every 10s, CBR, 1460B</td>
</tr>
<tr>
<td>GOSR</td>
<td>1850m² (topology unspecified)</td>
<td>N/S</td>
<td>N/S</td>
<td>68</td>
<td>N/S</td>
<td>N/S</td>
<td>PDR, HC</td>
<td>GSR</td>
<td>N/S</td>
</tr>
<tr>
<td>RBVT</td>
<td>1500m² L.A.</td>
<td>400m</td>
<td>Shadowing.</td>
<td>150, 250, 350</td>
<td>300s</td>
<td>802.11</td>
<td>PDR, ETE, HC</td>
<td>AODV, OLSR,</td>
<td>1-20 random</td>
</tr>
<tr>
<td>Series</td>
<td>Environment</td>
<td>N/S</td>
<td>N/S</td>
<td>Time (s)</td>
<td>Bandwidth (Mbps)</td>
<td>Methodologies</td>
<td>Pairs, CBR, 0.5-5 pps, 512B</td>
<td></td>
<td></td>
</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
<td>-----</td>
<td>-----</td>
<td>----------</td>
<td>-----------------</td>
<td>-------------------------------------------</td>
<td>-------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PP Series</td>
<td>3000m² Urban Map (unspecified)</td>
<td>250m</td>
<td>N/S</td>
<td>100-700 (±100)</td>
<td>300s</td>
<td>802.11b</td>
<td>PDR, ETE, HC</td>
<td>GPSR, PDGR, MOPR</td>
<td>20 random pairs, CBR, 1pps, 512B</td>
</tr>
<tr>
<td>EGPR</td>
<td>1000m² Grid (topology unspecified)</td>
<td>250m</td>
<td>N/S</td>
<td>20-120 (±20)</td>
<td>120s</td>
<td>802.11b</td>
<td>ETE</td>
<td>GPSR, PDGR</td>
<td>15 random pairs, CBR, 2pps, 512B</td>
</tr>
<tr>
<td>GPR</td>
<td>700m X 1000m Seoul</td>
<td>125m</td>
<td>N/S</td>
<td>100-200 (±10)</td>
<td>180s</td>
<td>802.11 (2Mbps)</td>
<td>PDR, Link breakage</td>
<td>GPSR, GPCR, GPUR</td>
<td>CBR, 1 pps, 512B</td>
</tr>
<tr>
<td>Borsetti et al</td>
<td>1000m² Grid (Derived topology)</td>
<td>N/S</td>
<td>WINNER-LOS/NLOS model [191]</td>
<td>N/S</td>
<td>802.11p (6Mbps)</td>
<td>PDR, ETE, HC</td>
<td>GPSR, CBF, GSR</td>
<td>CBR, 10 pps, 512B</td>
<td></td>
</tr>
<tr>
<td>RAR</td>
<td>8000m Highway</td>
<td>250m</td>
<td>N/S</td>
<td>160</td>
<td>N/S</td>
<td>802.11b (2Mbps)</td>
<td>PDR, OH</td>
<td>k-hop routing</td>
<td>CBR, 10 random pairs, 512B</td>
</tr>
<tr>
<td>SADV</td>
<td>4000m X 5000m – TIGER map (unspecified)</td>
<td>200m</td>
<td>N/S</td>
<td>50-300 (±50)</td>
<td>N/S</td>
<td>N/S</td>
<td>ETE, OH</td>
<td>VADD, Flooding</td>
<td>N/S</td>
</tr>
<tr>
<td>TrafRoute</td>
<td>500m² – real map topology unspecified</td>
<td>N/S</td>
<td>N/S</td>
<td>140</td>
<td>N/S</td>
<td>802.11b</td>
<td>PDR, ETE, OH</td>
<td>AODV, GPSR</td>
<td>1 random pair, CBR (60s)</td>
</tr>
<tr>
<td>ROAMER August 2011</td>
<td>1500m²</td>
<td>250m</td>
<td>Nakagami</td>
<td>30-150 (+20)</td>
<td>1200s</td>
<td>11Mbps</td>
<td>PDR, ETE, OH</td>
<td>RBVT</td>
<td>All vehicles, 1 request every 30s, 2s BI</td>
</tr>
<tr>
<td>ROAMER October 2011</td>
<td>1500m²</td>
<td>250m</td>
<td>Nakagami</td>
<td>100,300</td>
<td>1200s</td>
<td>802.11p (11Mbps)</td>
<td>PDR, ETE, OH</td>
<td>N/S</td>
<td>All vehicles, 1 request every 20s, 2s BI</td>
</tr>
<tr>
<td>ROAMER May 2012</td>
<td>1500m², 9000m²</td>
<td>300m</td>
<td>Nakagami</td>
<td>100,300</td>
<td>1200s</td>
<td>802.11p (6Mbps)</td>
<td>PDR, ETE, OH</td>
<td>RBVT, TrafRoute, SADV</td>
<td>All vehicles, 1 request every 30s, 2s BI</td>
</tr>
<tr>
<td>CAN DELIVER</td>
<td>9000m²</td>
<td>300m</td>
<td>Nakagami</td>
<td>50, 100-500 (+50)</td>
<td>1200s</td>
<td>802.11p (6Mbps)</td>
<td>PDR, ETE, OH</td>
<td>RBVT, TrafRoute, SADV</td>
<td>All vehicles, 1 request every 30s, 2s BI</td>
</tr>
<tr>
<td>RBNT</td>
<td>1000m² Grid</td>
<td>250m</td>
<td>N/S</td>
<td>Entry rate of 1-30 v/s</td>
<td>N/S</td>
<td>802.11b</td>
<td>ETE</td>
<td>AODV, GPSR</td>
<td>N/S</td>
</tr>
</tbody>
</table>

| N/S | Not Specified | | PDR | Packet Delivery Rate | | RR/BI | Radio Range/Beacon Interval | | ETE | End-to-End Delay | | TRG/FSL | Two Ray Ground/Free Space Loss | | OH | Overhead | | Sim Dur | Simulation Duration | | HC | Hop Count |

Table 2.2: Comparative Simulation Analysis Summary for Vehicular Routing Protocols
<table>
<thead>
<tr>
<th>Map Size</th>
<th>Max RR (m)</th>
<th>Channel Model</th>
<th>Vehicle Density</th>
<th>Sim Dur.</th>
<th>MAC</th>
<th>Results</th>
<th>Routing Protocol</th>
<th>App Traffic</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVLS</td>
<td>2500m x 2500m Cork City map</td>
<td>210m</td>
<td>TRG, Shadowing, Obstacle + Nakagami</td>
<td>~5-9 v/km</td>
<td>1000s</td>
<td>802.11p (6 Mbps)</td>
<td>QSR, PDR, ETE, OH, Location Accuracy</td>
<td>GHLS&lt; MBLS, ILS, ETSI TC ITS LS</td>
</tr>
<tr>
<td>GHLS</td>
<td>2500m² Grid</td>
<td>250m</td>
<td>N/S</td>
<td>100-2000 (+500 increments)</td>
<td>300s</td>
<td>802.11, 11Mbp</td>
<td>QSR, PDR, OH</td>
<td>AODV, DSR</td>
</tr>
<tr>
<td>ILS</td>
<td>900m², 1350m², 1800m² Grid (uniform 200m streets)</td>
<td>250m</td>
<td>N/S</td>
<td>80,180,320</td>
<td>50s</td>
<td>802.11b, DCF</td>
<td>QSR</td>
<td>GPSR(PM)</td>
</tr>
<tr>
<td>MBLS</td>
<td>2500m² Houston</td>
<td>250m</td>
<td>N/S</td>
<td>150-300 (+50 increments)</td>
<td>200s</td>
<td>802.11b, 11Mbp</td>
<td>QSR, Location Accuracy</td>
<td>GPSR(PM)</td>
</tr>
<tr>
<td>DMBLSDMBLS EMBLS</td>
<td>2500m² - 100000m²</td>
<td>250m</td>
<td>N/S</td>
<td>200km², 500km²</td>
<td>900s</td>
<td>802.11b</td>
<td>QSR, OH, ETE</td>
<td>GSR</td>
</tr>
<tr>
<td>VLS</td>
<td>2300m X 2700m, 4300m X 2700m Xi'an, China</td>
<td>250m</td>
<td>N/S</td>
<td>400</td>
<td>900s</td>
<td>802.11b</td>
<td>QSR</td>
<td>N/S</td>
</tr>
<tr>
<td>RLS</td>
<td>500m²; 1000m²; 2000m² L.A map</td>
<td>500m</td>
<td>N/S</td>
<td>300,400,500,600 (2000m scenario)</td>
<td>N/S</td>
<td>N/S</td>
<td>QSR, OH, ETE</td>
<td>N/S</td>
</tr>
<tr>
<td>HLSRG</td>
<td>100km²</td>
<td>250m</td>
<td>N/S</td>
<td>600-2400</td>
<td>1000s</td>
<td>N/S</td>
<td>OH</td>
<td>N/S</td>
</tr>
<tr>
<td>MGLES</td>
<td>800m²</td>
<td>100m</td>
<td>N/S</td>
<td>200</td>
<td>300s</td>
<td>802.11b</td>
<td>QSR, OH, ETE</td>
<td>N/S</td>
</tr>
<tr>
<td>QLSLSP</td>
<td>36000m²</td>
<td>300m</td>
<td>N/S</td>
<td>1000</td>
<td>800s</td>
<td>N/S</td>
<td>OH, Location Accuracy</td>
<td>N/S</td>
</tr>
<tr>
<td>LSFT</td>
<td>20000-590000m²</td>
<td>750m</td>
<td>N/S</td>
<td>160-4000</td>
<td>1000s</td>
<td>N/S</td>
<td>OH</td>
<td>N/S</td>
</tr>
<tr>
<td>N/S</td>
<td>Not Specified</td>
<td>PDR</td>
<td>Packet Delivery Rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RR</td>
<td>Radio Range</td>
<td>ETE</td>
<td>End-to-End Delay</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRG</td>
<td>Two Ray Ground</td>
<td>OH</td>
<td>Overhead</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: Comparative Simulation Analysis Summary for Vehicular Location Service Protocols
2.6 Chapter Summary

This chapter has discussed the context of international standardisation activities, projects and technologies, along with distributed and infrastructure based unicast geo-routing and location service protocols for vehicular environments. It further discussed the quantitative evaluations undertaken by state of the art vehicular routing and location service schemes. While there has been a plethora of protocols specified for both, none prioritise reliable packet delivery by availing of partial infrastructure or the case of location services, considering locality. Chapter 3 presents the proposed *Infrastructure Enhanced Geographic Routing Protocol* (IEGRP) protocol in detail which avails of infrastructure to improve packet delivery where possible. This protocol is used to route packets with the location of the destination device determined via the proposed locality aware and robust *Urban Vehicular Location Service* (UVLS), as described in the next chapter.
Chapter 3: Vehicular Hybrid Geo-Routing and Location Management

3.1 Introduction

The *Infrastructure Enhanced Geographic Routing Protocol* (IEGRP) is a hybrid geo-routing unicast protocol that exhibits significantly improved packet delivery rates by dynamically adapting the routing protocols forwarding algorithm to exploit the existence of infrastructure, where available, on a per packet basis. IEGRP is designed to be incorporated within existing vehicular standards and thus can be used for V2X unicast communications.

The *Urban Vehicular Location Service* (UVLS) protocol is a hybrid location service protocol that exhibits significantly improved and accurate query success rates by employing a robust and locality aware query mechanism improving receipt of update and query packets at location servers. As with IEGRP, UVLS is designed to be incorporated into existing standards.

Without detracting from the necessary generalities of the proposed protocols that are essential to ensure its successful applicability in many vehicular scenarios, the following common assumptions are made:

- Each vehicle can determine its own position via GPS or some other form of localisation system.
- The ID and position of single hop neighbours are extracted from periodic beacons.
- Every vehicle has navigation software installed with a digital map used to identify the closest intersection and infrastructure availability. However the availability of a pre-programmed route is not expected.
- It is assumed that RSUs have two interfaces, one to communicate wirelessly with mobile vehicles and a secondary interface to connect to other RSUs over some high speed backbone network.

The remainder of this chapter focuses on a technical description of the IEGRP and UVLS protocols.
3.2 Infrastructure Enhanced Geographic Routing Protocol Overview

IEGRP is a hybrid geo-routing unicast protocol. The following sub-sections describe relevant IEGRP terminology, packet formats, operation, complexity and provide a discussion of IEGRP with respect to other state of the art vehicular geo-routing protocols, as outlined in Chapter 2.

3.2.1 IEGRP Terminology

Commonly used geo-routing terms are now briefly explained:

- Source node $s$: a node that initiates data packet(s) towards a particular destination location.
- Forwarding node $f$: a node that receives a data packet either from $s$ or from another forwarding node and transmits or buffers the packet.
- Neighbour $n$: A node (vehicle or RSU) within radio range of $s$ or $f$ that may be chosen as a potential next hop for a packet according to the geo-routing algorithm in multi-hop communications.
- Data Packet: An application layer packet.

3.2.2 IEGRP Message Format

IEGRP makes use of beacons that are periodically transmitted between one hop neighbour vehicles. These are defined in the ETSI TC ITS reference architecture [83]. Any ISO/ETSI packet includes the GeoNet header structure, comprised of a common header and an extended header. The common header, comprising 36 octets, contains the geo-location of the packet sender. The content of the extended header is dependent on the packet functionality i.e. a unicast routing packet, a location service packet and so on.

Beacon packets contain the common header only, which subsequently contains the node’s location information, called a position vector. Upon receiving a beacon, each vehicle updates their Broadcast Table (analogous to a routing neighbour table). Importantly the availability of the location information of ‘neighbouring’ nodes within a vehicles radio range negates the need for explicit beaconing as part of the geo-routing protocol. Beacons are transmitted every 100ms as recommended in the standards specifications. IEGRP
extends these beacons to include RSU neighbour information so that vehicles can learn of two-hop infrastructure. The contents of the ETSI TC ITS position vectors and common header as specified in Sections 8.4 and 8.5 of [83] are detailed in Tables 3.1 and 3.2:

<table>
<thead>
<tr>
<th>Bits</th>
<th>0-3</th>
<th>4-7</th>
<th>8-11</th>
<th>12-15</th>
<th>16-19</th>
<th>20-23</th>
<th>24-27</th>
<th>28-31</th>
</tr>
</thead>
<tbody>
<tr>
<td>ETSI TC ITS Short Position Vector (PV)</td>
<td>GN_ADDR</td>
<td>TST</td>
<td>Latitude</td>
<td>Longitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long PV Extensions</td>
<td>Speed</td>
<td>Heading</td>
<td>Altitude</td>
<td>Accuracy</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IEGRP RSU PV Extension</td>
<td>RSU_ADDR</td>
<td>Latitude</td>
<td>Longitude</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: ETSI TC ITS Short Position Vector (20 octets) and Long Position vector (28 octets) with IEGRP extension

The fields in this table are as follows:

**GN_ADDR** - The network address of the geo-adhoc device (GeoNetworking Address).

**TST** - The timestamp (ms) associated with the advertised latitude and longitude.

**Latitude** – Latitude of the node expressed in 1/10 micro degree.

**Longitude** - Longitude of the node expressed in 1/10 micro degree.

**Speed** – Speed of the node (metres per second).

**Heading** – Heading of a GeoAdhoc node.

**Altitude** - Altitude of the node expressed in signed units of 1 metre.

**Accuracy of the position** - Accuracy indicator of the TST field. See [83].

**IEGRP RSU PV** – An IEGRP beacon extension to include the network address, latitude and longitude of a neighbour RSU so that other nodes can learn of 2 hop RSUs.
Chapter 3: Vehicular Hybrid Geo-Routing and Location Management

Table 3.2: ETSI TC ITS Common Header and Beacon Packet

The fields in this table are as follows:


*NH* - Type of header following the GeoNetworking header e.g. ANY (0) or IPv6 (3).

*HT* - GeoAdhoc Header Type e.g. Beacon (no packet payload), GeoUnicast or LS.

*HST* - GeoAdhoc Header Sub-Type e.g. LS_Request, LS_Reply.

*Reserved* - Media dependant functionality.

*Flags* - Type of ITS station.

*PL* - Payload Length.

*TC* - Traffic Class.

*HL* - Hop Limit.

*SEPV* - Long Position Vector of the sender node.

IEGRP also makes use of the ETSI TC ITS specified GeoUnicast packet format as illustrated in Table 3.3 [193] with the GeoNet header structure, to route data packets. As previously outlined, the header structure is comprised of a common header as shown in Table 3.2 but now also contains an extended header (described in Section 8.6 of [83]), specifically the GeoUnicast header. The GeoUnicast extended header is 52 octets in length, resulting in an overall GeoNet header of 88 octets [194].

Table 3.3 ETSI TC ITS GeoUnicast Packet Format
The fields in this table are as follows:

SN - Sequence number field.

LT - Lifetime field (maximum tolerable time a packet can be buffered until it reaches its destination.

Reserved - Media dependent functionality.

SO PV - Long position vector of the source node.

DE PV - Short position vector of the destination node.

3.2.2 IEGRP Operation

IEGRP is a geographic routing protocol designed to operate over a fully distributed or a partially/fully infrastructure based network. Unlike recently proposed infrastructure-reliant approaches, it does not demand particular network conditions with respect to RSU availability and placement in order to operate. Importantly, it allows the greedy and DTN recovery routing algorithms to be dynamically overridden to exploit infrastructure where available thereby improving the delivery rate of the routing protocol.

For fully distributed routing, IEGRP exhibits many ad-hoc characteristics that, in isolation, have been used as part of other vehicular routing protocols. The ideal criteria that a vehicular routing protocol should exhibit were outlined in [195] where the authors simulate and discuss the common challenges facing VANET routing protocols - these problems are not bound to a specific protocol but rather are inherent to geo-routing. A set of generic guidelines for improved VANET routing is recommended including the use of a store and forward paradigm to cope with temporary disconnections, extended beacon messages (though the extended content is not specified) and careful selection of forwarding criteria (though the exact criteria are unspecified).

IEGRP uses store and forwarding buffering to overcome temporary disconnections in the vehicular ad-hoc network. It also makes use of the extended WSA beacons described in the previous section to predict if a vehicle has moved out of the radio range since the timestamp of the last beacon and also to determine the next hop neighbour that will be
chosen by the advanced routing algorithm. In IEGRP, rather than utilising the default method of choosing the vehicle that will make the greatest greedy progress towards the destination, IEGRP also accounts for the direction in which the vehicle is travelling and so may choose a vehicle that achieves slightly less progress but is travelling in the direction of the destination. Such an approach has been discussed in the GeoNet final project deliverable [82] as being a possibility for a future extension in the GeoNet specification. In these ways, IEGRP fulfils the recommended criteria for routing in a fully distributed vehicular network. However the primary distinguishing factor of IEGRP is that it exhibits a number of hybrid characteristics:

1. IEGRP allows a vehicle’s default greedy algorithm to be dynamically over-ridden so that unlike other schemes that choose a neighbour vehicle that makes the greatest geographic distance towards the destination, IEGRP favours a RSU that makes less forward progress to the destination but has a backbone link to another RSU that can achieve a greater gain in geographical distance over the infrastructure based backbone. This ultimately offers a better geographical routing gain for packet delivery. This is referred to as IEGRP + Override Greedy Scheme (IEGRP + OGS) in the simulation analysis conducted in Chapter 5.

2. Similarly, a RSU that does not make any geographic distance towards the destination (in fact may make incur a geographic loss towards the destination) can be chosen if it can route the packet to another RSU geographically closer to the destination over the backbone. Thus in scenarios where the store-and-forward recovery technique would typically buffer a packet or greedy forwarding would be used, it instead “back-tracks” the packet to a RSU that can route over the backbone network.

3. RSU neighbours are advertised in periodic vehicle beacons so that indirect neighbour nodes may learn about infrastructure based two hop neighbours. Thus points 1 and 2 consider not only one hop neighbours but also two-hop infrastructure neighbours. This, along with point 2, is referred to as IEGRP + Override Recovery Scheme (IEGRP + ORS) in the simulation analysis conducted in Chapter 5.
These characteristics are illustrated in Figure 3.1. In Figure 3.1(a), the blue vehicle wishes to route a packet to the red vehicle. As the blue vehicle has reached the local maximum, with no neighbours towards which it can greedily forward, ordinarily a geo-routing protocol would simply buffer the packet until a new vehicle is encountered that can make greater geographic progress towards the destination [114, 115, 121, 122, 128]. However IEGRP exploits topology knowledge of RSU neighbours acquired indirectly via two hop beaconing to select an alternative node towards the packet will be forwarded i.e. dynamically overriding the default buffering mechanisms. The routing algorithm operating on the blue vehicle determines that it should multi-hop the packet via the black vehicle to the two-hop RSU. While this will not make a temporary gain towards the destination (it actually achieves lesser forward progress in the short term), it can route over the backbone network (or Internet) to another RSU that will achieve greater physical proximity to the target red vehicle. Similarly in Figure 3.1(b), the blue vehicle wishes to route a packet to the red vehicle. However instead of the IEGRP routing algorithm simply choosing the neighbour that achieves the greatest physical progress towards the destination i.e. the black vehicle, as per typical greedy behaviour, it forwards the packet to the RSU that does not make the best progress to the destination in the short term, but will the best progress to destination overall. Pseudocode for the main component of the IEGRP routing algorithm is shown in Figure 3.2.

3.2.3 IEGRP Complexity

As geo-routing is typically stateless and distributed, the computational complexity of each vehicle is determined by its number of neighbours. For a node \( u \) with a set of neighbours \( N(u) \), the complexity of calculating the neighbour distance is \( O(|N(u)|) \). If \( A \) is the average node degree, the computational complexity of the algorithm for each node can be generalised as \( O(A) \). Assuming \( N \) is the total number of vehicles in the network, the overall asymptotic complexity for the entire network is \( O(NA) \). In [196] it was shown that the minimum degree necessary to keep a network connected is \( O(\log N) \) so the \( O \) complexity of the network can be denoted as \( O(N(\log N)) \). The geo-routing protocols described in Chapter 2 comply with this. In IEGRP, the default greedy algorithm is modified such that not only will a node \( u \) check the distance to all of its neighbours but if
one of those neighbours is a RSU \( r \), \( u \) checks the distance between \( r \) and all of \( r \)'s neighbours \( N_r(r) \). Thus the complexity can be denoted as \( O(N \log N + r) \). While this increases the complexity of the algorithm, the finite number of neighbours that a vehicle has in its radio range as well as low RSU availability (maximum 1 per intersection – 61 possible placements in the 2.5km\(^2\) map considered in this thesis assuming full RSU density) means that this is not prohibitive and there is trade-off with significantly improved delivery rates.

Figure 3.1: IEGRP Routing Algorithm to favour RSU connectivity (a) Overriding Store and Forward Mode (b) Overriding Greedy Mode
IEGRP V2X Routing Algorithm:

Notations:
Input: Packet P
Destination: Vehicle/RSU D
S' Neighbour Table: N(s)
Source: Vehicle S
Radio Range: R

1: nextHop = S
2: currentDistance = distance(S, D)
3:   If (currentDistance < R)
4:     P is sent directly to D
5:   Else
6:     For all nbr in N(s)
7:       If nbr == RSU
8:         cRSU = closestRSU (Ns, D)
9:         If (cRSU has a backbone connection to a RSU closer to D than currentDistance)
10:            nextHop = nbr
11:            break to Line 29
12:       End If
13:   End If
14:   Else If ((distance (nbr, D) < currentDistance) && (suitable direction))
15:       nextHop = nbr
16:   End If
17:   End For
18:   End if
19:   //No greedy Neighbour identified
20:   If (nextHop == S)
21:     For all nbr in N(s)
22:       cRSU = closestRSU (nbr(Ns))
23:       Repeat Line Numbers 9-13
24:     End For
25:   If (nextHop == S)
26:     bufferPacket (P)
27:     break out of IEGRP
28:   End If
29:   sendPacket (P, nextHop)

Figure 3.2: IEGRP V2X Routing Algorithm
3.2.4 IEGRP Discussion

The drawbacks associated with distributed and infrastructure based schemes were outlined in Sections 2.3.1.1.1 and 2.3.1.2.1 respectively. Distributed schemes consider a RSU as a standard potential forwarding node in their routing algorithm and do not consider the progress that can be made towards the destination over the backbone network. Unlike those schemes, IEGRP can adapt its routing decisions to over-ride greedy and recovery routing logic to exploit infrastructure.

