# Safety Data Dissemination Framework for Vehicular Networks

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# Safety Data Dissemination Framework for Vehicular Networks

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# Declaration

I hereby declare that this submission is 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 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 the text.

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Date:

To PhDr. Zdeněk Eis, CSc. ...

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# Abstract

An effective transportation system is essential to modern societies with transportation having a significant influence on economic growth, social development and the environment. But this dependence on road mobility has had serious consequences in terms of rising crash costs that include deaths, injuries, lost productivity, material damage and congestion. The European Union and many other governments worldwide support active safety as being the next logical step in diminishing crash costs after passive safety (safety belt, ABS etc.) where drivers will be warned prior to reaching hazardous situations enabling them to react appropriately. While improving road safety is unanimously considered the major driving factor for the deployment of Intelligent Vehicle Safety Systems, the challenges relating to reliable multi-hop broadcasting are exigent in vehicular networking. Broadcast protocols for Vehicular Ad-hoc Networks (VANET) must guarantee fast and reliable delivery of information to all vehicles in the neighbourhood, where the wireless communication medium is shared and highly unreliable with limited bandwidth.

This thesis presents a broadcast communications protocol, the *Reliable Vehicular Geo-broadcast* (RVG) protocol specifically designed for Vehicular Ad-hoc Networks (VANET) where the emphasis is on satisfying requirements for safety applications with respect to delay, packet delivery and overhead. The RVG protocol was compared with existing broadcast protocols in a complex realistic vehicular simulation environment including sample urban and highway test network scenarios using safety warning and SOS warning services to test the effectiveness of the protocols in disseminating warning messages. The evaluation results highlight that the existing broadcast protocols for vehicular safety application dissemination are not satisfactory for safety application requirements (packet delivery, delay and overhead) across a range of vehicular network environments. In contrast, the RVG protocol has been demonstrated to overcome these drawbacks - RVG is a robust broadcast protocol suitable as a general purpose dissemination mechanism for a range of safety applications over diverse vehicular environments in targeted geographical areas that satisfies safety data dissemination requirements with high packet delivery, low delay and low overhead.

# Contents

# List of Publications

[1] **M. Koubek**, O. Brickley, S. Rea, and D. Pesch, “Application Driven Routing for Vehicular Ad Hoc Networks - A Necessity,” The First Annual International Symposium on Vehicular Computing Systems (ISVCS 2008), Ireland: 2008.

[2] **M. Koubek**, S. Rea, and D. Pesch, “A Novel Reactive Routing Protocol for Applications in Vehicular Environments,” The 11th International Symposium on Wireless Personal Multimedia Communications (WPMC 2008), Finland: 2008.

[3] **M. Koubek**, S. Rea, and D. Pesch, “Effective Emergency Messaging in WAVE based VANETs,” First International Conference on Wireless Access in Vehicular Environments (WAVE 2008), Dearborn, USA: 2008.

[4] O. Brickley, **M. Koubek**, S. Rea, and D. Pesch, “A Network Centric Simulation Environment for CALMbased Cooperative Vehicular Systems,” 3rd International ICST Conference on Simulation Tools and Techniques, Spain: 2010.

[5] **M. Koubek**, S. Rea, and D. Pesch, “Event Suppression for Safety Message Dissemination in VANETs,” 2010 IEEE 71st Vehicular Technology Conference: VTC2010-Spring 16–19 May 2010, Taipei, Taiwan: IEEE, 2010.

[6] **M. Koubek**, S. Rea, and D. Pesch, “Reliable Broadcasting for Active Safety Applications in Vehicular Highway Networks,” 2010 3rd IEEE International Symposium on Wireless Vehicular Communications: IEEE WiVEC 2010, Taiwan: 2010.

[7] G. Pastor, D. Pusceddu, S. Rea, O. Brickley, **M. Koubek**, and D. Pesch, “Vehicle-2-Vehicle Communication Channel Evaluation using the CVIS Platform,” 7th International Symposium on Communication Systems, Networks and Digital Signal Processing, UK: 2010.

[8] **M. Koubek**, S. Rea, and D. Pesch, “Reliable Delay Constrained Multi-Hop Broadcasting in VANETs,” EURASIP Journal on Advances in Signal Processing. 2010.

[9] **M. Koubek**, S. Rea, and D. Pesch, “Reliable Broadcasting for Active Safety Applications in Vehicular Networks,” International Journal of Ultra Wideband Communications and Systems (IJUWBCS). Under Review, 2010.

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# Acronyms

| Term | Definition |
|---|---|
| ACK | Acknowledgement frame |
| Broadcast | Transmitting a message to all nodes connected to a network |
| C2C-CC | Car-to-Car Communication Consortium |
| CALM | Continuous Air Interface for Long to Medium range |
| CALMnet | CALM-based Comprehensive Network-centric simulation environment |
| CCH | Control Channel defined by WAVE standard |
| CSMA/CA | Carrier Sense Multiple Access with Collision Avoidance is a wireless network multiple access method |
| CTS | Clear to Send frame |
| DRG | Distributed Robust Geocast broadcast protocol |
| DSRC | Dedicated Short Range Communications |
| ESSMD | Event Suppression for Safety Message Dissemination scheme |
| Geo-broadcast | Forwarding of a message to all nodes being located inside a geographical area. The area is defined by the originating node and transmitted with the data packet information |
| Geo-cast | It is a variant of Geo-broadcast where the data is disseminated in specific geographical direction |
| G-RVG | Geo-cast version of RVG protocol |
| ICT | Information and communication technologies |
| IEEE 802.11p | IEEE 802.11p is a draft amendment to the IEEE 802.11 standard to add wireless access in the vehicular environment |
| IVSS | Intelligent Vehicle Safety Systems |
| ITS | Intelligent Transport System |
| MAC | Medium Access Control |
| MANET | Mobile Ad-Hoc Network |
| MPR | Multipoint Relay is a small set of 1-hop neighbours |
| Multipoint relaying | It is broadcast scheme where a sender determines a small subset of neighbours and these neighbours forward the broadcast |
| Neighbour elimination | It is broadcast scheme where a receiver node decides to forward data if some of its neighbours have not received the data |
| OBU | On Board Unit is responsible for V2V and V2R communication |
| OFDM | Orthogonal Frequency Division Multiplexing |
| OPNET | Network simulation tool |
| PACK | Pseudo-Acknowledgement scheme |
| R2I | Roadside Unit-to-Infrastructure communication |
| R2V | Roadside Unit-to-Vehicle communication |
| RR-ALOHA | Reliable Reservation ALOHA is a scheme for increasing broadcasting reliability |
| RSU | Roadside Unit is responsible for R2V and optionally for R2I communication |
| RTS | Request to Send frame |
| RVG | Reliable Vehicular Geo-Broadcast protocol |
| SCH | Service Channel defined by WAVE standard |
| SFR | Synchronous Fixed Repetition is a scheme for increasing broadcasting reliability |
| Simple Flooding | Broadcast protocol where each node that receive initial pack rebroadcast the packet |
| SRMB | Slotted Restricted Mobility Based scheme |
| SUMO | Road traffic simulator |

| | |
|---|---|
| Topo-broadcast | It is a broadcast that restricts broadcasting to all nodes located up to a specific distance in terms of number of hops |
| TRADE | TRAcking Detection broadcast protocol |
| V2I | Vehicle-to-Infrastructure communication (communication over e.g. GSM/UMTS or WiMAX networks) |
| V2R | Vehicle-to-Roadside Unit (communication over WAVE interfaces) |
| V2V | Vehicle-to-Vehicle communication and also known as Car-to-Car (C2C) communication |
| VANET | Vehicular Ad-Hoc Network that is set up by the communication nodes without any pre-installed infrastructure |
| WAVE | It is IEEE 1609 family of standards for Wireless Access in Vehicular Environments |
| WSA | WAVE Service Advertisement packet defined in WAVE |
| WSM | WAVE Short Messages packet defined in WAVE |

# Chapter 1 Introduction

## 1.1 Road Safety – A Historical Perspective

In 1769, a French engineer and mechanic Nicolas Joseph Cugnot (1725 - 1804) introduced the first road vehicle to the World. The vehicle had only three wheels and had to stop every ten to fifteen minutes to build up sufficient steam power to propel the steam engine, which allowed a maximum speed of only 4km/h. This speed was relatively slow and it should not have been a cause for grievous concern for personal safety, but automobile safety became an issue almost from the beginning of the automobile era. In 1771 the first vehicle accident is reported when a second steam-powered vehicle crashed into a wall during a demonstration run. Almost 100 years later in 1865, the Red Flag Act [1] was passed that imposed a maximum speed limit of four miles an hour for automobiles in the countryside and two miles per hour in the town. In 1869, the first fatality attributed to a road traffic accident occurred when an Irish scientist Mary Ward (1827-1869) was killed when she fell under the wheel of steam car [2].

At the dawn of the 20th century the automobile era truly began when Henry Ford launched his highly popular Model T in 1908. In the UK by 1926, there were already 1,715,000 motor vehicles registered and 4,886 road fatalities with a ratio 2.9 fatalities per one thousand motor vehicles with the ratio dramatically rising to 4:1000 by 1944 [3]. The high number of fatalities on the roads was mainly as a consequence of little heed being paid to automobile safety. The typical car had a dashboard with many hard protrusions, no seatbelts, poor brakes, thin tyres, non-collapsible steering columns, doors that opened on impact and windshield glass that breaks easily.

In the early 1950s, after a half-century delay, the view on the automobile safety was changed and car companies finally started to equip vehicles with safety elements such as padding being placed wherever the driver's head was likely to hit a hard surface and seat belts as an option. In 1958, the United Nations established the first international auto safety standard [4] with a uniform set of regulations for vehicle design and over the following decades, the first cars began to be equipped with electronic stability control, ABS, adaptive headlights etc. with the goal being to decrease fatalities, injuries and accidents on the roads.

Road safety is considered a high priority concern globally, statistics from the World Health Organization [5] (Fig. 1.1) for the year 2000 shows that one quarter of all injury related deaths in the World were due to road traffic injuries where male fatalities are almost 3 times higher than female deaths and it is estimated that 1.26 million people worldwide died as a result of road traffic injuries. Statistics from 27 European countries [6] showed that in 2008 there were over 1.2 million traffic accidents, over 1.6 million injuries and over 38 thousand fatalities (Fig. 1.2) where 30% of all deaths for the age group 20-24 were as a result of road traffic accidents (Fig. 1.3). Road crashes in the EU each year lead to 97% of all transport deaths and to more than 93% of all transport crash costs [7]. Road accidents cost more than treatments for congestion, pollution, cancer and heart disease and have resulted in a death rate that was five times higher than the best performing Member States [6-8] in 2007.

The European Commission White Paper [9] on transport policy set an ambitious target for 2010 to reduce road accident deaths by 50%, in relation to the total for 2001 (Fig. 1.4).

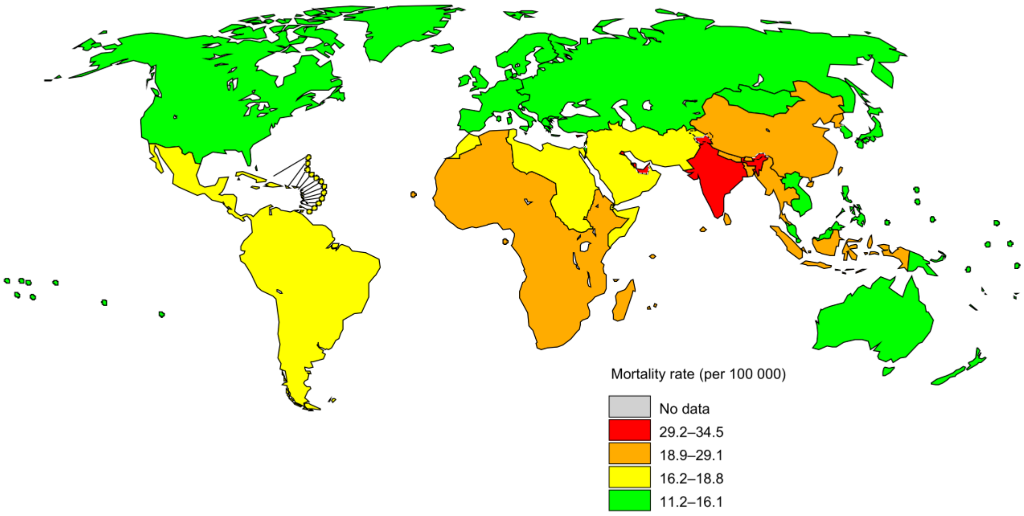


**Fig. 1.1. Global Road Traffic Mortalities for 2000 [6]**

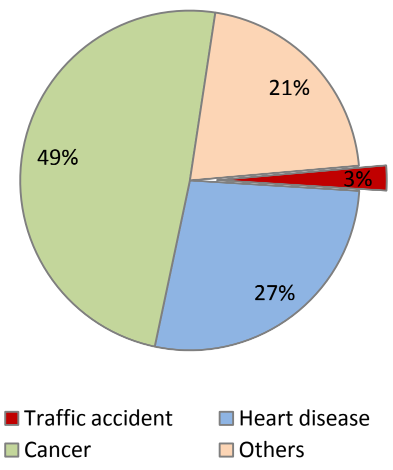


**Fig. 1.2. Mortalities in 27 EU Member States**

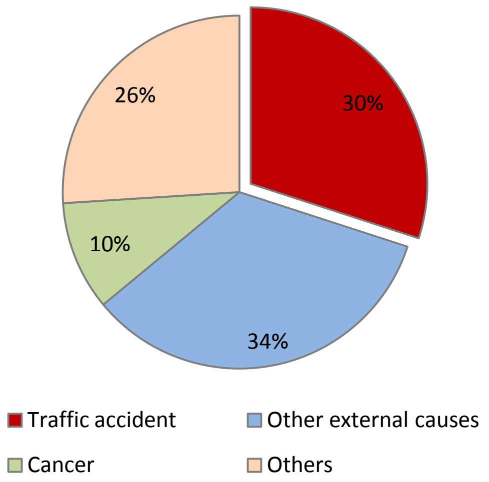


**Fig. 1.3. Mortalities among 20-24 age bracket in the EU**

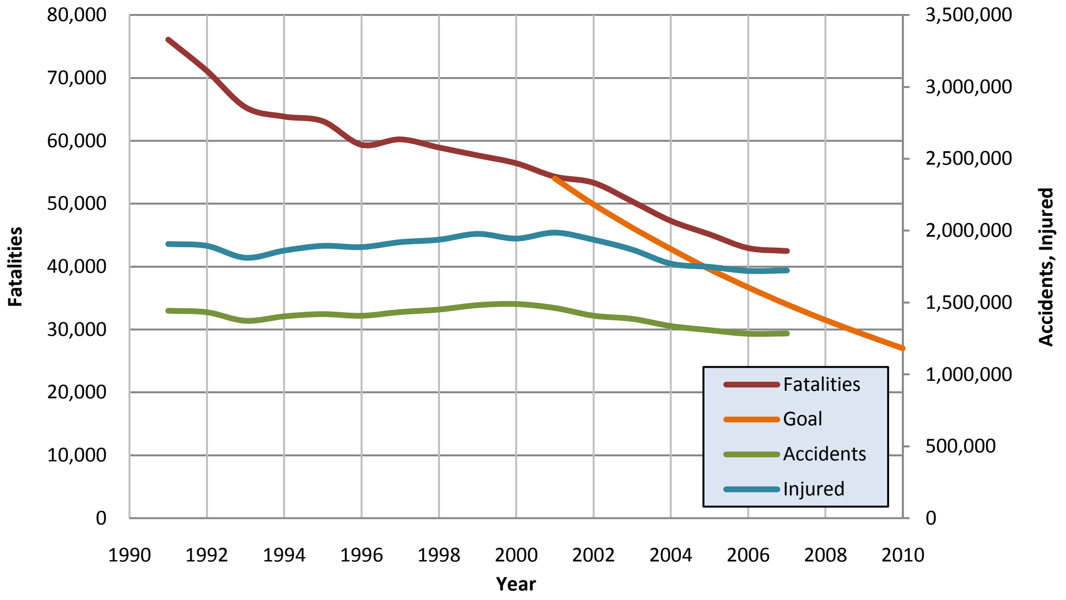


**Fig. 1.4. Road safety Evolution in the EU-27 from 1991 to 2007**

## 1.2 Motivation

Since the 1950s when the first automobile safety systems were introduced to the automobile marketplace, vehicle safety has rapidly evolved. Nowadays vehicles include a wide range of systems that protect the driver/passengers during crashes such as airbags, seatbelts, robust vehicle structure, breaks, suspension etc. and although these systems help to provide protection and to lessen fatalities, they do not assist in preventing road traffic accidents. Over recent years ambitious plans to create a system that would assist in the prevention of a crash were introduced. These systems are known as Active safety systems and differ from previous Passive safety systems (seatbelts, air bags, etc.) in that they add intelligence to vehicles and help avoid accidents. The main principle behind Active safety is that vehicles are able to detect unusual vehicle behaviour e.g. rapid breaking, activating electronic stability systems, breaking red lights, unsafe breaking distance between vehicles and are equipped with wireless communications systems that enable them to transmit a warning about the behaviour to close proximity vehicles. Drivers are then alerted via vehicle warning systems allowing them sufficient reaction time to stop the vehicle, reduce speed or to pass the dangerous situation safely. Active safety systems are envisaged to bring about a revolution in automobile safety just as the introduction of seat belts in the 1950s did and to significantly decrease fatalities, injuries and crash costs for road traffic.

For active safety systems to be realised a union of technologies from key research areas is needed, ranging from: informatics, telematics, electronics and communication systems, which needs cross industry active participation in the development of new standards and platforms co-designs. From 1987 the European Commission, through programmes like Prometheus (1987-1995)[10], Drive I and II (1988-1994) [10, 11], TAP (1994-1998) [12], IST in 5th [13], 6th [14] European Framework Programmes (FP) and in the ICT domain in FP 7 [15] (1998-2013), is driving the rollout of intelligent vehicle systems in both European and international markets, by supporting information and communication technologies (ICT) research and developments in the transportation area. In i2010 [16, 17] (under FP 7), eSafety [18] is a collaborative initiative involving the European Commission, industry and other stakeholders concentrating on hastening the development, deployment and use of Intelligent Vehicle Safety Systems (IVSS) as a means of increasing road safety and reducing the number of road traffic accidents within Europe with a focus on the marketplace up to 2020. Active safety in IVSS system is supported by vehicular ad-hoc networks (VANETs) where there is a continuous exchange of information among vehicles that are involved in or approach traffic accidents or hazardous road events where communications is based on vehicle-to-vehicle (V2V) or vehicle-to-(roadside) infrastructure (V2I) communications.

The success of active safety applications relies on two key concerns: how to detect a hazardous situation and how to warn drivers about the situation. Both problems require complex solutions that include detectors (radars), sensors to detect the hazard, on-board computer units to process and to wirelessly transmit safety message to close proximity vehicles where their units warn drivers through dashboard applications, i.e. the display of safety pictograms or audible warnings. Under the i2010 European programmes efforts have been focused on safety application development, V2V and V2I communication units, and human-machine-interfaces. There has been little effort paid to the development of reliable dissemination strategies that satisfy the requirements for safety applications, where the successful delivery of safety messages within driver reaction times is of paramount importance for the success of any Active safety system. The development of a reliable broadcast protocol for the dissemination of safety application data in vehicular ad hoc networks is the main motivation for this research work.

## 1.3 Research Objectives

Several categories of applications have been proposed and developed for vehicular networks ranging from electronic toll payments, internet on wheels, parking space reservation but the most important are those relating to automobile safety. In Fig. 1.5 a sample safety system for warning vehicles approaching a dangerous situation is shown. When a hazard is detected/accident occurs, a safety message is disseminated to close proximity vehicles to warn drivers over V2V communication. If any of these vehicles has a connection to infrastructure (V2I) or roadside unit (V2R) then the message is sent to a control centre from where it is further disseminated e.g. to detour traffic, call an ambulance and police. The work presented in this thesis focuses on safety applications and considers emergency events where a vehicle detects a dangerous situation and needs to warn other vehicles in close proximity about the danger. The underlying warning message dissemination mechanism is the key focus of the work presented in this thesis – while broadcasting the warnings is the most intuitive way to disseminate data over a target area quickly, heed must be given to reliability where this refers to the time taken to disseminate the application data and the overhead associated with the successful delivery of the data.

The broadcast dissemination mechanism must guarantee fast and reliable delivery of information to all vehicles in the neighbourhood, where the wireless communications medium is shared, very unreliable and with limited bandwidth. It must guarantee high delivery rates for priority messages with emergency payload data in diverse scenarios from small vehicle densities (rural areas) to crowded roads in cities during peak times where the communication network may well be saturated.

While there have been several approaches developed for multi-hop broadcasting in VANETs, there is no single approach that identifies itself as a reliable general purpose safety dissemination mechanism that can satisfy the requirements for safety services across a range of vehicular topographies (road topologies, vehicle density, traffic patterns). A broadcast protocol must be able to adapt to the current environment and cannot be restricted by rigid constraints such as set repetition rates and limited forwarding nodes while also being able to maintain reliability (packet delivery, delay) with low overhead. To support reliable multi-hop broadcasting in VANETs this thesis proposes the *Reliable Vehicular Geo-Broadcast* (RVG) protocol that has been specifically developed for safety data dissemination and has been shown to outperform existing approaches in terms of packet delivery, delay and overhead over a wide range of use case environments.

## 1.4 Contribution

The primary contribution of the work presented in this thesis is outlined as follows:

1) **Reliable Vehicular Geo-broadcast (RVG) protocol:** this is a robust broadcast protocol for safety data dissemination in targeted geographical areas that satisfies safety data dissemination requirements with high packet delivery, low delay and low overhead. The RVG protocol consists of two schemes namely the *Slotted Restricted Mobility Based* (SRMB) method and the *Pseudo-Acknowledgements* (PACK). These schemes can work individually but together they are referred to as the RVG protocol. Optionally, RVG can be used with the ESSMD extension (see 3 below). The RVG protocol performance was evaluated against existing mechanisms and protocols over urban and highway computer simulation environments with emulated hazardous event occurrences (Chapter 3). This performance analysis (Chapter 5) demonstrates the suitability of the RVG protocol as a reliable dissemination mechanism for VANETs.

2) **Pseudo-Acknowledgements (PACK) scheme:** This is an acknowledging scheme that can be applied to any broadcast protocol for increased reliability, which interprets successful multi-hop broadcast transmission through overhearing of successive rebroadcasts. The PACK method significantly increases delivery reliability, a crucial parameter for safety dissemination, with little additional overhead and delay (Chapter 3, Chapter 5).

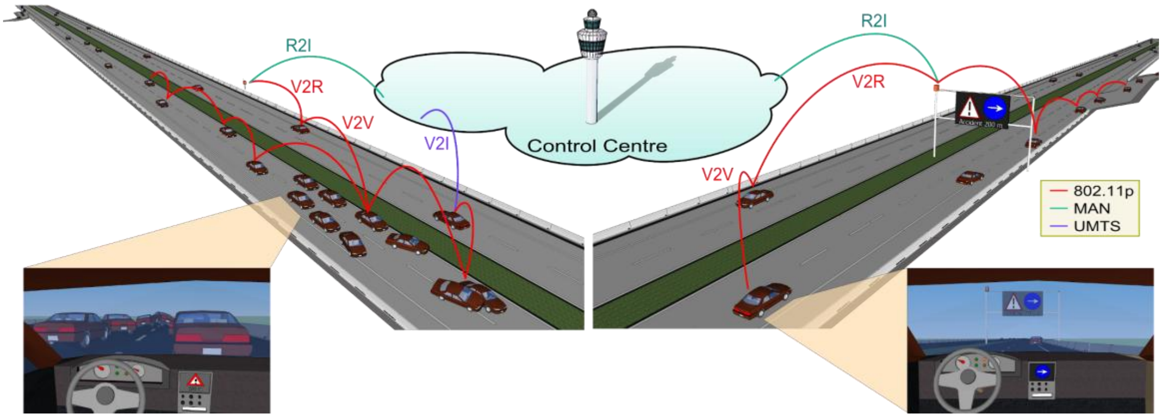


**Fig. 1.5. Intelligent Transportation Systems overview**

3) **Event Suppression for Safety Message Dissemination (ESSMD) scheme:** ESSMD restricts the number of source nodes that report on the same event. The ESSMD scheme maintains low time delays and dramatically decreasing redundant broadcast transmissions for packets carrying the same type of information. (Chapter 3, Chapter 5).

4) **CALMnet (CALM-based Comprehensive Network-centric) simulation environment**: in order to provide a realistic environment for simulating vehicle-to-vehicle communication, the CALMnet simulation environment was developed in conjunction with the work presented within this thesis. Creating a realistic test bed for Intelligent Transport System (ITS) is a difficult and complex task that requires implementing the necessary elements that include accurate modelling of radio propagation, vehicle mobility and networking with IEEE 802.11p and IEEE 1609 standards (Chapter 4). The CALMnet simulator was used for the evaluation of the work presented as part of this thesis (Chapter 4, Chapter 5).

## 1.5 Thesis Outline

The remainder of this thesis is organised as follows:

- Chapter 2 presents an overview of broadcast protocols with a particular emphasis on vehicular broadcasting and reviews prior research work that addresses current VANET broadcasting concerns while deriving a motivation for the proposed RVG protocol and reliability mechanisms that are presented in this thesis.

- Chapter 3 outlines WAVE, the proposed communications standard for vehicular networks. This chapter also describes in detail the structure and operation of the RVG broadcast protocol and the PACK and ESSMD extensions.

- Chapter 4 introduces the CALMnet simulation environment, a comprehensive network-centric simulation environment for CALM-based cooperative vehicular systems. Using the OPNET modeller simulation tool, a number of elements necessary for accurate emulation of the complex cooperative vehicular network are identified and addressed. Important areas of consideration include vehicle mobility, communications channel behaviour, application design sets and On Board Unit (OBU) device modelling to accurately simulate the envisaged ITS concept. Furthermore the evaluation scenarios are described.

- Chapter 5 presents the theoretical analysis and experimental computer simulation results for the proposed RVG protocol where urban and highway environments are considered.
- Chapter 6 provides a summary of the conclusions that can be deduced from the work presented and provides future directions that this research work can take.
- Appendix A presents requirements for multi-hop Safety Services defined for the 5GHz medium.

# Chapter 2 Vehicular Ad Hoc Network Broadcasting: Challenges & Solutions

## 2.1 Introduction

With modern civilisation heavily dependent on transportation mobility, society is experiencing severe problems in the transport sector including traffic congestion, an ever increasing need to construct higher capacity roads, but also harmful environmental effects and accidents that cause fatalities, injuries and material damage. Over all transport modalities (air, rail, road and water), road transport accounts for over 97% of all deaths and more than 93% of all costs arising from crash incidents in the EU [7]. Research indicates that human error is involved in over 90% of accidents and approximately 30% of drivers do not activate the brakes prior to a collision [17]. Current communication technologies have supported the development of Intelligent Transportation Systems (ITS) that enables interaction between drivers, vehicles and road infrastructure, which can mitigate the potential for traffic accidents.

In 2005, the European Commission’s Communication on the Intelligent Car [19] outlined Europe’s future strategy for the development of vehicles that are smarter, safer and cleaner and presented the i2010 Intelligent Car Initiative [16, 20]. The i2010 initiative introduces the GeoNet project [21] which amongst other targets is responsible for developing a reference specification for safety data dissemination protocols over IEEE 802.11p and the IEEE 1609 standards. Protocols that distribute data from a waypoint-to-multipoint (from one source node to many nodes - e.g. a warning relating to a safety critical event) are called broadcast protocols or geo-broadcast protocols if they distribute the data in predefined geographical areas.

Broadcast protocols for safety data dissemination must satisfy a range of requirements with the protocol being expected to operate over several scenarios in different environments with varying vehicles densities, from static to very high speed vehicles and in all cases the broadcast protocol has to provide a high probability of packet reception, low delay and low signalling overhead [22] in spite of a very unreliable communication channel with limited bandwidth and the potential for high packets losses [23]. Broadcast protocols [23-27] that have been proposed for data dissemination in VANETs have a common factor in that they cannot guarantee high reliability for safety related data dissemination with [23] concluding that the probability of successful reception of the data decreases with growing distance from the sender. Furthermore, the protocol must be capable of supporting vehicle-to-vehicle (V2V) communications as vehicle-to-infrastructure (V2I) or vehicle-to-roadside unit (V2R) communication may not ensure ubiquitous connectivity. These factors have serious consequences for safety related data dissemination where dangerous situations can be aggravated through unsuccessful broadcast communications. Ensuring reliable exchange of safety data information among vehicles in a network that is constructed on-the-fly is a challenging problem.

As the work presented in this thesis concerns itself with the development of a reliable broadcast protocol for VANET environments this chapter discusses the salient features of vehicular networks and associated broadcast techniques. An overview of several broadcast protocols that have been proposed in the literature is presented, with a particular focus on safety data dissemination within the vehicular environment. Also highlighted is the need for further development in this area.

## 2.2 Broadcasting - Characteristics & Challenges

V2V and V2R communication is ad hoc and relies on On Board Units (OBU), contained inside vehicles and Roadside Units (RSU), using wireless communication over an IEEE 802.11p radio interface. Such communications units are called nodes in this thesis. Nodes are equipped with one or many wireless transceivers according to the IEEE 802.11p and IEEE 1609 standards and use antennas that may be omnidirectional. A network that contains these nodes is called a Vehicular Ad-hoc Network (VANET) with characteristics that can be summarised under the following headings [28-30]:

1) **Packet loss**: as received transmission power levels, co-channel interference levels and wireless connectivity vary highly depending on time and nodes relative position in different environments, packet loss varies significantly.
2) **Capacity**: wireless link capacity differs due to effects such as multiple nodes accessing the channel simultaneously, fading, noise and interference.
3) **Energy**: nodes do not consider energy conservation as vehicles and RSUs act as a constant supply.
4) **Scale**: in principle the network size can be unlimited.
5) **Mobility**: the mobility pattern is predictable due to road layout, however it can involve nodes being static as well as nodes moving at very high speeds (>>hundred km per hour).
6) **Dynamic topologies**: RSU nodes are static while OBU nodes are free to move according to the mobility pattern, which is predictable as vehicle movement is usually limited to roadways. The topology changes with time and may consist of both bidirectional and unidirectional links that may last only a few seconds (highway scenario) and can be frequently disconnected.
7) **Security**: this is a crucial aspect in vehicular networks and requires robust security protocols to secure private data transfer over the network.
8) **Application distribution**: the range of applications running over a VANET can vary from low priority traffic such as email or web traffic to high priority data like emergency warnings. Consequently there is a need for service based differentiation that distinguishes between application types while ensuring high reliability for high priority application.

### *2.2.1 Safety Application Requirements*

The core contribution of this thesis is a broadcast protocol for safety data dissemination that is designed to operate over vehicular networks with the characteristics outlined above. Safety related applications for vehicular networks (see

Appendix A for details) are specified in terms of data repetition rate, maximum communications range and delay. The applications used in the test scenarios considered in this thesis are based on safety warnings and SOS warnings with a repetition rate of 1Hz, communication range up to 1000m with delay of up to 1s over the *broadcast zone*. Driver reaction times [31] range from 750ms-2s so in addition to satisfying the delay requirements of the application, the successful delivery of warnings within a time frame less than that of driver reaction times should also be considered as this can prompt faster driver reactions. Broadcast protocols for safety application dissemination must satisfy the following requirements [22]:

1) **High Packet Delivery (Reliability)**: the probability of reception for message dissemination must be very high. This is a measure that depends on the vehicle density and network topography. The protocol must disseminate warnings over the vehicles in a defined geographical area giving drivers sufficient time to react. For broadcast protocols to support reliable safety data dissemination successful packet delivery is the key goal with the objective being a 100% delivery rate in all environments for all possible scenarios. Many research contributions have proposed broadcast protocols for VANETs that have reached 100% reliability, however such protocols were tested over theoretical environments that are far from approximating reality. Safety Application specifications (such as those based on ETSI services outlined in Appendix A) do not explicitly identify an expected delivery ratio. When evaluating delivery ratio the application type and network scenario must be considered. Take for example, an application that generates a warning when an accident occurs (triggered by collision detection, air bag deployment etc.) close proximity vehicles need to be warned immediately so the delivery ratio within this zone should approach 100% whereas for distant vehicles the delivery ratio is less important as the vehicles have more time to react.
2) **Low End-to-End Delay**: the time delay between the initial transmission of a safety message and its reception by vehicles within the area of interest must be

as low as possible and should be a fragment of the driver reaction time [31] giving drivers sufficient time to react. This delay must also satisfy the safety application requirements outlined in appendix A.

3) **Minimal Overhead**: the packet overhead associated with safety applications should be minimal while maintaining acceptable delivery ratios and delay values. Repetitions of broadcasts must be incorporated within broadcast protocols to increase reliability but must not saturate the medium. The number of nodes that act as forwarders in the dissemination process must be considered as this effects the persistence of broadcast process and the load in the network. Safety applications while being of paramount importance are unlikely to be the only application running over a vehicular mesh network so the less bandwidth the safety application needs the less likely it is to suffer from packet losses and collisions.

The evaluation results presented in this thesis have been performed using a realistic simulation environment and have highlighted that existing broadcast protocols ) do not adequately satisfy safety application requirements across a range of vehicular network environments while demonstrating the suitability of the proposed *Reliable Vehicular Geo-broadcast* (RVG) protocol as a general purpose reliable broadcast mechanism for safety application dissemination over a range of vehicular network environments and scenarios. RVG consists of two schemes namely the Slotted Restricted Mobility Based (SRMB) and Pseudo-Acknowledging (PACK) schemes by default. These schemes can work separately but when SRMB and PACK are used together they are referred to as the RVG protocol. Optionally RVG can be used with the ESSMD scheme to further reduce redundancy.

## 2.3 VANET Broadcast Protocols & Classification

The primary problem for broadcast protocols in VANETs, which are formed in ad-hoc fashion by surrounding vehicles, lies in unreliable packet delivery. Solutions to increase reliability can be categorised into two main broadcast mechanisms used for

V2V: a store-based approach and a forward-based approach. In the store-based approach a message is stored and carried by a vehicle to a geographical location where it is broadcasted [32] while a forward-based approach immediately broadcasts the message to surrounding vehicles. The primary goal of safety applications is to warn nearby vehicles that they are in close proximity (relative to time & distance) to a dangerous situation; informing vehicles further away has lower priority and is a secondary goal. In this thesis, a forward-based broadcasting is considered the most suitable mechanism for safety message dissemination, since these applications require immediate transmission. Geo-broadcasting, a variant of conventional broadcasting, distinguishes itself by specifying a geographical region where the broadcast protocol disseminates data [33, 34]. Broadcast techniques for ad-hoc networks have been addressed by many researchers with a summary of such broadcast techniques being presented and categorised (Fig. 2.1) in [35-37], details of which are discussed in the following sections. The main objectives in the development of broadcast protocols are the reduction of redundant transmissions and the ensuring of a high packet reception.

### 2.3.1 *Simple Flooding*

Simple flooding (known as 1-persistance) or also called blind flooding is the easiest way to broadcast data to all nodes in an ad-hoc network. This method involves each node that receives the initial packet rebroadcasting this packet. This method has the desirable advantage of a high delivery ratio and an acceptable end-to-end delay in low density VANETs. However, in higher density networks the flooding broadcast principle

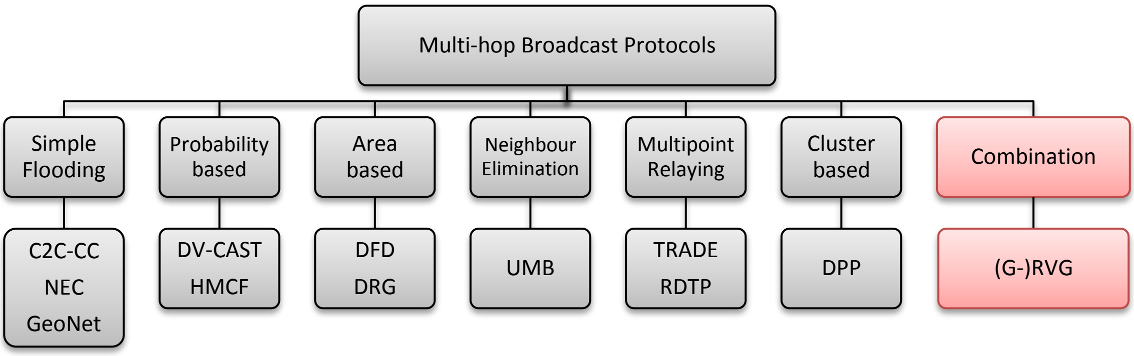


**Fig. 2.1. Classification of multi-hop broadcast protocols operating in forward mode**

fails as the delivery ratio falls off and there is a significant deterioration in end-to-end delay [35] because flooding over saturates the physical medium with a high number of redundant transmissions that collide due to the channel access CSMA mechanism employed by the IEEE 802.11p standard [38].

#### *2.3.1.a C2C-CC & NEC*

Simple flooding has serious drawbacks in terms of high redundancy which causes a deterioration in packet delivery ratio, making it unsuitable for safety application dissemination. Flooding is promoted as the core networking protocol for V2V communications by the Car-to-Car Communication Consortium (C2C-CC) [39] in Europe. The C2C-CC is the European industry consortium for vehicular communications, which considers inter-vehicle-communication and vehicle to roadside infrastructure communication in cooperative Intelligent Transport Systems (ITS). This broadcast method is based on simple flooding within a targeted geographic zone and is used by NEC in their commercially available CAR-2-X communications platform [40]. Simple flooding is used as the broadcast protocol for safety and non-safety applications.

Because flooding is promoted by leading companies in the ITS space, the *Reliable Vehicular Geo-broadcast* (RVG) protocol, proposed in this thesis, is compared with flooding and this comparison highlights the drawbacks of simple flooding in safety related dissemination.

### *2.3.2 Probability Based Broadcast*

In [35-37] the authors briefly describe probability based broadcast techniques and categorise them as *probabilistic* and *counter-based* schemes.

The *probabilistic-based* scheme is sometimes referred to as a p-persistence scheme where nodes forward the broadcast with a pre-determined probability *p*. The scheme is usable in relatively high density networks where only a subset of nodes partakes in the broadcast forwarding, thus reducing the transmission overhead and sparing the physical medium. In less populated networks restricting the number of nodes that participate in the broadcast effort can lead to a failing of the broadcast dissemination as the subset of forwarding nodes can be small and in some cases be empty where each node determines a probability (e.g. based on a random number or distance from the source) that causes it not to forward the broadcast.

The principle of a c*ounter-based* scheme is that within a set time interval a node counts the number of times it receives the same broadcast packet. After this time interval expires and if the count value is less than some set threshold, the node rebroadcasts; otherwise the broadcast packet is discarded. The *Distributed Vehicular Broadcast* (DV-CAST) and *Hybrid Method in Controlled Flooding* (HMCF) protocols are state-of-the art examples of this group and are relevant to the RVG protocol as they significantly decrease broadcast redundancy and improve packet delivery in VANETs.

#### *2.3.2.a Distributed Vehicular Broadcast (DV-CAST)*

The work presented in [41, 42] focuses on a *probabilistic-based* scheme where the probability of a rebroadcast depends on the distance from the transmitter. The authors propose the *Distributed Vehicular Broadcast* (DV-CAST) protocol which has been developed for vehicular communications and is entirely based on the local information ascertained by each node. They propose three schemes called:

1) Weighted *p*-Persistence
2) Slotted 1-Persistence
3) *p*-Persistence

where *p* is a probability that depends on the distance between a transmitter and a receiver. A higher probability is chosen for nodes further from the source and vice versa with a lower probability for closer nodes. After determining the probability a rebroadcasting node waits a specific time WAIT_TIME before rebroadcasting.

Presented in [43] is a comparison of DV-CAST and a previous version of the RVG protocol proposed in this work, called *Restricted Mobility Based* (RMB) broadcast protocol with RMB in most cases showing improvements over DV-CAST. In particular, RMB has a 10% improvement over slotted 0.5-persistence and a 90% improvement against all the schemes proposed in [41, 42] when looking at the broadcast transmission ratio, which reflects savings in the number of retransmissions sent over the medium.

#### *2.3.2.b Hybrid Method in Controlled Flooding (HMCF)*

The HMCF protocol is proposed in [44] and is based on the principle that a sender transmits a broadcast with its location. Each neighbour calculates the distance between itself and the sender and depending on the distance and neighbour density determines a waiting time. The shortest waiting times are assigned to nodes that are farthest from the sender and so these nodes transmit sooner. As with the *counter-based* schemes if a node’s counter reaches the threshold limit it silently discards its own transmissions.

The drawback of this approach is that in dense networks many nodes can calculate the same waiting time and transmit simultaneously or in close proximity which leads to collisions amongst the broadcasts resulting in broadcast failure and decreasing packet delivery.

### *2.3.3 Area Based Broadcast*

The principle of *area-based* schemes is that each node that has received a broadcast packet calculates the additional area that would be covered by its own transmission. There are two main approaches [37].

In *distance-based* schemes, the message at a node is retransmitted only if the distance to each neighbour that already retransmitted is higher than a pre-defined threshold. In *location-based* schemes potential forwarding nodes determine the additional coverage area and if this area is larger than a set threshold the node forwards.

Evaluation results presented in [37] show that *location-based* schemes offer the best performance in terms of saved rebroadcast packets and reachability of mobile hosts in mobile ad-hoc networks (MANETs). This concept significantly decreases redundancy in comparison to Simple Flooding, however high levels of redundancy still persist. In the case of very dense networks this can lead to the rebroadcasting of hundreds of redundant packets as large numbers of nodes calculate adequate coverage areas and so rebroadcast.

*Dynamic Forwarding Delay* (DFD) and *Distributed Robust Geocast* (DRG) are representative of state-of-the art examples in this group. Furthermore the DRG protocol is the most relevant to the work presented in this thesis, DRG relies on message repetitions over unsuccessful links to increase delivery rate and achieves a high packet delivery with low delay. The DRG protocol was used in evaluation of the proposed RVG protocol and results of this are shown in Chapter 5.

#### *2.3.3.a Dynamic Forwarding Delay (DFD)*

The principle of DFD, presented in [24], is that nodes locally decide to forward a broadcast. Each node that has received a broadcast calculates the size of the additional area its own rebroadcast covers. A node that calculates the largest size assigns the shortest backoff time while a node that calculates no additional coverage or small additional coverage area does not forward.

An advantage of the protocol is that it improves (decreases) transmission redundancy. On the other hand the protocol delivery reliability is not high and the end-to-end delay is large as forwarding nodes must wait until the backoff time expires to forward, making it unsuitable for the dissemination of application safety data.

#### *2.3.3.b Distributed Robust Geocast (DRG)*

DRG [45] is based on a *location-based* scheme where nodes calculate the coverage area using the geographical position of their neighbours. Each node that receives a broadcast schedules the rebroadcast using a *backoff* time calculated based on distance with the node that is furthest from the source node setting the shortest *backoff* time and so retransmits first. If a node with the same packet for rebroadcast overhears the transmission of this packet while in *backoff* it then silently discards its packet and does not rebroadcast. A node, which has rebroadcasted, repetitively broadcasts in short intervals (3 repetitions) and then in long intervals (2 repetitions) until the node receives at least two transmissions from different nodes which cover at least 78% of its own coverage area. If 78% coverage is reached then the node stops the repeat broadcasting.

The unsuitability of the DRG protocol for safety data dissemination is evident when used in highly dynamic environments (such as a highway vehicular network) where the broadcast process can often fail as nodes unable to maintain perfect knowledge of the location of their 1-hop neighbours due to rapid topology changes. In such environments nodes can wrongly estimate their coverage area and may not broadcast or can repeatedly broadcast which increases redundancies that negatively impacts on the packet delivery ratio and delay.

### *2.3.4 Multipoint Relaying*

Another family of broadcast approaches is called *multipoint relaying* or *source-dependent dominating sets* [46-48]. The principle of this approach is that a sender determines a small subset of neighbours, which is called a *multipoint relay set* (MPR), and only these neighbours will forward the broadcast. Other neighbours that have received the broadcast stay silent and do not forward. The primary advantage of this approach is in reducing the number of redundant transmissions over the physical medium but this reduction is achieved at the expense of requiring the nodes to have perfect neighbour knowledge and a decrease in the broadcast penetration. Nodes incur control traffic overhead as each node needs perfect knowledge about its one and two-hop neighbours in real time in order to properly choose the set of relay nodes. The second disadvantage is that only the *multipoint relay set* of neighbours forwards the message which means that in realistic environments if some *multipoint relay* neighbour does not receive the broadcast packet, due to interference, then the broadcast forwarding may prematurely terminate as non *multipoint relay* neighbour nodes do not rebroadcast. This effect is shown in [35, 49] where there is a significant falloff in delivery ratio in comparison with other protocols.

*TRAcking Detection* (TRADE) and the *Robust Data Transfer Protocol* (RDTP) are representative examples of this group [50].

#### *2.3.4.a TRAcking Detection (TRADE)*

The TRADE protocol presented in [50] is based on a principle that a source node chooses distant neighbouring nodes (one positioned in front and one positioned behind it), records their ID in the broadcast packet header and broadcasts. Nodes that recognise their ID in the packet, forward the message. The TRADE protocol needs to maintain a table of 1-hop neighbours with accurate position information. TRADE reaches a packet delivery ratio similar to the Simple Flooding protocol but with dramatically less transmissions with the TRADE protocol being used in the RVG performance evaluation in Chapter 5.

A disadvantage of this protocol is that choosing forwarding nodes close to the transmission range boundary can be dangerous (i.e. causes broadcast process to end) as it is difficult to determine the maximum transmit range in real environments where topological conditions can be highly dynamic [51]. Secondly, again only a subset of nodes is eligible to participate in the broadcast forwarding and thirdly in urban environments GPS does not work well (city canons) which means that nodes do not have accurate position information as precision is very poor (errors in the region of 15-30m are likely) which can make selecting forwarders in an urban environment difficult due to the relatively short transmission range.