It was noted in Section 2.3.1.2.1 that current infrastructure based schemes, require a fixed number of RSUs in fixed positions as a prerequisite to the correct operation of the routing scheme. Thus they cannot simply adapt with the RSU density or a given network topology with existing infrastructure. IEGRP however does not dictate that RSUs need to be positioned uniformly in particular parts of the network (though it is clear uniform distribution will help to improve delivery rates). It acknowledges that RSUs may likely be placed where there is existing infrastructure e.g. traffic lights and thus it can adapt to varied network topologies and will adapt its routing decision based on infrastructure availability.

Secondly, state of the art infrastructure based geo-routing protocols implement their own proprietary route discovery mechanisms to identify the location of the destination and to establish the route. Their solutions present tightly coupled routing and location service solutions, often utilising a pre-determined path to the destination. In contrast IEGRP works flexibly with any location service protocol that identifies the location of the destination and routing decisions are made on a stateless per packet basis, rather than following a prescribed route. This provides a more generalised solution that copes better with the changing connectivity of the mobile vehicular network.

Importantly, IEGRP specifies greedy and recovery routing schemes that can be overridden in the presence of infrastructure to maximise the possibility of packet delivery by incurring a temporary geographical drawback in greedy forwarding distance. This allows IEGRP to adjust dynamically in conjunction with the network topology under
consideration. Such methods are not considered by current infrastructure assisted schemes. Existing schemes (distributed and infrastructure based) also, for the most part, assume high vehicle density or high RSU density in the case of infrastructure based schemes. IEGRP does not make this assumption.

Thus all of the afore-mentioned schemes are designed to work well for particular network configurations e.g. specific vehicle or RSU density, but do not generalise well. Therefore, the hybrid routing protocol proposed in this thesis and whose operation is described in this chapter, differs from the afore-described protocols in that it does not dictate a mandatory availability or placement of RSU infrastructure, does not decree a particular location service discovery mechanism and provides greedy and recovery schemes that can dynamically adjust to best accommodate network conditions on a per packet basis, transitioning between distributed and infrastructure-based routing.

The performance of IEGRP is evaluated in Chapter 5 against GPSR, the routing protocol originally specified in the C2CNet architecture, reference routing protocol for the ETSI TC ITS specification and the base routing protocol for many vehicular simulation studies. Greedy routing with store and forward buffering as a recovery scheme, as specified in the ISO/ETSI GeoNet project, is also evaluated.

It should be noted that the primary goal of the proposed IEGRP algorithm is to adapt the routing decision in the presence of infrastructure. The distributed routing logic could be further improved to incorporate traffic density (either based on statistical information or real-time) and other characteristics such as channel conditions into its routing logic. Thus it does not claim to deliver the best performance over state of the art distributed routing protocols when no infrastructure is available.

3.3 Urban Vehicular Location Service Overview

UVLS is designed to robustly resolve location queries maintaining a high query success rate, where possible, by increasing access to location servers for update and query procedures. The distinguishing objective of UVLS is that it is focused on delivery and not
simply on reducing overhead costs at the expense of successful location resolution or accuracy. This is primarily addressed in its query strategy: which is locality aware as well as providing functionality to resolve wider area queries.

1. UVLS address locality awareness using a road topology aided directional unicast.
2. Wider area queries are resolved by forming a P2P overlay network of intersections. As the overlay network is formed of RSUs, no overlay maintenance overhead or inconsistencies arise.
3. Two simple optimisation features, location caching/opportunistic query resolution and passive updating are employed to further improve the success rate of the presented location service.

To the author’s knowledge, only 4 other vehicular location service protocols have presented a quantitative comparison against other vehicular equivalents (excluding derivatives of their own proposed protocol). In this thesis, a performance evaluation of the proposed location service protocol is provided against vehicular location services where simulation parameters and conditions are not simplified to facilitate a high delivery rate but rather provides a realistic evaluation of vehicular conditions.

3.3.1 UVLS Terminology

Commonly used location service terms are now briefly explained:

- Location Service Update: this is a location service packet transmitted by each vehicle to register its location information with its dedicated location server.
- Location Service Query: this is a location service message based on an extended version of the LS REQUEST packet format as defined by the ETSI TC ITS reference architecture [83] with extensions defined by the UVLS protocol (see Section 3.3.2.3.2). It queries the current location of a particular destination node.
- Location Service Reply: this is a location service packet initiated by a UVLS location server in response to a location service query packet and is based on the LS REPLY packet format as defined by the ETSI TC ITS reference architecture (see Section 3.3.2.3.2). It carries the last recorded location of the queried node.
Chapter 3: Vehicular Hybrid Geo-Routing and Location Management

- Location Server: a RSU at an intersection that elects itself as a ‘location server’ to store the location registrations or updates that it receives from vehicles in a location table. A location server will search its location table when it receives a query for a vehicle that it should maintain location information for and initiates a location reply packet. A location server can be a vehicle in infrastructureless UVLS.

- Source node: Similar to that defined in Section 3.2.1 with respect to location service packets. This includes registration of the source node’s location i.e. an update, querying the location of another vehicle or if a node has assumed the role of a location server, initiating a location service reply.

- Forwarding node: Similar to that defined in Section 3.2.1 with respect to location service packets.

- Local Neighbourhood Zone: Area within which ‘local’ queries can be resolved i.e. when the source and destination nodes are located in close proximity.

3.3.2 UVLS Operation

As noted in Section 2.4, the main components of a location service protocol includes the location server election and maintenance procedure, the location update or registration process (when and how location updates should be disseminated) and the query procedure (how to determine the location server(s) of a destination node given its ID in order to successfully resolve its current location).

A description of the UVLS protocol design is now provided to satisfy these criteria, with particular attention paid to the query aspects of the proposed protocol.

3.3.2.1 UVLS Location Server Management and Location Registration

In UVLS, static RSUs located at intersections are always favoured as location servers. As will be outlined in Section 3.3.2.2, local queries are resolved via a bounded topological unicast so explicit node updates are only required for queries spanning larger areas. Vehicles must firstly determine the frequency with which a vehicle should update its location information. A short update interval will ensure up to date information is stored at the location server but may lead to unnecessary overhead. Conversely a long update
interval may result in stale location replies. UVLS uses a combination of time and
distance based update triggers. Therefore, a vehicle updates when it has travelled a
distance that exceeds the distance threshold or based on an expiry timer, whichever
occurs first. The timer based update is triggered based on the time taken to travel the
distance threshold based on the vehicles average speed.

In UVLS, all RSUs in the vehicular network form a P2P overlay network using the Chord
structured Distributed Hash Table (DHT) algorithm [168]. Chord was originally
developed at MIT as a method for distributed data-centric storage. The algorithm maps an
$m$-bit identifier, derived by using the SHA-1 hash function, for both the nodes IP address
and port and the name of the data item, to form the node and key identifiers respectively.
Node identifiers are placed in ascending order on a 1-dimensional identifier circle known
as a ring, modulo $2^n$, with each key $k$ assigned to a successor node on the circle i.e. the
first node whose identifier is equal to or follows $k$ in the circle. Each node knows about
its successor and predecessor nodes on the ring and also maintains a small hash/routing
table known as a finger table, with a maximum of $m$ entries, consisting of a subset of its
neighbouring nodes. A finger table entry for node $n$ contains the first node on the ring
that succeeds $(n + 2^{k-l}) \mod 2^m$, $(l \leq k \leq m)$. Thus the number of hops required to resolve
a query in an $N$ node network is $O(\log N)$ with the distance to the queried ID at least
halved with every overlay hop. It should be noted that neighbour nodes in the ring are not
necessarily close in physical proximity. Key lookups are routed clockwise via the finger
table entries, with the query routed to the closest finger preceding the queried ID. If the
query reaches the immediate predecessor of the node responsible for the key, this node
forwards the query to its successor $s$ that is responsible for the queried content. Node $s$
will reply to the initiator of the query. Chord employs a mechanism of exchanging
packets to maintain consistency of the Chord ring and finger table entries in the face of
node churn i.e. joins and departures.

In UVLS, each RSU hashes its unique identifier to derive its Chord ID. All Chord IDs
form the overlay Chord ring. As RSUs will remain static and every RSU is aware of the
vehicular environment i.e. all other RSUs, bootstrapping and maintenance of the Chord

83
overlay is not a challenge. Similar to the process just outlined where a Chord node is responsible for keys in the P2P data storage overlay, each RSU is responsible for a given set of identifiers i.e. vehicle locations in the network. This process is illustrated in Figure 3.3, with a vehicle updating the relevant location server.

![UVLS RSU Overlay Network](image)

The UVLS update algorithm is shown in Figure 3.4 and is now described. Once a vehicle determines that it must update its location information, it must firstly determine the appropriate location server. In order to do this, UVLS vehicles transmit their location information to closest intersection with a RSU. As with all forwarding vehicles, the location server at this intersection caches the information in its location table to facilitate fast resolution of local queries. It then determines the vehicle’s location server by hashing the unique identifier of the updating vehicle determined via the common SHA-1 hashing function. This location server is the RSU with the closest succeeding ID to the hashed identifier of the updating vehicle. A timer is associated with the update that allows servers to invalidate entries shortly after a new update entry is expected. This timer is calculated based on the current time, the time the update was issued and the speed the vehicle was travelling at the time of issuing the update.

Figure 3.3: UVLS RSU Overlay Network
UVLS Location Update Algorithm:

1: If \((\text{dist\_since\_last\_update} > \text{threshold}) \text{ or } (\text{timer\_expiry} = \text{TRUE})\) then
2: send update packet \((\text{veh\_ID}, \text{Lat, long, S, Dir})\) to the closest RSU intersection
3: \(\text{reset\_update\_timer} = \text{threshold}/\text{veh\_avg\_speed};\)
4: If \((\text{forwarding\_node is not Location Server}) \text{ or (no entry in location\_table) then}\)
5: \(\text{cache\_location\_update}\)
6: \(\text{set update\_expiry} = (\text{threshold}/\text{S}) \times 1.5\)
7: else
8: \(\text{cache\_location\_update and set update\_expiry}\)
9: If \((\text{closest\_successor(hash(rsu\_lat, rsu\_long), hash(veh\_ID))) == \text{false})\) then
10: forward update to closest\_successor

---

**Figure 3.4: UVLS Location Update Algorithm**

### 3.3.2.1.1 UVLS Update Message Format

An update packet format is not specified in the ETSI TC ITS reference architecture as a simple topologically scoped broadcast is assumed. Thus UVLS proposes a new location update packet, entitled *LS UPDATE*. Assuming the common header as previously described to ensure ETSI TC ITS standards compliance, the format of this packet is shown in Table 3.4.

<table>
<thead>
<tr>
<th>Bits</th>
<th>0-3</th>
<th>4-7</th>
<th>8-11</th>
<th>12-15</th>
<th>16-19</th>
<th>20-23</th>
<th>24-27</th>
<th>28-31</th>
</tr>
</thead>
<tbody>
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<td><strong>UVLS Update Packet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Common Header 36 octets</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SO PV</td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>INT Longitude</td>
</tr>
<tr>
<td><strong>UVLS Payload</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FN PV 1</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FN PV n</td>
</tr>
</tbody>
</table>

**Table 3.4: UVLS Update Packet Format**

The fields in this table are as follows:

*SO PV* - Long Position vector of the vehicle registering their location information.

*INT Latitude* - Latitude of the target intersection at which a location server should be located.
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**INT Longitude** - Longitude of the target intersection at which a location server should be located.

**FN PV** – The position vectors of \( n \) forwarding nodes. This is discussed further in Section 3.3.2.2.1.

### 3.3.2.2 UVLS Location Query Procedure

As stated in Section 3.3, the goal of UVLS is to prioritise robustness i.e. receipt of location update packets at the correct location server and accurate location resolution. UVLS further addresses locality awareness i.e. where the source and destination vehicles are located in nearby proximity. Thus UVLS is designed to resolve local and wide area location queries and does so by employing a dual approach: firstly seeking the location of the queried destination in the *local neighbourhood zone* (a geographical area with a bounded Hop Limit (HL) or Lifetime) followed by a wide area search if the location is not resolved. It is envisaged that when, in the future, the parameters and requirements of vehicular infotainment applications become clearly defined, that sub-classification of infotainment applications could be identified i.e. whether they are bounded locally or not, in which case UVLS can use one or both of these query mechanisms. In the described protocol implementation, it is assumed that the locality aware query resolution approach is first employed, followed by a wider area search if the queried location is not resolved.

To provide locality awareness and resolve local queries, UVLS initially attempts to determine the location of the queried destination vehicle within a five hop perimeter, i.e. the *local neighbourhood zone*. Five hops has been chosen as this is considered to be the mean upper hop count for successful packet delivery in mobile ad-hoc networks [197] and the ETSI C2CNet specification utilises a five hop limit for its local query resolution. However unlike the ETSI C2CNet location service which broadcasts a packet with a HL of five hops, or similar quorum-based location service approaches, UVLS uses unicast packets rather than local broadcasts. This minimises the number of nodes within the *local neighbourhood zone* that need to be involved in the query or reply process, or involved in the location caching process (described further in Section 3.3.2.2.1). Therefore if a source vehicle queries the location of a particular destination node, the query is transmitted as a
unicast with each interim forwarding node that receives the query packet looking up its own location database to check whether the queried location can be resolved. If an entry exists, a unicast reply message is generated and transmitted towards the source vehicle, where this location information is used to communicate with the destination. Alternatively if no entry exists in the location database the location query packet is forwarded. The location query is dropped when the HL reaches zero i.e. when it reaches the boundary of the five hop local neighbourhood zone.

Importantly, when the source vehicle initiates the location query, it sets a timeout threshold, the local query timeout, on the transmission of the query with the local query zone. In the case that the local query timeout expires and the source vehicle has not received a location reply packet, it will deduce that the local query has failed and a wide area query is issued. The local query timeout, $Q_{l,timeout}$ (3.1) is derived from the maximum time take to transmit and receive a unicast packet within the HL bounded local neighbourhood zone.

$$Q_{l,timeout} = \left( \frac{P_{size}}{D_{rate}} + \frac{T_{distance}}{c} + (AIFSN(ac) \times T_{slot}) + SIFS \right) \times HL$$

where

- $P_{size}$ is the size of a UVLS query packet that is transmitted over the wireless medium, containing the UVLS extensions, ETSI TC ITS and MAC headers. A UVLS query packet is 150 bytes by default (UVLS header of 70 bytes minimum, IPv6 header of 40 bytes and MAC header of 40 bytes (MAC and ACK headers)).
- $D_{rate}$ is the network data rate (bps).
- $T_{distance}$ is the propagation distance (m) between the forwarding (transmitting) vehicle and the target destination (receiving) vehicle. As this is not known when estimating the timeout value the maximum radio range is chosen.
- $c$ is the speed of light (3.0E+08 m/s)
- $AIFSN(ac)$ is the minimum number of slots and is dependent on the specified access category (ac). As the utilised access category for location service traffic is
marked as "background" i.e. non-emergency or safety related (there are 4 access categories in total), this is set to 9 slots.

- $T_{\text{slot}}$ is the duration of the physical layer time slot (13µs).
- $SIFS$ is the Short Inter-Frame Space, the interval between a data frame and its ACK. This is a constant value of 32µs.
- $HL$ is the bounded hop limit field specified in the UVLS query packets transmitted within the local neighbourhood zone. This is set to 5, as previously outlined.

When a packet arrives for transmission, if the channel is idle for a period longer than the $AIFS$ (Arbitrary Inter-Frame Spacing) period ((AIFSN(ac) * $T_{\text{slot}}$) + $SIFS$), as specified by the 802.11e MAC, the node can immediately transmit. As previously stated, the 802.11e ECDA (Enhanced Distributed Channel Access) MAC has been adopted as part of the 802.11p WAVE standard. Given the utilised access category (ac), the AIFS period is 149µs i.e. $(9 * 13\mu s) + 32\mu s$. The timeout threshold assumes that the network has moderate load and does not consider a congested network where if a transmission occurs during the Backoff interval, a new Backoff interval is set, adding to the transmission delay. Thus assuming a $HL$ value of 5, the local query timeout is set to $\sim 17.5$ms by default.

The author acknowledges that this incurs an immediate delay for vehicles that are not in close proximity. However as noted at the beginning of this section, it can be expected that future advancements in the specification and requirements of particular infotainment applications, will lead to the categorisation of particular application service classes that could specify the utilisation of a single UVLS query approach or the preference to first invoke the wide area approach over the local area approach for example.

An important distinguishing feature of the local UVLS query mechanism, in addition to the use of a unicast, is the consideration of the underlying road topology. As previously stated a bounded geographical area is considered with a HL specified in the location service query packet. However a source or forwarding vehicle located within proximity
of an intersection duplicates the query packet as a unicast on all exiting road segments. This is based on the reasonable assumption that vehicles will be enabled with an on-board navigation system and map of the city. Consequently, each vehicle is aware of its current location, the road segment it is on (extracted from the urban map) and whether it is in range of an intersection. The query packet is therefore transmitted in all exiting directions, choosing a point on the road topology exceeding the radio range in order to choose a neighbour to make the greatest greedy progress in the direction specified by the road topology. In practice the road topology is extracted from the road map. In the evaluation conducted in this thesis, this is simulated by parsing XML files with all streets represented as vectors (lengths and shape). Curves are composed of a series of straight line segments. A special purpose flag is included in the packet (SF flag) to prevent packets being replicated more than once at the same intersection. This process occurs at all encountered intersections, with the query packet unicast on every exiting road segment according to the topology, until the HL is reached. Each interim forwarding vehicle caches the location of the source and previously encountered vehicles before forwarding the query.

If the **local query timeout** expires without the source vehicle receiving a location reply packet, the source vehicle will next route the query to the location server at the closest intersection. The location server at this intersection will consult its own location database and, assuming that an entry does not exist, will take a particular action depending on the location server type. To facilitate wide area queries, the location server also forwards the updated location information to the closest intersection with a RSU. This RSU forwards the query to the RSU location server at the intersection with the closest succeeding ID determined via the common hashing function as previously outlined. UVLS is designed to operate in a partially or fully equipped RSU network. However in an infrastructureless network, it can still function with vehicles at intersections assuming the role of mobile location servers and thus the location service would operate in a flat manner. Pseudocode outlining the UVLS query algorithm is shown in Figure 3.5.
UVLS Location Query Algorithm:

1: If (data packet received from upper layer) then
2: returned_location = check_neighbour_table(queried_veh_ID)
3: If (returned_location == NULL) then
4: return_location = check_cache_table(queried_veh_ID)
5: If (returned_location == NULL) then
6: send_local_query_unicast(queried_veh_ID) in all road directions
7: set local HL and $Q_{\text{timeout}}$
8: if ($Q_{\text{timeout}} < \text{current\_time}$) then
9: Go to step 13
10: else if (reply packet received == TRUE) then
11: Go to step 34
12: end if
13: forward_query_to_closest_rsu_intersection(queried_veh_ID)
14: if (forwarding_node != Location Server) then
15: update UVLS payload with the forward node’s position vector
16: cache_location_update(src_veh_pos_vector, list(fwd_veh_pos_vector))
17: else
18: cache_location_update(src_veh_pos_vector, list(fwd_veh_pos_vector))
19: for every pos_vector in few_veh_pos_vector
20: calculate hashed_server(few_veh_ID) and forward
21: end for
22: if ($(closest\_successor == \text{current}\_\text{RSU}) == \text{TRUE})$ then
23: returned_location = check_location_table(src_veh_ID)
24: send_location_reply(src_veh_ID, returned_location)
25: Go to line 34
26: else
27: forward_query_to_closest_successor(src_veh_pos_vector)
28: end if
29: end if
30: end if
31: end if
32: end if
33: end if
34: send_waiting_data_packet(returned_location)

Figure 3.5: UVLS Dual Query Algorithm
3.3.2.2.1 UVLS Query Extensions

The packet delivery rate of UVLS is further improved by employing two simple optimisation features.

The first extension uses location caching and opportunistic routing where forwarding vehicles cache the location information that they overhear from buffered and forwarded packets. This includes the position vectors of the source vehicle that initiates the UVLS packet but also the position vectors of the interim forwarding nodes. To avoid the situation where stale information is cached and returned to the querying vehicle, a vehicle considers this passive location information to only be valid for a maximum time of $t/s$, the time it takes a vehicle to exceed the radio range at maximum speed. Thus if a vehicle receives a location query and is not the location server but has an entry stored in their extended location table or determines that it is the destination being queried, it directly sends a location reply to the source vehicle and drops the location query packet. This simple optimisation approach improves location service QSR, delays and reduces query path lengths. Furthermore the busier the network becomes i.e. greater dissemination of UVLS updates, queries and replies, leads to greater opportunistic location resolution.

Secondly, a side effect of including the current position vectors of forwarding nodes in UVLS packets is that when a RSU location server receives an update, not only does it initiate the direct update or query process as intended but it updates the relevant RSU location servers (determined by hashing the GN_ADDR in FN PV as discussed in next section) with this passively acquired information, resulting in accurately stored location information.

3.3.2.2.2 UVLS Query and Reply Message Formats

Similar to IEGRP, UVLS extends and reuses packet formats defined in the ETSI TC ITS reference architecture [83] to facilitate standards integration. The GeoNet common header format as outlined in Section 3.2.2 is assumed with UVLS extensions to the LS REQUEST and LS REPLY extended headers defined. The default LS REQUEST and LS REPLY packet formats as outlined in Section 8.6 of [83] are shown in Tables 3.5 and 3.6.
along with the relevant UVLS extensions. It can be noted that the fields are the same as specified in the GeoUnicast extended header outlined in Section 3.2.2 with the exception of SO PV which represents the long position vector of the node is querying a location and Request GN ADDR which is the address for the geo ad-hoc node whose location is being requested.

<table>
<thead>
<tr>
<th>[Bits]</th>
<th>0-3</th>
<th>4-7</th>
<th>8-11</th>
<th>12-15</th>
<th>16-19</th>
<th>20-23</th>
<th>24-27</th>
<th>28-31</th>
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<td>Common Header 36 octets</td>
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<td>LS Longitude</td>
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<td></td>
<td></td>
<td>FN PV n</td>
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</tr>
</tbody>
</table>

Table 3.5: ETSI TC ITS LS Request with UVLS Extensions

UVLS field extensions include:

**LS Latitude** - Latitude of the identified Location Server.

**LS Longitude** - Longitude of the identified Location Server.

**LW** - Local vs Wide Flag to identify whether the UVLS query should be treated as a locality aware topologically scoped unicast with directed duplicates created at intersection or directed towards the indicated intersection for wide area processing.

**SF** - Split flag to indicate whether a directed duplicate of the locality aware query should occur when in range of an intersection. If set to 1, it indicates that this has already occurred and this flag will be reset to 0 when out of range of the intersection.