#### *2.3.4.b Robust Data Transfer Protocol (RDTP)*

The RDTP protocol presented in [52] is based on each sender transmitting a small request packet to all its 1-hop neighbours before broadcasting. Each neighbour replies to the request with a small message containing their speed and location. After a set wait time has expired the sender selects one of its neighbours to act as a forwarder and transmits. This procedure is repeated at each forwarder, which contributes to increased end-to-end delay over the broadcast lifetime which makes this unsuitable for safety application data dissemination and is therefore not considered for evaluation in this thesis.

### *2.3.5 Neighbour Elimination*

*Neighbour elimination* or *source-independent dominating set* [53] is another category of broadcast algorithm where a receiver node decides to forward data again based on local information. Intermediate nodes (potentially forwarding nodes) eliminate themselves from broadcasting if all of their neighbours have already received the message so the forwarding of the message would be redundant. Each receiver calculates its neighbour coverage; nodes whose neighbours are not within coverage choose a random number of backoff time slots in a contention window and rebroadcast.

The evaluation presented in [35] shows that *neighbour elimination* does not reach the redundancy reduction that can be achieved with *multipoint relaying* and has increased end-to-end delay with increasing network size. End-to-end delay is the main disadvantage of this approach as this measure is a critical parameter in safety related application dissemination. One of the best known broadcast protocols from this category is the *Urban Multi Hop Broadcast Protocol* (UMB).

#### *2.3.5.a Urban Multi Hop Broadcast Protocol (UMB)*

The principle of *neighbour elimination* is used in [25] where the UMB protocol for VANETs is described. This is a multi-hop broadcast protocol that uses a form of handshaking for broadcasting. Before transmitting a “broadcast in a direction” a sender transmits a request packet - “RTS to broadcast”. All nodes receiving the packet calculate the *black-burst* time slot after which to reply to the sending node with a “CTS packet”. The time slot is calculated locally at nodes, this depends on the distance between the sender and node that received the packet. The shortest time slot is again assigned to the farthest node and that node sends the CTS. Other nodes silently discard their own CTS packets as they hear the reply from the farthest node. The sender then broadcasts the data to the farthest node and this node then acknowledges the reception of this message with an ACK packet who then forwards the message using the same procedure.

There are a few issues concerning the UMB protocol. The authors use the phrase “broadcast in a direction” or a “directional broadcast” (where nodes select the farthest node in front of it) without specifying details of how the farthest node in the direction is chosen because the transmission is received by all nodes in any direction inside transmission range of the sender. So nodes at the boundary of the transmission range will send a CTS packet at the same time and this will lead to collisions at the sender. Secondly, each node has to subscribe to a location service where positions of repeaters at intersections are maintained. The repeaters forward the broadcast packets and also provide the position of surrounding repeaters. UMB relies on fixed repeaters at each intersection to disseminate the broadcast over all directions to warn vehicles approaching the intersection. This incurs an infrastructure cost and requires nodes to maintain an up to date database of repeaters. Failure of the repeaters to rebroadcast restricts the numbers of vehicles that are warned. The focus of this thesis was the development of a multi-hop V2V broadcast protocol and did not consider V2R communication consequently UMB was not considered for performance evaluation.

### *2.3.6 Cluster Based Broadcast*

*Cluster-based* broadcasting is another alternative for dissemination. Proposed in [32] is the *Direction Propagation Protocol* (DPP) that elects two gateway nodes in a cluster, one node as a “header” and one node as a “trailer”. Each node in the cluster then maintains a route to the gateways. If any node has a message to disseminate it sends the message to a gateway in direction of dissemination using unicast forwarding. The gateway transmits the message to gateways within radio range in other clusters.

The message is routed through the clusters and acknowledgements from the clusters are sent to the gateway.

The disadvantage of this approach is that clustering is an expensive technique, in terms of maintenance overhead, in dynamic environments where vehicles can be faster or slower than others in the same cluster, vehicles can join or leave the cluster at intersections and the cluster can be extremely large or indeed very small. These possible situations can require extensive message exchange for electing cluster heads and maintaining cluster groups in highly dynamic environments and can cause excessive overhead making it unsuitable for safety data dissemination.

### *2.3.7 Proposed Reliable Vehicular Geo-broadcast Protocol*

In [35, 54] independent comparisons among *location*, *neighbour elimination* and *multipoint relay* schemes are presented where results show that all schemes reach a 100% delivery ratio in well-connected networks but exhibit worsening performance in sparsely connected networks. Further results presented in [35] show that with increasing load the delivery ratio reliability rapidly drops off for all schemes.

In less populated networks where nodes have few neighbours, the *probability based* and *neighbour elimination* schemes [24, 41, 42, 44, 45] lead to failure in the dissemination of messages. The limitation is in calculating coverage area (in terms of the additional neighbouring nodes that they can forward the broadcast to) as it is estimated based on the theoretical transmit range. If a node calculates based on the theoretical transmission range that it can achieve none or small additional coverage by its transmitting it then discards any broadcasts it has for forwarding. The actual transmission and theoretical ranges may be vastly different due to obstacles and interferers in the physical environment with nodes close to the boundary of the transmission range still being able to receive packets.

In denser networks calculating coverage can lead to flooding in the network as nodes are likely to have a large local neighbourhood and so many nodes invariably forward the same broadcast. The concern with *mobility-based* approaches presented in [25, 41, 42, 44, 45] is that nodes calculate forwarding time on the basis of mobility behaviour. Consider in densely populated networks in vehicular environments the mobility patterns of nodes can be similar; these nodes then calculate a comparable forwarding time (backoff) and broadcast the message in close time proximity. This leads to message collisions and dissemination failures.

Simple Flooding saturates the network with a high number of redundant transmissions that leads to packet collisions as nodes receive multiple copies of the same broadcast packet simultaneously, which leads to a failure of the broadcast forwarding.

The *multipoint relaying* scheme looks to selecting a subset of nodes to act as forwarders for the broadcast process. The success of this method for broadcasting lies in the selection of appropriate nodes to include in the multipoint relay set. The nodes used as forwarders are selected solely by the transmitter but in highly dynamic vehicular networks it is hard to estimate the best forwarders as the mobility of neighbouring nodes is unknown in the network. Some approaches use two-hop knowledge [55] and others only one [50, 52] including location information. Another issue is the radio propagation model used in simulation to test the success of the multipoint relay selection algorithm. The radio propagation model must accurately reflect physical conditions. In dense and/or high speed networks radio propagation can have dramatic effects on packet reception rates and nodes that have been chosen as forwarders may not actually receive the broadcast packet and dissemination fails, as has been shown in [35, 49] where dense VANETs with high background traffic were investigated.

A core part of the RVG protocol is the *Slotted Restricted Mobility-Based* (SRMB) scheme. SRMB is responsible for the dissemination of a message over a specified distance in a network. SRMB is based on a combination of the *multipoint relaying* and *neighbour elimination* schemes described above with a *mobility-based* approach that prioritizes nodes with similar mobility behaviour for forwarding the broadcast. *Multipoint relaying* in SRMB assists in maintaining low redundancy and high reliability.

If the *multipoint relaying* scheme fails then *neighbour elimination* is used to avoid failure of the SRMB mechanism. The SRMB broadcast algorithm is able to disseminate a message with high reliability through diverse networks with distinct mobility.

1) The SRMB scheme is better than a Simple Flooding protocol as Simple Flooding over saturates the physical medium in denser networks with a high number of transmissions therefore more packets collide and packet delivery drops off.
2) The SRMB scheme is better than *area-based* protocols as *area-based* protocols are based on the principle of calculating additional area using a constant derived from the theoretical transmission range. But as the real transmission range can vary strongly over time and can be dramatically different for distinct environments, the constant (the theoretical transmission range) becomes inaccurate; schemes wrongly estimate covered nodes and nodes may not forward resulting in broadcast failure and a decreasing packet delivery ratio.
3) The SRMB scheme is better than *multipoint relaying* since in *multipoint relaying* protocols only a predefined small set of nodes forward the broadcast. If a broadcast is overheard by a non MPR node, the node does not forward. SRMB use the *multipoint relaying* scheme but in the situation where broadcasts are overheard at non MPR nodes these can substitute MPR nodes, thus avoiding failure of the protocol.
4) The SRMB scheme is better than *neighbour elimination* protocols as these protocols use the same constant based on the theoretical transmit range as is the case for *area-based* schemes where the number of covered nodes is estimated. Furthermore, nodes beyond the theoretical transmit range cannot be considered in the *neighbour elimination* algorithm but they may in practise be able to receive the packets. In contrast, SRMB uses a *neighbour elimination* scheme only when the *multipoint relaying* scheme fails. In the situation where both schemes fail then a *pseudo-acknowledgement* (PACK) scheme detects unacknowledged links and repeats forwarding.

5) SRMB uses the *mobility-based* scheme to assess 1-hop neighbours. Nodes with similar speed, comparable motion vector and those that are close to the theoretical transmit range of broadcast originator become a multipoint relaying (MPR) node. Other nodes listen to the physical medium and if they do not hear a transmission from the MPR node after expiration of a waiting time then the second most appropriate node substitutes and forwards.

## 2.4 Methods for Increasing Broadcast Reliability

A primary concern for broadcast protocols is reliability in terms of successful dissemination of data over the network, a measure of reliability is delivery ratio. In V2V communication the IEEE 802.11 family of standards are used, which are based on the *Carrier Sense Multiple Access with Collision Avoidance* (CSMA/CA) medium access control (MAC) layer that a node wishing to transmit data has to first listen to the medium to determine whether or not the medium is free to transmit without collisions. A disadvantage of the CSMA/CA is that it does not enable the detection of collisions during transmission. This disadvantage is partly solved in unicast transmissions through use of the *RTS-CTS* handshake mechanism to reserve the medium prior to transmission from the destination before transmitting the unicast data. After the data is received successfully an acknowledgement, *ACK*, is transmitted by the source node who originated the handshake. For broadcasting this handshake option is not used. A sender prepares broadcast data, waits until the physical medium is free and then transmits the data. The sender does not receive any kind of acknowledgement from its neighbours to indicate that the transmission was successfully received at a destination. The acknowledgement of broadcast data can be very important especially in cases where nodes are broadcasting safety related data. The following section discusses methods used to increase broadcast reliability. These methods are shown in Fig. 2.1 where they are categorised into two main groups. Multi-hop mechanisms were developed for use with multi-hop broadcast protocols with the second group focusing on 1-hop broadcast protocols which after some modification can also be used for multi-hop broadcast protocol.

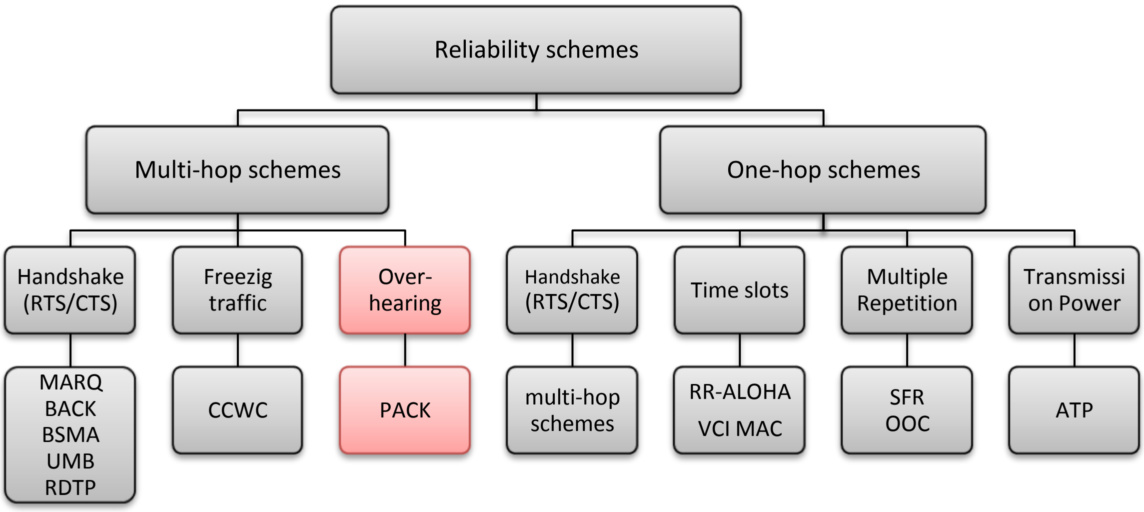


**Fig. 2.1. Reliability broadcast schemes**

## 2.4.1 Multi-Hop Broadcast Schemes

For multi-hop broadcast protocols several works have proposed acknowledgment techniques to increase reliability in *Multiple-receiver Automatic Repeat Request* (MARQ) [56], *Broadcast Acknowledgement* (BACK) [57] and *Broadcast Support Multiple Access* (BSMA) [58] schemes. These methods are based on reserving time slots where a sender allocates virtual time slots for all its neighbours and transmits the broadcast data. All its neighbours transmit ACKs in their virtual slot. The reserving of virtual time slots for individual ACK transmissions is problematic in denser networks as it leads to a dramatic increase in delay; a fundamental concern for the dissemination of safety related data. Similar principles can be found across broadcast protocols used in the *Urban Multi Hop Broadcast Protocol* (UMB) [25] and *Robust Data Transfer Protocol* (RDTP) [52].

In [59] priority is given to the transmission of safety messages over the communication medium using two approaches presented as part of the *Congestion Control in Wireless Communications* (CCWC) scheme. The first approach is *Queue freezing,* this is where if a node hears a safety message it refrains from transmitting any non-safety messages for a specific time. The second approach is called *Adaptive QoS parameter* where if nodes hear safety messages they double the Contention

Window size for non-safety messages. All of these approaches have one significant disadvantage, while prioritising safety messages, collisions can still occur when a source node generates a safety message if nodes within the 1-hop sphere transmit simultaneously.

There is no appropriate method to increase broadcast reliability in multi-hop broadcast protocols for vehicular networks which does not suffer from dramatically rising delay and/or increased load on the physical medium through numerous redundant transmissions.

### *2.4.2 One-Hop Broadcast Schemes*

In [60] the authors have identified protocols that increase the reliability of one-hop broadcast schemes and have classified the schemes based on their channel access methods.

#### *2.4.2.a Handshake*

The first group is based on CSMA/CA where these protocols [56-58] use a handshake mechanism comprising of short packets similar to RTS/CTS/ACK packets. This handshake approach was discussed in 2.4.1.

#### *2.4.2.b Time Slots*

The second group of protocols relies on reserving time slots in the physical medium. The *Reliable Reservation ALOHA* (RR-ALOHA) protocol presented in [61] has been developed within the European research project CarTalk2000 [62]. This is a slotted technique (TDMA access) where nodes rely on synchronised time slots for communications with nodes being assigned a single dedicated slot for transmission. The RR-ALOHA requires that vehicles continuously exchange 2-hop information to reserve free time slots and to support synchronisation e.g. with GPS. Central coordination units do not have to be used for synchronisation.

Using time slots for broadcasts leads to a high delivery ratio due to minimum collisions in particular slots. This increases end-to-end delays as nodes rebroadcasting the data must also reserve slots which accumulates delays over the lifetime of the broadcast. In the case of RR-ALOHA, the delays reached can be large depending on the network size which cannot be tolerated for safety-related data dissemination [63]. Another disadvantage of slotting is that it decreases throughput in densely loaded networks which corresponds with the throughput performance when comparing CSMA/CA access with ALOHA access.

The *Variable Control Channel Interval multi-channel MAC* (VCI MAC) scheme [64] decreases the slot size for the Control Channel (CCH) and so increases the Service Channel (SCH) interval which increases the throughput in the service channel and packet delivery ratio. Although the authors focused on service data utilization on the SCH and not safety data utilization on the CCH, the principle can be considered as another approach to increase reliability for broadcast protocols but before a communication starts, nodes need establish links with the same CCH interval size this would require additional packet handshaking to establish this which lengthens delay and can exceed the delay requirements for safety services. In addition to support this scheme, fundamental changes in the IEEE 1609 standards for vehicular communication would be necessary.

#### *2.4.2.c Multiple Repetition*

The third group relies on the repetition of broadcast transmissions. The *Synchronous Fixed Repetition* SFR [65, 66] protocol randomly repeats broadcast transmissions. The authors in [60] propose the *Optical Orthogonal Codes* OOC code that dynamically affects the number of repetitions. The OOC method performed better against SFR [60, 67], but for fast moving vehicles the OOC protocol has difficulties with codeword synchronisation.

Repeating broadcasts leads to increased delivery ratio but it also increases the number of transmissions in the network. This can lead to flooding the network with repetitions and can decrease the delivery ratio in denser networks. The throughput results in [63] show that the SFR scheme can easily saturate the network under higher loads which leads to a rapidly decreasing delivery ratio.

#### *2.4.2.d Transmission Power*

Another approach for increasing reliability has investigated changing the transmission power used in broadcasting messages to control the wireless range [68-70]. The *Adaptive Transmission Power* (ATP) protocol [68] changes the transmit power depending on the number of one-hop neighbours and the *Opportunistic-driven Adaptive Radio Resource Management* (OPRAM) [70] scheme changes the transmit power depending on the current transmission power and packet data rate based on vehicle's position and its proximity to an area where a traffic accident could occur (i.e. an intersection) to guarantee traffic safety requirements . The authors in [71] highlight that changing transmit power leads to dangerously reduced transmission ranges for emergency data and this is counterproductive where emergency data should be typically sent on the maximum transmit power to cover as many nodes as possible over minimum hops.

### *2.4.3 Proposed RVG Protocol - Pseudo Acknowledgment (PACK) Scheme*

In recent years several one-hop broadcast schemes have been developed for VANETs while little emphasis was placed on improving existing multi-hop broadcast schemes. For safety related data dissemination there will be a prerequisite to disseminate data beyond a single hop with high reliability for data delivery over several hops with minimal delay and low data collisions (see Appendix A).

From the results presented in [63] it can be construed that the methods for increasing one hop broadcast reliability have some strong disadvantages that preclude them from being used in a multi-hop broadcast protocol designed safety data dissemination. Acknowledging transmissions from all receivers [25, 52, 56-58] and using TDMA [61] slotted access is problematic as it leads to rapidly increasing end-to-end delays. Multiple repetitions of the broadcast [60, 66] rises to a significantly high number of redundant transmissions that can flood the physical medium and decreasing transmission power of background traffic [63] does not markedly affect the broadcast performance.

In contrast, the proposed *Pseudo Acknowledgement* (PACK) scheme, which is part of the RVG protocol, contributes by incurring no additional overhead, interpreting successful multi-hop broadcast transmission through overhearing successive transmissions of the broadcast packet. As the broadcast packet traverses the network, each hop creates a *dynamic time slot* in which to transmit a broadcast. Intermediate hops that receive the broadcast wait until the *dynamic time slot* expires and then transmit the broadcast thereby acknowledging a link between itself and previous hop. If the previous hop does not overhear the broadcast transmission it repeats the transmission of the broadcast.

PACK is further discussed in section 3.7 and has been embedded within the RVG broadcast protocol to increase packet reception in multi-hop broadcasting. Chapter 5 shows the evaluation of the PACK scheme where SFR and RR-ALOHA schemes were used for analysis with PACK significantly outperforming these approaches in terms of end-to-end delay, reducing redundancy, increasing delivery ratio and throughput.

## 2.5 Data Aggregation & Suppression for Vehicular Networks

Consider the scenario where a vehicle on the road unexpectedly stops due to an accident. On board sensors detect the pressing of the brake and an airbag activation, which is processed as an emergency event (SOS Services, see Appendix A) by an on board unit (OBU). The OBU then sends an emergency warning to approaching vehicles which is used to warn drivers about the accident. In urban or motorway environments several vehicles can be in close proximity to each other and the reactions of one driver (related to e.g. Emergency Electronic Brake Lights, see Appendix A) has a ripple effect over all vehicles close by; consequently a large number of vehicles can almost simultaneously generate a warning message relating to the same event. From a global perspective this translates to a large number of vehicles attempting to broadcast packets that carry the same or a very similar payload. Because broadcasting is a very expensive technique in terms of communications channel use, sending many broadcasts in close time proximity leads to an overload of the physical medium with a high quantity of packets carrying the same class of event information that can dramatically affect the broadcast performance.

Data aggregation is used to reduce the number of data transmissions in the communications medium [72]. Data aggregation can be used to rapidly decrease data redundancy and has been used in sensor networks to improve the energy efficiency of nodes by aggregating smaller inbound individual packets to create a single larger packet for outgoing transmission. Energy efficiency however is not a concern in vehicular ad-hoc networks with data aggregation here primarily focused on reducing redundant information.

Shown in Fig. 2.2 are possible infrastructure-less aggregation and suppression strategies for VANETs where infrastructure-less aggregation strategies [73] can be classified as:

- *Centralised aggregation*: a single node aggregates data centrally.
- *Fully distributed aggregation*: each node aggregates data locally.
- *Group-based aggregation*: multiple nodes aggregate data in different groups.

Centralised aggregation is not a suitable solution as it leads to excessive communication overhead near the central node; fully distributed aggregation is very robust but leads to exponentially growing communication overhead with increasing numbers of nodes; group-based aggregation is considered as the most suitable

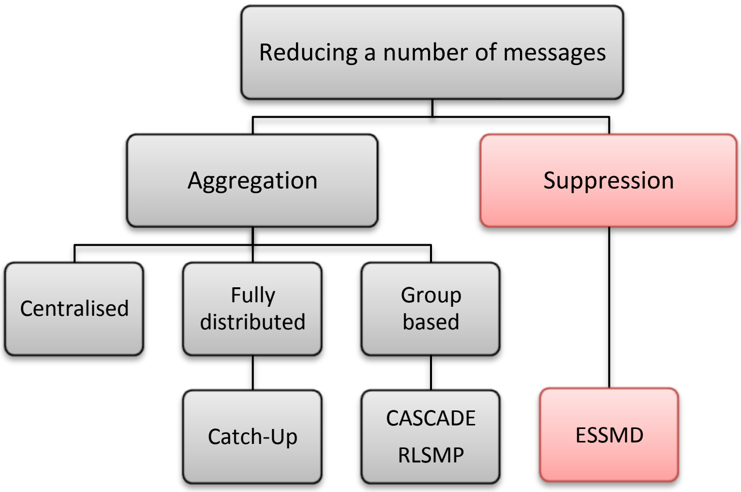


**Fig. 2.2. Schemes for reducing volume of transmitted packets**

strategy for VANETs because it reduces data communication overhead by aggregating data in parallel.

Presented in [74] is CASCADE (*Cluster-based Accurate Syntactic Compression of Aggregated Data in VANETs*). This is a method for the accurate aggregation of traffic information in VANETs, featuring cluster-based compression. CASCADE can aggregate both safety and non-safety information but the evaluation results show that end-to-end delay is in the order of hundreds of milliseconds which is unacceptable for safety related applications (Appendix A).

In [75] the authors have proposed an aggregation strategy called *Region-based Location Service Management Protocol* (RLSMP), which uses geographical clustering to minimise signalling volume overhead, but this method again has long end-to-end delays making it unsuitable for safety-related data dissemination.

Presented in [76] is a strategy called *Catch-Up* that can adaptively change the forwarding delay of individual events to increase delivery reliability but this is also unsuitable for safety related data aggregation in VANETs because again the end-to-end delay grows linearly with increasing distance and can reach the order of seconds.

### 2.5.1 *Proposed Event Suppression for Safety Message Dissemination (ESSMD)*

A review of existing data aggregation approaches has shown that they are unsuitable for the dissemination of safety-related data in VANETs as they rapidly increase end-to-end delay as a consequence of the aggregation process. Presented in this thesis is a scheme called *Event Suppression for Safety Message Dissemination* (ESSMD) that can be implemented with broadcast protocols over IEEE 802.11p, which is inspired by the principles of data aggregation, i.e. the lessening of redundant transmissions. Rather than aggregating information from several sources at a single point this suppression scheme looks to restricting the number of sources that report on the same event. ESSMD does not aggregate or suppress distinct messages from different class - it restricts the number of sources that carry the same class of messages with the same or similar meaning.

In contrast to other approaches, the proposed *Event Suppression for Safety Message Dissemination* (ESSMD) scheme forwards the first received message without delay while other received messages relating to the same class are not forwarded for a set interval. This approach maintains a low delivery delay and significantly reduces the number of redundant transmissions.

## 2.6 Conclusion

This chapter has discussed broadcast protocols for VANETs and in particular has focused on broadcast protocols suitable for the reliable dissemination of safety related data. There has been a plethora of broadcast protocols [24, 25, 32, 39-42, 44, 45, 50, 52] proposed for VANETs but these have a significant disadvantage in that they cannot satisfy emergency dissemination requirements (see Appendix A), mainly due to high packet redundancy and high end-to-end delay parameters. Methods for increasing reliability of broadcast protocols [25, 52, 56-58, 60, 61, 65-69] have been presented and these involve repeating broadcast transmissions, using time division access or reducing transmit power. While these methods increase the delivery reliability they rapidly swell the end-to-end delay or flood the physical medium with high volumes of redundant transmissions. To reduce overloading of the medium, aggregation methods [73-76] have been devised to collectively combine several data sources.

1) Section 2.3 presented an overview of current broadcast protocols with a particular emphasis on vehicular broadcasting and satisfying safety data requirements. The Simple Flooding protocol over saturates the physical medium in denser networks with a high number of transmissions which increases packet collisions, packet delivery drops off and end-to-end delay deteriorates. *Area-based* and *neighbour elimination* schemes are based on the principle of calculating additional area coverage/neighbour coverage and for this purpose they use a constant derived from the theoretical transmission range. But as real transmission ranges vary in time and in distinct environments, the constant becomes inaccurate with schemes wrongly estimating covered nodes and nodes may not forward causing the broadcast process to fail and packet delivery drops off. The *multipoint relaying* scheme which requires perfect neighbour knowledge fails when collisions at forwarders leads to nodes not being able to identify themselves as forwarders which prematurely terminates the broadcasting and packet delivery dramatically falls. In contrast to the schemes above, the SRMB scheme was proposed which consists of a combination of *multipoint relaying*, *neighbour elimination* schemes and *mobility-based* approaches that prioritise nodes with similar mobility behaviours for forwarding the broadcast. In SRMB the *multipoint relaying* scheme is the main method with *neighbour elimination* being used as a supportive scheme to continue the broadcast process if the MPR nodes fail to broadcast which ensures that the broadcast process does not unexpectedly cease.
2) Section 2.4 discussed schemes that increase broadcast reliability. Some schemes (MARQ, BACK, BSMA) are based on sending acknowledgments from every node that has received the broadcast which causes problems in allocating virtual slots for each acknowledgment and it leads to rapidly growing delays in packet

delivery making them unsuitable for safety application dissemination. Other schemes (such as RR-ALOHA) use TDMA access over the physical medium and again delay grows as every node has to wait for its associated slot to transmit. Lastly presented were schemes based on repetitions of the broadcast at source nodes (SFR). The SFR scheme has the advantage of increasing reliability in low density networks since the broadcast is repeated several times. However, it over saturates highly populated networks by dramatically increasing the number of redundant transmissions. This leads to over saturation of the physical medium which causes packet collisions to increase and packet delivery to fall. By contrast, the proposed *Pseudo Acknowledgement* (PACK) scheme interprets successful multi-hop broadcast transmission through overhearing successive transmissions of the broadcast packet.

3) Data aggregation and suppression were discussed in section 2.5. The unsuitability of common aggregation techniques in reducing the number of safety transmissions was highlighted, noting that these rapidly increase the time delay. The proposed *Event Suppression for Safety Message Dissemination* (ESSMD) scheme restricts the number of source nodes that report on the same event.

This chapter has highlighted the primary drawbacks of existing approaches for broadcast protocols, reliability schemes and aggregation methods and has illustrated their unsuitability for use in VANETs for safety data dissemination. Chapter 3 presents the proposed *Reliable Vehicular Geo-broadcast* (RVG) protocol in detail and describes the constituent components, namely: SRMB, PACK and ESSMD. By default, the RVG protocol includes SRMB and PACK schemes and optionally the ESSMD scheme. RVG, due to SRMB, reduces the number of redundant transmissions, maintains a very low end-to-end delay, and as a consequence of PACK, keeps a high probability of packet reception with ESSMD being used to dramatically reduce the number of source nodes that report on the same event.

# Chapter 3 Reliable Vehicular Geo-broadcast protocol (RVG)

## 3.1 Introduction

The *Reliable Vehicular Geo-broadcast* (RVG) protocol is a p-persistent CSMA/CA broadcast protocol that reduces redundant broadcast transmissions and increases reliability by interpreting successful multi-hop broadcast transmissions as acknowledgements through overhearing successive rebroadcasts by its neighbours. RVG is specifically designed to be incorporated within the IEEE 1609 "Family of Standards for Wireless Access in Vehicular Environments (WAVE)" [77-81] and to be used as a dissemination protocol for safety messages.

The key performance attributes of the RVG protocol are that it:

- Maintains very low end-to-end delay suitable for safety data dissemination
- Provides very high delivery ratio
- Significantly decreases transmission redundancy
- Acknowledges broadcast transmissions
- Repeats overheard broadcast transmissions
- Reduces information redundancy arising from many sources disseminating the same event warnings by using event suppression

The following section describes the WAVE standard and message formats relevant to the RVG protocol. The remainder of this chapter focuses on a technical description of the RVG protocol.

## 3.2 Wireless Access in Vehicular Environments - WAVE Overview

One of the major goals of V2V and V2I wireless communication is to improve driving safety and in-vehicle comfort. In 1999, the Federal Communications Commission (FCC) of the U.S. and the European Telecommunications Standards Institute (ETSI) [22, 82-84] in 2005 approved a band for wireless communications between vehicles and roadside infrastructure. At present the Institute of Electrical and Electronics Engineers (IEEE) is completing the final version for the IEEE P1609 "Family of Standards for Wireless Access in Vehicular Environments (WAVE)" [77-81]. Due to the success of IEEE 802.11 in the area of wireless data communication, it presupposes that this standard will be one of the main wireless technologies implemented in vehicular networks, more specifically IEEE P802.11p [38] which is defined by an IEEE working group. In the draft WAVE specification seven channels each of 10MHz bandwidth are defined. The spectrum frequency is 5.9GHz [84] and it defines single-channel and multi-channel units with and without time synchronisation [79]. Periodically repeating time slots for high priority messages (safety messages) which every station must listen to during the specified time are defined. Seven channels are split over one Control Channel (CCH) and six Service Channels (SCHs) [79]. The CCH channel consists of beacon messages, which are periodically broadcasted, at 100ms intervals and are called WAVE Service Advertisement (WSA) and the CCH also supports high priority WAVE short messages (WSM) used for safety messages [77]. A SCH is switched to optionally and used for non-safety applications. Single-channel units without time synchronization have to continuously monitor the CCH and single-channel units with time synchronisation can periodically switch between the CCH and one of the SCHs, depending on time slots. Multi-channel units can continuously receive and transmit data on the CCH and one of the SCHs independently in time.

## 3.3 RVG Overview

RVG is a reliable multi-hop, flat (non-clustered), distributed, p-persistent CSMA/CA broadcast protocol that includes four main cornerstones:

1) *Slotted Restricted Mobility-Based* (SRMB) scheme – based on knowledge of the position of its 1-hop neighbours a transmitting node selects a subset of those neighbours as forwarding nodes (Multi-Point Relay - MPR set). The source node

then records these MPR nodes in the packet header and transmits. A node that receives the packet and is a MPR node, will assign a dynamic time slot for rebroadcasting. The dynamic time slot assignment is based on what order the MPRs appear in the packet header. A non-MPR node which receives the packet assigns the dynamic time slot which is always longer than that of the MPR nodes. To avoid redundant transmissions during broadcasting each node $M^i$ (MPR and non-MPR) assesses whether all of its neighbours have received the broadcast packet based on its position and that of its neighbours and estimated transmission distance. If $M^i$ determines that all of its neighbours have received the broadcast and the $M^i$ has the same broadcast to transmit then $M^i$ silently discards the waiting packet (see details in section 3.6).

2) *Pseudo Acknowledgements* (PACK) scheme – this method interprets successful multi-hop broadcast transmissions through the overhearing of successive rebroadcasts by its neighbours. As the broadcast packet traverses the network, each hop creates dynamic time slots in which to rebroadcast. Intermediate hops that receive the broadcast wait until the dynamic slot time expires and then rebroadcasts thereby acknowledging a link between itself and previous hop. If the previous hop does not overhear the rebroadcast during expiring repetition interval it repeats the rebroadcasting (see details in section 3.7).

3) *Geo-broadcast* (RVG) and *Geo-cast* (G-RVG) methods are discussed in section 3.8 and these methods restrict data dissemination to a specific geographical area using a *minimum broadcast distance* in the case of the RVG protocol and by using a *minimum broadcast distance* and *dissemination direction* in the case of the G-RVG extension.

4) *Event Suppression for Safety Message Dissemination* (ESSMD) method – this is discussed in section 3.9 and focuses on reducing the number of simultaneously invoked safety messages relating to the same event.

Two types of messages defined in WAVE standard are extended by the RVG protocol. The WAVE Service Advertisement (WSA) which is 1-hop broadcast message periodically exchanged between terminals and is extended to carry position information of the transmitting node in the WSA packet. The WAVE Short Message (WSM) is a common message used to exchange information between terminals in 1-hop and multi-hop fashion. The WSM is extended to carry broadcast information by the RVG protocol.

### *3.3.1 Terminology*

- WSA message: this is a WSA message as defined by the WAVE [77] and ETSI [22] standards (see Section 3.4.1). This message is periodically broadcasted by each node to its 1-hop neighbours.
- WSM message: this is a WSM message as defined by the WAVE standard [77] with a payload defined by the RVG protocol (see Section 3.4.2) that carries emergency data as well as broadcast data.
- Originating node: a node that initiates a WSA message or WSM message to be processed and possibly retransmitted by other nodes in the VANET. An originating node is a node that senses a dangerous event such as breaking vehicles through radar or slippery roads via steering wheel sensors and the node initiates warnings or emergency message using WSMs to warn other vehicles in its vicinity. WSM packets are usually multi-hop broadcasts.
- Transmitting node: a node that transmits a WSM message.
- Forwarding node: a node that receives a WSM message either directly from an originating node or from another forwarding node and transmits the WSM message.
- MPR (Multipoint relay) node: a node that is selected by a transmitting node (previous hop) as being suitable for forwarding. Such a node finds its short MAC address in the WSM header.
- Non-MPR node: a node that is not MPR node and is 1-hop away from a transmitting (previous hop) node.

- Retransmitting, rebroadcasting: a node, which receives a WSM message from a transmitting node and decides to send the message farther down the network. The node retransmits/rebroadcasts the original WSM message.
- Repeated transmitting: this is the repeated transmission of a previously sent broadcast.

## 3.4 Message Format

As previously stated, two packet types, WSA and WSM frames, are used by the RVG protocol. A WSA message is periodically transmitted in accordance with the WAVE standard [77] and WSM packets have been modified to include the broadcast header information and the related emergency data payload.

### *3.4.1 WSA Message Format*

The format of the WSA frame is illustrated in Table 3.1. It contains the standard WSA format defined in WAVE [77], the position, speed and heading fields defined by ETSI [22] with 16 bits each. It is presumed that all vehicles are equipped with a positioning system such as GPS and that they are able to determine their position using the World Geodetic System (WGS) [85]. The last four digits of the geodetic position represent the longitude (Long) and latitude (Lat) fields e.g. in the case of $8^{0}$31.8266W and $51^{0}$53.0550N they are represented as 8266 and 0550.

TABLE 3.1. WSA FORMAT DEFINED ACCORDING TO WAVE [77] AND ETSI [22]

| **bits** | **8** | **16** | **24** | **32** | **40** | **48** | **56** | **64** |
|---|---|---|---|---|---|---|---|---|
| *Standard WSA pkt.* | 384bits | | | | | | | |
| *ETSI extension* | Long | | Lat | | Speed | | Heading | |

TABLE 3.2. WSM FORMAT WITH BROADCAST HEADER AND EMERGENCY PAYLOAD

| **bits** | **8** | **16** | **24** | **32** | **40** | **48** | **56** | **64** |
|---|---|---|---|---|---|---|---|---|
| *Broadcast header* | Type | | Priority | | Broad ID | | Hop Count | |
| | Orig MAC Addr | | | | | | | |
| | MPR1 | | MPR2 | | MPR3 | | MPR4 | |
| *Emergency payload* | MinDist | | DissDirec | | Event ID | | OrigLong | |
| | OrigLat | | Optional Field | | | | | |

### *3.4.2 WSM Message Format*

The WSM frame shown in Table 3.2 contains the broadcast header, which carries the information used for broadcasting and the emergency payload, which is used to describe the emergency event. The complete WSM frame contains 320bits and the particular fields represent:

- Type: this field specifies which payload is in WSM Data. If Type is set to 01 then the WSM packet contains the broadcast header of the RVG protocol and the emergency payload.
- Priority: this specifies the priority of a message. The priority flag is used by the WAVE MAC layer (similar to 802.11e) to assign the packet to the appropriate traffic class for transmitting.
- Broadcast ID: this uniquely identifies a particular broadcast as is assigned in conjunction with the originating node’s MAC address. The Broadcast ID is incremented by one only by the originating node. Rebroadcasting nodes do not change the Broadcast ID as a broadcast traverses the network.
- Hop Count: the number of hops from the originating node to the node currently processing the broadcast.
- Originator MAC Address: the MAC address of the node that originated the broadcast.
- MPR address: short MAC address of a MPR node. The MPR address contains the first 16 bits from the MAC address of the MPR node.

- Minimal Distance: this number specifies the *minimum broadcast distance* from the originating node that the data dissemination should reach to satisfy safety application requirements.
- Dissemination Direction: this specifies in which *dissemination direction* the data should be disseminated when using directional RVG (see section 3.8, G-RVG).
- Event ID: this field contains the class of an event as is selected from a list of predefined safety related events.
- Long and Lat: these refer to the position of an originating node. The format of these is as described above in section 3.4.1 (WSA Message Format).
- Optional Field: this field is used if vehicle-to-infrastructure (V2I) or Roadside Unit-to-Infrastructure (R2I) communication is enabled. Then the originating node definition refers to a node that receives a WSM frame from the infrastructure and is able transmit the frame over the CCH interface. Usually such nodes are either roadside units that have both interfaces (R2V, R2I) or nodes (vehicles) that are equipped with an interface to the infrastructure e.g. with UMTS and CCH interfaces (V2I). Then Optional Field contains:
- Event Originator MAC Address: MAC address of a node that senses or detects an event and broadcasts.
- Event Long and Lat: position information of the event originator.

## 3.5 RVG Operation

This section describes the events under which the RVG broadcast WSA and WSM frames are generated and how the message data is handled. In order to process the messages correctly, certain state information has to be maintained in the *broadcast table* entries. WSA and WSM messages are sent through the CCH using the appropriate service class.

### *3.5.1 WSA Messages (Hello Messages)*

WSA messages are 1-hop broadcasts transmitted by each node every 100ms (HELLO_INTERVAL) according to the WAVE standard in the lowest traffic quality class called *background*. A WSA frame contains the latest position measurement for the originating node and each node receiving the WSA message updates their *Broadcast Table*.

### *3.5.2 Broadcast Table*

Every node must maintain a *Broadcast Table* with the most recent broadcast route information, which contains the following fields:

- IPv6 address: this is the IPv6 address of the originating node. If the IPv6 internet protocol is not being used at the originating node the field is empty.
- CCH MAC address: contains the 64bit MAC address of the Control Channel (CCH) interface of the originating node.
- SSH MAC address: contains the 64bit MAC address of the Service Channel (SCH) interface of the originating node if available, otherwise the field is empty.
- Next Hop CCH MAC address: this is the CCH MAC address of the next hop.
- Next Hop SCH MAC address: this is the SCH MAC address of the next hop node.
- Hop Count: the number of hops from the originating node to the node currently processing the broadcast.
- Originator Latitude: the latitude of the originating node.
- Originator Longitude: the longitude of the originating node.
- Tx Power: this represents the transmit power and is extracted from the TxPwr Level field in the WSA frame [77].
- Rx Power: this is a measure of the received power during the reception of a WSA or a WSM frame.

- Channel ID: this value indicates if a node has a SCH interface and if so over which SCH it operates.
- Entry State: this value defines the freshness of an entry in *broadcast table*. An entry becomes invalid when ACTIVE_ROUTE_TIMEOUT expires.
- Expire Time: this value defines a time (ACTIVE_ROUTE_TIMEOUT) when an entry expires and becomes stale.

When a WSM packet is received the following fields are updated

- Broadcast ID: this contains the last Broadcast ID number in the WSM packet from the originating node.
- Event ID: the number contains the last Event ID number in WSM packet from originating node.
- Event Time: this is record of the time that the last WSM packet was received from a specific originating node.

For the optional case of V2I or V2R communication the following additional fields are used:

- Event Originator MAC Address: MAC address of a node that senses or detects an event and broadcasts.
- Event Long and Lat: position information of the event originator.

When a node receives a WSA frame from a neighbour it checks for an entry for the node in its *Broadcast Table*. If there is no corresponding entry for that node, an entry is created if the entry exists it is updated. The field *Entry State* is changed to valid, Expire Time (ACTIVE_ROUTE_TIMEOUT) is activated again and the other fields are filled with the available information.

When a node receives a WSM frame, an entry is updated only if:

- The WSM frame contains a higher Broadcast ID than the corresponding entry in *broadcast table*, or

- The WSM frame contains a lower Hop Count than the corresponding entry in *broadcast table*.

### 3.5.3 Generating WSM Frame

A node invokes and disseminates a WSM frame when it senses or detects an unexpected event for example the sudden deceleration of a vehicle in front of the driver or a hazard such as ice on the road. The originating node invokes a WSM frame that contains the priority of the event, last Broadcast ID incremented by one, hop count set to 20 (MAX_HOP), node's MAC addresses, *minimum broadcast distance* (BR_DISTANCE) that the dissemination should reach, *dissemination direction* (BR_DIRECTION) if it is geo-broadcast, identification of detected event *Event ID*, position and MPR addresses. Before broadcasting the WSM frame, the originating node waits until the CCH slot is active and then transmits.

## 3.6 RVG - Slotted Restricted Mobility-Based (SRMB) Scheme

The RVG broadcast protocol uses the *Slotted Restricted Mobility-Based* (SRMB) scheme that was cultivated based on an extension of the previously developed broadcast methods called *Restricted Mobility-Based* (RMB) and *Mobility-Based* (MB) broadcasting. The SRMB broadcast scheme is a multi-hop, flat (non-clustered), distributed, p-persistent CSMA/CA scheme. The main goal of SRMB is broadcast data with a high delivery ratio, low end-to-end delay (relative to safety application stringent requirements) and to reduce redundant transmissions.

The basic principles of the RVG-SRMB scheme are:

1) **Multipoint Relay Principle** - Based on knowledge of the position of its 1-hop neighbours, a transmitting node selects a subset of those neighbours as forwarding nodes (Multi-Point Relay, MPR, set). The transmitting node then records these MPR nodes in the packet header and transmits. The purpose of having two types of nodes (MPR and non-MPR) lies in reducing the number of redundant transmissions on the physical medium. See details in section 3.6.1.

2) **Dynamic Time Slot Principle** - A node that receives a broadcast packet and is a MPR node assigns a *dynamic time slot* for rebroadcasting. The *dynamic time slot* assignment is based on the ordering of the MPRs in the packet header. A non-MPR node that receives the packet assigns a *dynamic time slot* which is always longer than that of the MPR nodes. *Dynamic time slots* are used to minimise the hidden terminal problem and to prioritise channel access for nodes over the physical medium. See details in section 3.6.2.

3) **Neighbour Elimination** - To avoid redundant transmissions during each broadcasting phase each node (MPR and non-MPR) assesses whether all of its neighbours have received the broadcast packet based on its position and that of its neighbours and the estimated transmission distance. If a node determines that all of its neighbours have received the broadcast and the node has the same broadcast to transmit then the node silently discards the waiting packet. See details in section 3.6.3.

### 3.6.1 Multipoint Relay Principle

The Multipoint Relay Principle as used by RVG-SRMB was developed as part of the RMB and SRMB broadcast protocols. Two categories of nodes are used: MPR and non-MPR nodes with MPR nodes being used to reduce the number of broadcast transmissions to avoid flooding the physical medium with redundant frames. The MPR nodes are chosen by the transmitting node depending on their position and mobility knowledge of 1-hop neighbours (from the viewpoint of the transmitting node).

After transmitting a WSM frame, 1-hop neighbours receive the frame and in the most cases the MPR nodes forward the frame and non-MPR nodes stay silent. But in some cases where a MPR node fails to forward a broadcast, a close proximity non-MPR node after its allotted back off time has expired can forward the broadcast instead of the MPR and so avoids a premature termination of the broadcast process. This is referred to as a substitution of an MPR node by a non-MPR node.

The Multipoint Relay Principle relies on the probability equations shown in (3.1). A node $M^i$, processing a WSM packet assesses each 1-hop neighbour, $M^i_n$ using its distance $p_{dist}$, motion vector $p_{vector}$ and speed $p_{speed}$ with a node that is closest to the edge of transmit range, with the smallest relative motion vector and the smallest relative speed being assigned the highest $p_{total}$ and this is chosen to be a MPR node[1],

$$p_{dist} = \frac{tx_{dist_{max}} - |M^i - M^i_n|}{tx_{dist_{max}}}$$

$$p_{vector} = \frac{180^0 - abs\left(\overrightarrow{M^i} - \overrightarrow{M^i_n}\right)}{180^0} \qquad \textbf{(3.1)}^{2}$$

$$p_{speed} = \frac{speed_{max} - abs\left(speed\left(M^i - M^i_n\right)\right)}{speed_{max}}$$

$$p_{total} = \frac{p_{dist} + p_{vector} + p_{speed}}{3}$$

where:

- *tx_dist*$_{max}$ is the theoretical *transmission distance* (TX_DISTANCE) that a packet can reach and still be successfully received using the maximum possible transmit power. This threshold is derived using the empirical radio model used in the computer simulation environment (see chapter 4.2) and this distance varies with different simulation scenarios (urban and highway).
- $M^i$ is a node that processes WSM frame in order to transmit.
- $M^i_n$ is a 1-hop neighbour of $M^i$.
- $\overrightarrow{M}$ is the motion vector of node M. If both nodes $M^i$ and $M^i_n$ are static or below a speed of 5m/s then the subtraction of the mobility vectors is 0 otherwise if one node is static and the other node has a speed less than 5m/s then the difference is equal to $180^0$.
- $speed_{max}$ is the maximum relative speed that nodes can reach between each other. If the relative speed is higher than $speed_{max}$ then $p_{speed} = 0$. In simulations the maximum speed is set to a threshold of 80m/s (MAX_SPEED) which should be sufficient in most cases.