**FN PV** – Position vectors of forwarding nodes.

Similarly, the ETSI TC ITS LS Reply follows the same format with an amended meaning to the **SO PV** field and the addition of a **DE PV** field. No UVLS amendments were made.
### Table 3.6: ETSI TC ITS LS Reply

<table>
<thead>
<tr>
<th>[Bits]</th>
<th>0-3</th>
<th>4-7</th>
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<th>20-23</th>
<th>24-27</th>
<th>28-31</th>
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</thead>
<tbody>
<tr>
<td>Common Header and LS Reply Packet Header</td>
<td>Common Header 36 octets</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>SN</td>
<td>LT</td>
<td>Reserved</td>
<td>SO PV</td>
<td>DE PV</td>
<td>FN PV 1</td>
<td>.....</td>
</tr>
</tbody>
</table>

The fields in this table are as follows:

**SO PV** - Represents the long position vector of the Request GN_ADDR of the corresponding LS Request.

**DE PV** - Represents the short position vector of the destination node i.e. the node who initiated the location query.

**FN PV** – Position vectors of forwarding nodes.

#### 3.3.3 UVLS Discussion

The drawbacks associated with individual distributed and infrastructure based location service schemes were outlined in Sections 2.4.1.1 and 2.4.1.2 respectively along with a summary and discussion in Section 2.4.1.3.

As stated in Section 2.4.1.3, many location service protocols are focused on reducing the asymptotic cost of overhead rather than on prioritising delivery, making false assumptions about connectivity and density. UVLS specifies that RSUs should always be used as static location servers where possible. Once a RSU is reaches the query will be resolved over the backbone network as only intersections containing infrastructure are considered to act as location servers. As an overlay network is employed, the solution is scalable as if a RSU is new deployed in the network, it will be added to the overlay network and the location load redistributed amongst RSUs in the DHT. Furthermore, as will be outlined in Section 3.3.2.2, local queries are resolved via a bounded topological unicast so explicit node updates are only required for queries spanning larger areas.
It was further discussed in Section 2.4.1.3 that current infrastructure based location service protocols assume full and dense RSU deployment with infrastructure either available at every intersection or more commonly located centrally within an arbitrarily chosen grid. While UVLS makes use of infrastructure, it does not dictate particular RSU placement providing a solution that is more generic in its applicability to a variety of road topologies.

The used of aggregated update and query mechanisms have also been described in Section 2.4.1.3 with scheme specific update mechanisms dictating the frequency and operation with which vehicles update their location described in Section 2.4.1.1 and 2.4.1.2 respectively. While UVLS passively 'aggregates' information by gathering forwarding node's position vectors as the update or query is being routed, it does not delay the forwarding of this information to the relevant location server. Furthermore it achieves greater accuracy due to its location server selection scheme and passive updates. The benefits of flat versus hierarchical schemes were also discussed in Chapter 2. UVLS employs a flat approach but circumvents the traditional drawbacks as it utilises RSUs as location servers with a backbone network thus vehicles need to route to their closest RSU. By employing a flat approach, UVLS also does not incur any reported location inaccuracies or overhead due to requirement to re-issue updates when crossing level boundaries as is the case in the afore-described schemes or issues with deploying road topology aware partitioning schemes that may limit its applicability.

UVLS explicitly considers locality awareness by employing a topologically scope unicast mechanism so that if a vehicle pair are located in close proximity, the location be easily resolved. To ensure high delivery, this local query mechanism accounts for the road topology by duplicating the unicast according to the exit mechanism at intersections. The premise is to maintain a high query success rate similar to a flooding broadcast based approach but incurring less overhead. Thus a location service will be unable to reliably facilitate V2X communication unless it is robust in order to maximise query resolution and to accommodate close proximity between vehicles.
Therefore, the hybrid vehicular location service protocol proposed in this thesis and whose operation is described in this chapter differs from the afore-described protocols in that it does not dictate a mandatory availability or placement of RSU infrastructure, considers locality awareness, prioritises query resolution and provided accurate location resolution. The performance of UVLS is evaluated in Chapter 5 against the C2CNET (a restricted vehicular flooding approach), GHLS (a flat MANET hashing technique), MBLS (a hierarchical VANET hashing technique) and ILS (a flat VANET overlay technique).

It should be noted that the primary goal of the proposed UVLS protocol is to develop a robust and locality aware location service to maximise delivery of location packets and increase accurate query resolution in the presence of infrastructure. The wide area query approach utilised makes use of infrastructure and the author acknowledges that it is a flat scheme so if infrastructure is drastically reduced to close to an infrastructureless state, UVLS is susceptible to the traditional drawbacks of flat approaches. However it is not the goal of UVLS to optimise a location service protocol for delivery in an ad-hoc network and the author does not claim that it delivers the best performance over state of the art distributed location service protocols when no infrastructure is available. Thus future work could look to utilising a hierarchical, quorum approach or other advanced technique to improve infrastructureless performance. The distributed routing logic could perhaps be further improved to incorporate traffic density (either based on statistical information or real-time) and other characteristics such as channel conditions into its routing logic.

3.4 Chapter Summary

This chapter has described the operation of the *Infrastructure Enhanced Geographic Routing Protocol* (IEGRP) protocol that has been proposed to operate in hybrid vehicular networks by adapting its routing decision on a per packet basis in the presence of infrastructure. IEGRP is designed to be compliant with the ETSI TC ITS standards and message formats. A discussion of how IEGRP differs from existing geo-routing protocols was also provided. The *Urban Vehicular Location Service* (UVLS) was also described, which has been designed to maximise packet delivery rate by providing robust locality aware
location resolution for geo-routing protocols. An overview of the UVLS operation including server placement, query and update methods was provided along with details pertaining to UVLS extended ETSI TC ITS packet formats. A discussion on how UVLS differs from existing location service protocols was also outlined.
Chapter 4: IVC Simulation Environment

4.1 Introduction

This thesis makes extensive use of computer simulation, which is a prevalent method for evaluating the performance of communication models and paradigms. While it is desirable to evaluate protocol implementations in real test-bed environments using physical hardware, scalability, logistical and monetary challenges make simulated quantitative evaluations a preferred and more economical approach for protocol validation. It is also often necessary to have a repeatable and reproducible computerised evaluation of communication protocol and network performance, with instructive visualisation, so that newly proposed systems can be replicated for comparative purposes in a controlled environment. Simulation tools further expedite experimentation and predict behaviour while still considering many design options and scenarios making them an attractive option. Additionally, in contrast to their mathematical analytical counterparts, quantitative simulation analysis allows for more detailed models.

This chapter describes the Inter Vehicle Communication (IVC) simulation environment developed as part of this research, with the high level architecture outlined in Section 4.2. An overview of network and mobility modelling techniques is provided in Section 4.3 and Section 4.4 respectively, along with the reasoning behind why certain simulation tools were chosen. Details pertaining to the individual components comprising the implemented simulation environment are provided in Section 4.5 and Section 4.6, with the chapter summarised in Section 4.7.

4.2 IVC Simulation Framework Overview

As there are a number of critical aspects that can influence the outcome of the analysis presented in this thesis, the basis for the discussed simulation analysis is now described.

This has been developed to reflect, as much as possible, the anticipated future behaviour of vehicular communication networks. Simulation of vehicular networks is especially complex as realistic vehicular conditions and traffic modelling must be provided as well as advanced communication protocols and wireless radio conditions. While some hybrid
vehicular simulators have been devised, as outlined in Section 4.4, they largely neglect to implement the required level of detail. As a result custom IVC environments are typically developed using separate yet inter dependant network and traffic simulators. However as highlighted in Section 2.5, many simulation environments used for vehicular protocol evaluation in literature choose unlikely parameters and/or are poorly defined, with many schemes evaluated based on unrealistic or unsubstantiated environment parameters and models. Therefore this thesis endeavours to provide a thorough and realistic simulation environment with this chapter describing in detail a comprehensive vehicular simulation platform for evaluating IVC protocols and systems using the WAVE stack for V2V communications, vehicular channel modelling, geo-routing and location services along with vehicular traffic and mobility modelling. A high level overview of the devised simulation platform is shown in Figure 4.1. Particular attention is paid to models developed or extended by the author.
4.3 Network Communication Simulators

Network simulation tools provide an environment for designing and analysing the performance of networks, devices, protocols and applications. Specifically, this thesis uses the Optimised Network Engineering Tools (OPNET) package [198], a commercial discrete event simulator, to develop and evaluate the performance of the proposed hybrid location service and geo-routing protocols as well as for the modelling of user-defined VANET communication simulation scenarios. OPNET models the operation of a system as a sequence of events, with each event occurring at a particular instant in time, indicating a change in the system state [199]. Other frequently used simulators include NS-2 [200], NS-3 [201], OMNeT++ [202], GloMoSim [203], QualNet [204] and SWANs [205]. Their main features and the drawbacks that led to them being eliminated as the chosen communication platform for this thesis are presented in Table 4.1. A more comprehensive survey of these simulators is provided in [206, 207].

<table>
<thead>
<tr>
<th>Simulator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NS-2</strong></td>
<td>A license free network simulator, widely favoured by the open source and academic community. It was developed as part of a large collaboration under the Virtual Inter Network Testbed (VINT) project, with the first release in 1996. It was extended for wireless networks by the RICE University Monarch project and is widely used in MANET research. Official support ceased in 2008 in favour of NS-3.</td>
</tr>
<tr>
<td>Origin:</td>
<td>NS-2 is composed of blocks of C++ code, which is used to model node behaviour such as communication protocols with additional Objective Tool Command Language (OTcl) scripts used to control the simulation parameters and the network topology. Widespread community support has resulted in high availability of contributed models, with a very active mailing list, though the validity of these models may be questionable as thorough documentation and comparative validation results are often not provided.</td>
</tr>
<tr>
<td>Features:</td>
<td>The addition of new components or the modification of existing components is not straightforward and requires familiarity with the OTcl scripting language. An additional GUI (Network Animator - NAM) is required which is not user friendly. There is limited documentation.</td>
</tr>
<tr>
<td>Drawback:</td>
<td></td>
</tr>
<tr>
<td><strong>NS-3</strong></td>
<td>An open sourced license free network simulator, developed by the University of Washington as a replacement for NS-2. It was first released in June 2008.</td>
</tr>
<tr>
<td>Origin</td>
<td>Provides modular support for model development in C++ and removes the NS-2 requirement for OTcl scripts favouring complete C++ development. Additional support is also provided for Python development. NS-3 has improved scalability by utilising architectural concepts from the Georgia Tech Network Simulator (GTNetS) as well as providing improved model documentation.</td>
</tr>
<tr>
<td>Features</td>
<td></td>
</tr>
</tbody>
</table>

99
<table>
<thead>
<tr>
<th>Simulators</th>
<th>Drawbacks</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>OMNeT++</strong></td>
<td>Manual integration of NS-2 modules is required and it is not designed to be backwards compatible with NS-2. The contributed model library is still not mature with slow migration from NS-2 to NS-3.</td>
<td>OMNeT++ provides a programmable, modular framework with GUI for the evaluation of wired and wireless networks. It is comprised of “simple” modules that model a particular behaviour such as a communication protocol (C++) and “compound” modules comprised of multiple linked simple modules e.g. representing a host. Such linking of simple modules is specified using the Network Description Language (NED), subsequently translated into C++ code upon compilation [208].</td>
</tr>
<tr>
<td><strong>QualNet/GloMoSim</strong></td>
<td>There are fewer prebuilt modules and protocols than other network simulators.</td>
<td>QualNet provides a modular and scalable simulator that can operate on a distributed set of machines using parallelised programming. It has an advanced GUI.</td>
</tr>
<tr>
<td><strong>SWANS/JiST</strong></td>
<td>SWANs ceased development in 2005. However the original source code has, in recent years, been used as the basis for vehicular specific extensions.</td>
<td>Specific development tailored for MANET environments and communication protocols. Has demonstrated scalability over equivalent simulators.</td>
</tr>
</tbody>
</table>

**Table 4.1: Features and Drawbacks of Network Simulators**

OPNET was selected as the communication platform for this thesis as it is specifically targeted at application and network performance analysis, providing a comprehensive development environment for the specification, simulation and performance analysis of communication networks using custom specific models as well as an extensive existing protocol library of standards-based and vendor models. Other deciding factors include its flexibility, modular design that supports logic autonomy and facilitates troubleshooting, as well as its wide range of support options for developers. OPNET has a comprehensive FAQ database, an active user forum mailing list and also hosts the annual OPNETWORK...
conference, the largest conference of its kind in network and application modelling and simulation, from which a vast array of presentations, case studies, tutorials and lab documents are made available. A “Contributed Model Depot” is also provided where researchers can submit functionality and models that they have developed to make it available to the wider research community.

Most importantly to this thesis, the OPNET Modeler package allows users to extend existing system components as well as to develop new ones, with different levels of complexity. The engine of the OPNET Modeler is a Finite State Machines (FSM) model in combination with an analytical model. At its very core it consists of C programs, enabling detailed control of the model by the user [209]. As previously stated, the development and integration of custom logic is at the heart of the simulation environment considered in this thesis due to the number of protocols evaluated and the cross layer nature of the communication stack involved. By developing custom models, a deep and complete knowledge of the system is gained, allowing for greater control and a better understanding of the system parameters and functions as well as the interaction between the system layers. Such in-depth knowledge is not achievable with models that have been procured as it is extremely challenging to reverse engineer user contributed models that may not have been implemented according to original specifications.

The research conducted in this thesis and the comparative routing protocols and location services that are evaluated required significant custom process model development. OPNET’s hierarchical structure to modelling is now described in general terms with details relating to its specific implementation in a VANET context further described in Section 4.6. The hierarchical structure of OPNET is comprised of network, node and process models, with each level of the hierarchy describing different aspects of the complete model being simulated:

- **Network models** define a network topology, representative of a communication network and consist of instances of node and link models.
• The internal structure and behaviour of each node in the network is dictated by the *node model*. Processors are the general purpose building block of the node model, are fully programmable and represent an instance of a parent and one or more child process models. Node models resemble block diagrams where each block is a processor. This facilitates modularisation, similar to the OSI model, and thus has the benefit of grouping together conceptually similar functions and allowing new functionality to be easily developed and integrated without affecting the integrity of the entire node architecture.

• Finally *process models* represent communication protocols, algorithms, or in general, any decision-making logic. Process models define the logic using PROTO-C, a high-level programming language based on C. PROTO-C provides a FSM abstraction, allowing the high-level behaviour of an algorithm or protocol to be specified graphically using a State Transition Diagram (STD). Blocks of C code can then be associated with particular transitions or states in order to fully define the process model behaviour. The full power of the C language is available, and extensive code libraries are provided by the OPNET API that implement many common tasks.

### 4.4 Vehicular Traffic Simulators

Vehicular mobility modelling is significantly more challenging than for generic mobile ad-hoc networks in that vehicular movement is constrained by characteristics such as the road topology, traffic control mechanisms and speed restrictions, the movement of other vehicles in the network as well as human driver behaviour and reactions. Realistic mobility modelling is a particularly important environmental characteristic to consider when evaluating IVC protocols as it can have an influential impact on ad-hoc network connectivity and, as a consequence, isolated vehicles. This in turn impacts routing protocol performance and the level of robustness that can be offered to vehicular applications.

Traffic flow theory and simulation is a well-established field, spanning several decades. Originally motivated by the need for civil engineers to design road networks, represent realistic traffic flows and evaluate the impact of transportation control systems, this
research has resulted in the development of mathematical models describing vehicle behaviour (platooning, overtaking etc.) and realistic traffic modelling on a variety of road topologies. Such models have been widely analysed and found to be consistent with empirical traffic measurements. This research into the fundamentals of traffic flow theory provides the basis for the modelling and analysis of IVC protocols and paradigms.

Traffic flow models can be categorised as macroscopic, mesoscopic or microscopic, according to the level of detail with which the traffic is modelled [210]. Macroscopic models describe traffic as an aggregated flow using parameters such as density and average speed. In contrast, mesoscopic models provide finer granularity by modelling individualised vehicle interaction, but with these interactions based on the general characteristics of the “platoon” e.g. an aggregated speed density function. Finally, microscopic algorithms model individual vehicle behaviour along with its interaction with the preceding vehicle and surrounding topology. As the simulation of VANET IVC protocols needs precise details relating to individual vehicle positions on the road at a given time $t$ with respect to surrounding vehicles and road characteristics and as macroscopic and mesoscopic models do not provide this level of granularity, microscopic modelling is deemed the most suitable. It therefore forms the basis for the majority of IVC traffic simulators. Furthermore, microscopic traffic simulators typically display such models visually and provide a mechanism to export such mobility traces to a dump file.

In order to accurately model individual vehicle behaviour that takes into account real road topologies, realistic vehicle movement and interaction as well human driving behaviours, microscopic traffic simulators need to utilise advanced mobility models. Two categories of models can be considered: Cellular Automaton (CA) models [211] in which space and time are discrete or Car Following models in which space and time are continuous. CA models are reduced in complexity, describing a road topology as a lattice of equal size cells. A car following model regulates vehicle behaviour based on the movements of the preceding vehicles, thereby controlling vehicle acceleration/deceleration, avoiding vehicle overlap and maintaining a safe minimum distance between vehicles. Car following models that are in widespread use in IVC traffic
simulators include the Intelligent Driver Model (IDM) [212] and the Krauß model [213] amongst others. Brockfeld et. al [214] evaluated the accuracy of these models and concluded that all approaches provide comparably valid mobility results for use in a network simulator.

This thesis uses SUMO (Simulation of Urban Mobility) [215] as the mobility traffic simulator of choice in order to specify an urban road topology and to generate vehicular traffic with varying degrees of density. SUMO is a free microscopic traffic simulator, developed at the German Aerospace Centre (DLR) that supports the Krauß car following model. Other IVC traffic simulators include VanetMobiSim [216], VISSIM [217], CORSIM [218] and PARAMICS [219]. Their main features and the drawbacks that led to them being eliminated as the chosen traffic platform are presented in Table 4.2. A more comprehensive comparison and performance review of vehicular mobility simulators is provided in [220].

<table>
<thead>
<tr>
<th>Simulator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VanetMobiSim</td>
<td>Extends the JAVA CANU Mobility Simulation Environment (Eurecom) for vehicular specific mobility.</td>
</tr>
<tr>
<td>Features:</td>
<td>Supports user defined topologies, GDF and TIGER maps and clustered Voronoi maps. Mobility Model: FTM (Fluid Traffic Model), IDM-IM (Intersection Management) and IDM-LC (Lane Changing). Produces traces for OPNET, NS-2 and GloMoSim.</td>
</tr>
<tr>
<td>Drawback:</td>
<td>Less active community support. Poor GUI support.</td>
</tr>
<tr>
<td>VISSIM</td>
<td>Developed by Planung Transport Verkehr AG.</td>
</tr>
<tr>
<td>Features:</td>
<td>Supports urban, highway and rural environments. Advanced GUI support with 3D option. Allows varied number of lanes, ramps, roundabouts, traffic restrictions etc.</td>
</tr>
<tr>
<td>Drawback:</td>
<td>Commercial simulator (special dongle required). Not open source.</td>
</tr>
<tr>
<td>CORSIM</td>
<td>The Corridor Traffic Simulation Model was developed by the U.S. Department of Transportation and Federal Highway Administration (FHWA).</td>
</tr>
<tr>
<td>Features:</td>
<td>Comprised of NETSIM (an arterial simulator) and FRESIM (a freeway simulator). Complex simulation logic. Output is summarised into tables.</td>
</tr>
<tr>
<td>Drawback:</td>
<td>Commercial simulator. Limited GUI.</td>
</tr>
<tr>
<td>PARAMICS</td>
<td>Developed by Quadstone Ltd.</td>
</tr>
<tr>
<td>Features:</td>
<td>Supports urban, highway and rural environments. Advanced GUI support with 3D option. Provides environmental simulation in conjunction with traffic simulation. Advanced statistical analysis available. An API is available for customised developed.</td>
</tr>
</tbody>
</table>

Table 4.2: Features and Drawbacks of Mobility Traffic Simulators
The mobility traffic simulators described in Table 4.2 are used in isolation from the network simulation software. Typically the mobility traffic simulator generates mobility trace files detailing vehicle movement over time with these traces files subsequently imported into the network simulator. Both simulators act in isolation with no interaction.

In recent years, additional tools that facilitate strong integration between simulators have been developed, usually via an interface module to allow for bilateral communication. These include TraNS [221], VEINS [222], iTETRIS [223] and SWANS++ [224]. Hybrid simulators have also been proposed that provide a single, fully integrated simulation platform. These include GrooveNet [225], NCTUns [226] and ASH [227]. The reason that one of these packages is not used as the basis for the simulation presented in this thesis is that in most cases the functionality of either the traffic simulator or the network simulator is compromised, resulting in an overly simplified environment. Integration is provided at the expense of complex vehicular modelling or the availability of advanced communication protocols. It is essential to have a highly detailed and comprehensive network environment and mobility model available when studying IVC protocols. A more comprehensive review and discussion on vehicular simulations tools is provided by Olariu et al [228]. The main features of these semi/fully integrated approaches are presented in Table 4.3.

<table>
<thead>
<tr>
<th>Simulator</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TraNS</td>
<td>Developed by researchers at the Laboratory for Computer Communications and Applications at École Polytechnique Fédérale de Lausanne (EPFL), Switzerland. Provides integration between NS2 and SUMO via the Traffic Control Interface (TraCI) interface thereby allowing information pertaining to the state of the network to influence vehicle mobility and vice versa. A TCP based client/server architecture is used. This simulator is no longer supported.</td>
</tr>
<tr>
<td>VEINS</td>
<td>Developed by researchers at the Computer and Communication Systems group at the University of Innsbruck. Provides integration between SUMO and OMNeT++, allowing bidirectional communication via TCP, enabling nodes in OMNeT++ to react to vehicular mobility events and vice versa.</td>
</tr>
<tr>
<td>iTETRIS</td>
<td>Funded via the EU FP7 funded iTETRIS project.</td>
</tr>
</tbody>
</table>
### IVC Simulation Environment

#### Features

This is the successor of TraNS providing integration between SUMO and NS-3 via a module, the iTETRIS Control System (ICS) to facilitate bidirectional communication.

#### SWANS++

**Origin:** Developed by researchers at Cornell University.

**Features:**
Integrates the mobility model STRAW (Street Random Waypoint) \[229\] with the network simulator SWAN. Considers real maps based on the US Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) database but this is limited to the US and STRAW uses a simple random waypoint mobility model.

#### GrooveNet

**Origin:** Developed by researchers at the Real-Time and Embedded Systems Lab at the University of Pennsylvania.

**Features:**
A hybrid vehicular simulator, formerly known as GrooveSim that was formed as an extension to the roadnav simulator. GrooveNet provides inter node communication, accommodates real map topologies in the form of TIGER maps and includes car-following vehicular models. However communications models are not validated. Furthermore, unlike tightly integrated simulators, vehicular motion is not influenced by network events and given that standalone simulators provide comparable functionality with much more mature communication models, the benefits of this approach are negligible.

#### NCTUns

**Origin:** This simulator is named after the university at which it was developed, the National Chiao Tung University (NCTU).

**Features:**
The NCTU network simulator (NCTUns) was originally developed as a network simulator in which both wired and wireless IP networks could be modelled. NCTUns 4.0 subsequently included integrated traffic simulation functionality such as road map topologies and a controller for vehicular movement. Further extension of the integrated environment is not trivial and communications models have not been validated. This simulator also has a commercial version called EstiNet.

#### ASH

**Origin:** Developed by researchers at the Old Dominion University.

**Features:**
Application-aware SWANS with Highway mobility (ASH) extends the SWANS network simulator for a number of vehicular specific extensions including the IDM car-following and MOBIL lane changing mobility modelling.