---

[1] Probability equations are uniformly distributed in this stage of work. In future work the parameters could be tuned to e.g. give higher weight to distance and less to speed and motion vector.

[2] If $M^i_n$ is further from $M^i$ than $Tx\_dist_{max}$ then $p_{dist}$ is greater than 1.

Shown in Table 3.3, Table 3.4 is the pseudo code used in the SRMB MPR selection. Fig. 3.1 shows how the directional sectors are specified. Before broadcasting a transmitting node $M^i$ (either the originating or the forwarding node) determines a small set of its neighbours $MPR^i_{1,..,N}$ (Multipoint Relay set as used in OLSR [55]) with each neighbour lying in a geographically different sector (maximum $N \le 4$ sectors, MAX_SECTORS) with a $90^0$ spread (Fig. 3.1) and overlapping each other. The number of sectors is chosen depending on how many sectors are needed to cover all the neighbours of the node $M^i$ (see the algorithm in Table 3.3). For an originating node, the first sector $S_1$ is chosen in a direction opposite to where the hazardous event is detected or in a backward direction to a node's motion if a node senses an undirected event such as ice on the road for example. The other sectors are derived as follows: the next sector ($S_2$) is chosen opposite to the first sector, the third sector ($S_3$) is chosen to the left of $S_1$ and finally the fourth ($S_4$) is chosen on the right with a maximum $N \le 4$ sectors. For a forwarding node, the first sector is opposite to the direction from where the originating node is located and the other sectors lay on the left and right sides of the first sector with a maximum of $N \le 3$ sectors (the sector that lies in the direction of the originating node is omitted).

The transmitter $M^i$ separates its whole set S of neighbours $M^i_{1,..,n}$ into the sectors $S_{1,..,N}$ according to their position, (Fig. 3.1), where $N \le 4$ ($N \le 3$ in the case of a forwarding node). Then the following algorithm in Table 3.3 is applied to select the appropriate MPR nodes in each sector for dissemination of a message:

TABLE 3.3. MULTIPOINT RELAY PRINCIPLE

```
1. $S^{/}=\emptyset$ empty set
2. for ($o$ = 1; $o \leq$ maximum sectors $N$; $o$++)
   a. Set $S_o$ of neighbours in sector $o$ as a subset of set of all neighbours ($S_o \subset S$)
   b. According to equation (3.1)  chose node $MPR^{i}_{o} \in S_o$ with the highest probability $p_{total}$ as a MPR node
   c. $S_o=\emptyset$ empty set
   d. for ($p$ = 0; $p$ < maximum number $n$ of neighbours $M^{i}_{1,..,n}$; $p$++)
      i. if (distance between $|MPR^{i}_{o} , M^{i}_{p}| \leq tx\_dist_{max}$)
         1. $M^{i}_{p} \in S_o$
   e. $S^{/} = S^{/} \cup S_o$ ($S^{/}$ is union with $S_{1,..,o}$ from previous runs)
   f. if (all $M^{i}_{1,..,n} \in S^{/}$)
      i. break, algorithm ends having all $MPR^{i}_{1,..,N}$ nodes where $N = o$ that it needs
```

The Multipoint Relay Principle (Table 3.3) chooses the minimum number of $MPR^{i}_{1,..,N}$ nodes from all the neighbours of $M^{i}$ in order to reduce the number of transmissions forwarded by non-MPR nodes. In some cases where the network is scarcely populated a node may not have any neighbours with the resultant MPR list then being empty.

The transmitter $M^{i}$ records the shortened (16 bits) MAC addresses of the $MPR^{i}_{1,..,N}$ nodes in the WSM frame and broadcasts. A node $M^{j}$ that receives the frame buffers the frame to the *WSM Buffer* and continues processing based on the following algorithm in Table 3.4:

TABLE 3.4. MULTIPOINT RELAY PRINCIPLE (CONT.)

```
1. $M^{j}$ receives a message from $M^{i}$ with a MPR list $MPR^{i}_{1,..,N}$ addresses
2. if ($M^{j} \in MPR^{i}_{1,..,N}$){
   a. if (distance | $M^{j}$, $M^{i}$ | $\leq$ minimum broadcast distance)
      i. $M_{j}$ waits until its selected dynamic time slot expires and then performs broadcasting based on a selection of its own $MPR^{j}_{1,..,N}$ (Table 3.3).
   b. else if (distance | $M^{j}$, $M^{i}$ | > minimum broadcast distance)
      i. $M_{j}$ waits until its dynamic time slot expires and then creates a WSM frame with an empty $MPR^{j}$ list. The purpose of this transmission is to act as an acknowledgement for the previous broadcast sent by the node $M^{i}$.
3. else if ($M^{j} \notin MPR^{i}_{1,..,N}$){
   a. if (distance | $M^{j}$, $M^{i}$ | $\leq$ minimum broadcast distance)
      i. $M^{j}$ waits until its dynamic time slot expires and then performs broadcasting based on a selection of $MPR^{j}_{1,..,N}$ only if $M^{j}$ can achieve additional coverage of its neighbour nodes in comparison to the coverage achieved by the node $M^{i}$ (based on Neighbour Elimination, section 3.6.3).
   b. else if (distance | $M^{j}$, $M^{i}$ | > minimum broadcast distance)
      i. $M^{j}$ does not rebroadcast
```

where:

- *Minimum broadcast distance* (BR_DISTANCE) specifies the minimum distance from the originating node that the data dissemination should reach to satisfy safety application requirements (Appendix A). This metric is encapsulated within the WSM frame (Table 3.2).
- *Dynamic time slot* is described in section 3.6.2.

### 3.6.2 Dynamic Time Slot Principle

A node $M^i$ transmits a WSM frame, its neighbours $M^i_{1,..,n}$ receive the frame almost simultaneously. If the neighbours $M^i_{1,..,n}$ retransmit the frame with a delay based on only that incurred at the MAC layer (based on the numbers of backoff time slots) then a potentially high number of transmissions would collide and the broadcasting dissemination would terminate prematurely as intended receivers would not receive the broadcast frames correctly (Fig. 3.2).

To minimise this problem (the hidden terminal problem) rebroadcasting is carefully scheduled (spread in time) using *dynamic time slots*. Each node that receives a broadcast packet assigns a *dynamic time slot* for transmitting to ensure that nodes

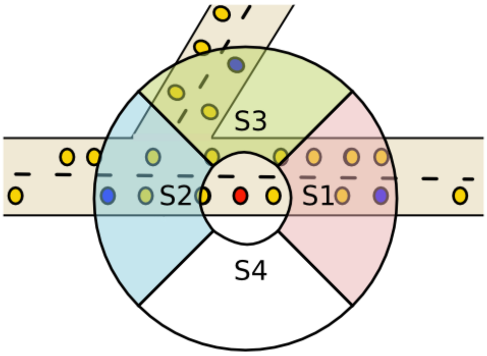


**Fig. 3.1. Directional sectors are defined about the transmitting node with a radius defined by the theoretical transmission distance with each sector having a $90^0$ spread.**

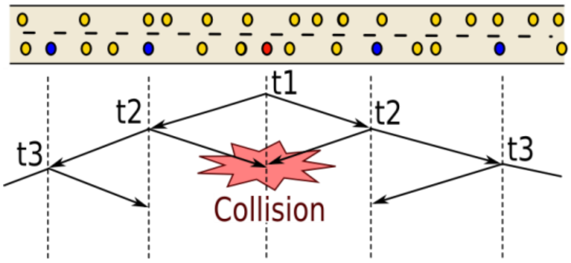


**Fig. 3.2. Hidden Terminal Problem**

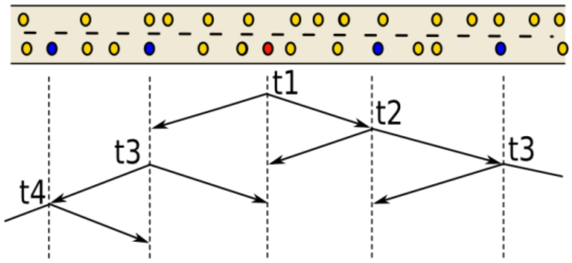


**Fig. 3.3. Dynamic time slot Principle**

have sufficient time to avoid collisions between forwarding (Fig. 3.3). All MPR nodes first transmit one by one from individual sectors and then if some non-MPR node identifies that a MPR has not forwarded then some non-MPR substitutes and transmits.

Two types of dynamic slots are used: *Sector Wait Time* and *Non-MPR Wait Time. Sector Wait Time* is used at each node that will perform broadcasting i.e. MPR and non-MPR nodes while *Non-MPR Wait Time* is used only on non-MPR nodes.

### *3.6.2.a Sector Wait Time*

*Sector Wait Time* is derived from the maximum transmission time $T_{L\_MAC}$ (3.2) including processing at lower MAC layer and the time needed for transmission:

$$T_{L\_MAC}(ac) = \frac{L_{DATA}}{R_{DATA}} + \frac{D}{c} + SIFS + T_{BOslot} \cdot (AIFSN + CW[ac]) \qquad \textbf{(3.2)}^{3}$$

- $L_{DATA}$ is the size of data transmitted over the physical medium in bits. It contains the data payload, WAVE and MAC headers.
- $R_{DATA}$ is data rate in bits per seconds.
- *D* is the theoretical transmission distance (TX_DISTANCE) that can be reached by the packet to be successfully received at a node. This depends on the environment radio propagation characteristics. In simulation the transmission distance that is used is based on the empirical data measurements and is described in section 4.2.
- *c* is the speed of light set to $3\text{x}10^8$m/s.
- *SIFS* is the short inter-frame space with a length of 32µs.
- $T_{BOslot}$ is duration of a backoff slot with a length of 16µs.
- *AIFSN* specifies the number of "slot" periods within the AIFS (Arbitration Inter Frame Space) value used by an access category during contention (Table 3.5).
- *AIFS* is the difference in time between the medium becoming idle and the time when the access category starts or resumes a random Backoff period.
- *CW* is a number of slots in a particular Contention Window (Table 3.5).

---

[3] The equation is valid for light to moderately loaded networks. In busier networks if any transmission is heard while a node is in *Backoff* then a new *Backoff* time is set and the transmission delay is lengthened

- *AC* is Access Categories used by 802.11e and WAVE MAC to manage different traffic classes (voice, video and data).

TABLE 3.5. PARAMETERS IN DIFFERENT TRAFFIC CATEGORIES

| Access Category | AIFSN | $CW_{max}$ |
|---|---|---|
| CW[background~WSA] | 7 | 15 |
| CW[voice~WSM] | 2 | 3 |

The *Sector Wait Time* $T_{slot}$ (3.3) is added at each receiving node that will potentially transmit:

$$T_{slot}(J) = (J-1) \cdot m \cdot max\left(T_{L\_MAC}\right) \tag{3.3}$$

If the address of a node $M^j$ is in the list $MPR^i_{1,..,N}$ then:

- *J* is $J \in (1 \leq N)$ this is the position a node $M^j$ in the list of $MPR^i_{1,..,N}$.
- *m* is a multiplier added to avoid collisions when the network becomes busy and equation (2) expires. This value is set to 1.5, which has been determined from simulation investigation.

Else if the $M^j$ address is a non-MPR (it does not match any address of $MPR^i_{1,..,N}$) then:

- *J = N+S.*
- *N* is the number of MPR in the list $MPR^i_{1,..,N}$.
- *S* is the order of the sector where $M^j$ is positioned (Fig. 3.1). A sector is defined about the transmitting node with a radius defined by the theoretical *transmission distance* ($tx\_dist_{max}$) with each sector having a 90 degree spread.

### *3.6.2.b Non-MPR Wait Time*

*Non-MPR Wait Time* $T_{non-MPR}$ is added after $T_{slot}(J)$ at each non-MPR node to create a sufficient spread in time between any non-MPR nodes, which would potentially rebroadcast. It is calculated based on the probability equations in (3.1) where $M^i$ is a non-MPR node that receives the WSM frame and $M^i_n$ is the node that transmitted the packet. The *Non-MPR Wait Time* function $T_{non-MPR}$ is:

$$T_{non-MPR} = |1 - p_{total}| \cdot k \tag{3.4}$$

- Where *k* is a time constant (NON_MPR_TIME_SLOT) defined in chapter 3.10.

The shortest time $T_{non\text{-}MPR}$ is assigned to non-MPR nodes that are closer to the theoretical *transmission distance* (TX_DISTANCE) boundary and longer times are assigned to those nodes that are closer to the originating/forwarding node.

### 3.6.3 Neighbour Elimination

To avoid redundant transmissions during broadcasting each node (MPR and non-MPR) assesses whether all of its neighbours have received the broadcast packet. The principle is based on hearing WSM frames during *dynamic time slot* and calculating which 1-hop neighbours should have theoretically received the frame. The process is called calculating neighbour coverage. After the expiration of the *dynamic time slot* a node calculates neighbour coverage from all previous transmissions and if any node is not covered then the node transmits, otherwise it silently discards the frame. This functionality is further described by the following algorithm in Table 3.6:

TABLE 3.6. NEIGHBOUR ELIMINATION

```
1. $U = \emptyset$ empty sets, S is set of all neighbours $M^j_{1,..,n}$ of node $M^j$
2. do (listen to the physical medium)
   a. If (the same WSM frame is received from node e.g. $M^i$) && (distance $|M^j, M^i| > \alpha \cdot tx\_dist_{max}$))
      i. for ($p = 0$; $p <$ maximum neighbours $n$ at $M^j$; $p$++)
         1. if (distance between $|M^j_p, M^i| \le tx\_dist_{max}$)
            a. $M^j_p \in U$
   b. else if (the same WSM frame is received from node e.g. $M^i$) && (distance $|M^j, M^i| \le \alpha \cdot tx\_dist_{max}$)
      i. break, Neighbour Elimination algorithm ends, $M^j$ does not transmit and silently discards the WSM frame
3. while (expired dynamic time slot)


4. if ($U == S$) && ($M^j \notin MPR^{i,..,k}_{1,..,N}$) where all $M^j_{1..n} \in S$ and $i,..,k$ is the index of all nodes that transmit the WSM frame
   a. $M^j$ does not transmit and silently discards the WSM frame
5. else ($U \ne S$) || ($M^j \in MPR^i_{1,..,N}$)
   a. $M^j$ create own list $MPR^j_{1,..,N}$ and performs broadcasting
```

- α is a constant to avoid multiple broadcasts being sent in close proximity. It is set to 0.1.

Non-MPR nodes use *neighbour elimination* scheme based on calculating neighbour coverage to reduce transmissions while MPR nodes always perform broadcasting even if they calculate that all nodes have already received the WSM frame. The reason for

MPR nodes to always transmit is that in sparsely populated networks some nodes can be just beyond the *transmission distance* boundary of $M^j$ and so the algorithm does not consider them but they may in fact receive the transmission and so prevents the dissemination from prematurely ending.

## 3.7 RVG - Pseudo Acknowledgments (PACK)

The RVG broadcast protocol relies on the *Pseudo Acknowledgements* (PACK) scheme to increase the reliability of the broadcast dissemination. The main goal of the PACK method is to avoid the hidden terminal problem by listening to the medium for subsequent transmissions. The PACK scheme interprets successful multi-hop broadcast transmissions through overhearing successive rebroadcasts by its neighbours. As the broadcast packet traverses the network, each hop creates *dynamic time slots* in which to rebroadcast. Intermediate hops that receive the broadcast wait until the *dynamic time slot* expires and then rebroadcasts thereby acknowledging a link between itself and previous hop. If the previous hop does not overhear the rebroadcast it repeats the rebroadcasting. The maximum number of repetitions in the simulation is set to 2 (BROADCAST_RETRIES).

The principle of the PACK method is that nodes $MPR^i_{1,\ldots,N}$ broadcast one by one without collisions after being selected for rebroadcasting by the previously transmitting node $M^i$. As described in section 3.6.1 a broadcasting node defines geographical sectors and selects its MPR set ($MPR^i_{1,..,N}$) and broadcasts. The selected neighbours of $M^i$ that receive the broadcast say $M^j$ and $M^k$ then rebroadcast. The rebroadcasting by $M^j$ and $M^k$ is also received (overheard) at $M^i$ (Fig. 3.3) assuming no collisions. Collisions are mitigated due to the spreading of the retransmissions over *dynamic time slots* and so each rebroadcast node should transmit in turn and be overheard by $M^i$. This overhearing is interpreted by the PACK method as a form of *pseudo-acknowledgement* for the individual sectors. If an unacknowledged sector(s) remains after some predefined time called *repetition interval* then the node $M^i$ repeats the broadcast with a new list of $MPR^i_{1,..,M}$ ($M \leq N$) that contains only the missing sector(s). The algorithm is repeated until all sectors are acknowledged or a maximum number of repetitions (BROADCAST_RETRIES) are reached for the broadcast. The broadcast *repetition interval* $T_{rep}$ is calculated according to equation (3.5):

$$T_{rep} = 2 \cdot N \cdot max(T_{L\_MAC}) + rand(N \cdot max(T_{L\_MAC})) \tag{3.5}$$

- *N* is the maximum number of nodes in $MPR^{i}_{1,..,N}$.
- $T_{L\_MAC}$ is the maximum transmission time defined in (3.2).
- *rand* is a random value uniformly distributed in the range 0 to $(N \cdot max(T_{L\_MAC}))$ to further randomise repetitions over a short time interval to avoid collisions.

The PACK scheme partly solves the *Hidden Terminal Problem* by using repetitions (Fig. 3.4). In RVG with PACK only specific nodes act as forwarders for the broadcast and in turn create *dynamic time slots* during the broadcast process at the upper MAC layer to further randomise the channel access time to decrease packet collisions. Nodes set the start of the *dynamic time slot* based on the time the packet is received so global synchronisation is not required and the slot size is determined using equation (3.3). After this *dynamic time slot* expires, the broadcast packet is passed from the upper MAC layer to the lower MAC layer for transmission according to the MAC standard [86] and the *repetition interval* (3.5) begins to count down. If transmissions are not heard from all sectors covered by the $MPR^{i}_{1,..,N}$ nodes after expiration of the *repetition interval* the node repeats the transmission of the broadcast.

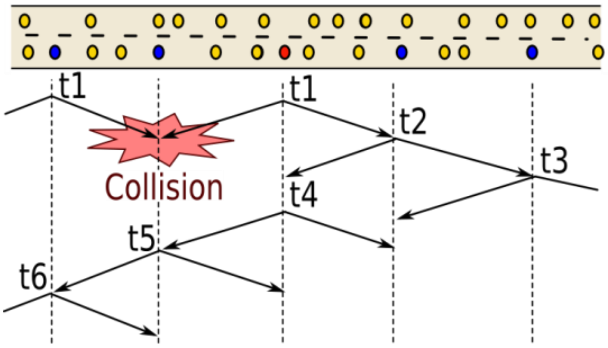


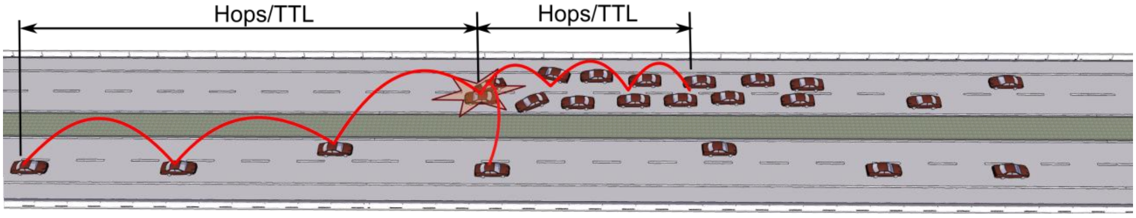
Fig. 3.4. PACK

## 3.8 RVG - Broadcast Methods: Geo-broadcast (RVG), Geo-cast (G- RVG)

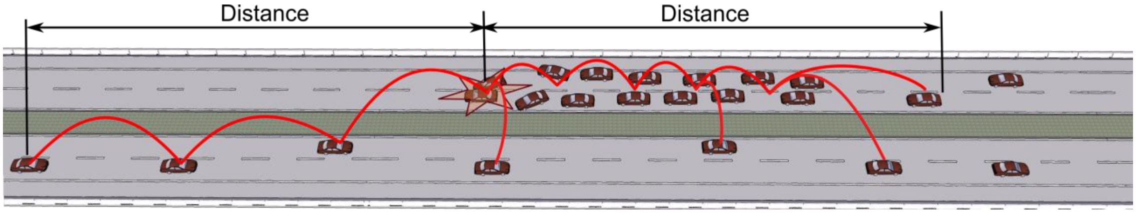
In this thesis three potential methods for broadcasting are considered (Fig. 3.5 a-c):

1) Topo-broadcast: This is a topology broadcast that is based on topology information and disseminates data up to a specific distance in terms of specifying a maximum number of hops (MAX_HOP).
2) Geo-broadcast: This is a geographic broadcast technique that is based on position information of the nodes and disseminates data up to a set distance (BR_DISTANCE) from the node that invoked the broadcast. The Geo-broadcast principle is used in the proposed RVG protocol.
3) Geo-cast: this is a variant of Geo-broadcast where the data is disseminated in a specific geographical area, called a sector, that is defined by the direction of interest (BR_DIRECTION) up to a distance of (BR_DISTANCE) from the node that originated the broadcast and the spread of the sector is defined by the angle (ANGLE_DIRECTION). The Geo-cast principle is used in extension of RVG protocol which is referred to as G-RVG.

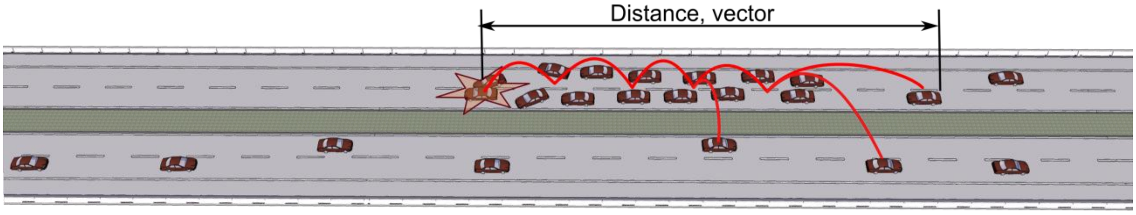
Topo-Broadcast protocols rely on a *Time To Live* (TTL) hop limit metric to restrict data dissemination inside a specific region around the source node. However, TTL restrictions effectively stop broadcasting and it does not have any relevance with the physical size of the region or a minimum distance that the broadcasting effort should reach (Fig. 3.5a). Another disadvantage of using the TTL metric is that TTL hop limits can significantly vary based on the environment. Consider an urban environment, where empirical testing [87] has shown that, transmission distances over a single hop are approximately 50m whereas in highway scenarios the transmission distance is in the region of 120m for tolerable packet loss. To avoid imprecise TTL restrictions two alternative metrics are considered. The first metric is used by RVG and G-RVG and is the *minimum broadcast distance* (BR_DISTANCE), which specifies the minimum



**a) Topo-broadcast**



**b) Geo-broadcast**



**c) Geo-cast**

**Fig. 3.5. Broadcast methods**

distance that the data dissemination should reach to satisfy safety application requirements (Fig. 3.5b).

This metric has a size of 2 bytes and is encapsulated within the safety application packet (Table 3.2). The other metric used by G-RVG is the *dissemination direction* (BR_DIRECTION) with a size of 2 bytes within the safety packet, which specifies in which direction data should be disseminated (Fig. 3.5c). This is to restrict the direction in which the broadcast is sent and is to minimise the use of the communications medium, for example consider a two lane highway with a traffic jam on one lane, drivers in the other lane are not interested in receiving information relating to the traffic jam. This metric is defined by the originating node and selects the forwarding nodes based on their position. Shown in Fig. 3.1 is an example of four directional sectors created around an accident point within a highway lane. The directional sector of interest is sector $S_1$ as this will send the warning broadcast to vehicles approaching the accident point. G-RVG, the geo-casting algorithm is similar to the SRMB algorithm (in Table 3.4) with the differences being highlighted below (in bold font) in Table 3.7:

TABLE 3.7. GEO-BROADCAST ALGORITHM

```
1. $M^j$ receives a message from $M^i$ with a MPR list $MPR^i_{1,..,N}$ addresses
2. if ($M^j \in MPR^i_{1,..,N}$){
   a. if (distance | $M^j$, $M^i$ | ≤ minimum broadcast distance)
      i. $M_j$ waits until its selected dynamic time slot expires and then performs broadcasting with based on a selection of its own $MPR^j_{1,..,N}$ (Table 3.3).
   b. else if (distance | $M^j$, $M^i$ | > minimum broadcast distance)
      i. $M_j$ waits until its dynamic time slot expires and then creates a WSM frame with an empty $MPR^j$ list. The purpose of this transmission is to act as an acknowledgement for the previous broadcast sent by the node $M^i$.
3. else if ($M^j \notin MPR^i_{1,..,N}$) {
   a. if (distance | $M^j$, $M^i$ | ≤ minimum broadcast distance) && ($M^j$ lies in a sector defined at originating node $M^k$ with BR_DIRECTION, ANGLE_DIRECTION)
      i. $M^j$ waits until its dynamic time slot expires and then it performs broadcasting based on a selection of $MPR^j_{1,..,N}$ only if $M^j$ can achieve additional coverage of neighbour nodes in comparison to the coverage achieved by the node $M^i$ (based on neighbour elimination, subchapter 3.6.3).
   b. else if (distance | $M^j$, $M^i$ | > minimum broadcast distance) || ($M^j$ does not lay in a sector defined at originating node $M^k$ with BR_DIRECTION, ANGLE_DIRECTION)
      i. $M^j$ does not rebroadcast
4. }
```

## 3.9 RVG - Event Suppression (ESSMD)

To minimise the number of broadcasts generated relating to a single emergency event, an event suppression method has been proposed in this thesis. When an accident or emergency related event occurs (related to SOS Services, see Appendix A) vehicles in nearby locations detect the event in a similar time frame (related to e.g. Emergency Electronic Brake Lights, see Appendix A). These vehicles process the event, create an emergency packet and prepare the packet for broadcasting. The number of invoked broadcasts is equal to the number of vehicles that detect the situation. Because all these vehicles report on the same event (or very similar event), it can lead to a dramatic message redundancy. To avoid this, the *Event Suppression for Safety Message Dissemination* (ESSMD) method has been proposed.

Consider a set of vehicles or nodes $V_{1,\ldots,J}$ that detects a dangerous situation. The emergency situation is identified and the type of event is classified as $E_o$. These vehicles $V_{1,\ldots,J}$ prepare to broadcast packets $B_{1,\ldots,J}$ for the same event $E_o$ and randomly choose a time to transmit $T_{1,\ldots,J}$ in the Control Channel slot (CCH) with a slot size of 50ms as specified in the WAVE standard [77-81]. A node $V_1$ with shortest time $T_1$ transmits the packet $B_1$ first. As the other nodes in the set $V_{2,\ldots,J}$ are in close proximity to node $V_1$, these nodes ideally receive the broadcast $B_1$. These nodes $V_{2,\ldots,J}$ have also invoked their own broadcast packets $B_{2,\ldots,J}$ and are waiting to transmit packets relating to the same event $E_o$.

In the *ESSMD* scheme each node maintains a local *Event table* where each entry in the table contains an event type and time when the event was transmitted at the node. More generally if a node $V_i$ receives an event $E_o$ in a packet $B_j$ from $V_j$ or the node itself invokes a broadcast $B_i$ for the event $E_p$, the algorithm shown in Table 3.8 is performed before storing $E_o$ in the *Event table*.

TABLE 3.8. EVENT SUPPRESSION ALGORITHM

```
1. if (an event $E_o$ is invoked at node $V_i$) && (time $T_i$ to transmit expires) && (other $E_o$ or higher
   priority event $E_q$ is not in the Event table for EVENT_SILENT_TIME)
    a. $V_i$ transmits its own $B_i$ with event $E_o$ repeated 3 times (EVENT_REP)
2. else
    a. the broadcasting $B_i$ is not performed

3. if (an event $E_o$ in $B_j$ is received at $V_i$) && (other $E_o$ or higher importance event $E_q$ is not in the Event
   table for a EVENT_SILENT_TIME)
    a. $V_i$ rebroadcasts $B_j$ with $E_o$
4. else
    a. the broadcast $B_j$ is not performed
```

Continuing with the same scenario as before; at time $T_1$ node $V_1$ broadcasted $B_1$ and nodes $V_{2,\ldots,N}$ received the broadcast packet $B_1$. Subsequently all vehicles $V_{2,\ldots,N}$ perform the broadcasting of $B_1$ according to the broadcast algorithm (e.g. RVG) and nodes discard their own broadcast packets $B_{2,\ldots,N}$ because the $E_o$ event in packet $B_1$ has already been broadcast. This principle idea is to reduce the number of simultaneous broadcasts relating to the detection of the same event so that a reduced number of redundant packets are transmitted over medium which increases the chances of a successful transmission. This scheme has an advantage over aggregation methods as it does not add any extra time delay because the messages are sent immediately when the CCH slot is used. Another advantage is that *ESSMD* improves packet reception in low, medium and high density networks. ESSMD does not focus on the application layer packet generation but rather it limits the number of vehicles that generate broadcast reports on the same event. ESSMD sends fewer packets over the physical medium which increases the probability for packet reception at the start of the broadcast process. Fig. 3.6 shows how the delivery ratio falls off as the broadcast is disseminated over the network however, in the case of hazard detection it is important that close proximity vehicles are warned immediately. In contrast having all vehicles that detect a hazard generate a broadcast in fact gives rise to a lower delivery ratio at the start of the broadcast process as many nodes transmit simultaneously. Fig. 3.6 shows how the delivery ratio increases as the broadcast is disseminated over the network.

To take advantage of the increasing delivery ratio profile achieved with more vehicles reporting (this is akin to increasing the rate at which packets are generated relating to the same event) the number of repetitions was set to 2 (EVENT_REP) in the simulation experiments presented here (3 packets in total, the original packet followed by 2 repetitions).

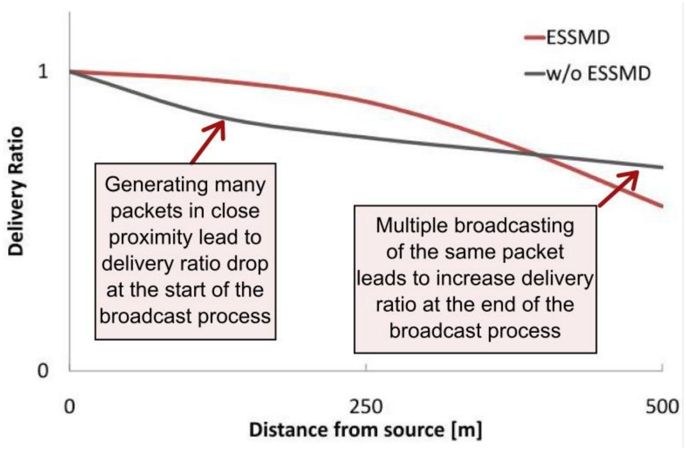


**Fig. 3.6. Delivery ratio**

## 3.10 RVG - Parameter Configuration

Table 3.9 specifies the default values for the parameters associated with the RVG protocol operation:

TABLE 3.9. CONFIGURATION PARAMETERS

| Parameter | Value | Description |
|---|---|---|
| ACTIVE_ROUTE_TIMEOUT | 1s, 5s | Specifies how long an entry in a *Broadcast table* is active than is erased. For 1-hop neighbours this is set to 1s and for farther away nodes it is set to 5s. |
| HELLO_INTERVAL | 100ms | Specifies how often each node transmits a beacon (WSA frame). |
| BROADCAST_RETRIES | 3 | Specifies how many times a broadcast is repeated by a transmitting node if the node has not overheard transmissions from all sectors. This parameter is used by PACK scheme. |
| TX_DISTANCE | 40 – 150m | This is theoretical transmission distance of a node that transmits with maximum transmit power. The value is derived from an empirical model. See chapter 4, section 4.2. |
| BR_DISTANCE | 500m<br>1000m | This is the *minimum broadcast distance* that each broadcast should reach. The distance is set by requesting service (see Appendix A) at the originating node. For evaluation purposes it was set to 500m in urban and 1000m for highway environments. |
| BR_DIRECTION | -1 | Default value is set to -1 which means broadcasting is performed in all directions (not geo-casting). The value specifies the direction (axes) of a broadcasting sector in degrees where nodes perform forwarding of the WSM frame. |
| ANGLE_DIRECTION | $90^0$ | Specifies an angle of a broadcasting sector at the originating node. |
| MAX_SECTORS | 4 | Maximum number of MPR nodes that a node can choose. |
| MAX_SPEED | 80m/s | Maximum speed between two nodes. |
| NON_MPR_TIME_SLOT | 2ms | This specifies the maximum length of the time slot for non-MPR nodes. During this time non-MPR should either forward or silently discard the frame. |
| MAX_HOP | 20 | Maximum hop limit that a broadcast can reach before being discarded. Each hop decrements the hop count by 1 in the WSM frame |
| EVENT_RETRIES | 1s | This specifies the interval between the broadcasting of WSM frames that are repeated at a node that continuously senses or detects an event [88, 89] (see column *Update Rate* in Appendix A). |
| EVENT_SILENT_TIME | 1s | This time determines how long a node should refrain from broadcasting based on the time that it received an event. In simulation this is set to a time of 1s which is sufficient not to overload the network and to maintain fresh event information in the vehicle event tables. |
| EVENT_REP | 2 | This specifies how many broadcast of the same event is sent by originating node in *ESSMD* scheme |

## 3.11 Applicability Statement

The RVG broadcast protocol is a reliable network protocol that is designed to be compliant with the IEEE 1609 standards and provides an upper layer network-layer service. In the IEEE 1609.3 [77] draft from 2007 beacon messages are used without a node’s mobility status while in ETSI TS 102 636-1 [22] from 2010 beacons messages include the mobility status i.e. position, heading speed etc. The RVG protocol uses beacon messages defined by the IEEE 1609.3 draft and includes mobility according to ETSI TS 102 636-1, the RVG protocol continuously exchanges geographical location information amongst 1-hop neighbours.

Generally, RVG can be used to disseminate any type of application data but it has been optimised for the dissemination of safety related messages where RVG satisfies safety application requirements through high packet reception and low delay (see requirements in Appendix A). While RVG has been primarily designed as a broadcast protocol it can also be used as a route discovery mechanism in reactive routing protocols. From the route discovery perspective routes are built based on delay, bandwidth consumption and mobility of nodes in the source-destination path. Nodes with similar mobility behaviour (speed, motion vector) are selected as intermediate hops as this supports the generation of stable routes and reduces route maintenance overhead.

The RVG protocol is designed for vehicular ad hoc networks with populations from tens to hundreds per km on a road. RVG can handle nodes with static, cities, rural and highway mobility rates with high reliability in terms of delivery of WSM messages. The RVG protocol can work in low penetration networks with only a small number of vehicles being equipped with On Board Units (OBUs) for wireless communications as well as in high penetration networks including a high number of these vehicles. However, in low penetration or sparsely populated networks RVG does not perform well as V2V communication is difficult to sustain as the VANET network is highly disconnected. For dissemination in larger areas an infrastructure that supports V2I and I2V and/or V2R and R2V communication is required. In contrast, when VANET network becomes well connected, from medium to very high numbers of vehicles then RVG performs with high reliability. By default, RVG broadcasts in all directions due to road layouts in urban/city environments whereas in highways RVG can optionally broadcast in specific directions due to lane restrictions.

RVG is designed for use in networks where the nodes can all trust each other as malicious intruders nodes are not considered although malicious nodes that decide not to forward are substituted by other non MPR nodes assuming there are sufficient nodes in the network.

## 3.12 Conclusion

This Chapter 3 has described the operation of the *Reliable Vehicular Geo-broadcast* (RVG) protocol that has been proposed for safety data dissemination in vehicular ad-hoc networks. The RVG protocol is designed to be compliant with the IEEE 1609 standards and their messages formats where the payload incorporates the broadcasting and event information (section 3.4). Section 3.5 described the conditions under which the RVG protocols generates WSA and WSM frames and updates *broadcast table*. In addition the four main cornerstones of the RVG protocol are introduced: *Slotted Restricted Mobility-Based* (SRMB) method that is responsible for the dissemination of messages over a specified distance in the network and this relies on *multipoint relaying* and *neighbour elimination* schemes (as described in section 3.6); the *Pseudo Acknowledgement* (PACK) scheme interprets successful multi-hop broadcast transmission through overhearing successive transmissions of the broadcast packet (section 3.7); G-RVG is used to restrict broadcasting to a geographical area (section 3.8); and finally ESSMD is used to reduce the number of simultaneously invoked safety messages (section 3.9). Finally an applicability statement for the RVG protocol is discussed from the viewpoint of standards compliance, technology penetration, network density, malicious intruders and lastly the use of RVG in route discovery is described.

# Chapter 4 Simulation Environment

## 4.1 Introduction

Prior to commercial deployment of any new technology, realistic testing must be performed. In communication and computer networks research, simulation is the most practical method of evaluation. Simulation allows engineers to test scenarios that might be otherwise difficult or expensive to emulate using real hardware and it allows designers to test new protocols or make changes to existing protocols in a controlled and reproducible environment. Currently, since neither ITS infrastructure nor communications exist, except for small scale prototypes [90-92], simulation is the only economically viable and fast way to develop new protocols for ITS.

In this chapter the CALMnet simulator (Fig. 4.1), a Comprehensive Network-centric simulation environment for CALM-based (Continuous Air Interface for Long to Medium range) cooperative vehicular systems is presented. This is a complex realistic platform for testing new protocols and includes the following elements, which are necessary for accurate modelling:

1) Realistic channel modelling: channel model parameters were deduced from empirical measurements recorded in urban and motorway environments using on-board IEEE 802.11p communication enabled units.
2) Mobility modelling: realistic mobility patterns were exported from the SUMO traffic simulator [93].
3) Network modelling: the computer simulation tool OPNET [94] was used in conjunction with SUMO to develop the network topology with communications being modelled using the empirically derived channel parameters and the relevant features of the WAVE protocol stack were implemented using OPNET to support V2V communications.

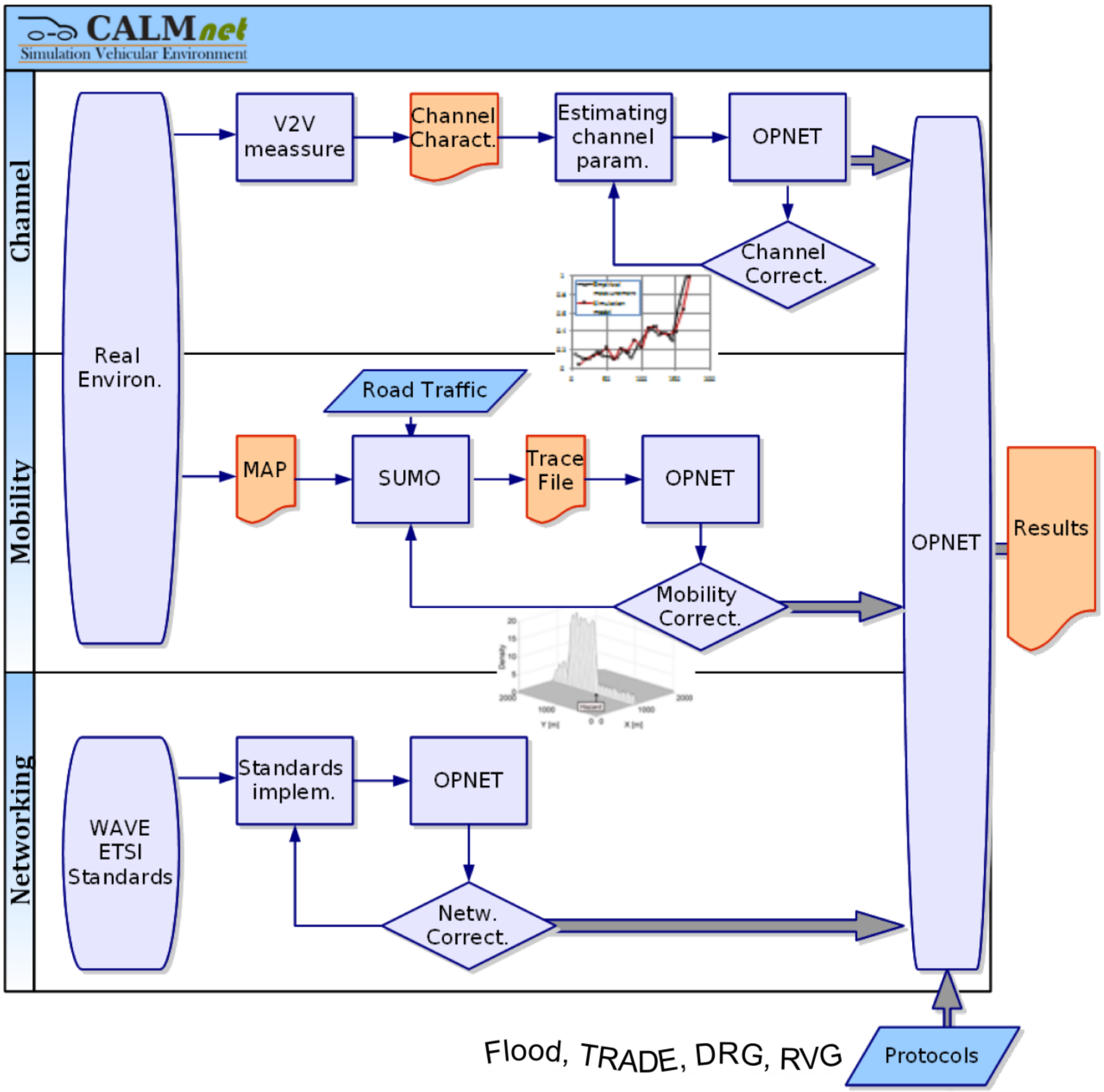


**Fig. 4.1. CALMnet**

## 4.2 Channel Modelling

As wireless signals traverse along the path from a transmitter to a receiver, they will be diffracted, scattered and absorbed by surrounding obstacles such as the terrain, trees, buildings, vehicles and people. These obstacles may cause: a greater radio attenuation than free space conditions, time dispersion as the signal take multiple paths and frequency dispersion as the transmitter and the receiver are in motion. These factors affect the quality of the signal at the receiving antenna and impact on whether the signal will be correctly decoded.

Typically, wireless network simulators assume a generic propagation model for V2V communications, such as *Free Space* model or *Two-Ray Ground* reflection model coupled with a shadowing model [95] which are inadequate to model real world environments. These assumptions lead to inaccuracies in recorded performance metrics [23, 96] such as reliability, end-to-end delay or coverage. Selecting an appropriate propagation model is a critical factor for testing higher layer protocols.

Several works have presented radio propagation measurements for V2V communications in real environments [97-99] however the packet loss ratio metric was ignored. This measurement is a crucial parameter for higher layer protocols as it establishes the probability that a packet is received correctly without errors [100].

Channel modeling is a complex task and is not within the scope of this thesis. The CALMnet simulator relies on an empirically derived estimate for packet loss ratio as this is considered fundamental to the evaluation of upper layer protocols (e.g. broadcasting in this case). Using IEEE802.11p-enabled prototype on-board units (OBUs) developed as part of the EU FP6 CVIS [90] project, measurements were performed using two vehicles travelling at various speeds and distances from each other in different scenarios. As channel characteristics differ in diverse environments, measurements were gathered in two distinct driving environments.

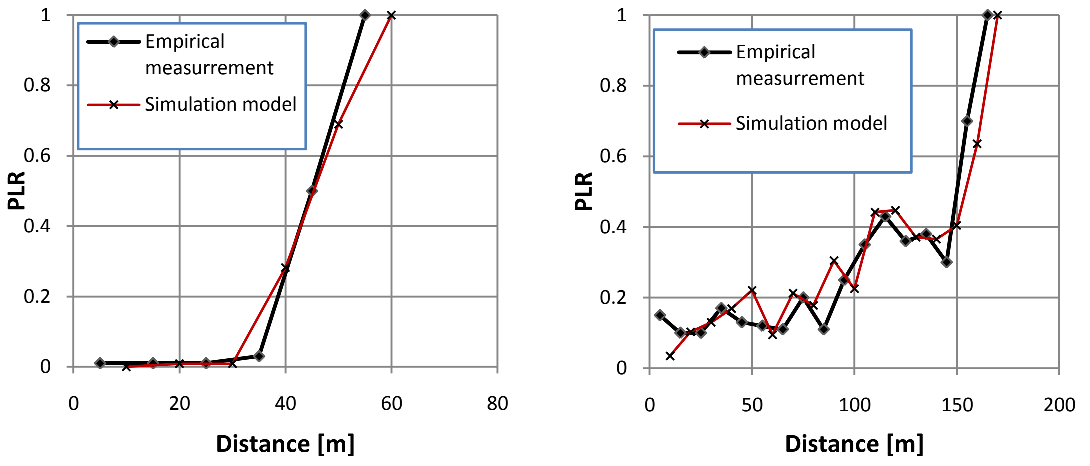
- *Highway:* with two lanes in each direction and little or no surrounding structures, vehicles travelled up to 120km/h on the N8 motorway between Cork and Fermoy in medium busy traffic (estimated based on time of day).
- *Urban*: city centre dense traffic scenario with between one and two lanes in each direction; many junctions and traffic lights resulting in intermittent driving periods with maximum speeds of 50km/h. The urban environment was surrounded by high buildings and measured in Cork city centre at peak time.

The test platform consisted of a number of software and hardware components [87]. Two cars were each equipped with a prototype CVIS OBU with a Microwave Communication Module (MCM) containing two M5 Atheros AR5212 radio cards and a GPS (Global Positioning System) module. The CVIS rooftop antenna prototype included a GPS antenna, a collinear M5 antenna and a patch M5 antenna. Each test lasted at least one hour with one car acting as transmitter and the other as a receiver with varying inter-vehicle distances and traffic conditions in both LOS and NLOS communication states. During each test scenario, the vehicle acting as transmitter sends a beacon requests every 100ms to the other vehicle. A description of the test system parameters is presented in Table 4.1.