<table>
<thead>
<tr>
<th>Features of Hybrid Vehicular Simulators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Table 4.3</strong></td>
</tr>
</tbody>
</table>

As noted earlier, SUMO has been chosen as the vehicular traffic platform in the IVC simulation environment used in this thesis. It was chosen for its support of a variety of input map formats, its advanced traffic modelling functionality and mobility model, its visualisation features, as well as its extensive and configurable output measurements depending on the level of granularity required. Furthermore, it is considered to be a pioneering mobility simulator with widespread community support and an active mailing list. As evidence of this, a conference dedicated solely to the use and advancement of
SUMO was launched in 2013 [230]. As discussed in Chapter 2, Joerer et. al [190] conducted a review of the reproducibility of IVC simulation analysis based on the level of detail presented in published papers and also identified the level of usage of particular parameters, technologies and simulators. Importantly, they found SUMO to be the leading road traffic simulator, in contrast with VanetMobiSim, the usage of which has steadily declined over recent years and VISSIM, the commercial road traffic simulator, which maintains steady but small usage.

As previously stated the research conducted in this thesis requires extensive configuration and integration of SUMO and related tools as well as custom process model development for integration with OPNET. SUMO’s structure is now described and illustrated in general terms with details specific to the presented research further described in the next section.

The SUMO implementation consists of a central SUMO module with several additional modules that can be used to customise the road topology, traffic flow and simulation output. Specifically, the SUMO modules that are used in this thesis are:

- **NETCONVERT** (command line network importer)
- **DUAROUTER** (command line module that imports traffic flow configurations and computes the shortest routes through the network)
- **SUMO** (microscopic command line simulation – core module)
- **GUISIM** (microscopic simulation with graphical user interface)
- **MPL Density file** (Python script that takes an aggregated edge dump file output from the SUMO module and generated a density image file).
- **TRACEEXPORTER** (command line tool to export vehicle traces for input to a network simulator).
- **POLYCONVERT** (importation of polygons from an input map format for visualisation in GUISIM)
4.5 IVC Mobility and Traffic Modelling

Fundamentally, three tasks are necessary in order to generate vehicular mobility traces for use in the network simulator. Firstly the road network must be determined from real maps, secondly, traffic must be generated and lastly the simulation must be performed and visualised with mobility exported as a set of trace files for importation into the network simulator. This process is now described.

A number of geographical map input formats are supported by SUMO including Vissim and Visum (provided by PTV), ArcView (NavTech-Files) [231], map shape files provided by the US Census Bureau Topologically Integrated Geographic Encoding and Referencing (TIGER) database [232] or XML input formats such as those provided by OpenStreetMap (OSM) [233]. In this thesis the OSM input format is used as it provides freely editable world-wide geographic data and maps without legal or technical restrictions. The TIGER database contains geographic data relating only to the USA and VISSIM is a commercial simulator requiring a special dongle. In contrast, OSM is not beholden to any restrictions and is in widespread use in both academic and non-academic projects. Despite being freely editable, its accuracy has been verified and has been the source of significant study, including work presented by the authors in [234] that specifically studies the accuracy of OSM in Irish cities in comparison with Google and Bing Maps. Comparable results were found. Furthermore many services such as the popular Open Route Service [235] base their entire service on OSM data, highlighting the widespread high level of confidence in its accuracy. However it should be noted that the coordinates necessary to specify a fixed size area of the OSM map were retrieved from Bing Maps.

In this thesis the road layout of a 2500m x 2500m sub section of Cork City based in Southern Ireland is considered. A screenshot of the Cork City OSM map can be seen in Figure 4.3(a). Prior to using this map in SUMO as the basis for the road network, it is necessary to manipulate the OSM map to reflect real vehicular conditions. In this thesis, a separate software package entitled Java Open Street Map (JOSM) [236], an OSM editor, is used to edit the Cork City map for three purposes:
• Firstly to specify pedestrian and one way streets so that traffic flows are restricted according to real vehicular conditions.

• Secondly, the maximum speed limit restriction within the Cork City OSM file has been modified to 50 km/h as the default speed restrictions associated with the imported edges were by default too high for safe motoring within an urban environment.

• Finally and importantly, JOSM is used for specifying data relating to building coordinates which is vital as part of an obstacle model to simulate accurate radio channel conditions. OSM maps not only provide data relating to road layouts but also allow users to specify buildings, amongst other road characteristics. This is used as the basis for the implemented channel model discussed further in Section 4.6.3. However while the downloaded Cork City OSM file included some specified buildings, details were scant and thus it was necessary to use JOSM to specify the majority of the building coordinates in the area. The screenshot of JOSM displayed in Figure 4.3(b) shows a specified building outlined in yellow. These building specifications are later read by the SUMO POLYCONVERT module.

Once the OSM map has been modified to accurately reflect real vehicular conditions, it is next used by the NETCONVERT module to create a road network file. The NETCONVERT module is a command-line tool that converts the input OSM formatted map file into a SUMO format, by generating a *.net.xml file representative of the road network. The results of this can be seen in Figure 4.3(c) as displayed by the SUMO GUI tool. Once the road network file has been created, polygons representing buildings can be modelled in SUMO using the poly XML element specified in an additional file linked to the main configuration file. The POLYCONVERT module imports this data from the OSM file, using a typemap to specify the types that should be selected. In this thesis, only building information is extracted with information relating to OSM elements such as waterways, local amenities etc. ignored. The extracted information is stored in a *.poly.xml file which is then visualised by the SUMO GUI tool. Figure 4.3(d) shows an example of Cork City with modelled polygons.
Once the road network is built, the vehicular traffic patterns must be generated. SUMO can build demands in a number of ways using trip definitions, route definitions, random routes and manually specified routes. In all cases, a route file, *.rou.xml is specified by the user, that describes the vehicle characteristics. A trip definition specifies the starting and finishing edges for a single vehicle along with its time of departure. Similar to a trip definition, a flow definition file specifies a starting and finishing edge however this specification is applied to multiple vehicles as opposed to a single vehicle with vehicles arriving according to a specified inter-arrival period. A manually specified route is analogous to a trip definition, however it not only contains the first and the last edge, but also all the edges the vehicle is required to travel through. The SUMO DUAROUTER module then computes the vehicles route using the Dijkstra shortest path algorithm based on the route file and the demand definition file. In this thesis, eight separate flow definitions (*.flows.xml) are specified with rerouters (*.add.xml) used to redirect vehicles to an alternative route to prolong time in the network. A summary of the mobility modelling parameters is shown in Table 4.4:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Length</td>
<td>5m</td>
</tr>
<tr>
<td>Maximum Speed</td>
<td>50 km/h</td>
</tr>
<tr>
<td>Reaction Time – Acceleration, Deceleration</td>
<td>2.6, 4.5</td>
</tr>
<tr>
<td>Vehicle Mobility Model</td>
<td>Krauß car following model</td>
</tr>
<tr>
<td>Lane Width</td>
<td>3.2m</td>
</tr>
<tr>
<td>Inter Lane/Vehicle Spacing</td>
<td>0.1m, 2.5m</td>
</tr>
<tr>
<td>Time to teleport</td>
<td>disabled</td>
</tr>
</tbody>
</table>

Table 4.4: Vehicular Road Traffic Parameters

Finally, once a realistic road topology has been constructed (*.net.xml file) and the traffic modelling is complete (*.rou.xml), it is necessary to generate output traces that can be used by the network simulator in order to evaluate IVC protocol performance. To do this, configuration parameters, such as the paths to the road network file and the route file, amongst other parameters, are passed as part of a SUMO configuration file to a module entitled NETSTATE which generates a detailed output file in XML format describing the whole network and the positions of vehicles at given time intervals. It must be noted however that as this format is not suitable for input into OPNET, our chosen network
simulator, the structure of the file needs to be manipulated using the SUMO TRACEXPORTER module. This module converts NETSTATE dump files into a structure acceptable by NS2 by generating three outputs: an activity dump indicating the entering and leaving times of every vehicle, the configuration file with general simulation parameters and the mobility dump that includes the vehicle ID, timestamp, x, y and z coordinates of every vehicle. In this thesis the mobility dump output of the TRACEXPORTER module is further pre-processed for use in OPNET. Importantly, it must be further noted that the author of this thesis fixed a bug in the TRACEXPORTER module relating to the curvature of the road which was contributed back to the open source community. It was previously stated that the coordinates of the polygons, representing buildings in the area, are used as part of an obstacle model discussed in Section 4.6.1. The obstacle coordinates are also exported and parsed into OPNET for use in the channel model.

This process is illustrated in Figure 4.2 with the output from each stage of the process shown in Figure 4.3.
Chapter 4: IVC Simulation Environment

1. Road Network Generation
   - OSM
     - *.osm file
   - JOSM
     - Modified *.osm file
   - NETCONVERT

2. Traffic Modelling
   - DUAROUTER
     - "*.net.xml file"
     - "flows.xml file"
     - "vehicle.rou.xml"
     - "*.rou.xml file"

3. Simulation and Export
   - SUMO
     - edge_density.xml
     - "*.sumo.cfg"
     - *net.xml
     - *.edge_dump.add.xml
     - *.poly.xml
     - *.add.add.xml
     - rerouter.xml
   - Density Python Script
     - density.png
   - TRACE EXPORTER
     - mobility.xml
   - POLYCONVERT
     - *.poly.xml
   - OPNET

Figure 4.2: Mobility Modelling
Chapter 4: IVC Simulation Environment

Figure 4.3: Core Vehicular Traffic and Topology Modelling Components of the IVC Simulation Environment

(a) Open Street Map Representation of Cork City (2500m x 2500m)
(b) JOSM Building Specification in a sub-section of the Cork City map
(c) POLYCONVERT model to represent building polygons in a sub-section of the Cork City map
(d) SUMO NETCONVERT to represent road layout
(e) Traffic Modelling using flows and rerouters
(f) Python Script to represent mean vehicular density
(g) Mobility Modelling in the network simulator OPNET
4.6 IVC Network Modelling

The core communication components of the vehicular simulation platform illustrated in Section 4.2 and described in Section 4.3 have been developed using the OPNET network simulator. As previously stated, integration of custom logic is supported in OPNET, with process models representing the heart of custom simulation development. The implemented IVC simulation platform described in this chapter and the communication protocols proposed in this thesis required extensive custom development at both node and process model level, across all layers of the communication stack. In total 2 node models and 8 custom process models were developed with a further 5 process models extended, of which 2 required significant extension, with the remainder requiring lesser modifications for integration purposes. The core OPNET components of network, node and process models were outlined in Section 4.3 and a subset of the implemented IVC platform, representative of each of these components, can be seen in Figure 4.4.

![Figure 4.4: Core OPNET Components of the IVC Simulation Environment](image-url)
In order to implement the communication components of the IVC simulation platform, the following custom implementations and modifications were made:

- Development of the proposed IEGRP geo-routing process model as well as two comparative geo-routing process models, including integration, custom statistics and attributes as described in Section 4.6.1.
- Development of the proposed UVLS location service protocol as well as three comparative location service models, including integration, custom statistics and attributes as described in Section 4.6.2. This further includes development of an application layer distributed hash table process model for use in ILS/UVLS location services.
- Vehicular channel modelling required development of new wireless pipeline stages as described in Section 4.6.3 as well as specification of custom attributes and statistics.
- Incorporation of 802.11p WAVE and PHY standards as described in Section 4.6.4.
- Application models needed modification for custom statistics and custom source-destination distance ranges. Application configuration is described in Section 4.6.5.
- Integration of vehicular mobility and RSU placement required modification of the OPNET mobility management process model and development of a custom child model to parse and update vehicle positions according to external SUMO specified vehicle trajectories. This is referenced in Sections 4.6.6 and 4.6.7.

Simulations are replicated 5 times for each configuration with varying random seeds until a stable outcome is achieved. The underlying Random Number Generator (RNG) is initialised using the seed environment variable which can be changed in the configuration dialog box. In the simulations described in this thesis, the RNG impacts the time at which packets are transmitted, chosen destination nodes and the hashed IDs allocated to vehicles and intersections amongst other functions and thus plays an integral role in the presented simulation analysis. The default RNG used by earlier versions of OPNET is
based on the operating systems \textit{random()} implementation with random numbers drawn from a single random number sequence and is invoked in simulations using OPNET specific kernel procedures. However as outlined in [237], this default RNG has been shown to exhibit a number of limitations, including that it fails a p-value test checking the uniformity of the outputted values. Newer versions of OPNET, including the version used in this thesis (12.1), employ a RNG based on the Mersenne-Twister [238] which generates random numbers with a period of $2^{607} - 1$. This is in contrast to the original RNG model which has a period of $2^{31} - 1$. This RNG is therefore considered to be of a high quality and suitable for the presented simulation analysis.

4.6.1 Geo-Routing Modelling

The implementations of the proposed vehicular geo-routing protocol, IEGRP, along with comparative geo-routing protocols, C2CNET/GPSR and ISO/ETSI GeoUnicast used in the simulation evaluation, are now described. These models were the most complex element of the developed IVC platform and required significant development and customisation within OPNET.

The geo-routing models are implemented as child process models of \textit{manet\_rte\_mgr}, which in turn is a child process model of the \textit{ip\_dispatch} process model of the \textit{IP} processor. A “child” means that they represent process models invoked by another process model. It should be noted that aside from the development of core geo-routing logic, custom geo-routing model development required significant integration and in-depth knowledge of the OPNET MANET model internals and interfaces, in order to integrate the models with upper and lower layers in the communications stack. This included:

- Creation of child routing process models attached to the parent \textit{manet\_rte\_mgr} process model with addition of the custom protocols in IP header files.
- Integration with \textit{ip\_dispatch} to check if the custom routing protocols are configured on node interfaces and to facilitate invocation.
**Chapter 4: IVC Simulation Environment**

- IP and node model modification to handle incoming/outgoing packets at the IP layer and to add routes to the IP Common Route table.
- Creation of UDP process handles and dedicated ports.
- Creation of new custom packet formats including fields, headers, packet size etc.
- Geo-routing protocol specific custom attributes and statistics. Attributes are the properties or parameters of the protocol that characterise how it should behave. These attributes can be configured dependent on the purpose of the simulation. Statistics are the metrics that gather results from the simulation. It is possible to specify custom metrics and the frequency with which the metric is sampled.

Once the custom models are integrated into the OBU and RSU node models, logic specific to the geo-routing protocol can be implemented. The STD process model for the proposed geo-routing protocol, IEGRP, is shown in Figure 4.5. Similar process models were developed for the comparative routing protocols C2CNET/GPSR and ISO/ETSI GeoUnicast but are not shown for brevity. It can be noted from Figure 4.5, that the model is comprised of 6 states, each of which has an enter and exit state. Within each state, functions defined within the Function Block (FB) can be invoked to minimise the length of code within each enter/exit state (the FB can be noted in the blue circle). An unforced state is marked as red if the DES is required to wait for an interrupt (event) to occur before it can transition to the exit state whereas a forced stated, marked as green, can execute its code and transition to the next state without an event occurrence. Other important model components include temporary variables (defined in the TV block) which are only valid within a state, state variables (defined in the SV block) which are valid between state transitions and variables defined in the Header Block (HB) which is analogous to a C header file i.e. global variables within a process model (particular to one instance of a node).

The IEGRP model, shown in Figure 4.5, is comprised of a number of states, with similar models devised for comparative geo-routing protocols:
**Init:** Once this process model is initially invoked (begsim interrupt) the simulation enters this state, parsing simulation attributes, reading simulation inputs, registering the routing protocol with IP, obtaining the subnet coordinates and node location etc. It then transitions to the "**Wait**" state.

**Wait:** This is a dummy state where control resides between each transition to another state. It can receive four interrupts in total, two self-interrupts and two packet-interrupts.

**Spawn_loc_service:** This state is invoked once, creating and invoking the appropriate location service process model depending on the configured location service attribute.

**Pkt_arrival:** This state determines whether the packet is a location management packet or a data packet and queues the packet accordingly. Location management packets are sent
to the `iegrp_rte_send_loc_request_create_ip_pkt` function where they are encapsulated accordingly. Data packets are directed to the `iegrp_rte_pkt_arrival_handle` function which invokes the `iegrp_rte_app_pkt_arrival_handle` or the `iegrp_rte_lower_pkt_arrival_handle` functions depending on whether the packet is travelling up or down the communication stack.

**Check_send_buf:** This state is invoked each time that a vehicle/RSU receives a WAVE WSA, indicating the arrival of a new neighbour or the updated location of an existing neighbour. It checks its list of buffered packets to see if any can be offloaded to a better forwarding node according to the routing algorithm for determining the best path.

**Remove_expired:** When a packet is buffered, a timeout threshold is set according to the configured store and forward timeout attribute and a self-interrupt is scheduled. This state is executed if the packet is still buffered when the threshold is reached and the `iegrp_remove_expired_buffered_packets` function is invoked. If the packet is offloaded to another vehicle/RSU before the threshold the interrupt for this state is cancelled.

Finally, the geo-routing characteristics and behaviour is configurable via a custom set of node attributes.

### 4.6.2 Location Service Modelling

The implementation of the proposed vehicular location service protocol, UVLS, along with comparative location service protocols, GHLS, MBLS and ILS used in the simulation evaluation, are now described. These location service models are implemented as child process models of the developed IEGRP, C2CNET/GPSR and ISO/ETSI Geo Unicast process models described in the previous section and can be observed, circled in red, in Figure 4.5.

As ILS and UVLS require a DHT a separate process model has been developed as part of a processor module (entitled Chord) that directly interacts with UDP in the vehicle/RSU node models. This can be observed in Figure 4.4 (b). As with IEGRP, location service modelling required the specification of custom location service query and reply and packets in OPNET.
As described in Chapter 3, the proposed location service algorithm specifies that a vehicle updates its location server when it travels a distance that exceeds the distance threshold or based on an expired timer, whichever occurs first. The timer based update is triggered based on the time taken to travel the distance threshold based on the vehicles average speed. The distance based update occurs when a distance threshold is exceeded. In order to provide a consistent evaluation of UVLS with comparative location services the same radio range (discussed further in the next section) and distance thresholds are considered. If location update packets are transmitted too frequently, this results in a significant increase in network overhead however if they are not transmitted frequently enough, stored location information can be stale. While reasoning as to why particular distance thresholds were specified in comparative literature are not provided, it has been observed that the location update is typically in the range of 40-45% of the transmission range (e.g. 100m of the 250m radio range for ILS, VLS and RSLS and ~336m for the 750 radio range for RLSMP) and thus a similar distance update threshold of 45% of the maximum theoretical radio range of 210m has been evaluated in this thesis for all location service protocols i.e. 94.5m. The UVLS model, shown in Figure 4.6, is comprised of a number of states, with similar models developed for comparative location service protocols.

![Custom Developed OPNET UVLS Process Model (STD)](image)

Figure 4.6: Custom Developed OPNET UVLS Process Model (STD)
**Init:** Once this process model is invoked by the geo-routing protocol, the simulation enters this state where it parses simulation attributes, build a table of intersection coordinates amongst other functions. It then transitions to the “Wait” state.

**Wait:** This is a dummy state where control resides between each transition to another state. It processes packet, remote and self interrupts.

**Update_position:** This state is invoked based on a timer initiated self-interrupt or a remote interrupt from the *SUMO_mobility* process model. *SUMO_mobility* is a custom developed process model that was developed as a child of the *random_mobility_mgr* process model (part of the Mobility Config object) as shown in Figure 4.7. It parses SUMO vehicular and RSU traces and updates vehicle positions. The *SUMO_mobility* model initiates a remote interrupt when a vehicle travels a distance greater than the update threshold, based on the threshold value configured in the location service node attributes. The *uvls_send_location_update* function is then invoked.

**Handle_packet:** This state determines whether the packet is a location query packet or a location update packet and queues the packet accordingly. A remote interrupt could also be issued from this state to the Chord DHT process model if the node in question is a location server.

**Init_Chord_join:** This state is invoked if a RSU recognises that it is acting as a location server at an intersection. If so the location server is part of an overlay network and must maintain overlay information, including a location service table at the application layer. A remote interrupt is sent to the Chord processor as shown in Figure 4.4 (b).

**Query:** This state accepts location query requests from the geo-routing protocol and initiates a location query packet to the location determined via the location server hashing algorithm. Once the query packet has been created the state invokes its parent geo-routing process model.
Finally, the location service characteristics and behaviour is configurable via a custom set of node attributes.

4.6.3 Channel Modelling

The radio propagation model employed when simulating protocol performance can have a significant impact on successful packet reception. However, channel modelling is complex and its accuracy is often inherently linked to a specific environment. In this thesis, eight channel models have been considered and given the lack of available channel models in OPNET, considerable custom development was required. It should be noted however that while the implemented channel models have been validated via simulation and channel conditions modelled to reflect urban vehicular conditions as accurately as possible, this is not the primary focus of this thesis.

In recent years, many publications have outlined results from empirical testing [239,240]. Empirical models do not always generalise to other environments and while worthwhile information is presented, it is often either overly complex to model or the model is not made explicit to allow for the model to be replicated. Channel models may be categorised as deterministic or probabilistic with both approaches characterising the impact of pathloss on the received signal power as a function of the distance between the transmitter and receiver. Deterministic channel models such as the Friis/Free Space Loss
(FSL) [241, 242] and Two-Ray Ground (TRG) models return a single signal strength value based on the distance traversed, but disregard other attenuation characteristics. As outlined in [243], two other main factors, in addition to distance based path loss, play a role in determining the power of a received signal: shadowing and multipath fading. Probabilistic models take these attenuation characteristics into account and are therefore more realistic than their deterministic counterparts. Shadowing models the impact of the surrounding obstacles on the mean signal attenuation at given distances. This is commonly modelled by Log-Normal Shadowing. Multipath fading results from the reception of multiple time delayed attenuated replicas of the transmitted signal at the receiver, frequently modelled by Nakagami, Rayleigh and Ricean distributions [241].

The OPNET Modeller package simulates wireless packet transmission in fourteen radio transceiver "pipeline stages" which are a sequence of C procedures that determine if a packet is to be received or not. The pipeline stages are modelled transceiver attributes with stages 0-5 associated with the radio transmitter and 6-13 associated with the radio receiver. The channel models now discussed were implemented by modifying the seventh "received power" pipeline stage.

The Friis FSL deterministic model is firstly considered with received power modelled as per Equation 4.1. This propagation model is available as part of the standard simulation models in the OPNET Modeller package.

\[ P_{r_{\text{fsl}}} (d) = \frac{P_t G_t G_r \lambda^2}{16\pi^2 d^2 L} \]  \hspace{1cm} (4.1)

where \( P_t \) is the transmit power, \( G_t \) and \( G_r \) are the transmitter and receiver power gain, \( \lambda \) is the wave length, \( d \) is distance between the transmitter and receiver in metres and \( L \) is the loss factor.

The Two-Ray Ground deterministic model was also evaluated with the received power modelled as per Equation 4.2. This channel model was implemented by the author of this
thesis as it was not available as part of the standard OPNET models. The parameters are the same as with the Friis model with the exception of $h_t$ and $h_r$ which are the heights of the transmitting and receiving antennas and $d_c$ which is the crossover distance in metres.

\[
P_r = \begin{cases} 
P_{r,\text{fd}} & \text{if } d \leq d_c \\
\frac{P_{r,\text{eg}}}{d^4L} & \text{if } d > d_c
\end{cases}
\]

where \( d_c = \frac{(4\pi h_t h_r)}{\lambda} \)  \hspace{1cm} (4.2)

The third model is a shadowing model that calculates the received power by multiplying the deterministic received power (modelled by distance-based path loss) with an additional component that reproduces the random variability of wireless links, analogous to fading. This is implemented by the author of this thesis using a combination of two previously contributed OPNET models. The path loss is modelled as per Equation 4.3.

\[
P_{L,\text{shadow}}(d) = -10\alpha \log \left( \frac{d}{d_0} \right) - X_\sigma
\]

where \( \alpha \) is a path loss exponent in the range [2.7 - 5] for urban scenarios and \( X_\sigma \) represents a log-normal distribution with zero mean and a standard deviation of 4dB [244] based on recommended values [243] and empirical measurements from suburban and urban city experiments [245]. In the evaluation discussed in this thesis, a path loss exponent of 2.8 is used which is in line with empirical measurements for vehicular urban environments [245, 246]. With uncorrelated shadowing, a received power is output from a distribution for each individual transmission. In reality, attenuation of signals and therefore received powers will typically increment and decrement in a less diverse way for the same transmitter and receiver pair. Therefore a separate fourth correlated shadowing model considers this by correlating shadowing values based on the previous six values between the same transmitter and receiver pair.