TABLE 4.1. TEST SYSTEM PARAMETERS

| | |
|---|---|
| Transmission power | 18dBm |
| Receiver Sensitivity | -110dBm |
| Transmission frequency | 5.89GHz |
| Beacon request generation interval | 100ms |
| Data rate | 6Mbps |
| Packet Delivery Ratio threshold | 70% |

The proposed channel model is developed for simulation of V2V communication. The core of the model is based on the *Free Space* model where log-normal shadowing is added. To obtain the pathloss and shadowing model parameters from the empirical data, the RSSI, packet loss and inter-vehicle distance for each data set was computed. Linear regression is then used to estimate the pathloss exponents for the *Free Space* approach in different environments (urban, highway). The packet loss statistics for the urban and highway environments are shown in Fig. 4.2 and it can be seen that the maximum transmission distance is around 60m for the urban scenario and 160m for the highway scenario.



a) Packet Loss Ratio in urban environment b) Packet Loss Ratio in highway environment

Fig. 4.2. Packet Loss Ratio

## 4.3 Mobility Modelling

Another important parameter for VANET simulations is the movement pattern of vehicles which is often referred to as *the mobility model*. The mobility model determines the location of nodes on the road topology over time and this defines the network connectivity. The importance and effect of the mobility model choice on the network protocol performance has been shown in [101], which underpins the need for the use of an appropriate model in vehicular network simulation and evaluation.

Mobility models may be classified into four categories [102]:

1) Synthetic Models: based on mathematical models.
2) Survey-based Models: mobility patterns extracted from surveys that contains statistics e.g. arrival times at work, lunch time, pedestrian dynamics and workday time-use such as meeting size, frequency, and duration.
3) Trace-based Models: mobility patterns generated from real mobility traces.
4) Traffic Simulators-based Models: mobility patterns extracted from a dedicated traffic simulator (CORSIM [103], TRANSIMS [104], VISSIM [105], SUMO [93]).

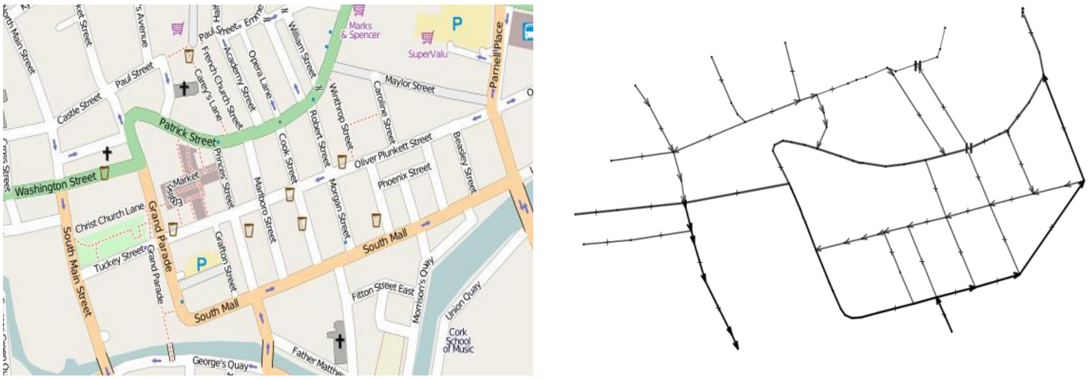
The open source Simulation of Urban MObility (SUMO) v0.11 package was selected as the road traffic simulator employed to generate realistic microscopic vehicular mobility patterns. SUMO allows high performance simulations of huge networks with roads consisting of multiple lanes, as well as of intra-junction traffic on these roads, either using simple right-of-way rules or traffic lights. Vehicle types are freely configurable with each vehicle following statically assigned routes, dynamically generated routes, or driving according to a configured timetable.

SUMO supports maps from NavTech-Files that are stored in the ArcView database format, maps from other simulation suppliers such as PTV (VISSIM, VISUM), TIGER maps and can also support the importing of road networks from OpenStreetMap (OSM) [106]. OpenStreetMap is a project whose aim is to create and provide free geographic data such as street maps to users. The maps are created using data from portable GPS devices, aerial photography, local knowledge or other free sources that contain rich information sets which are used by SUMO in configuring the simulated road network and therefore dictating vehicle mobility rules. Such information includes the presence of traffic lights, the number of lanes present, the type of street, (e.g. pedestrian, highway etc), local speed limits etc.

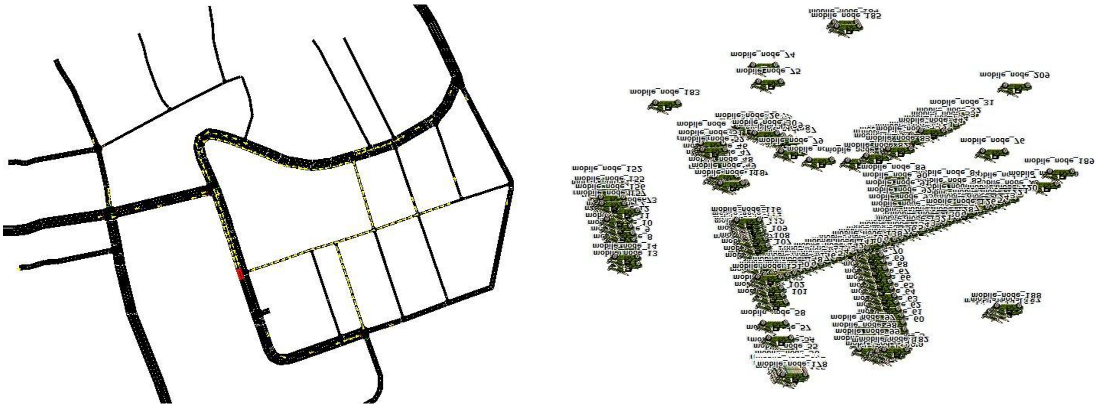
A powerful tool for realistic mobility simulation, SUMO allows complete configuration flexibility. Multiple vehicle classes with diverse characteristics can be defined to follow different pre-defined or random routes and realistic driver behaviour representation is inherent. Vehicles obey traffic signals, can change lanes and perform overtaking. Likewise, lanes can be restricted to allow only certain traffic types, e.g. bus lanes etc, enabling realistic simulation of vehicle movement in the simulated scenario. During SUMO simulation runs, each vehicles mobility trace data is logged and filed offline. These generated trace files are imported to the CALMnet environment where the mobility manager model handles vehicle movement. Here, position updates happen on demand. Each vehicle's current position is calculated only when such information is required, minimising the models reliance on interrupt mechanisms and therefore resulting in more efficient simulation runs.

Steps involved in generating a realistic mobility model to import into the OPNET environment are shown in Fig. 4.3. An ‘area of interest’ is selected for simulation in the

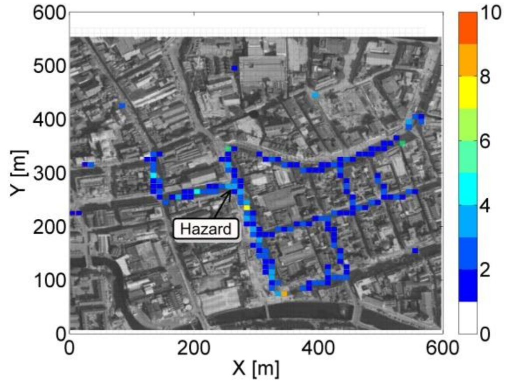
Open Street Map [106] web page (a) and exported in XML format to the map editor JOSM [107] (b) where the map can be edited. The map is then imported to SUMO (c) where traffic is generated and the mobility trace is exported to a text file, which includes the vehicle position and speed in intervals of 1s. The mobility model file is read by OPNET and a mobility pattern is assigned to individual nodes (d). Finally the mobility patterns are used to illustrate the vehicle density at snapshot times over the course of the simulation (e).



**a) Open Street Map** **b) JOSM**



**c) SUMO** **d) OPNET**



**e) Presented Vehicle density**

**Fig. 4.3. Mobility modelling**

### *4.3.1 Highway Environment*

The highway environment is represented by a real 2km stretch of highway Cork-Fermoy with 3 lanes in each direction with the width of each lane being 3m and with a gap of 4m separating the opposing directions. The traffic model contains dynamically moving vehicles in each lane with varying speeds that were restricted to a maximum speed of 120km/h. The environment includes free flow traffic, a traffic hazard where the effectiveness of the broadcast protocols in warning surrounding vehicles was examined. The Highway Free Flow Scenario (Fig. 5.2) contains traffic at night time with a total of 50 vehicles in the network and up to 200 vehicles in the network during peak time with one hazardous location (e.g. Road Condition Warning, Vehicle-Based Road Condition Warning, see Appendix A) being emulated in the middle of the highway with vehicles within 100m of this hazard invoking a broadcast to warn about this. The Highway Accident Scenario was simulated to provide a traffic jam that builds up at peak time forcing a stoppage of all the traffic in one direction. At the time the accident occurred the traffic jam grew rapidly and vehicles were forced to reduce their speed and stop (Fig. 5.5). All vehicles that were in the *hazard zone* (i.e. within a radius of 100m from a centre of the accident) invoked a safety message (e.g. SOS Services, Post-Crash Warning, see Appendix A). The free flow traffic and development of the traffic jam were considered in stages where the broadcast performance was measured as shown in Table 4.1.

A numbers of measures are recorded in Table 4.2 and describe the scenario depending on the time of day – ranging from low densities at night time to high densities at peak time. For the free flow and accident scenarios the number of vehicles over the complete simulation is specified by the max value as indicated in Table 4.2, this value

TABLE 4.2. HIGHWAY TRAFFIC SPECIFICATION

| Scenario | | Max No. Vehicles in Broadcast region | Length of traffic jam [m] | Avg. distance between vehicles [m]/in one lane [m]/traffic jam | Avg. number of entering/leaving vehicles per 10s |
|---|---|---|---|---|---|
| **Free flow** | **Traffic Pattern** | | | | |
| | Night time | 50 | - | 51/240/- | 4/4 |
| | Lower Medium | 100 | - | 22/120/- | 7/7 |
| | Higher medium | 150 | - | 17/80/- | 12/12 |
| | Peak time | 200 | - | 14/60/- | 15/15 |
| **Accident** | **Time since accident (s)** | | | | |
| | 0 | 200 | 0 | 14/60/- | 15/15 |
| | 70 | 300 | 330 | 12/40/6 | 15/15 |
| | 140 | 400 | 660 | 11/30/6 | 15/10 |
| | 210 | 500 | 1000 | 11/24/6 | 15/10 |

varies slightly over the simulation time with vehicles entering and leaving but never increases beyond the max value, as is shown in the last column in Table 4.2 measured over 10s intervals. For the accident scenario during traffic jam build up vehicles are stationary in one direction across all the lanes in that direction and so do not leave the simulation (i.e. at the 140s, 210s intervals since the accident occurred). The average distance between vehicles across lanes in both directions is calculated for each scenario (shown in Table 4.2 as *Avg. distance between vehicles*) also the average distance between vehicles in the same lane is shown (as *in one lane*). The average distance between vehicles in the traffic jam across all lanes in one direction is also calculated for the accident scenario (shown in Table 4.2 as *traffic jam*).

### *4.3.2 Urban Environment*

The urban environment is represented by a real road network in Cork city (Ireland) with an area of 600m x 600m. The traffic model contains dynamically moving vehicles with varying speeds restricted to a maximum speed of 50km/h. The scenarios include both free flow traffic and a traffic accident where the protocol performance was examined. First, the Urban Free Flow Scenario (Fig. 5.8) reflects a night time scenario with 20 vehicles in the network and, during peak time, this rises up to 320 vehicles with one hazard location (e.g. Road Condition Warning, Vehicle-Based Road Condition Warning) where vehicles invoke a broadcast within 50m of the hazard. In the second scenario (the Urban Accident Scenario, Fig. 5.11) a traffic jam built up as a consequence of a traffic accident occurring at a crossroad in a medium busy road network that stopped all traffic. At the time the accident occurred the traffic jam grew rapidly and vehicles were forced to reduce their speed and stop. All vehicles in the *hazard zone* (as in the highway scenarios) invoked safety messages (e.g. SOS Services, Post-Crash Warning). The free flow traffic and development of the traffic jam were considered at specific time intervals where the broadcast performance was measured as shown in Table 4.3.

TABLE 4.3. URBAN TRAFFIC SPECIFICATION

| Scenario | Traffic / Time since accident occur | No. Vehicles in Broadcast region | Avg. min. dist. between vehicles [m]/stdev | Ave. number of entering/leaving nodes per 10s |
|---|---|---|---|---|
| **Free flow** | **Traffic Pattern** | | | |
| Free flow | Night time | 20 | 46/43 | 2/2 |
| | Lower Medium | 50 | 18/22 | 4/9 |
| | Medium Busy | 150 | 8/9 | 12/11 |
| | Higher medium | 230 | 8/17 | 6/9 |
| | Peak time | 320 | 6/5 | 6/4 |
| **Accident** | **Time since accident (s)** | | | |
| Accident | 0 | 150 | 8/9 | 12/11 |
| | 30 | 160 | 7/8 | 12/5 |
| | 60 | 170 | 8/12 | 7/14 |
| | 120 | 190 | 6/12 | 8/2 |
| | 180 | 220 | 6/11 | 6/1 |

As with the highway scenario similar measures are recorded in Table 4.3 and describe the urban environment depending on the time of day. Again for the free flow and accident scenarios the number of vehicles over the complete simulation is specified by the max value as indicated in Table 4.3. The average minimum distance between vehicles across both directions is calculated for each scenario (shown in Table 4.3as *Avg. min. dist. between vehicles*). The average minimum distance between vehicles is recorded based on the distance between a vehicle and its nearest neighbour rather than all neighbours as was used in Table 4.3. The standard deviation is used to show the spread of the vehicles in the environment.

### 4.3.3 Network Modelling

Due to resource, safety and feasibility constraints, the testing of the proposed ITS solutions are fundamentally reliant on computer simulation. Many network simulators are available, including ns2 [108], ns3 [109], OPNET [94], QUALNET [110], GlomoSim [111] and JIST/SWANS [112] which allow researchers to evaluate proposed applications and protocols under different operating conditions. These network simulators provide reliable models of well known communication layer protocols for numerous types of network technologies; however none yet offer a complete, standalone ITS simulation solution. Because OPNET provides diverse statistics modules at different levels and provides free university licences with technical support, it was decided to use OPNET as the network simulation tool.

The OPNET modeller simulation tool includes many wireless modules such as 802.11 a/b/g/e, 802.15.4 and GSM/UMTS. However the IEEE802.11p specification incorporating the WAVE stack was not realised. For the purpose of evaluating and testing of a broadcast protocol for VANETs, a test bed with the WAVE stack was required to be developed.

In the current WAVE implementation, each multi-channel unit supports one Control Channel (CCH) and multiple Service Channels (SCHs). The WSMP [77] protocol is implemented on the CCH to process WSA messages which are periodically transmitted every 0.1s. Safety-related messages based on the WSM format are also transmitted on the CCH. The CCH and SCH TimeSlot intervals (CCH TS, SCH TS) are both 50ms in duration and the beginning of each channel timeslot is marked by a *guard interval* of 5ms. Time slots are synchronised based on the OPNET global simulation time to approximate GPS synchronization. WSA and WSM messages are transmitted strictly in CCH TS over the CCH interface. IP data packets are transmitted over the SCH interface.

The following sections discuss the WAVE simulation model implementation at different layers of the OPNET node model. Table 4.4 summarises the model parameters and Fig. 4.4 shows the current implementation of WAVE in the OPNET simulator.

### 4.3.4 Physical Layer

WAVE units operate on a simplified IEEE 802.11p standard which is an extension of the pre-existing IEEE 802.11a model provided in OPNET. In the current implementation, the 5.9GHz band is used with 7 channels (1xCCH, 6xSCH) each with a bandwidth of 10MHz. The OFDM modulation scheme is configured and the data rate is set at 6Mbit/s, this is the optimal data rate for vehicle safety communications as specified in [113].

### *4.3.5 Link Layer*

The Link layer according to the WAVE standard is called the WAVE MAC. The WAVE MAC is based on the IEEE 802.11e standard and allows service differentiation using data classification priorities that prioritises critical safety packets according to [22, 79, 86]. The WAVE MAC uses the 802.11e-based channel coordination function for each of node's network interfaces. In the current implementation, the 802.11e MAC is extended to support synchronisation of the CCH and SCH timeslot intervals. This ensures that all data (WSMP or IPv4) is transmitted in the correct time slots (CCH TS, SCH TS) and over the correct interface (CCH, SCH).

### *4.3.6 Higher Layers*

The WAVE standard specifies the use of IPv6 at the communications network layer. In the actual implementation, the simpler IPv4 protocol is currently used for data communication over the SCH. Also, a simplified WSMP protocol is implemented for transmission over the CCH. Here, both beaconing and safety-related message types are supported based on the WSA and WSM formats.

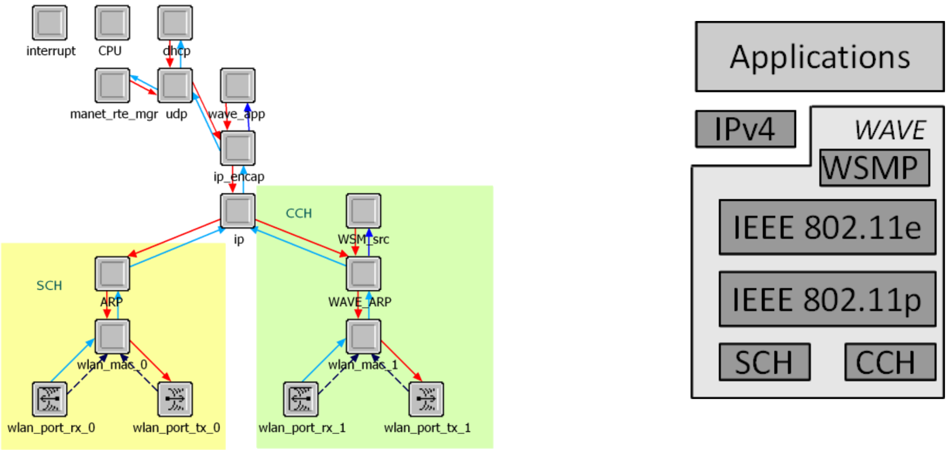
## 4.4 Conclusion

Computer simulation is necessary in analysing mathematically intractable systems and is used to investigate system performance prior to real-world deployment. This chapter has discussed computer simulation modelling and described the constituent models used to implement the stochastic discrete event vehicular ad hoc simulator developed as part of this study. When designing a computer simulation environment accurate modelling must be used, as crude system modelling will not capture the significant characteristics of the real system and will generate misleading performance evaluations. The CALMnet simulator developed as part of this work is a network centric simulation environment designed specifically for the evaluation of VANET networking protocols. CALMnet is built using realistic models to underpin the accuracy of the simulation environment. Channel model parameters have been estimated based on empirical measurements captured in urban and motorway environments using IEEE 802.11p radio interfaces. Realistic mobility modelling is critical for the evaluation of VANET broadcast protocols as the performance of a broadcast protocol is strongly correlated with mobility. To generate mobility patterns that are reflective of realistic movement the mobility model implemented as part of the developed simulator is based on real world map topologies. The OPNET network simulator tool is the core of the CALMnet environment which has been extended to incorporate the relevant features of the WAVE protocol stack to support V2V communications.

The following chapter presents simulation evaluations of the proposed safety data dissemination framework: namely the proposed RVG, PACK and ESSMD algorithms with the CALMnet simulation environment presented in this chapter being used to extract the performance results presented in Chapter 5.

TABLE 4.4. OPNET NODE MODEL WAVE PARAMETERS

| Protocol | WAVE | WAVE in OPNET |
|---|---|---|
| **Node Type** | | |
| Single Channel unit | yes | no |
| Multichannel unit w/o time synchronization | yes | no |
| Multichannel unit w/ time synchronization | yes | yes |
| **Type of network interface** | | |
| OBU | 802.11p/WAVE | 802.11p/WAVE |
| RSU | Not specified | 802.11p/WAVE<br>UMTS |
| **Physical layer** | | |
| Standard | 802.11p | 802.11a |
| Band | 5.9GHz | |
| Bandwidth of channel | 10MHz | |
| Data rate | 6Mbit/s [113] | |
| Channels | 1xCCH, 6xSCH | |
| **Link layer** | | |
| Protocol | WAVE MAC | 802.11e MAC w/ Channel Coordination |
| QoS | yes | yes |
| Timeslots | yes | yes |
| **Network layer** | | |
| Network protocol | WSMP, IPv6 | WSMP, IPv4 |
| Safety-related messages | WSM (368b) | WSM (368b) |
| Beacon messages | WSA (416b) | WSA (480b) |
| Beaconing interval | 100ms | 100ms |



**a) OBU model implementation in OPNET** **b) OBU model stack**

**Fig. 4.4. WAVE and UMTS model**

# Chapter 5 Safety Data Dissemination Framework Evaluation

## 5.1 Introduction

This chapter presents a theoretical analysis of the expected end-to-end delay for the RVG protocol and compares it against the end-to-end delay arising from the Simple Flooding delay, which is used as a baseline to gauge the performance of the RVG protocol. A comprehensive computer based simulation evaluation of the proposed RVG protocol (chapter 3.5), PACK (chapter 3.7) and ESSMD (chapter 3.9) methods discussed in Chapter 3 are presented.

## 5.2 Theoretical End-to-End Delay

A theoretical analysis of the end-to-end delay achievable with the RVG protocol is described in this section and is compared against the performance of the Simple Flooding (chapter 2.3.1) protocol. This analysis in addition to being used as a benchmark for RVG performance evaluation is also used to underpin the validity of the results obtained from simulation. According to the WAVE [79] standard, time is divided into frames (referred to as a *sync interval*) with a length of 100ms. Each frame contains two slots - the Control Channel (CCH TS) and the Service Channel (SCH TS) time slots each with a length of 50ms. Each of these slots begins with a *guard interval* of 5ms to allow a unit to switch from one channel to another. In the *guard interval* no messages may be sent. Beacon messages and safety messages are sent only in CCH TS after the *guard interval* has elapsed. If a safety message is sent in the CCH TS the beacon message is omitted to prevent overloading the medium.

In order to determine the theoretical channel access time the following application scenario is considered: a vehicle in a hazardous area repeats a broadcast every 1s [88, 89] (EVENT_RETRIES, see Appendix A) and the repetition of the safety message is uniformly distributed across the *sync interval* with a length of 100ms. If a safety message was invoked during the SCH TS 50ms interval or the *guard interval* 5ms window then the safety message is buffered until the beginning of the CCH TS. It is then sent with a transmission time uniformly selected over the initial 5ms of the slot. The mean time delay $T_{H\_MAC}$ that a safety data (WSM frame) packet waits at the higher MAC layer before being passed to the lower MAC layer to access the CCH TS for transmission is calculated according to (5.1):

$$\overline{T_{H\_MAC}} = \frac{T_{SCH+G}}{T_{sync}} \cdot \frac{T_{SCH+G}}{2} \approx 15ms \tag{5.1}$$

- $\overline{T_{H\_MAC}}$ is mean time delay a safety data packet waits at the higher MAC layer to be placed in CCH TS.
- $T_{SCH+G}$ is time in length of SCH TS (50ms) plus *guard interval* (5ms) when safety data cannot be sent.
- $T_{sync}$ is the length of the *sync interval* set to 100ms in WAVE [79].