This large scale shadowing with correlation propagation model was then extended to include small scale characteristics such as multipath fading. The Nakagami-\textit{m} distribution
is used which utilises the mean received power to determine the strength of each
individual radio signal in a probabilistic manner. The \( m \) parameter specifies the intensity
of the fading [247] with \( m=1 \) resulting in Rayleigh fading (modelling harsh NLOS
scenarios) and \( m>1 \) in Ricean fading (modelling LOS scenarios). When \( m<1 \), the fading
is even more severe than Rayleigh fading. This model has been proven to accurately
reflect the impact of environmental conditions on the received power. The path loss is
modelled as per Equation 4.4.

\[
P_{L_{\text{nakagami}}}(d) =
\begin{align*}
10\gamma_1 \log_{10} \left( \frac{d}{d_0} \right) + X_{(m,\Omega)} & \quad \text{if } 0<d<d_1 \\
10\gamma_1 \log_{10} \left( \frac{d_1}{d_0} \right) + 10\gamma_2 \log_{10} \left( \frac{d}{d_1} \right) + X_{(m,\Omega)} & \quad \text{if } d_1<d<d_2 \\
10\gamma_1 \log_{10} \left( \frac{d_1}{d_0} \right) + 10\gamma_2 \log_{10} \left( \frac{d_2}{d_1} \right) + 10\gamma_3 \log_{10} \left( \frac{d}{d_2} \right) + X_{(m,\Omega)} & \quad \text{if } d>d_2
\end{align*}
\]

where \( X(m, \Omega) \) is a random variable following a Gamma distribution representing the
Nakagami multipath fading component with \( m \) representing the shape parameter and \( \Omega \)
controlling the distribution spread. An \( m \) value (\( m_f \)) of 1.5 has been chosen in accordance
with the recommended value for urban environments [248] decreasing according to \( d_{0,m} \)
and \( d_{1,m} \) thresholds depending on the distance between the transmitter and receiver. Path
loss is assumed to follow a dual-slope model described in [249] with path loss exponents
\( \gamma_1, \gamma_2, \gamma_3 \) and crossover thresholds \( d_1 \) and \( d_2 \) described in Figure 4.8 (a).

The next propagation model is based on empirical measurements of Cork City by Pastor-
Grau et al [250] who subsequently developed an OPNET model. This radio propagation
model considers path loss due to distance based on the deterministic FSL model, obstacle
interference via shadowing (based on empirical measurements) and models fast fading using the Nakagami-$m$ distribution. The results of the empirical measurements provides 100% delivery rate up to 35m with the probability of successful delivery decreasing accordingly up to a maximum radio range of 55m where 100% packet loss is experienced.

A computationally inexpensive channel model derived by Sommer et al [251] is next implemented by the author of this thesis that specifically differentiates between Line of Sight (LOS) and Non-LOS (NLOS) in the communication path between the source and destination transmitter. It derives a shadowing component to be included as an extension to well-established deterministic path loss models, representative of obstacles such as buildings. This implemented model required the definition of OSM building polygons in JOSM and exportation of the OSM obstacles from SUMO. This process was previously described in Section 4.5. The model is represented according to Equation 4.5.

$$P_{dBm} = P_0 + 10\log\left(\frac{G_iG_rA^2}{16\pi^2d^a}\right) - \beta_n - \gamma d_m$$

where $\beta_n$ represents the attenuation in dB that results from the wireless signal traversing exterior brick walls and $\gamma d_m$ represents the loss as a consequence of traversing the internal structure of the building in dB/m. Once the SUMO obstacle file is parsed into OPNET, a custom pipeline stage model was developed to implement the obstacle and fading model outlined in Equation 4.5. This channel model is then associated with the attributes of the wireless receiver as shown in Figure 4.8 (b).

Finally the aforementioned implemented obstacle channel model described by Sommer et al was extended by the thesis author to include small-scale characteristics such as multi path fading, modelled via the Nakagami-$m$ distribution as previously discussed. This is the channel model that has been used as the basis for the described simulations. The channel parameters used to validate the described models are outlined in Figure 4.8 with the findings of the model validation now discussed.
Chapter 4: IVC Simulation Environment

To validate the accuracy of the described channel models, the Packet Loss Ratio (PLR) is calculated as a function of increasing distance between source and destination vehicles. To eliminate the possibility of noise and interference caused by simultaneously transmitting antennas, a single transmitting and receiving antenna was employed. Two topologies, representing LOS and NLOS were considered, with a visual contextualisation shown in Figure 4.8 (a). In the first LOS scenario, represented with the green line, the transmitting vehicle remains stationary (marked by ‘X’) with the receiver vehicle moving approximately 240m away from the source in a straight unobstructed line. The stationary vehicle transmits ICMP 64B frames at 10ms intervals. Both vehicles are initially positioned 2.5m apart as typically recommended by traffic safety guidelines. In the second NLOS scenario, represented with the red line, the receiver vehicle travels away from the stationary source, traversing the block of buildings, which forms an obstruction to the wireless signal, before returning to the starting point. The distance the vehicles travel relative to the simulation time is shown in Figure 4.8 (a-b) with the simulation results shown in Figure 4.8 (c-d).

As expected, it can be noted that the FSL and TRG models incur no packet loss up to a distance determined from the chosen transmit power and the receiver sensitivity threshold (~210m). They do not take into account the difference in LOS and NLOS conditions and does not incorporate attenuation as a result of obstacles in its model, with no packet loss experienced in the NLOS scenario. The lack of suitability of the TRG model in vehicular networking simulations (although it is commonly used) is further highlighted, as it can be noted that the TRG model incurs exactly the same path loss as the FSL model for both scenarios. This is as a result of the crossover distance, $d_c$, shown in Equation 2, which is largely impacted by the antenna heights and frequency transmission band. Antenna heights of 1.5m are used in these experiments as the typical height of a standard motor vehicle is 1.4m and the IEEE 802.11p CCH centre frequency of 5.89GHz is used to calculate $\lambda$. This results in a crossover distance of approximately 488m. Under realistic channel conditions, 802.11p WAVE communications in urban areas are highly unlikely to reach this far [252] and thus use of the TRG model simply mimics the FSL model.
### Propagation Parameters

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Value</th>
</tr>
</thead>
<tbody>
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<td>Transmit Power</td>
<td>8 dBm</td>
</tr>
<tr>
<td>Receiver Sensitivity Threshold</td>
<td>-85 dBm</td>
</tr>
<tr>
<td>Antenna heights</td>
<td>1.5m</td>
</tr>
<tr>
<td>$d_0$</td>
<td>1m</td>
</tr>
<tr>
<td>Shadowing path loss exponent $\alpha$</td>
<td>2.8dB</td>
</tr>
<tr>
<td>Shadowing deviation (Outdoor) $\sigma$</td>
<td>4dB</td>
</tr>
<tr>
<td>Nakagami $d_1$, $d_2$</td>
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</tr>
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<tr>
<td>Nakagami $m_1$, $m_2$, $m_3$</td>
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<td>LOS/NLOS path loss exponent $\beta_m$</td>
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</tr>
<tr>
<td>$\gamma d_m$</td>
<td>0.45dB/m</td>
</tr>
</tbody>
</table>

---

**Figure 4.8 (L-R):** Visual Contextualisation of the NLOS/LOS scenario (a) vehicle channel parameters (b) vehicle distance travelled as a function of simulation time (c-d) Propagation Model Evaluation of Packet Loss Ratio as a function of simulation time for LOS and NLOS scenarios respectively.

---

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It can be noted that log normal shadowing improves on deterministic models by modelling the attenuation caused by fading. However, the uncorrelated shadowing model (green line) does not consider the spatially correlated nature of shadowing and so correlated shadowing is also considered (purple line). Both of these models are not scenario specific and therefore do not adequately reflect NLOS conditions. The probabilistic Nakagami channel model is next evaluated (also considering correlated log normal shadowing) and the impact of multi path fading on the PLR can be noted (yellow line). None of the aforementioned models are NLOS specific. It can be observed that the empirical Cork City model [250] results in a 100% packet loss above 55m. While this model is based on empirical testing, it is disregarded as the underlying propagation model for the evaluation discussed in this thesis as it is considered to be overly pessimistic, limited experiments were undertaken and the experimental test equipment (CVIS OBU with Microwave Communication Module and CVIS rooftop antenna) may have led to inaccurate measurements. Consequently, the propagation model proposed by Sommer et al was also evaluated with an obstacle model specific to the network topology under evaluation that specifically considers NLOS scenarios. It can be observed for the NLOS scenario (orange line) that this has the impact of loss of packet delivery when buildings obstruct the LOS between transmitter and receiver. However in LOS scenario, it does not consider any small scale characteristics such as multipath fading and thus acts as a simple deterministic model. It can be observed that it does not exactly mirror the FSL model as might be expected, as Sommer et al recommend a path loss factor of 2.2 in accordance with their empirical urban measurements. In contrast when this model is extended to include Nakagami fading more realistic conditions are modelled (pink line) and this propagation model has thus been chosen to represent the radio channel for the experiments described in this thesis.

It should be noted that none of the aforementioned models consider the effect of V2V wave-guiding. Wave-guiding models wireless wave propagation in street canyons or tunnels. It is thus of special interest in urban vehicular environments though as noted in [253] the equations for dielectric wave-guiding [254, 255] should be amended for real world vehicular environments. This is because vehicular environments differ from
theoretical assumptions in a number way of ways e.g. street canyons do not have continuous walls but rather are broken by cross streets, surfaces are rough and the wave guide itself is not empty but filled with other obstacles i.e. other vehicles etc. [256]. Wave guiding can yield a smaller path loss exponent than free space loss and failure to consider it can lead to underestimation of the received signal strength. This is an area that is largely unexplored in the simulation of V2X channel conditions but is beyond the scope of this thesis.

4.6.4 Data Link and PHY Modelling

The PHY and MAC layers are modelled for V2V communication according to the 802.11p Wireless Access for Vehicular Environments (WAVE) specification which modifies the IEEE 802.11 technology for vehicular conditions. WAVE operates in the 5.9 GHz frequency band and is implemented in OPNET based on a contributed model by Koubek et al [257], shown in Figure 4.9, along with the configuration parameters in the default OPNET WLAN attributes. The WAVE PHY layer is based on an extended version of the OPNET IEEE 802.11a model based on Orthogonal Frequency Division Multiplexing (OFDM) with a data rate of 6Mbps [258] and a dedicated control channel. The MAC layer is based on an extension of the 802.11e standard using the 802.11e-based channel coordination function for each of node’s network interfaces, with a separate interface used to model the service and control channels (SCH and CCH respectively). The channel coordination function is based on the Distributed Coordination Function (DCF) based on collision avoidance (CSMA/CA) but can employ the EDCA mechanisms for categorising and prioritising traffic to improve QoS (separate queues corresponding to specified application classes). The 802.11e MAC is extended to support synchronisation of the CCH and SCH timeslot intervals and ensures that all data is transmitted in the correct time slots and over the correct interface.
4.6.5 Application Modelling

Detailed application modelling is not the primary focus of this thesis nor has modelling of non-safety based DTN/non DTN V2X applications been adequately addressed in research literature due to the infancy of the field. However application traffic is modelled to reflect indicative vehicular infotainment traffic which utilises the proposed routing algorithm and locations service.

Two methods for deploying application traffic are available in OPNET. Firstly, MANET node models support raw packet generation by specifying start/stop time, packet inter-arrival rate, packet size and the destination IP address. This is used when supplied “standard” applications do not fit application modelling requirements. Secondly, node models can use the “standard” application profiles that allow more detailed application specification. This is the method that is employed and extended in the developed IVC simulation platform. In OPNET, application traffic is modelled according to a three step process as illustrated in Figure 4.10. The “Application object” defines the configuration for every application modelled in the simulation with a number of standard application models supplied in the default OPNET Modeller package. The “Profiles object” describes the user behaviour. Within each profile object, the applications associated with the profile, its operation mode, start time, duration and repeatability is specified. A profile has been created for each vehicle participating in the vehicular network. Finally profiles are deployed with nodes selected as clients, serves or both. Importantly, the C executable file that randomly selects a destination vehicle was modified to incorporate particular
source-destination distance ranges i.e. destination selection is normalised but within a
given range specified in metres. This is based on a custom configurable OBU and RSU
node attribute.

![Configuration Diagram]

Figure 4.10: OPNET Application Modelling

In-depth categorisation of vehicular infotainment applications is largely missing from
literature with more general categorisations existing relating to safety, traffic
management and infotainment. However it can be considered that infotainment
applications may broadly categorised into two broad areas ranging from real-time
applications with stringent QoS requirements e.g. fast paced gaming to those that are
more delay tolerant e.g. file sharing, puzzle based games.

Considering the first category, researchers such as Boban et. al, have studied real-time
game modelling in a vehicular context over completely infrastructureless VANETs,
assuming an idealised routing protocol (all paths to the destination were known) [187,
188, 259]. They considered a “First Person Shooter” game modelled by Farber et. al
[260] noting that gaming sessions can be accurately modelled exponentially with a mean
duration of 1.5 minutes. End to end latency of less than 50ms is considered excellent
gameplay, 50-100ms considered good gameplay, 100 – 150ms resulting in noticeably
decreased gameplay, 150-200ms representing significantly affected gameplay and finally
delays exceeding 200ms considered intolerable. In the second category applications such
as CodeTorrent [261], CarTorrent [262] have been proposed and similar to web
browsing, delays in the matter of seconds are tolerable.
For the purpose of the work presented in this thesis delay tolerant application traffic is modelled (as detailed application modelling is not the focus of this thesis). However a discussion of the results examining IEGRP and UVLS applicability with respect to the possible broad application categories just outlined is provided in Chapter 5. A file transfer application is modelled with the file size generated according to an exponential distribution with a mean of 1MB. UDP is used for transporting the application layer traffic. The author acknowledges that TCP is typically used as the transport protocol for file transfer protocols such as FTP traffic over the Internet. However the performance degradation of TCP over wireless multi-hop networks is well documented [263, 264]. This problem is further exacerbated in vehicular environments due to high mobility and a harsh fading environment [265] leading to authors such as Viriyasitavat et. al recently proposing a solution for a VANET Transport Control Protocol that out performs existing TCP for delay tolerant applications in VANETs. However this work is in its infancy and thus to avoid packet loss as a result of issues with the transport layer, UDP is employed. This is deliberately employed so as to best analyse the routing protocol performance thereby avoiding packet collisions or packets loss due to reduced network throughput. It can thus be concluded that packet loss occurs solely because of a non-existent path link in the case of an idealistic scenario or as a drawback of the particular routing/location service scheme being evaluated.

A constant density of vehicles is maintained in the network at all times with all vehicles exist in the network at start-up where they are moved to their initial starting positions according to the vehicular mobility traces. The routing protocol then starts and beacons are exchanged. To allow old neighbour entries to be removed from the vehicle routing tables and as some vehicles are moved to their starting position at a slightly later time than the majority, a warm-up period of 25s is employed during which vehicles move but no application traffic is generated. Therefore, any event prior to the time instance equal to initialisation period in addition to the warm-up period is not evaluated. The simulation analysis conducted in this thesis is focused on robust and timely packet delivery. Thus evaluating the performance of system under varied application loads is therefore not the
main objective and the application load is kept consistent across simulations while vehicle density is varied in order to remain comparable.

The number of communicating pairs in the simulations is kept constant regardless of the considered vehicular density in order to provide comparable results, with 20 vehicles communicating simultaneously on average (10 pairs). This is chosen to generate a sufficient amount of application traffic to gather meaningful results without any negative consequence of overloading the channel. Randomly chosen vehicles execute their applications with an exponentially distributed session duration time of 90 seconds. Application characteristics are summarised in Table 4.5

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport Protocol</td>
<td>UDP</td>
</tr>
<tr>
<td>Number of Senders</td>
<td>20 vehicles (10 pairs)</td>
</tr>
<tr>
<td>Packet Inter-arrival Time</td>
<td>50ms (20 pkts/s)</td>
</tr>
<tr>
<td>Session Duration</td>
<td>Exponential (90s)</td>
</tr>
</tbody>
</table>

Table 4.5: Summary of Application Communication Parameters

In IEGRP, or any geo-routing scheme that employs a buffering mechanism in order to overcome temporary disconnections in the network connectivity, a buffering timeout value must be specified after which a packet is destroyed as further buffering and successful packet delivery is no longer of use to the application. As tolerable delays are inherently application specific, it is envisaged that when deployed the proposed geo-routing protocol would tailor the value of the ETSI TC ITS Lifetime field of the GeoUnicast packet according to the application layer protocol. However in this research in order to study the end to end delays incurred for delivery, a high Lifetime field in the extended GeoNet (GeoUnicast and LS) extended header fields of 30s is used.

When evaluating the proposed and comparative vehicular location services, accurately and robustly deriving the location of the destination is the key measure of performance i.e. the Query Success Rate (QSR). It can be assumed that current location information can be piggybacked in subsequent data packets to maintain accurate location information as the application session continues. Thus a single application data packet is initiated with
Chapter 4: IVC Simulation Environment

10 randomly chosen communication pairs maintained per second. This results in close to 10,000 data points.

4.6.6 Vehicular Density

The density of vehicles is an important consideration when evaluating the performance of vehicular communication protocols via simulation. Not only does it have an impact on the connectivity of the ad-hoc network and consequently whether a path exists to successfully route a packet to the destination but it also impacts the duration of the link. Link duration in sparsely connected networks that are free of vehicular congestion may be more fleeting in nature as vehicles may travel faster and are not as obstructed by preceding vehicles as in a densely populated network. Vehicle densities have been selected ranging from 5 – 9 vehicles/km, with evaluations increasing in 1 vehicle/km increments. These vehicle density parameters are in line with related studies in the current literature and summarised in Section 2.4.1, with the evaluated densities ranging from 1.5 to 17.5 vehicles per km as shown in Table 4.6. The map sizes and road topologies employed were summarised in Section 2.5. In line with realistic traffic scenarios, the vehicular densities utilised in the simulation analysis described in Chapter 5 is not uniform in nature.

| GSR GPCR | 6.6 | Gyta | 4 – 7 |
| ASTAR | 5.4 - 8.62 | Louvre | 10 |
| VADD | 3.4 - 4 | TO-GO | 12 – 17 |
| MURU | 11 – 17.5 | SADY | 1.5 – 4 |
| PDGR | 3 – 6.5 | EBGR | 10 |

Table 4.6: Simulated number of vehicles considered in comparable vehicular routing schemes per km

To gain visual insight into the simulated vehicular density, the SUMO-GUI can be used for manual inspection as the simulation is executed. However in addition, an open source Python script, previously contributed via the SUMO community, was used to read the network file and an "edge-dump" file generated once the simulation has completed. However as this script was not functional as it had been written for a deprecated version of SUMO and could not parse the current edge dump files, it was amended by the thesis author, a bug report submitted to the SUMO mailing list with the modified script now available to the wider SUMO community. Streets with a low density are marked as green.
and those with a high density value are marked as red. This can be noted in Figure 4.11. For values between the specified low (0.0) and high (1.0) range, the colour is determined using linear interpolation [266]. Roads upon which vehicles did not travel are excluded from the density heat map.

Figure 4.11: Vehicular Density for (a) 5 and (b) 9 veh/km (156 and 520 vehicles)

The prolonged rollout of vehicles equipped with 802.11p enabled radios is another factor that must be considered when undertaking vehicular simulation studies, as a high prevalence of non-equipped vehicles will have an impact on the ad-hoc network connectivity of applications. This is referred to as the vehicular penetration rate. The definition of the penetration rate can vary with Lochert et al [267] defining it as the average number of equipped vehicles per radio range of the road. However it commonly refers to the number of WAVE equipped vehicles divided by the total number of vehicles present in the network. This is the definition used in this thesis. The vehicular penetration rate will largely depend on the projected market prevalence over the coming years as currently 802.11p devices are largely being researched by manufacturers of high end vehicles. In this thesis, the impact of varied market penetration rates is not specifically evaluated via simulation as it has been shown by Wisitpongphan et al, based on data gathered from the I-80 California interstate [268], that the ad-hoc network connectivity provided at a vehicular penetration rate less than 100% is comparable to that provided by a lower vehicular density assuming 100% penetration. The author acknowledges that explicitly considering penetration rates could potentially lead to reduced vehicle speed and movement dictated by the density and other vehicles may influence radio propagation
however such a study is outside the scope of this thesis. Thus based on the findings by Wisitpongphan et. al, considering vehicle densities of 156, 225, 306, 400 and 520 vehicles is the equivalent of considering penetration rates of 30%, 43%, 59%, 77% and 100% of the 520 vehicle scenario and thus evaluates the impact of penetration rates less than 100% during initial VANET deployments.

### 4.6.7 Road-Side Unit (RSU) Infrastructure Density

In this thesis the use of infrastructure is evaluated to overcome the disconnected nature of ad-hoc networks, with a routing protocol and location service proposed that exploits infrastructure where available to improve the packet delivery and query success rates. However a fully deployed RSU infrastructure may be labour intensive to deploy and may not be economically feasible in the short term e.g. Savari RSUs cost approximately $6,000 per unit [269]. Therefore a partial RSU infrastructure in urban environments is a more imminent reality, particularly in the early years while vehicular networks are being adopted. This thesis considers varying levels of RSU density in the undertaken simulation analysis to evaluate its impact on the proposed routing protocol and urban location service.

To achieve this, the described scenario using the Cork City map was extended to include stationary RSUs. Assuming that RSUs will be based where there is existing infrastructure, e.g. traffic lights, 61 possibilities exist for RSU placement in the Cork City map as denoted in red in Figure 4.12 (a). It can be observed that much of the existing infrastructure is situated on the top right and centre of the map, concentrated around the city centre. As it is not computationally feasible to consider all possible RSU densities, a subset is considered ranging from 0 RSUs (ad-hoc only communications) to the maximum of 61. In order to discount the possibility of a biased evaluation as a consequence of the random placement of RSUs, a subset of permutations is chosen according to:

- RSUs clustered in a particular part of the network. Four clusters are considered for a 10 RSU scenario as highlighted in Figure 4.12 (b).
- RSUs evenly distributed throughout the network and evaluated with the RSU density increasing by 10 RSUs at a time.
- 10 RSUs located around the perimeter of the network with two such permutations considered.

Figure 4.12: (a) Possible 61 RSU Positions in the Cork City Map (b) Clustered RSU Placements
4.7 Chapter Summary

In this chapter, the concepts and tools behind vehicular network and traffic simulation modelling are firstly discussed. The custom IVC environment is then described by interlinking the traffic simulator SUMO and the network simulator OPNET. Importantly, extensive cross layer development was required with custom models to accurately model the wireless channel, MAC/PHY layer, routing, location service, mobility and application traffic. Particular attention was given to the determination of carefully chosen parameters to build a realistic urban specific vehicular platform as it has been shown that many comparative schemes either do not specify key parameters or choose unsuitable parameters. This was discussed in Section 2.5 with the deficiencies of existing schemes summarised in Tables 2.2 and 2.3. In contrast to existing approaches, IEGRP and UVLS evaluations are simulated for a sufficiently long period to gather a statistically significant number of samples. Both protocols are evaluated against equivalent vehicular protocols, consider the 802.11p wireless standard, a propagation model suitable for urban channel conditions and are explicit in their application modelling. The next chapter demonstrates the importance of such detailed modelling for the performance evaluation of the proposed protocols, IEGRP and UVLS.
Chapter 5: Location Management Performance Evaluation

5.1 Introduction

This chapter describes the simulation evaluation of the proposed hybrid routing protocol, LEGRP (Section 3.2) and location service, UVLS (Section 3.3), as outlined in Chapter 3. The chapter is organised as follows:

Section 5.2 provides a network context of the vehicular environment within which the performance of the proposed protocols are simulated and evaluated.

Section 5.3 discusses and analyses vehicular routing protocol performance. Specifically, Sections 5.3.1 and 5.3.2 describe the routing-specific experimental evaluation environment, benchmark performance metrics and the comparative vehicular routing protocols under consideration (algorithm specific nuances and simulation parameters). Sections 5.3.3-5.3.6 evaluate the performance of LEGRP and comparative vehicular routing protocols over varied source-destination vehicle distance ranges, vehicular densities, RSU densities and with respect to delay and hop count, respectively.

Section 5.4 describes vehicular location service performance. Specifically, Sections 5.4.1 and 5.4.2 describe the location service experimental evaluation environment in relation to algorithm specific nuances of the comparative vehicular routing protocols under consideration and benchmark performance metrics. Sections 5.4.3 to 5.4.5 inclusive evaluate the performance of UVLS and comparative vehicular location service protocols over varied source-destination vehicle distance ranges, vehicular densities, RSU densities and with respect to location accuracy, server placement, overhead and latency respectively.

Finally, Section 5.5 summarises the findings from the described analysis and draws the main concluding remarks from this chapter.
5.2 Vehicular Network Environment – Contextual Description

Current simulation tools do not provide the contextual information that is necessary for the correct understanding of the underlying vehicular environment and therefore the subsequent interpretation and analysis of results. It is important to provide information by which the context of the topological characteristics and dynamics of the mobile vehicular network can be understood to ensure the validity of the results to be benchmarked and interpreted correctly. This is particularly challenging given the highly dynamic and transitive nature of the wireless network environment. Such tools are currently lacking in the literature and the freeware/open source community, though a high demand for such software has been expressed by researchers in this space. Ideally, an IVC simulation tool could provide information such as traffic density per edge over time, average vehicle density per km², number of vehicles travelled on an edge via a feedback loop, average connection duration of V2V connections, number of neighbour vehicles and would provide a visual representation of the temporary wireless links, amongst other characteristics.

A limited amount of research has been conducted to characterise the context of vehicular networks. Pallis et. al [270] from the University of Cyprus, propose a set of metrics that can be used to describe a vehicular environment with respect to localised metrics (node degree, lobby index and link duration), network wide metrics (diameter, closeness/betweenness/bridging centrality) and community metrics (number of clusters, clustering coefficient, number of communities). Loulloudes et. al, researchers from the same laboratory, described similar but slightly re-categorised metrics in [271], grouped as network oriented metrics, centrality metrics, link level metrics and clustering metrics. Importantly, Spanakis et. al, also from the University of Cyprus, seem to be the only authors to have attempted to address the challenge of visualising and producing quantitative environmental metrics for vehicular simulation by developing a simulation tool, VIVAGr (Visualization tool of VAnet Graphs in real-time) [272]. This tool was tested and evaluated by the author of this thesis. Unfortunately key features, as described in the literature, were not functioning and are no longer supported. Communication with the developers confirmed this, though it is expected an improved revision, with many
new advanced features, will soon be made available via GitHub. Thus the situational
description of the vehicular environment utilised in this chapter was derived as described
in Chapter 4, so as to set the context for the performance evaluation of the vehicular
routing protocols. In accordance with a subset of the network oriented and link level
metrics outlined by Loulloudes et. al., [271] two metrics are considered, with the
definitions now provided. These metrics are considered to be the primary metrics to
represent network connectivity in a vehicular environment. These metrics are also in line
with those derived by frameworks such as the IMPORTANT framework for MANET
[273] and the VERGILIUS trace analyser used for TIGER maps [274].

*Vehicular Node Degree:* The number of vehicles within radio range of a given vehicle,
reflective of the wireless network connectivity.

*Link Duration:* The time duration of a wireless communication link between a pair of
vehicles.

To provide situational context of the vehicular environment considered in the presented
simulation analysis, Figure 5.1(a-c) depicts probability density functions of the vehicular
node degree, with Figure 5.1(d-e) illustrating the vehicular link durations. These metrics
are shown over three considered vehicular densities of 90, 225 and 520 vehicles. Table
5.1 shows the mean, minimum and maximum node degree and link durations for all
considered vehicular densities. Vehicular densities were chosen to consider a range of
sparsely, freely moving and densely populated traffic scenarios and are in keeping with
the densities considered in comparable vehicular quantitative evaluations as outlined in
Section 4.6.6 of Chapter 4. Furthermore, the vehicular edge density in the form of heat-
maps was visualised in Section 4.6.6 over 2 densities (156 vehicle (approximately 5
veh/km) and 520 vehicles (approximately 9 veh/km) and were shown in Figure 4.11. It
can be noted from Figure 5.1 and Table 5.1 that the 90 vehicle scenario (approximately 4
veh/km) is significantly more sparsely connected than the 520 vehicle scenario with a
mean of 8.8 and ~46 neighbouring vehicles respectively. Figure 5.1 (d-f) graphs the mean
link durations in seconds for the vehicles in the network, with the mean, minimum and
maximum link durations summarised in Table 5.1 (b).
Figure 5.1. Situational description (probability density function) of the vehicular evaluation environment as a function of node degree (a-c) and link durations (s) with varied node densities (d-f).
5.3 Vehicular Routing Protocol Performance Evaluation

The simulation evaluation of the proposed hybrid routing protocol, IEGRP, its advanced derivatives and comparative vehicular routing protocols is now described. The performance metrics and comparative routing protocols considered are described in the following two sub-sections with their performance evaluated in the subsequent 4 sub-sections.

5.3.1 Routing Experimental Evaluation and Performance Metrics

The performance of IEGRP and comparative routing protocols is evaluated with respect to the metrics now described.

(1) **Packet Delivery Rate (PDR):** The PDR is the ratio between the data packets generated at the source vehicle to those successfully delivered to the destination vehicle. An idealised location service is provided as a benchmark for how the routing protocol would perform if perfectly accurate location information for the destination vehicle was immediately provided on demand.
(2) **Routing Path Length:** The number of wireless hops incurred between the source and destination vehicles in order to successfully deliver the packet.

(3) **Routing Delay:** The delay from when a data packet is transmitted at the source vehicle to when it is successfully delivered to the destination vehicle application process. This includes all MAC layer and routing delays.

The first metric, PDR, is the most important when highlighting the significance of the improved performance of the proposed protocol, IEGRP. It must be noted however, that while improved delivery rates are vital to sustain communications, the timeliness of packet delivery is also important if particular application types are to be supported.

### 5.3.2 Comparative Routing Protocols

As discussed in Chapter 2, a prevalent unicast geo-routing protocol has yet to emerge in the literature or in the vehicular community. As such, vehicular routing protocols were chosen in accordance with EU standardisation best practice and specification. A high level overview of these protocols was provided in Chapter 2. Specific protocol nuances, simulations parameters and implementation details are now highlighted that impact the simulation and analysis of the protocol performance.

C2CNET specifies the use of the Greedy Perimeter Stateless Routing (GPSR) protocol (hence forth entitled C2CNET/GPSR). GPSR is the earliest geo-routing protocol specified for generic ad-hoc networks. When a packet needs to be transmitted and assuming the location of the destination is provided from a location service protocol, a node forwards the packet to whichever of its one hop neighbour is geographically closest to the destination node i.e. basic greedy forwarding. As discussed in Chapter 2, greedy forwarding does not perform well over topologies that do not have a uniform distribution of nodes or contain voids where it is likely that a packet reaches a local maximum i.e. a forwarding node cannot find a one hop neighbour that is closer to the destination than itself. In order to circumvent this void, GPSR introduces the concept of the ‘perimeter routing’ recovery scheme, utilising the right-hand graph traversal rule. This recovery scheme specifies that when a node first enters into recovery mode, its next forwarding
hop is selected sequentially counter-clockwise to the virtual edge formed by it and the destination. Subsequently, the next hop is chosen counter-clockwise to the edge formed by the current forwarding node and the previous forwarding node (See [105] for more details). The algorithm exits perimeter mode when a node is encountered that can greedily route to the destination. The right-hand rule requires that all edges are non-crossing, proposing either the Relative Neighbourhood Graph (RNG) [107], which is the method implemented in this thesis, or the Gabriel Graph (GG) [106] to get a planar network graph with no crossing edges. A specific planar algorithm implementation was not specified by C2CNET. GPSR is often used as a comparative scheme as noted in Table 2.2 of Section 2.5 in Chapter 2 and is the derivative of many vehicular geo-routing schemes.

The second comparative vehicular routing protocol is specified as part of the ISO/ETSI TC ITS reference architecture (originally devised by GeoNet). Its greedy algorithm operates in the same way as that of C2CNET/GPSR but rather than employing a perimeter mode recovery when a void is encountered, delay tolerant store and forward buffering techniques are used, where the packet is buffered until a suitable forwarding vehicle can be found.

The proposed hybrid vehicular geo-routing protocol, IEGRP, as described in Section 3.2 of Chapter 3, is evaluated in this chapter via simulation analysis. In order to evaluate the impact of each feature, a number of derivatives of IEGRP are considered in the simulation evaluation and are labelled as follows in the simulation evaluation:

IEGRP: This routing scheme does not prioritise infrastructure amongst a vehicle’s neighbours however if the default greedy algorithm chooses a RSU as the forwarding node, IEGRP will ensure that the RSU forwards the packet over the available backbone network rather than solely using the wireless VANET.

IEGRP + Override Greedy Scheme i.e. IEGRP + OGS: This routing scheme allows the default greedy algorithm to be overridden to favour a RSU one hop neighbour that makes
less forward progress to the destination than other neighbour nodes but has a wired connection to another RSU that can achieve a greater gain in geographical distance over the infrastructure based backbone.

**IEGRP + Override Recovery Scheme i.e. IEGRP + ORS:** This routing scheme advances IEGRP + OGS further by allowing forwarding nodes to be chosen that can incur a temporary geographic loss towards the destination as long as the node can ultimately route the packet to another RSU geographically closer to the destination over the backbone or can offload the packet to a two hop neighbour that can do the same.

The next 4 subsections (5.3.3-5.3.6) discuss the performance of IEGRP and comparative schemes over varied source-destination distance ranges, vehicular densities, RSU densities and application latencies/path lengths.

### 5.3.3 Scenario 1: Source Destination Distance Ranges

Source-Destination distance ranges refer to data packets destined for a target vehicle within a particular radius of the source vehicle, in order to examine the impact of node proximity, and in particular, its impact on the PDR of the respective routing protocols. A destination vehicle is chosen within a specified minimum and maximum range from the source. This distance is chosen at the time at which the packet is generated and may increase or decrease dependant on the trajectories of the source and destination vehicles. Destination vehicles that are less than 210m from the source are not chosen as such packets can be delivered based on single hop routing from information in the source vehicle’s neighbour table (populated through periodic beaconing). Therefore ranges starting at 210m-420m are considered, increasing in 210m increments (maximum theoretical radio range). The impact of these distance ranges on each routing protocol for 520 vehicles (approximately 9 veh/km) is shown in Figure 5.2(a-b), which illustrates the mean PDR (standard deviations are negligible) for a fully infrastructure-equipped network topology i.e. 61 RSU placements (described in Section 4.6.5) and a completely infrastructureless VANET respectively.
It can be observed from Figure 5.2(a-b) that across all source distance ranges, IEGRP and its derivatives outperform both comparative schemes to achieve the best delivery ratio. As expected, given the design of IEGRP, this is especially the case when infrastructure is available (Figure 5.2(a)). This improved PDR becomes particularly notable as the distance between the source and destination vehicle increases, with IEGRP derivatives making better use of infrastructure to find a path to the destination. IEGRP + OGS notes
an increase in PDR of 34.15%, 34.35% and 49.31% when compared with C2CNET/GPSR (an overall improvement of 67.9%, 84.73% and 201% respectively) for 630m-840m (approximately, 4-6 hop), 840m-1050m (approximately, 5-7 hops) and 1050m-1260m (approximately, 6-8 hops) distance ranges. It incurs an increase in PDR of 20.47%, 23% and 39.32% when compared with ISO/ETSI GeoUnicast (an overall improvement of 31.99%, 44.32% and 114% respectively) over the same distance ranges. This large improvement occurs for two reasons. Firstly, RSUs route packets over the backbone network in order to make greater greedy progress towards the destination vehicle. Secondly, the greedy routing algorithm can be overridden if a RSU is a neighbour as the algorithm recognises that it may not be located to make the greatest temporary greedy progress in the first instance but can make greater gains over the backbone network with respect to the overall delivery. It can be observed that IiEGRP + ORS exhibits a further increase in PDR when compared with IiEGRP + OGS of 4.75%, 5.61% and 12.16% for the 630m-840m, 840m-1050m and 1050m-1260m scenarios (an overall improvement of 5.63%, 7.49% and 16.48% respectively). This is because it allows the greedy scheme to be overridden to choose a node that makes a temporary loss in progress but can route closer to the destination over the backbone network. Furthermore IiEGRP + ORS incorporates an alternative to the store and forward scheme where packets can be backtracked to a RSU (potentially two hop).

In contrast, the delivery rates of C2CNET/GPSR and the ISO/ETSI GeoUnicast protocol are highly dependent on the distance between the transmitting and receiving vehicles with an almost linear decrease in successful packet deliveries noted as distance increases, rendering them essentially inoperable. This is mainly as a consequence of increased reliance on multi-hop communications through the VANET which is more susceptible to partitions in the network. The sharp decrease in the performance of C2CNET/GPSR is as a result of its recovery scheme which is not suitable for highly dynamic environment i.e. the challenges in the forming and maintaining a planar graph in vehicular networks, given high vehicle mobility, negatively impacts such a routing scheme leading to routing loops and poor delivery rates. Furthermore, despite the ISO/ETSI scheme employing store and forward buffering and noting an improvement over the face routing recovery scheme of
C2CNET/GPSR for all distance ranges, the PDR performance is still highly susceptible to increase in the distance ranges. However IEGRP and its derivatives are not as susceptible to increases in distance range and are relatively distance insensitive as the protocol is designed to exploit infrastructure where possible. It can be noted that IEGRP notes minimal improved delivery rates in the 210m-420m (approximately 2-4 hops). The reason for this is the closer proximity between nodes, reducing the likelihood of a preferable path over the wired infrastructure.

Figure 5.2(b) shows the incurred PDR performance of one of IEGRP’s derivatives and comparative routing protocols over a completely infrastructureless network. As the distinguishing factor of IEGRP is that it exploits infrastructure where available, it incurs minor PDR improvements in a completely ad-hoc network. However in accordance with the criteria set out in Section 3.2, it employs a greedy scheme (albeit one designed for infrastructure assistance), a store and forward buffering scheme and additional advanced forwarding characteristics in that it selects forwarding vehicles not only based on distance, but also based on their direction of travel in order to maximise delivery. Thus, IEGRP still incurs marginally improved PDR (approximately 3%) by considering the direction of the next hop mobile neighbour. However, as with all completely distributed routing solutions designed for vehicular networks, it is susceptible to impacted delivery rates when density is decreased and the network is partitioned i.e. when a path does not exist to the destination.

5.3.4 Scenario 2: Vehicular Density

In order to evaluate the impact of vehicular density on the routing protocol performance, traffic densities between 4 and 9 vehicles/km were simulated, as described in Chapter 4. Thus far, the results discussed in the preceding section assumed 520 vehicles in the network at all times. The performance of the routing protocols as a function of the number of vehicles can be observed in Figure 5.3(a-c). This is graphed across three distance ranges for full infrastructure.
Figure 5.3. Mean PDR for IEGRP and comparative routing protocols as a function of increasing vehicular density over a variety of source-destination distance ranges.
Chapter 5: Location Management Performance Evaluation

It can be observed that as the vehicle density increases, all protocols experience an increase in the packet delivery ratio. This behaviour results from increased network connectivity in the VANET. At low traffic density of 4 vehicles/km (90 vehicles), it may not be possible, in many cases, to establish a communication path between the source and destination vehicles due to the lack of multi-hop connectivity. In contrast at higher vehicular densities, network connectivity improves and thus more packets are delivered to their destination.

Overall, it can be observed from Figure 5.3, that IEGRP clearly outperforms comparative protocols, demonstrating much improved delivery rates, especially with higher vehicle densities. At lower densities of 90 vehicles, for a distance range of 630m-840m, as shown in Figure 5.3(b), IEGRP + ORS achieves a PDR of 75.7%, a considerable increase in the PDR incurred for C2CNET/GPSR (26.98%) and ISO/ETSI GeoUnicast (41.78%) as well as the PDR incurred for derivatives of its own scheme, IEGRP (66.1%) and IEGRP + OGS (66.6%). As the vehicular density is increased to 520 vehicles, the PDR of IEGRP + ORS grows to 89.19%, which is an increase in PDR of 38.9% and 25.22% over C2CNET/GPSR and ISO/ETSI GeoUnicast as well as 14.43% and 4.75% more than its own derivatives (overall improvement 77.35%, 39.42%, 19.3% and 5.62% respectively).

When the distance range increases to 1050m-1260m as shown in Figure 5.3(a), an increase in vehicular density lends negligible improvement in delivery rates for C2CNET/GPSR and ISO/ETSI GeoUnicast due to the lack of a path through the multi-hop network over a larger distance. Both achieve a PDR of only 9.8% and 23% respectively over a 90 vehicle network, increasing to only 24.48% and 34.47% respectively for 520 vehicles. For C2CNET/GPSR, these performance issues exist because of the absence of a suitable recovery scheme leaving the protocol susceptible to temporary disconnections in the network. ISO/ETSI GeoUnicast does not suffer degradation for this reason as increased density enables it to overcome voids in the network thereby increasing the likelihood of offloading the packet to a neighbour; however at larger distances this improvement does not sustain adequate delivery rates.
It can be further observed from Figure 5.3(c) that IEGRP offers minor performance benefits for the 210m-420m distance for the same reasons as outlined in the previous section i.e. proximity of vehicles negating use of infrastructure.

5.3.5 Scenaro 3: RSU Density

The previous sections, considered either a fully equipped network or a completely infrastructureless VANET. The impact of varying density and placement of partial infrastructure is now evaluated along with its impact of varied vehicular density. The maximum number of RSUs considered is 61, assuming a RSU available at every intersection where there is existing infrastructure as described in Section 4.6.7. These experiments were conducted over the RSU placements outlined in Figure 4.10. RSUs clustered in particular areas of the network are labelled blue, green, red or purple depending on the cluster to which they belong, two perimeter mode configurations were considered and finally RSUs distributed uniformly throughout the map were evaluated.

Research into optimal and cost effective RSU placement has increased significantly in the last year [275-279] and it can be expected that this will continue as research in infrastructure assisted vehicular networks continues to attract more attention. It can be observed from Figure 5.2 that RSU placement has a significant impact on the PDR of all protocols, validating the need for such research. The benefits associated with clustered RSUs and RSUs located around the periphery of the network can be observed to be negligible and are similar in performance to an infrastructureless VANET. This is particularly the case over longer distances with a range of 1050m-1260m considered in Figure 5.4. However for uniformly distributed partial RSU infrastructure, IEGRP notes a significant improvement as observed on Figure 5.4(a). Figure 5.4(b) further examines the performance of IEGRP and comparative protocols over decreasing density of uniformly distributed RSUs. It can be observed that with even as little as 4 RSUs in the 6.25km² area, an increase in PDR of ~22% can be realised.
Figure 5.4: Packet Delivery Rates as a function of (a) varied RSU densities for the 1050m-1260m distance range (b) varied uniformly distributed RSU densities for the 1050m-1260m distance range
5.3.6 Scenario 4: Application Latency and Path Length

IEGRP performance has thus far been discussed with respect to the PDR metric and has demonstrated that it outperforms other protocols with respect to reliable packet delivery in partially and fully equipped vehicular networks across a wide range of conditions. However application performance metrics must also be considered, as even though a packet may be delivered, this delivery may be rendered meaningless if it does not meet the delay requirements of the application. Table 5.2 summarises the distribution characteristics of the packet latencies by IEGRP and comparative protocols for three source-destination distance range assuming 520 vehicles and full infrastructure. The mean, minimum, maximum, standard deviation and 90\textsuperscript{th}/95\textsuperscript{th} percentiles are shown in seconds. The PDR improvement noted for IEGRP is also highlighted.

It can be noted that despite IEGRP + ORS incurring noteworthy increases in PDR relative to C2CNET/GPSR for full infrastructure (% PDR Increase column) IEGRP schemes incur comparable maximum delays and significantly reduced minimum delays over C2CNET/GPSR and ISO/ETSI GeoUnicast. C2CNET/GPSR incurs much lower delays than other schemes but with considerably worse delivery rates as it does not employ buffering techniques. Significantly, it must be observed that IEGRP derivatives incur a lower mean delay than ISO/ETSI GeoUnicast despite both schemes employing delay tolerant store and forward buffering. In particular, for the IEGRP + ORS derivative, it can be noted that 90\% of packets incur a delay of 5ms or less and 95\% of packets incur a delay of approximately 3.9s by making better use of available infrastructure. While 5ms is tolerable for infotainment applications such as fast paced gaming applications (<200ms is satisfactory), delays in the region of seconds are not suitable. However the delays of approximately 3.9s or less would be tolerable for applications such as a delay tolerant file transfer application or a puzzle based challenge gaming application. Vehicular infotainment and specifically delay tolerant applications are gaining traction including KioskNet [280], CarTel [281,282], the EMMA project [283], Drive-Thru [284] and CONDOR [285] amongst others. As recently noted by Pereira et. al [286] in a survey on
vehicular delay tolerant applications, few routing schemes are designed to accommodate delay tolerant applications though the literature in this area is increasing.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Min (x 10^6)</th>
<th>Max</th>
<th>Mean</th>
<th>Std. dev</th>
<th>Percentile 0.95</th>
<th>Percentile 0.99</th>
<th>% PDR Increase</th>
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</thead>
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<tr>
<td>210m-420m</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>C2CNET/GPSR</td>
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<td>0.0107</td>
<td>0.0011</td>
<td>0.0007</td>
<td>0.0015</td>
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<tr>
<td>ISO/ETSI GeoUnicast</td>
<td>8.2</td>
<td>26.881</td>
<td>0.96599</td>
<td>4.0605</td>
<td>7.9867</td>
<td>24.836</td>
<td>5.16</td>
</tr>
<tr>
<td>IEGRP</td>
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<td>4.1764</td>
<td>2.867</td>
<td>24.802</td>
<td>7.08</td>
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<td>0.25802</td>
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<td>12.806</td>
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<td>0.005</td>
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<td>0.0017</td>
<td>0.0066</td>
<td>0.0118</td>
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<td>3.7266</td>
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<td>28.069</td>
<td>61.47</td>
</tr>
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</table>

Table 5.2. Distribution characteristics for the packet delivery latencies (seconds) experienced over increasing source destination distance ranges with full infrastructure

Figure 5.5(b-c) shows the mean, minimum and maximum hop counts incurred for successfully delivered packets for each routing schemes across varied source destination distance ranges. The number of hops is a commonly examined metric when comparing routing protocol performance as it can often impact the end to end delay.

It can be noted that C2CNET/GPSR has the highest path length. While buffering schemes may intuitively incur lower path lengths in terms of hops, higher delays may be incurred as packets are stored and carried. It can be further observed from Fig. 5.5(a) that IEGRP incurs higher path lengths than its advanced derivatives as it only selects forwarding vehicles based on distance, with vehicles that achieve the greatest distance from the source vehicle preferred, thus not prioritising infrastructure. Given this, as IEGRP + OGS and IEGRP + ORS prioritise the wired network, a shorter path length occurs. The author
noted that C2CNET GPSR incurred a much higher failed hop count than other schemes which is in line with the drawbacks of perimeter face routing producing lengthy paths. By seeking to traverse a void in a mobile urban environment, routing loops occur which as well as leading to lower PDR, leads to higher failed path lengths. Typically in multi-hop wireless networks, higher hop counts leads to higher probability of packet drop or channel contention issues.

Figure 5.5: Path Length as a function of varied source-destination distance ranges, both (a) with and (b) without infrastructure.
5.4 Vehicular Location Service Protocol Performance Evaluation

The simulation evaluation of the proposed location service protocol, UVLS and comparative location services is now described. The performance metrics and comparative location service protocols considered are described in the following two sub-sections with their performance evaluated in the subsequent 3 sub-sections.

5.4.1 Location Service Experimental Evaluation and Performance Metrics

The performance of UVLS and associated location service protocols is evaluated with respect to the following metrics:

(1) **Query Success Ratio (QSR):** A query is a lookup made by the routing agent of a node \( s \) requesting the location of a node \( d \). This excludes queries that \( s \) can resolve from its one hop neighbour table. Distinct from the PDR, a query is considered successful if it receives a location reply from the location server that stores \( d \)'s location information. Therefore the QSR is the ratio of location replies successfully received by source vehicles relative to the overall number of location queries generated.

(2) **Packet Delivery Rate (PDR):** As defined in Section 5.3.1.

(3) **Location Service Accuracy:** The difference in metres between the returned location coordinates relative to the destination vehicle’s actual position.

(4) **Average Location Service Delay:** The delay from when a query packet is generated at the source vehicle to when a location reply is received.

(5) **Location Service Load:** The ratio between all location service control packets transmitted by all vehicles to the total number of replies received i.e. the number of control packets (updates, queries, replies and protocol specific control traffic) required to identify a destination’s location.

The first metric, QSR, is the most important when highlighting the significance of the described UVLS scheme when compared with state of the art location services. It must be noted however, that similar to IEGRP, QSR and other metrics are not completely independent and must be considered as a whole. For example, schemes that exhibit low QSR may still have good accuracy despite a small number of replies (such samples are
often biased in favour of smaller path lengths and thus have less delay) and longer end to end delays related to location query or reply packets will have an impact on the reported location accuracy.

### 5.4.2 Comparative Location Service Protocols

Location service protocols to represent flat, hierarchical and overlay based location service schemes have been chosen and evaluated as part of the described simulation analysis. An overview of the operation of these protocols was provided in Chapter 2. Protocol specific nuances and implementation details that impact their performance are now highlighted and are important to consider for the presented simulation evaluation.

IEGRP + ORS is used to route all location service packets but it should be noted that UVLS can work with any routing protocol.

**GHLS** [144] is a flat MANET location service protocol that is commonly used for quantitative comparison in [153, 162, 173] and thus can be considered a baseline, similar to GPSR for routing. The operation of GHLS is described in Section 2.4.1.1 and is illustrated in Figure 5.6. In the GHLS evaluation, the distance threshold $d$, is set to 200m based on a radio range of 250m. However to ensure a comparable simulation evaluation between schemes, a common update distance threshold of 45% of the radio range is employed as discussed in Section 4.6.2. As also noted in Section 2.4.1.1, GHLS specifies a mechanism to restrict the generated hashed location server coordinates to a central part of the network based on a configured $\alpha$ factor. The thesis author conducted analysis of GHLS with $\alpha$ factors of 0.25, 0.5, 0.75 and 1.0 respectively and found that the performance of GHLS with respect to QSR when varying this parameter was negligible as the assumption of nodes clustered in the centre of a network when applied in a vehicular context is not valid. GHLS with an $\alpha$ factor of 0.5 performed marginally better than the others and thus the analysis discussed in Sections 5.4.3 to 5.4.5 inclusive examines GHLS with a configured $\alpha$ factor equal to 0.5. This is based on a maximum increase in QSR of 3.18% and a mean of 2.38% when evaluated for all distances ranges with three vehicular densities in an infrastructure-based and infrastructureless network.
Very importantly, the authors of GHLS state that a node’s unique identifier is hashed into a location with the node closest to that location assuming the role of the location server. However given the frequently disconnected nature of vehicular networks, a forwarding node may consider itself to be the closest node, though not within radio range of the hashed location server coordinates, thereby storing a vehicle’s location information and assuming the role of location server. As expected this has a negative performance impact as when another vehicle queries the location, the query will only be resolved if the packet opportunistically encounters the ‘rogue’ location server. To examine the impact of this given that the GHLS authors assumed a dense ad-hoc network and did not make explicit how GHLS should act in such an instance, the analysis discussed in Sections 5.4.3 to 5.4.5 inclusive will evaluate GHLS with respect to “GHLS LS RR” (i.e. GHLS with a location server within radio range of the hashed coordinates) and “GHLS LS Non RR” where it’s considered not to be the case.

ILS [167] is a flat P2P VANET location service. In the ILS evaluation, \( d = 100\text{m} \) is assumed based on a radio range of 250m. As discussed in Section 4.6.2, \( d = 94.5\text{m} \) is chosen in this thesis. The operation of ILS can be seen in Figure 5.7. It is assumed stabilization, predecessor checks and “fix fingers” control messages necessary to maintain overlay consistency adhere to the same interval as specified in [287].
MBLS [170] is a hierarchical location service designed specifically for vehicular ad-hoc networks that assumes that vehicles located at intersections (waypoints) are selected as location servers. The operation of MBLS was described in Section 2.4.1.1 and is illustrated in Figure 5.8. Given that a static hierarchy of 3 is chosen and the simulation evaluation conducted in this thesis is over a 2500m² map, a first order square is 625m². An important point to note is that MBLS does not explicitly address the situation where an intersection/waypoint does not exist within a particular order square (most likely an order 1 square). While this is unlikely given the size of the first order squares, it is assumed in the implementation of the protocol that the updating/querying vehicle forwards the packet to the next highest order square.

The **ETSI TC ITS Location Service (LS)** protocol [83] is a broadcast bounded protocol with a hop limit of 5 (bounded flooding). This is described in Section 2.4.1.1 of Chapter 2. The next 3 sections (5.4.3-5.4.5) discuss the performance of UVLS and comparative schemes over varied source-destination distance ranges, vehicular densities, RSU densities and with respect to location accuracy, server, latency and overhead.
It should be noted that each of the comparative location services discussed in this thesis employed a different distance threshold in their evaluations. ILS, MBLS and GHLS use distance thresholds of 40%, 50% and 75% respectively of the radio range. As none of these thresholds are integral to the function of each location service, all evaluated schemes in this thesis utilise a common distance threshold of 45% of the radio range or 94.5m to facilitate a relative performance comparison. This is discussed in Section 4.6.2.

5.4.3 Scenario 1: Source Destination Distance Ranges

Similar to the IEGRP evaluation described in Section 5.3.3, source-destination distance ranges starting at 210m-420m are considered in this evaluation, increasing in 210m increments (maximum theoretical radio range). The impact of these distance ranges on each location service protocol for 90 vehicles (approximately 5 veh/km) is shown in Figure 5.9, which illustrates the mean QSR for (a) a fully infrastructure-equipped network topology and (b) a completely infrastructureless VANET respectively. A low vehicular density has purposely been chosen to emphasise the performance impact of the proposed location service protocol.

It can be observed from Figure 5.9(a-b) that across all source distance ranges, for both infrastructure based and infrastructureless scenarios, UVLS outperforms comparative
location service schemes to achieve the best QSR. As expected, given the design of UVLS, the QSR is best when infrastructure is available (Figure 5.9(a)). What is notable is that UVLS maintains high performance (given the considered vehicle density) as distance between the source and destination pairs increases. It maintains performance similar to an idealised location service which will be outlined later in this section. It can be observed from Figure 5.9(a) that UVLS incurs a 16.37%, 13.45%, 42.34% and 6.25% increase in QSR when compared with GHLS RR, MBLS, ILS and ETSI TC ITS LS respectively (overall improvement of 27.5%, 21.54%, 126% and 9%) for the 630m-840m (approximately 4-6 hop) distance and 10.14%, ~1% (negligible), 33.03% and 64.9% for the 1050m-1260m (approximately 6-8 hops) distance.

GHLS RR exhibits a QSR of 56.44%, 59.53% and 54.76% for 210m-420m, 630m-840m and 1050m-1260m in the infrastructure based network (Figure 5.9(a)) and 16.98%, 11% and 9.7% in the infrastructureless network (Figure 5.9(b)). The cause of GHLS' reduced performance is two-fold. Firstly GHLS is a flat scheme. Thus a node's ID is hashed to a set of location server coordinates with the proximity between the node and its location server not considered. This means that location server updates and queries may need to traverse long distances increasing reliance on multi-hop communications through the VANET which is more susceptible to partitions in the network (particular noted in Figure 5.9(b)). It can be observed from Figure 5.9(a) that GHLS performance improves when infrastructure is utilised by the underlying IEGRP scheme to route a packet over wider areas. However the long distances incurred by choosing location server coordinates anywhere within the network, even with a reduced location server area (α factor of 0.5), still negatively impacts performance, particularly given the low vehicular density. This can be further observed as the QSR is maintained at a steadily consistent rate regardless of the proximity between the source vehicle and the queried node and thus is not affected by the range of queries. A slightly improved QSR is noted for the shorter distance range of 210m-420m in the infrastructureless scenario but this is caused by opportunistic resolution of queried destination locations en-route to the location server coordinates.
Secondly, as GHLS was designed for MANETs (yet is frequently used as a baseline comparison) there is a lack of correlation between the location server placement strategy and the underlying topology causing particular hashed server coordinates in areas where there is not a high density of vehicles or frequently isolated and even in positions that are not within radio range of the road topology and thus permanently isolated.
It can be noted that *GHLS RR* notes an increase in QSR of 20.55%, 22.87% and 21.35% when compared to *GHLS Non RR* (210m-420m, 630m-840m and 1050m-1260m respectively) for the infrastructure based network (overall improvement of 57.27%, 62.36% and 63.88%) and an increase in QSR of 13.09%, 9.22% and 9.69% for the infrastructureless network. As discussed in Section 5.4.2, given the frequently disconnected nature of vehicular networks, a forwarding node may consider itself to be the closest node to the hashed location server coordinates, though not within radio range, thereby storing a vehicle’s location information and assuming the role of location server. This has a negative impact on protocol performance when a vehicle queries a location to the expected location server coordinates with such queries only resolved if the query packet opportunistically encounters the rogue location server. Thus the improvement noted by *GHLS LS RR* occurs as a result of assuming a DTN approach and buffering updates and query packets until it reaches the closest node with radio range of the coordinates as opposed to the local maximum in the multichip network. Figure 5.9(a-b) considers the QSR only with no guarantee that receiving a reply from the location service protocol will result in successful delivery of the packet. Failure of the QSR to translate into a successful PDR result can result from lack of network connectivity and lossy channel conditions but may also result from inaccuracy in the returned location information. The PDR incurred by GHLS and other schemes will be considered later in this section.

MBLS provides similar delivery rates to UVLS when full infrastructure is available (particularly at higher distance ranges) incurring a QSR of 71.32%, 62.45% and 64.14% for 210m-420m, 630m-840m and 1050m and 6.36%, 1.25% and 0% in the infrastructureless network (Figure 5.9 (a-b)). A number of factors contribute towards declined MBLS performance, even in the case of full infrastructure. Firstly, MBLS uses a static hierarchical partitioning scheme, independent of the underlying road topology. Thus in cases where vehicles are located in close proximity but exist in different order 1 or in particular order 2 squares, query packets may likely need to traverse a long distance to resolve the location i.e. it effectively suffers similar drawbacks to GHLS. As with many other location service schemes a path through the network with high ad-hoc density
is assumed in the MBLS evaluation. This is exacerbated further as MBLS, unlike GLS (its MANET based equivalent) does not employ a location server in each sibling square within a particular order square. Secondly MBLS relies on a chain of location servers, one per order square, located at intersections. Empty lower order location servers i.e. empty intersections result in the overall failure of an update or query transaction. This situation is emphasised in Figure 5.9 (a-b). Even with infrastructure, a RSU does not exist at every intersection and given the low vehicle density considered, a mobile node may not exist to assume the role of location server. Even if a mobile location server exists, non-infrastructure based lower order servers are responsible for forwarding updates and queries to higher order servers, relying solely on a connected path through the ad-hoc network. If this fails, subsequent queries from vehicles in remote order grids will not be resolved by the closest location server as a location will not be stored. Finally, the update mechanisms employed in MBLS has a negative impact on performance with regard to the accuracy of the reported location. This is discussed further in Section 5.4.5. As with GHLS, QSR improves for MBLS with the availability of infrastructure, especially as it considers location servers to be located at intersections. Increased distance ranges have a considerable impact on MBLS performance in an infrastructureless network, particular given the low vehicular density (Figure 5.9 (b)). The impact of increased distance range lessens as infrastructure is made available (Figure 5.9 (a)) although the resolution of vehicles in close proximity is higher, as expected. As already noted however the arbitrary nature of the grid impacts the performance in this respect.

ILS, as with other schemes performs significantly better when infrastructure is available (33.34%, 33.56% and 31.87% for 210m-420m, 630m-840m and 1050m-1260m respectively for the infrastructure based scenario). The scheme is shown to fail completely in an infrastructureless network (3.1%, 1.98% and 0% for 210m-420m, 630m-840m and 1050m-1260m respectively), despite results to the contrary presented in the ILS evaluation. There are two primary reasons for this. Firstly, ILS is based on the premise of every intersection in the network becoming part of the P2P overlay network. As noted with MBLS not every intersection will have a RSU. The overlay operates with every Chord node i.e. intersection maintaining a finger table (analogous to a routing table
for allocating the keyspace i.e. vehicle locations, to particular intersections). Thus a location server at an intersection may need to forward the update or query packet to an intersection at the other side of the network. Furthermore even if the packet reaches this intersection it could be forwarded back to an intersection at the other side of the network again. This is commonly referred to as “overlay stretch” i.e. there is no actual proximity between close proximity in the overlay ring and physical proximity in the network. Given low density and an infrastructureless network even longer path lengths than a flat scheme such as GHLS exist. Secondly and very importantly, ILS bases its claim of robustness to empty areas of the network or intersections on the ability of the overlay to be “self-healing” i.e. when an intersection is empty it is phased out of the overlay ring with its location entries transferred to another intersection so that location entries are maintained and location servers always known the correct intersection to direct the query to. However this is based on the assumption of intersections i.e. Chord nodes, being able to frequently exchange periodic stabilisation and notify control packets to maintain the consistency of the overlay network and prevent disruption due to overlay node churn. With low vehicular densities, frequent disconnections in the vehicular network and lack of proximity between overlay nodes, overlay inconsistency results in incorrect operation leading to the overlay becoming permanently partitioned, intersections being accidently phased out of the overlay network and incorrect DHT successor and predecessor pointers. This is well documented challenge for P2P overlays in mobile networks and one which is exacerbated in high speed vehicular networks [287,288]. While ILS performs better with infrastructure, leading to less overlay inconsistency and negating some of the drawbacks associated with overlay stretch, the same challenges exist. Locality awareness in construction of the overlay network is not provided [289]. Distance between queries has no direct impact on the location service scheme. Furthermore, the lack of a timeout policy to phase out stale entries at location servers also impacts accuracy, in turn affecting the PDR. This is discussed further in Section 5.4.5.

The ETSI TC ITS LS protocol exhibits comparable performance to UVLS for queried vehicles within the specified 5 hop broadcast limit (83.488%, 83.41% and 69.65% for 210m-420m, 420m-630m and 630m-840m ranges respectively). This decreases to
13.55% for the 840m-1050m scenario for the infrastructure-based scenario. This is to be expected given the broadcast nature of the solution but is at the cost of higher overhead as discussed further in Section 5.4.5. It can be noted that it incurs marginally increased QSR when compared with UVLS of 0.012% and 2.07% (overall improvement of ~0% and 2.54%) for the 210m-420m and 420m-630m scenarios (overall improvement of x% and y% respectively). This occurs for reasons: Firstly, UVLS makes use of cached locations i.e. passive location updates based on forwarded packets. This can occur in instances when a vehicle's speed has changed significantly causing its current location to vary from the cached location, which is being stored for a prolonged period based on its lower past speed. Such instances only cause an issue if the vehicle has travelled a distance greater than the maximum theoretical radio range from the reported location as otherwise it will be correctly routed based on an entry in the forwarding vehicle's one hop neighbour table. Secondly, as UVLS employs unicast rather than broadcast, mechanisms, lossy channel conditions are more likely to impact successful end to end packet delivery. However as ETSI TC ITS LS is essentially a flooding based approach, limited by the configuration of the hop limit parameter, a sharp decrease in noted for the 840m-1050m distance range when many queried destinations cannot be resolved within the 5 hop limit, depending on the preceding forwarding nodes chosen. After this distance range, the location service ceases to function. Infrastructure does not impact on ETSI TC ITS LS performance as it is broadcast based.

UVLS considers locality awareness similar to ETSI TC ITS LS but also wider area queries by availing of infrastructure located at intersections and the overlay network to maintain consistently high QSR, even with low vehicle density. It does not succumb to the drawbacks associated with the ILS overlay as the DHT ring is formed only of static RSUs connected over a high speed backbone, negating the drawbacks associated with overlay inconsistency. In this way as new RSUs are deployed, they can easily join the overlay network with the location information keyspace redistributed throughout the overlay network. For wider area queries, UVLS is limited only by its ability to multi-hop location updates or queries to the closest RSU i.e. dependant on vehicle density and the availability of infrastructure. The impact of increased vehicular density and reduced

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infrastructure on UVLS is discussed in Section 5.4.4. Furthermore while ETSI TC ITS LS maintains comparable QSR to UVLS for local queries, UVLS incurs less overhead. This is further analysed in Section 5.4.5. It can be observed that for wider area queries UVLS performance decreases in the infrastructureless network (19.1%, 10.01% and 9.01%). This is dependent on vehicular density though it should be noted that it still performs marginally better than GHLS, due to passive updating and location caching.

The PDRs incurred by each scheme over a fully infrastructure based and infrastructureless network are shown in Figure 5.10 (a-b). This is shown as an indication of the accuracy of the locations returned by the location service protocols. It can be noted that UVLS incurs close to perfect PDR (based on an idealised location service) for locality aware queries and out performs all others schemes over increased distance ranges. Importantly, it is acknowledged that the PDR can be impacted by other factors such as availability of a route to the destination and thus no definitive conclusions can be drawn from examining the PDR alone but it is noteworthy to observe that the PDR and QSR (Figure 5.10) for UVLS, GHLS, ETSI TC ITS LS and ILS are very similar. There is greater variation between the QSR and PDR for MBLS. As it is important to evaluate location reply accuracy, as inaccurate information can have a negative impact on the PDR and lead to incorrect forwarding decisions by the routing protocols, this is examined further in Section 5.4.5.
5.4.4 Scenario 2: Vehicular and RSU Density

In the previous section a low vehicular density was evaluated. The impact of increased vehicular densities of between 4 to 9 vehicles/km on the location service protocol performance is now evaluated. The QSR of the location service protocols as a function of the number of vehicles can be observed in Figure 5.11 for a 1050m-1260m distance range over full infrastructure. It can be noted that as expected, Figure 5.11 shows that as the density of the network increases and the network becomes more connected all schemes experience improved QSR. A particularly notable improvement is not experienced with GHLS Non RR but, as already described, this does consider a partitioned ad-hoc network. ILS still experiences overlay consistency drawbacks. It can be observed that UVLS, MBLS and GHLS RR all exhibit an upward trend in QSR and while UVLS performs marginally better for the considered 1050m-1260m distance range as queries are intentionally directed towards intersections with RSUs, other schemes also provide a high QSR (UVLS QSR of 89.55% with GHLS and MBLS QSR of 83.73% and 85.1% respectively for 520 vehicles). However it should be noted that the QSR does not reflect the accuracy of the returned location which is addressed in the next section.
The performance of the location service protocols is next evaluated with decreasing RSU availability as shown in Figure 5.12. A low vehicular density of 90 vehicles, a distance range of 1050m-1260m and RSUs distributed as uniformly as possible throughout the network are considered. This distribution is determined given the restricted options for RSU placement where there is existing infrastructure as already discussed in the IEGRP evaluation in Section 5.3.5. GHLS, MBLS and ILS are particularly susceptible to decreasing RSU availability for the reasons discussed in Section 5.4.3. UVLS is also susceptible to the decrease in infrastructure but as it deliberately directs update and query packets to location servers at infrastructure based intersections and as it employs location caching and passive updating, it does not suffer as severe degradation in performance, as noted in Figure 5.12(a). Furthermore as UVLS employs a topologically scoped unicast for locality aware queries, it performs well with the reduction in infrastructure only causing a minor impact as a result of lack of connectivity. UVLS incurs QSRs of 63.5%, 53.7% and 12.53% for the 10, 6 and 2 RSU configurations respectively for the 1050m-1260m distance range and 85.84%, 82.01% and 78.84% for the 210m-420m distance range. It can be noted that as infrastructure is decreased, UVLS more closely resembles GHLS LS RR. This is because it is a flat location service scheme. However it still out
performs this scheme by employing location caching and by utilising infrastructure at intersections rather than arbitrarily chosen location server coordinates.

As the results shown in Figure 5.12 are for 90 vehicles, to evaluate the performance with increased vehicular density Figure 5.13 shows the QSR for the 1050m-1260m distance range

Figure 5.12: QSR as a function of varied RSU densities for the (a) 1050m-1260m distance range (b) 210m-420m distance range for 90 vehicles
range over declining infrastructure for 520 vehicles. It can be observed that UVLS incurs improved QSR with less degradation than comparable schemes.

![Graph showing QSR as a function of varied RSU densities for the 1050m-1260m distance range for 520 vehicles.]

**Figure 5.13: QSR as a function of varied RSU densities for the 1050m-1260m distance range for 520 vehicles**

### 5.4.5 Scenario 3: Location Inaccuracy, Latency and Overhead

The performance of the location service protocols are now examined from the perspective of the returned location inaccuracy latency and overhead incurred. These performance metrics are inter-related and provide insight into the difference between the PDR and the QSR and the overall performance of the location service protocols. For example:

- The location stored at the location server could be accurate but a delay in delivering the reply to the querying vehicle impacts the reported accuracy.
- The distance to the location server increases dependency on the multi-hop network or availability of infrastructure. It increases likelihood of unsuccessful receipt of updates, which depending on the location service scheme, can contribute to inaccurate locations or absence of recorded location information. Similarly it impacts successful receipt or query and reply packets.
As noted in Section 5.4.3, the accuracy of the reported location service coordinates merits further examination as it impacts the subsequent IEGRP routing decisions. The difference between the QSR and the PDR is minor across most schemes as observed in Figure 5.10(a-b). This is indicative of little location service inaccuracy, verified in Figure 5.13 which shows a CDF of the location error for all location service protocols i.e. the difference between the location of the queried vehicle reported by the location service protocol and its actual location. It can be observed that UVLS, GHLS Non RR and ILS incur small location errors (approximately 80% of queries are resolved with location errors of 90.9m, 88.9m and 95.35m or less respectively). It must be noted however that while ILS and GHLS Non RR do not incur high inaccuracy, they experience lower QSR than UVLS as previously highlighted. It can be further observed from Figure 5.14 that GHLS RR incurs location errors of up to 635m with MBLS incurring location error of up to 1km with 86.7% and 80.2% respectively of the reported locations under the maximum theoretical radio range of 210 metres.

A likely cause of location inaccuracy can be linked to the delays incurred from when a query packet is issued to when a reply is received. Thus Table 5.3 investigates the location service delays (s) incurred by each scheme for two distance ranges in a fully
infrastructure based and infrastructureless network. The mean QSR and PDR incurred by each scheme are also listed as a reference point (highlighted). Prohibitive delays inevitably occur for nearly all schemes given the low vehicle density of 90 vehicles (for others the perceived low delays are as a result of a small sample size). It is particularly notable with respect to the location accuracy incurred by MBLS and GHLS that while prohibitive delays occur, it can be observed from the 95th percentile that long delays are not hugely prevalent. This, along with an examination of the recorded data values collected during the experimentation indicates that the location service delays incurred are not the primary source of the location inaccuracies noted for GHLS RR and in particular MBLS as shown in Figure 5.14. Rather it is determined that the update mechanism employed by each location service, can significantly contribute to location inaccuracy as now described.

<table>
<thead>
<tr>
<th>LS Protocol</th>
<th>Max (s)</th>
<th>Mean (s)</th>
<th>Std. dev (s)</th>
<th>Percentile 0.95 (s)</th>
<th>Percentile 0.99 (s)</th>
<th>QSR (%)</th>
<th>PDR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVLS</td>
<td>1.23</td>
<td>0.0239</td>
<td>0.089</td>
<td>0.0025</td>
<td>0.99</td>
<td>83.476</td>
<td>83.465</td>
</tr>
<tr>
<td>GHLS Non RR</td>
<td>4.234</td>
<td>0.134</td>
<td>3.01</td>
<td>0.00123</td>
<td>4.254</td>
<td>35.886</td>
<td>31.589</td>
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<tr>
<td>GHLS RR</td>
<td>29.538</td>
<td>0.666</td>
<td>3.554</td>
<td>0.0343</td>
<td>22.501</td>
<td>56.44</td>
<td>45</td>
</tr>
<tr>
<td>MBLS</td>
<td>29.7919</td>
<td>0.59927</td>
<td>3.1347</td>
<td>0.00718</td>
<td>20.2279</td>
<td>71.32</td>
<td>53.52</td>
</tr>
<tr>
<td>ILS</td>
<td>30.45</td>
<td>0.834</td>
<td>3.9234</td>
<td>0.0103</td>
<td>25.345</td>
<td>33.34</td>
<td>29</td>
</tr>
<tr>
<td>ETSI TC ITS LS</td>
<td>1.03</td>
<td>0.0187</td>
<td>0.019</td>
<td>0.002</td>
<td>0.678</td>
<td>83.488</td>
<td>83.488</td>
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</table>

(a) Full Infrastructure (210m-420m)

<table>
<thead>
<tr>
<th>LS Protocol</th>
<th>Max (s)</th>
<th>Mean (s)</th>
<th>Std. dev (s)</th>
<th>Percentile 0.95 (s)</th>
<th>Percentile 0.99 (s)</th>
<th>QSR (%)</th>
<th>PDR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVLS</td>
<td>2.56</td>
<td>0.0298</td>
<td>0.070</td>
<td>0.0047</td>
<td>1.07</td>
<td>80.65</td>
<td>80.23</td>
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<tr>
<td>GHLS Non RR</td>
<td>26.384</td>
<td>0.659</td>
<td>3.865</td>
<td>0.05948</td>
<td>24.7634</td>
<td>3.89</td>
<td>3.5</td>
</tr>
<tr>
<td>GHLS RR</td>
<td>29.711</td>
<td>0.421</td>
<td>2.611</td>
<td>0.2346</td>
<td>12.4228</td>
<td>16.98</td>
<td>13.08</td>
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<tr>
<td>MBLS</td>
<td>5.1806</td>
<td>0.0343</td>
<td>0.3275</td>
<td>0.07766</td>
<td>0.0821</td>
<td>6.36</td>
<td>5.54</td>
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<tr>
<td>ILS</td>
<td>35.42</td>
<td>0.948</td>
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<td>0.4345</td>
<td>25.836</td>
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<td>ETSI TC ITS LS</td>
<td>2.04</td>
<td>0.0244</td>
<td>0.023</td>
<td>0.0019</td>
<td>0.987</td>
<td>81.1</td>
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(b) Infrastructureless (210m-420m)

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### LS Protocol

<table>
<thead>
<tr>
<th>LS Protocol</th>
<th>Max (s)</th>
<th>Mean (s)</th>
<th>Std. dev (s)</th>
<th>Percentile 0.95 (s)</th>
<th>Percentile 0.99 (s)</th>
<th>QSR (%)</th>
<th>PDR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVLS</td>
<td>25.938</td>
<td>0.3928</td>
<td>2.816</td>
<td>0.00504</td>
<td>17.893</td>
<td>64.9</td>
<td>61.456</td>
</tr>
<tr>
<td>GHLS Non RR</td>
<td>27.8766</td>
<td>0.27688</td>
<td>2.16</td>
<td>0.00175</td>
<td>13.27</td>
<td>33.414</td>
<td>26.869</td>
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<tr>
<td>GHLS RR</td>
<td>29.84</td>
<td>0.443</td>
<td>2.8227</td>
<td>0.009</td>
<td>18.4534</td>
<td>54.76</td>
<td>36.086</td>
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<tr>
<td>MBLS</td>
<td>29.827</td>
<td>0.557</td>
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<td>0.00519</td>
<td>19.828</td>
<td>64.14</td>
<td>39.87</td>
</tr>
<tr>
<td>ILS</td>
<td>32.56</td>
<td>0.92</td>
<td>3.784</td>
<td>0.0211</td>
<td>26.007</td>
<td>31.87</td>
<td>27.9</td>
</tr>
</tbody>
</table>

(c) Full Infrastructure (1050m-1260m)

<table>
<thead>
<tr>
<th>LS Protocol</th>
<th>Max (s)</th>
<th>Mean (s)</th>
<th>Std. dev (s)</th>
<th>Percentile 0.95 (s)</th>
<th>Percentile 0.99 (s)</th>
<th>QSR (%)</th>
<th>PDR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UVLS</td>
<td>19.23</td>
<td>0.3996</td>
<td>2.168</td>
<td>0.965</td>
<td>10.23</td>
<td>10.01</td>
<td>6.34</td>
</tr>
<tr>
<td>GHLS Non RR</td>
<td>19.6245</td>
<td>0.543</td>
<td>3.1795</td>
<td>0.1899</td>
<td>12.4506</td>
<td>0.01</td>
<td>0.01</td>
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<tr>
<td>GHLS RR</td>
<td>24.76</td>
<td>0.454</td>
<td>2.4077</td>
<td>1.13</td>
<td>12.89</td>
<td>9.7</td>
<td>4.367</td>
</tr>
<tr>
<td>MBLS</td>
<td>0.21557</td>
<td>0.0682</td>
<td>0.089</td>
<td>0.207</td>
<td>0.21399</td>
<td>0.002</td>
<td>0.0</td>
</tr>
<tr>
<td>ILS</td>
<td>2.345</td>
<td>0.0742</td>
<td>0.0974</td>
<td>0.046</td>
<td>0.938</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

(d) Infrastructureless (1050m-1260m)

Table 5.3. Distribution characteristics for the location service resolution latencies (s) experienced over two distances ranges with and without full infrastructure.

Recall that ILS updates are based on exceeding the distance threshold only with no expiry of the location data at the server i.e. it is simply overwritten by the next more recent update. This leads to the reporting of stale location entries. However the challenges associated with maintaining ILS overlay consistency are so detrimental to performance that this does not cause high inaccuracies in the presented evaluation (overlay consistency is discussed in the context of ILS in Section 2.4.1.1 and in terms of the Chord overlay (used for UVLS) in Section 3.3.2.1). GHLS updates are also based on distance but when an update is issued a timeout value is included. The timeout is calculated based on the time taken to move the GHLS distance threshold when travelling at the current speed. If the current speed is zero there is no timeout value placed on the update. As a result this leads to stale entries if a vehicle subsequently updates while moving but this update never reaches the location server. Importantly, as with GHLS, UVLS updates are based on a distance and a timer expiry, whichever occurs first. An expiry of 1.5 times the predicted timeout is used. If a location update with a current speed of 0 is recorded, it is phased out of the location server table after 1.5 times the time it takes to travel the maximum radio range at the maximum speed. Thus, in UVLS, stale entries are timed out at a location...
server with any inaccurate replies as a result of intolerable delays receiving the location service reply.

However the large location inaccuracies incurred by MBLS are primarily caused by its location update and expiry strategy. When an MBLS location server receives a query, it replies with the predicted location of the vehicle based on its previously stored coordinates and speed as opposed to the actual cached location. In an effort to reduce the location service overhead that is typically associated with periodic updates, a vehicle updates its location only when it passes a new intersection and when crossing a boundary between order squares. This approach decreases the accuracy of the returned location as it does not consider large distances between intersections leading to fewer updates (this is acknowledged by the authors), particularly if subsequent update packets are not successfully delivered. Furthermore the update expiry threshold is calculated as the time taken to travel between intersections in addition to the time taken to travel the radio range at the current speed. Thus if a vehicle updates when moving at a reduced speed or is stopped at an intersection based on a stop sign or traffic light (likely given that MBLS nodes initiate an update packet when at intersections), the timeout associated with the update is very high and does not consider that vehicles do not move at a constant speed.

To summarise, UVLS provides an accurate QSR that out-performs other location service schemes. However, in order to evaluate if this improved QSR is at the expense of a significant increase in overhead, Figure 5.14 examines the location service overhead i.e. the number of location service protocol control packets (e.g. updates, query and reply packets) necessary to successfully receive a location service reply. The overhead for each location service protocol for the three distance ranges over an infrastructure based and infrastructureless network is considered. Overall it can be observed that, for the most part, all schemes incur similar overhead. Most importantly, UVLS does not incur any significant additional overhead despite improved QSR performance and improved/comparable accuracy. ETSI TC ITS LS incurs the highest overhead for the infrastructure based scenario as it employs a flooding mechanism. ILS also incurs higher overhead than other schemes as a result of overlay stretch. In Figure 5.15 (b) it can be
observed that failure of MBLS to successfully many replies despite transmitting a high number of location service control packets causes significant overhead. A similar situation was noted for ILS though no data point was recorded for ILS for the 1050m-1260m distance range as no replies were received and thus the overhead tended toward $\infty$.

![Location Service (LS) Protocol Overhead](image.png)

Figure 5.15. Location Service (LS) Protocol Overhead
5.5 Chapter Summary and Discussion

In this chapter, the performance of the proposed hybrid geo-routing protocol, IEGRP, and the proposed vehicular location service protocol, UVLS, was evaluated. A contextual discussion of the vehicular environment was provided along with a summary of protocol nuances and simulation parameters that impact the performance of comparable routing and location service protocols.

The most significant result of the IEGRP analysis is that the proposed protocol demonstrates significantly improves packet delivery rates over comparable routing protocols for increasing distance ranges, over full and partial infrastructure. Intuitively, this steadily improves as vehicular density is increased but it can be observed that IEGRP performs steadily even with moderately low vehicular densities while incurring less delay and comparable path lengths. Importantly, unlike existing schemes that make use of infrastructure, it does not dictate mandatory RSU density or placement in the network in order to function but rather dynamically adjusts the routing decision to exploit infrastructure on a per packet basis.

UVLS and comparable location service protocols were evaluated over varied distance ranges, vehicular and RSU densities. Existing location service protocols demonstrate failure to address locality awareness, proximity between vehicles and their respective location servers or ability to overcome low vehicular densities by exploiting the existence of partial infrastructure. Further simulation analysis demonstrates UVLS’ ability to address this with its main contribution in providing higher query success rates in partial and full infrastructure networks while maintaining comparable accuracy, delays and overhead. UVLS demonstrates similar PDR performance to an idealised location service for an infrastructureless and fully infrastructure equipped network, over increasing distance ranges. An estimate of the performance of IEGRP using UVLS as a location service can be achieved by applying the location accuracy rates of UVLS as a probability input to IEGRP.
It is important to consider how the performance results of IEGRP and UVLS would generalise to other road topologies and also to non-urban environments. Both protocols easily generalise for a number of reasons:

- IEGRP adapts its routing decisions on a per packet basis, based on the existence of infrastructure and makes no pre-requisite assumptions relating to RSU placement or density. Thus IEGRP adapts to other urban road topologies or to a highway environment where RSUs may not be located at intersections.

- UVLS uses a topologically scoped unicast for local query resolution with the query split at intersections according to the underlying road topology. Such a solution thus generalise to all environments, from urban to highway, as long as a vehicle has a digital map.

- Furthermore, UVLS routes update and query packets to the closest RSU as it is aware of the presence of infrastructure via the digital map. This again lends itself to generalisation.

Unlike static or even indoor wireless networks, the dynamism and complex nature of vehicular networks does not easily lend itself to the specification of prescriptive results. Thus, in most instances, it is reasonable to assume that a different physical environment can easily produce different results, which is an intrinsic characteristic of such highly complex and dynamic systems. However this motivates why it is important to consider a single physical environment when evaluating and comparing protocol performance while ensuring simulations are carefully designed in all their aspects, particularly relating to the overall validation, comparison and impact of individual parameters. The performance of any communication protocol evaluated in a particular vehicular environment is, for the most part, majorly impacted by parameters such as vehicular density, RSU density, channel conditions and the distance and placement of the transmitter and receiver. Thus, this chapter focused on evaluating IEGRP and UVLS with respect to these parameters.

It is also interesting to consider how the findings from the performance evaluation discussed in this chapter may scale if the road topology is increased, considering similar
vehicular and road densities. As IEGRP performance is dependent on the ability to exploit infrastructure and is largely limited by having a multi-hop path to a RSU, such an approach is largely unaffected by a scaled network map assuming RSU and vehicular density remain constant. A similar scenario occurs for UVLS with update and query packets routed as appropriate via the overlay network on the underlying backbone once a RSU is reached. Scaling the area of the considered map may add some minor delays as a single overlay hop may constitute a large geographical distance in the underlying network and may cause packets to “zig-zag” over the network (known as overlay stretch). However this can be resolved by constructing a topologically aware overlay network [290], an area well studied in P2P networks, and given the high bandwidths associated with backbone networks, delays are considered negligible.
Chapter 6: Conclusions and Future Work

6.1 Conclusions

The increased maturity of IVC research has identified the motivation for next generation vehicular applications beyond safety and traffic management services. Infotainment and comfort applications, facilitated via multi-hop ad-hoc communications or partial infrastructure, have emerged as an attractive class of services. Their success however relies on the ability of a geo-routing protocol to deliver communication packets in a challenging wireless multi-hop environment with highly transient wireless links. Furthermore, to achieve this, the geo-routing protocol must determine the location of the destination vehicle. Until these challenges are adequately addressed, V2V and I2V application adoption will continue to be limited. The principal motivation of this thesis is to investigate a unicast geo-routing protocol that would improve packet delivery in the presence of infrastructure and the provision of a robust and locality aware location service to maximise the resolution of vehicle locations.

The difficulty associated with providing a unicast geo-routing protocol that exhibits high packet delivery rates is that it is constrained by the connectivity of the multi-hop environment or the wide spread availability of infrastructure. Current geo-routing approaches either assume connectivity via a completely ad-hoc network or assume complete RSU infrastructure with the necessary available RSU density. Others dictate prescribed RSU placements. Discussion in Chapter 2 highlighted the need for a hybrid approach that would operate in partial infrastructure in the interim years while costly full infrastructure is being deployed. Such a geo-routing protocol should be able to operate in multi-hop distributed fashion but exploit infrastructure, where available, as much as possible, to maximise packet delivery. Furthermore such a solution should generalise to any network topology.

This led to the proposal of the IEGRP algorithm that adapts its routing decisions on a per packet basis allowing it to dynamically adjust to the network topology within which it is operating. Simulation analysis validated the significance of employing methods in the
routing algorithm to override default greedy and recovery schemes to favour infrastructure if available. As a result IEGRP showed superiority in producing significantly increased packet delivery rates when compared against C2CNET GPSR and GeoNet ISO/ETSI GeoUnicast over a full and partial infrastructure based network. This is its main achievement. It was observed in Chapter 5 that IEGRP is not as susceptible to the almost linear decline in PDR incurred by the compared routing schemes as distance ranges are increased. It was also highlighted that with infrastructure, IEGRP does not incur the same sharp decline in PDR noted for other schemes when vehicular density is decreased. Notably, while IEGRP displayed improved PDR, it does so with comparable path lengths to GeoNet ISO/ETSI GeoUnicast and, more importantly, with significantly reduced delays, even over modest vehicular densities. As expected, IEGRP incurs only a marginal improvement over compared schemes in an infrastructureless network. This marginal improvement occurs as a result of considering vehicle speed and direction when choosing a forwarding vehicle but it must be noted that while employing best practice as described in Chapter 3, it is not the goal of IEGRP to seek to optimise geo-routing for delivery in a fully ad-hoc network.

Location service protocols were also discussed in this thesis. Such protocols are vital to successful geo-routing operation and should provide timely and accurate resolution of a destination's location towards which the geo-routing protocol can forward the packet. Geo-routing is not possible if a destination location is unresolved and if inaccurate location information is returned by the location service protocol, incorrect geo-routing occurs, potentially resulting in successful packet delivery. As discussed in Chapter 2, the main limitations of existing protocols are that they, similar to geo-routing protocols, are designed for either fully distributed networks assuming high vehicle density or fully infrastructure based networks. Similarly approaches that employ RSUs typically prescribe RSU placement and density. Furthermore they present drawbacks in their ability to handle close proximity between vehicles, minimise distance to a vehicles location server and minimise the volume of update traffic, while maintaining a high accurate query success rate. This led to the proposal of a robust and locality aware location service, UVLS, which will operate in vehicular environments to increase the
query success rate. It satisfies the outlined conditions while exploiting partial infrastructure support and, similar to IEGRP, generalises to any considered road topology. As a result, UVLS demonstrates increased query success rates, often close to an idealised location service, when compared to GHLS, MBLS, ILS and ETSI TC ITS LS, over a full and partial infrastructure based network. It was observed in Chapter 5 that UVLS notes this improved query success rate even over a modest vehicular density as distance ranges are increased. More notably, it is further observed that this results in a significantly increased subsequent PDR due to the improved accuracy of UVLS, especially when compared against schemes that achieve somewhat similar QSRs at given distance ranges. MBLS performance increases with infrastructure (low vehicle density and full infrastructure) and at higher distance ranges converges with UVLS. However as noted in the subsequent PDR MBLS incurs much higher location inaccuracy. Importantly, UVLS does not incur additional delays or overhead when compared against existing schemes. However it was observed that UVLS incurs less QSR that ETSI TC ITS LS for lower distance ranges but this is a marginal decrease and it was noted that ETSI TC ITS LS incurs significantly higher overhead.

As outlined in Chapter 4, a comprehensive IVC simulation environment that adequately addresses both network communication and vehicular mobility requirements does not exist and is a difficult and complex task to implement. Such a complex environment is provided in this thesis to ensure the validity and realism of the presented results with modelling of the radio channel, geo-routing, location service protocols, vehicular mobility and 802.11p and ETSI network and MAC layer communications provided.

### 6.2 Future Work

As just outlined, the research presented in this thesis has realised its main objectives of exploiting infrastructure in geo-routing decisions to improve packet delivery as well as providing a robust and locality aware location service protocol and evaluating both over a comprehensive IVC modelling environment. However it is envisaged that future related work could encompass four areas:
Firstly, in the work presented in this thesis, a hybrid geo-routing protocol was presented that routes greedily in an ad-hoc environment while considering a potential forwarding vehicle’s speed and direction. Importantly, in the presence of RSUs (one hop or two hops), a vehicle’s routing decision, greedy or recovery, can be overridden on a per packet basis to favour infrastructure. Thus the proposed routing protocol, as with most traditional routing protocols, is optimised at a particular layer of communication stack and does not consider activity at other layers in its routing decisions i.e. it operates independently. However to further improve IVC communication, cross layer optimisation is necessary. Future work should consider integrating channel conditions with the hybrid RSU aware IEGRP routing decision i.e. interference aware geo-routing, as weak or NLOS radio conditions can impact successful multi-hop delivery and the overall performance of end to end communications. In a gesture to this, LOS neighbours are often only considered as potential forwarding nodes in existing routing schemes as it is considered the “safest” delivery approach. However a hybrid vehicular routing algorithm that makes forwarding decisions by also considering connectivity based on NLOS and LOS radio channel conditions could potentially increase end to end packet delivery and reduce delays caused by store and forward buffering. It could evaluate distance to the destination while also considering interference caused by retransmissions, fading, channel load and so on.

Currently, research addressing the impact of RSUs in vehicular networking and communications is in its infancy and a second future area of interest would be to evaluate the impact of infrastructure from two separate yet inter-related perspectives:

- RSU deployments are costly and research into determining the minimal number to deploy along with optimising RSU distribution or placement while providing the desired end to end connectivity is challenging. As noted in Section 5.3.5, this has begun to attract the attention of vehicular researchers in the last 18 months. While some interesting ideas have been proposed, it can be noted that the design and optimisation of wireless infrastructure is often ad-hoc in nature (requiring expensive testing and evaluation in the case of vehicular networks) or uses
complex qualitative optimisation models. Furthermore such optimisations are often environment dependant. A future area of research could be the development of a RSU design and optimisation simulation tool that could take input parameters such as a road topology map along with more advanced characteristics such as recorded vehicular traffic densities and mobility patterns (or provide a statistical model) to evaluate this from the perspective of coverage but also consider application/service QoS characteristics and routing protocol performance. Importantly, this could extend existing research in optimal mobile base station design for wireless networks. A tool already deployed for wireless indoor and embedded environments [291,292] could be further developed and integrated with aspects of the IVC platform presented in Chapter 4 to provide a design and optimisation tool for RSU deployment in vehicular networks. No such tool currently exists.

- Due to high vehicle mobility and high capacity during peak vehicular traffic times in urban environments, more advanced strategies are required to prevent RSUs from becoming overloaded - perhaps by load balancing between RSUs. This challenge is further compounded by the operation of hybrid geo-routing and location service protocols, such as those proposed in this thesis. An evaluation of the impact of these on RSU load and performance from the perspective of handling a large number of geo-routing or location service packets from vehicles clustered in high density urban areas would merit further research.

Thirdly, research into categorising the communication, QoS requirements and preferred parameters of non-safety and infotainment applications is required which could be used to adapt the proposed geo-routing and location service strategies. For example, the use of delay tolerant routing, particular buffering timeout parameters and preference for the use of the RSU based overlay location service technique over the proposed topologically scoped unicast query mechanism amongst other parameters and techniques could be determined based on categorisation of an application within a particular vehicular class. This would enable the protocols to adapt their logic depending on the application service class rather than devising a “one size fits all” approach. The location service protocol
could also be further evaluated within the context of service discovery rather than location discovery.

Finally, the implementation and real-world performance evaluation of the proposed IVC protocols and comparable equivalents in 802.11p RSU and OBU prototypes would represent a valuable contribution to the research field.
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