### 5.2.1 Simple Flooding Delay Analysis

The mean theoretical overall time delay for the multi-hop Simple Flooding broadcast protocol $T_{FLOOD}$ strongly depends on the window length parameter $T_{WL}$. As n-hop neighbours receive the transmissions almost simultaneously scheduling of rebroadcasts is uniformly distributed over a window length [35] that was set to 10ms and which is suited for emergency messaging requirements. The time delay $T_{FLOOD}$ is calculated as per equation (5.2), which is derived from (3.2) in Chapter 3:

$$T_{L\_MAC}(ac) = \frac{L_{DATA}}{R_{DATA}} + \frac{D}{c} + SIFS + T_{BOslot} \cdot (AIFSN + CW[ac])$$

$$T_{FLOOD} = T_{H_{MAC}} + H \cdot \left(rand(T_{WL}) + T_{L_{MAC}}\right) \tag{5.2}$$

$$\overline{T_{FLOOD}} \approx 65ms$$

- $T_{L\_MAC}$ is the maximum transmission time defined in (3.2).
- $L_{DATA}$ is the size in bits of a safety packet (WSM frame) with a value of 368 bits .
- $R_{DATA}$ is the data rate of 6Mbit/s.
- $H$ is the maximum number of hops per a broadcast process and for approximation was set to 10

(the mean number of hops in the simulations).

- $T_{WL}$ is the window length parameter which is set to 10ms.
- $\overline{T_{FLOOD}}$ is the mean time delay for a safety data packet between invoking the packet at the application layer at an originating node and the packet being received at the last node.

As the maximum available time for broadcasting is only 45ms in one time slot (CCH TS minus the *guard interval*) then the broadcasting may not have sufficient time to be completed in one time slot depending on the number of hops. In such an instance the time delay $T_{FLOOD}$ *is* extended as the broadcasting is stopped during the SCH TS and continues in the next CCH TS so $T_{FLOOD}$ is increased by 55 ms (SCH TS plus *guard interval*).

To further randomise medium access times in an effort to mitigate collisions among close proximity nodes a random window length parameter $T_{WL}$ is used as an additional wait time, where nodes prior to accessing the communications medium select a random wait time from the interval $T_{WL}$. While $T_{WL}$ adds an additional small latency to end-to-end delays for broadcast processes it further reduces the probability of simultaneous transmissions and subsequent retransmissions. As stated, the $T_{WL}$ interval has been set to 10ms, this value is a fraction of the CCH interval and has been determined based on simulation experimentation. The use of $T_{WL}$ can be seen as a mechanism for increasing collision free transmissions which contributes to improved delivery ratios and end-to-end delays that are less than driver reaction times (750ms--2s [31]) and safety application latencies (100ms-1s, see safety services in Appendix A). All broadcast protocols bar the proposed (G-)RVG protocol (RVG unlike the other test protocols uses slots to reduce collisions) used in the experimental evaluation presented in this chapter (section 5.4) use $T_{WL}$ which has contributed to all test protocols maintaining acceptable end-to-end delays for safety application dissemination (i.e. >100ms).

The theoretical analysis presented in this section is used to approximate the expected results for the results measured in CALMnet simulation environment. The time delay can be compared e.g. with the Urban Free Flow scenario (section 5.4.3) that includes a very sparsely connected networks as well as dense networks where the Flood protocol has to disseminate messages over a number of hops (Fig. 5.10f). When the network is sparsely connected, the Flood protocol broadcasts over 2 hops (Fig. 5.10f) causing an end-to-end delay of approximately 30ms (Fig. 5.10g). The delay is in the region of the theoretical delay plotted in Fig. 5.1 which was calculated as approximately as 25ms. As the network becomes more dense, the Flood protocol disseminates over more hops with the hop length reaching 14 hops (Fig. 5.10f) in the most dense Urban Free Flow Scenario causing an end-to-end delay of ca. 100ms (Fig. 5.10g). Although the theoretical delay is calculated as 140ms (Fig. 5.1) the difference is caused by over saturating the physical medium with the flooding of broadcasts in the simulated environment which results in broadcast processes terminating prematurely due to collisions which makes the end-to-end delay smaller than the theoretical value (see Fig. 5.10a).

### *5.2.2 RVG Delay Analysis*

The mean theoretical overall time delay for multi-hop RVG broadcasting $T_{w/oPACK}$ (not including the PACK algorithm) is calculated according to equation (5.3), which is derived from (3.2), (3.3) and (5.1):

$$T_{L\_MAC}(ac) = \frac{L_{DATA}}{R_{DATA}} + \frac{D}{c} + SIFS + T_{BOslot} \cdot (AIFSN + CW[ac])$$

$$T_{slot}(J) = (J-1) \cdot m \cdot max\left(T_{L\_MAC}\right)$$

$$T_{w/oPACK} = T_{H\_MAC} + H \cdot \left(T_{slot}(J) + T_{L\_MAC}\right) \qquad \textbf{(5.3)}^{4}$$

$$\overline{T_{w/oPACK}} \approx 20ms$$

- $T_{slot}$ is the *Sector Wait Time* defined in equation (3) .

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[4] It presumes that all transmissions were made in one CCH TS. Otherwise the $T_{H\_MAC}$ was extended to 55ms (length of SCH TS and *guard interval*)

- *J* is the position a node $M^j$ in the list of $MPR^i_{1..N}$.
- It is presumed that $T_{slot}$ with $J \in (1 \leq N)$ is the delay applied mainly at the originating node of the broadcast, where broadcasts are sent in different sectors. For approximation *J* represents the average number of MPR nodes per hop, based on simulation evaluation this was set to J = 1.5 and a number of hops *H* was set to 10.
- $\overline{T_{w/oPACK}\text{oPoPACK}}$ is the mean time delay for a safety data packet between invoking the packet at application layer at an originating node and the packet being received at the last node.

When the PACK extension is considered, the overall multi-hop delay $T_{RVG}$ is slightly increased due to repetitions (5.4):

$$T_{rep} = 2 \cdot N \cdot max\left(T_{L_{MAC}}\right) + rand\left(N \cdot max\left(T_{L_{MAC}}\right)\right)$$

$$T_{RVG} = T_{w/oPACK} + k \cdot T_{rep} \qquad \textbf{(5.4)}$$

$$\overline{T_{RVG}} \approx 43ms$$

- $T_{rep}$ is the *repetition interval* defined in equation (3.5).
- *k* is the number of repetitions. This value depends on the data traffic on the physical medium, in less busy (low density) network the repetition value was approximately 3 repetitions over the complete broadcast process and this went up to approximately 30 for high density networks. For approximation the *k* was set to 15 which represents a medium busy network.

Shown in Fig. 5.1 is the end-to-end delay depending on the number of hops and on different loads in the network. For the Simple Flooding protocol, the end-to-end delay increases with a growing number of hops and can easily reach a value that is the same as the length of the CCH TS, causing the broadcast process to be split over two CCH TS intervals. For the RVG protocol, the end-to-end delay is not strongly correlated with the number of hops as broadcast transmissions are transmitted in short slots but rather it is more dependent on the network load as repetitions are used. When the network load is low, fewer repetitions are transmitted in comparison to a highly loaded network. As equation (5.2) showed, Simple Flooding is less susceptible to the network load than RVG.

Again, the theoretical analysis of RVG can be used to approximate the expected results for the simulation environment. The end-to-end delay can be compared again

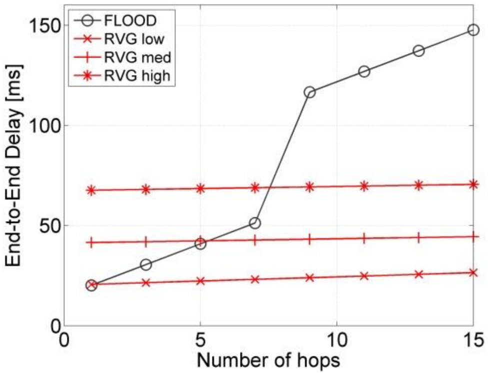


**Fig. 5.1. Theoretical End-to-End Delay for Flood & RVG protocols in Low, Medium and Busy Networks**

e.g. with the Urban Free Flow Scenario (section 5.4.3) where the RVG has to disseminate warnings over a number of hops (Fig. 5.10f). When the network is sparsely connected, RVG broadcasts over 2 hops (Fig. 5.10f) resulting in an end-to-end delay of approximately 20ms (Fig. 5.10g). This delay matches the theoretical delay plotted in Fig. 5.1 for a low density network. As the network becomes more dense, the RVG protocol disseminates over more hops with a maximum hop length of 15 hops (Fig. 5.10f) in the most dense network causing an end-to-end delay of ca. 35ms (Fig. 5.10g) which again matches the theoretical delay for medium dense network.

## 5.3 Broadcast Protocol Performance Metrics

In the simulated environment only two types of messages were transmitted. WSA beacon messages were transmitted every 100ms by each node and safety messages were encapsulated in WSM packets and broadcasted with the *minimum broadcast distance* being set to 500m in urban and 1000m in highway environments. Simulation results were collected from 3 seeds with at least 200 runs for each seed. The metrics recorded from the experiments are outlined below and are shown as three different groups of statistics. The first group (e.g. Fig. 5.2) describes the development and density of the vehicles in the tested scenario. The second group (e.g. Fig. 5.3) gives an overview of the network context where performances were measured and the last group (e.g. Fig. 5.4, Table 5.1) shows the performance of the test protocols.

The dissemination of safety messages in VANETs typically has requirements on delay, reliability and the dissemination area [22]. The metrics for delay and reliability were studied in relation to other quantitative metrics that can be used to assess the performance of any broadcast protocol in different communication scenarios.

Tradeoffs between the following metrics were studied:

1) **Number of neighbours** – this reflects the network connectivity and gives the average neighbour degree of a node (i.e. the average number of neighbours that a node has) across the network.
2) **Number of received packets at a node** – this measure shows the mean number of received packets (WSA, WSM) that are received above the packet reception threshold (-95dBm) per second at a node across the network. *Correct* messages are all messages that were processed up to the application layer while *Erroneous* messages are those that contained an error and are subsequently discarded.
3) **Topological rate of change** – this is a measure of the frequency at which the network topology is changing. It is measured as the number of newly added or expired entries in a node's neighbour table per second across the network.
4) **Delivery Ratio** – this is the mean delivery ratio taken as the number of nodes inside an area that have received a safety broadcast versus the number of nodes in that area. This area is called the *broadcast zone* and is defined by a source node as a circular area with the source node at the centre and the radius is defined by the *minimum broadcast distance*. The delivery ratio is measured in 4 zones defined by the source node, which lies at the centre of the broadcast circle with a set radius for each zone based on a fraction of the *minimum broadcast distance*. The first zone is called the *proximity zone* with radius of one quarter of the *minimum broadcast distance*, the second zone is one half of it, the third zone is three quarters and the last zone has a radius equal to the *minimum broadcast distance*, i.e. this is the *broadcast zone*. For the G-RVG

protocol the area was defined by the *minimum broadcast distance* and by the *dissemination direction*. For the SFR (chapter 2.4.2.c) scheme, this was measured based on the number of nodes inside a *broadcast zone* that have received safety broadcast (from any repetition) versus the number of nodes in the *broadcast zone*.

5) **Broadcast transmission ratio** – this measures the mean broadcast transmission ratio (also known as the link load), which is measured for each broadcast process and is the ratio of the number of nodes that transmit a broadcast packet against the number of nodes that have received the broadcast packet.

6) **Invoked broadcasts per second** – this is the mean measure of the number of invoked broadcasts at the originating nodes (nodes in the *hazard zone*) per second. The *hazard zone* is defined as an area inside a circle with the hazard at the centre and the radius is defined based on the scenario. All nodes passing or staying in the *hazard zone* detect the hazard and invoke a safety broadcast.

7) **Broadcast transmissions per second** – this measures the mean number of broadcast transmissions, which is the number of all broadcast transmissions in a network per second and shows the load on the network as a consequence of broadcasting.

8) **Transmissions per one broadcast** – this measure the mean number of broadcast transmissions for a single broadcast process, which is measured as the number of all broadcast transmissions in the network needed to disseminate the packet.

9) **Number of hops** – this measures the mean number of hops to reach the *minimum broadcast distance*. Number of hops is measured as the average of the maximum number of hops for each broadcast process. When the broadcast process accidentally ends without covering the whole *broadcast zone* the current number of hops reached is taken as the maximum number of hops for that broadcast process.

10) **End-to-end delay** – this is the mean time delay between the invoking of a safety message and the last node that receives the broadcast within the *broadcast zone* (all nodes have received the broadcast at this stage). This also covers the time delay contributed by the CCH and SCH time slots in the WAVE MAC protocol.

11) **End-to-end Busy delay** – this measure gives the mean time delay between the invocation of a safety message and the node that receives the broadcast transmission last. Because of successive rebroadcasts of the same packet nodes can receive/overhear a broadcast more than once and because of delays in rebroadcasting a broadcast process can continue within the network even after all nodes have been covered so this metric reflects the time between the generation of the original broadcast and the time of the last transmission of a packet belonging to this broadcast process. Again, this also covers the time delay contributed by the CCH and SCH time slots in the WAVE MAC protocol.

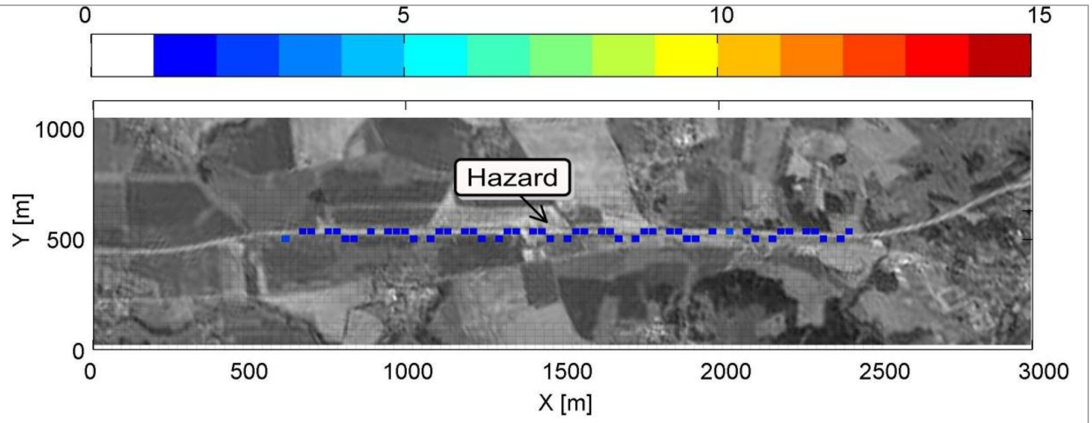
## 5.4 Experimental Evaluation

Based on the discussion presented in Chapter 2 the categories of broadcast protocols suitable for safety application dissemination are flooding, *area-based* broadcasting and *multipoint relaying*. From each of these categories a state of the art representative protocol has been selected to evaluate the performance of the proposed RVG and G-RVG protocols (where G-RVG is the RVG protocol that directionally broadcasts in the selected *dissemination direction* and is used in the highway environment) against. From the Flood group the Simple Flood protocol (section 2.3.1) is used and this acts as the baseline protocol for the performance evaluations. For *area-based* broadcasting the DRG protocol (section 2.3.3.b) is selected and lastly for the *multipoint relaying* the TRADE protocol (section 2.3.4.a) is used. The metrics (described in section 5.3) are recorded from the experimental scenarios and are outlined below with a summary of the primary evaluation metrics being presented in Table 5.5-Table 5.7.

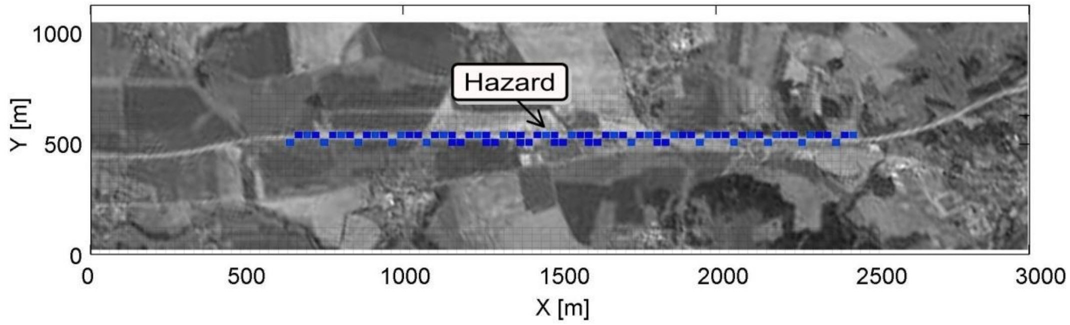
All the results presented in Fig. 5.1-Fig. 5.16 are represented for individual data points by the arithmetic mean values and as the data sets in most cases have a skewed distribution error bars at 2.5% and 97.5% of the data set are also shown.

### 5.4.1 Highway Free Flow Scenario

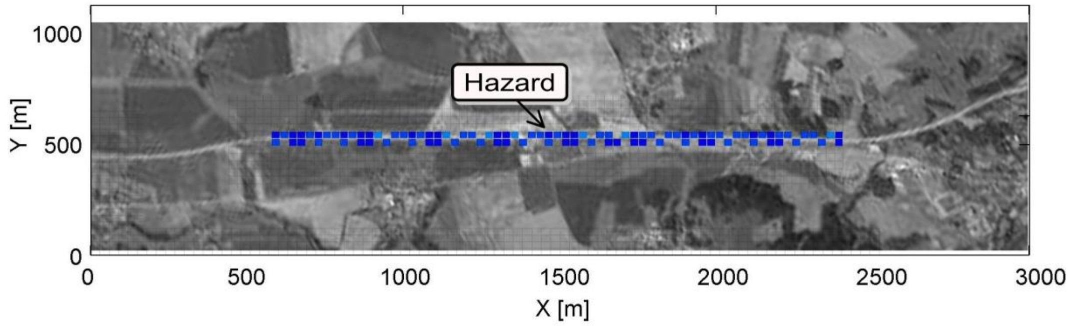
The Highway Free Flow Scenario ranges in representation of traffic at night time with a total of 50 vehicles in the network up to day time peak with 200 vehicles in the network with one *hazard zone* (e.g. pothole, ice, or oil on the road) being emulated in the middle of the highway where vehicles within 100m of the hazard are considered being within the '*zone of interest*' (Fig. 5.2). Vehicles passing or remaining in the *hazard zone* invoke a safety broadcast every 1s and the broadcasting must cover all nodes in the *broadcast zone* with a radius of 1000m.



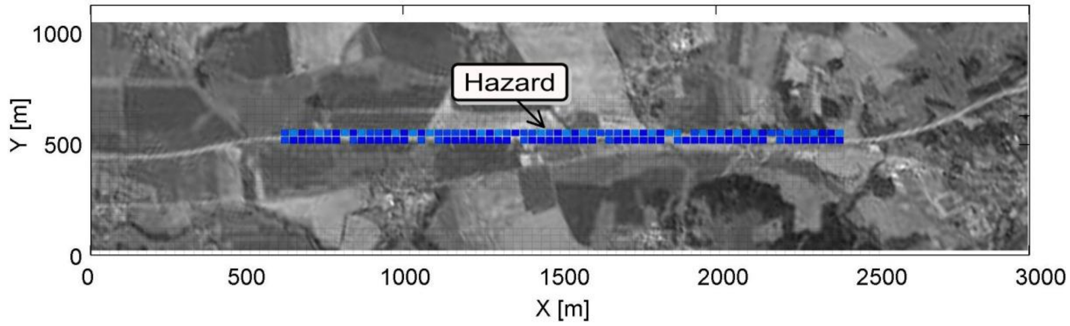
**a) Night time, approx. 50 vehicle per scenario**



**b) Lower medium traffic, approx. 100 vehicles per scenario**



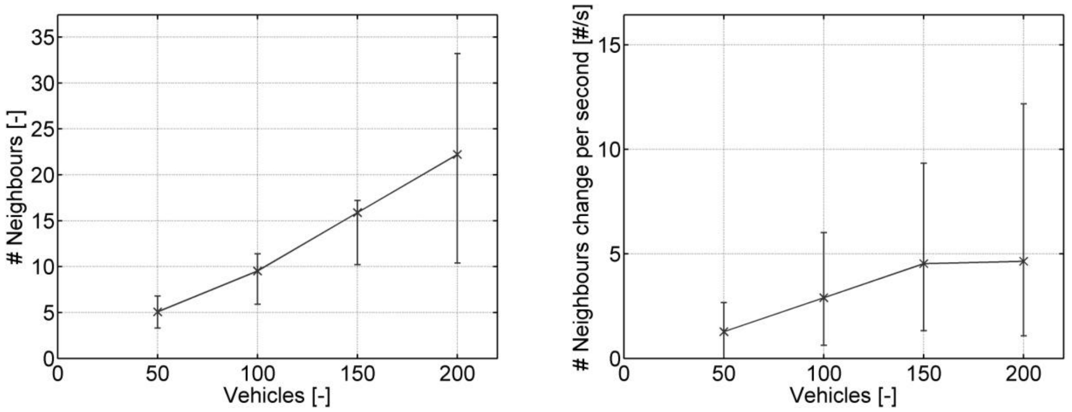
**c) Higher medium traffic, approx. 150 vehicles per scenario**



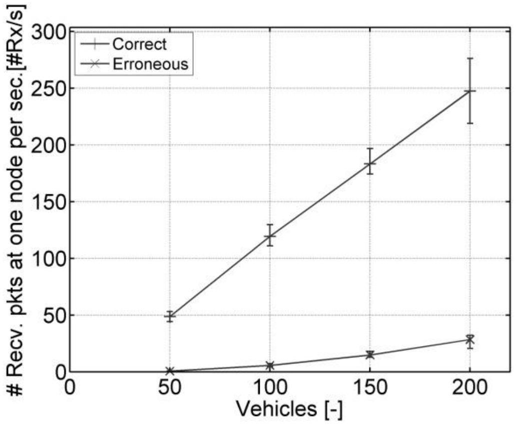
**d) Busy traffic, approx. 200 vehicles per scenario**

**Fig. 5.2. Highway Free Flow traffic is represented by a real 2km stretch of highway Cork-Fermoy with 3 lanes in each direction. The colour points in the map represent the number of vehicles in rectangular sections 10m wide x 30m long in each direction**

Shown in Fig. 5.3 is a contextual description of the network environment that was used to evaluate the broadcast protocols performance. At night time, the network was sparely connected with a mean of 5 neighbours per node (Fig. 5.3a), with a rate of one change per second in the *broadcast table* (Fig. 5.3b). This corresponds to 50 received packets per second as each neighbour transmits every 100ms with a very low number of erroneous packets (Fig. 5.3c). In higher density networks, the network became well connected with increased changes in the *broadcast table* as well as an increase in the number of received packets at one node per second, with more erroneous packets being received.



**a) Number of neighbours** **b) Topological rate of change**



**c) Number of received packets**

**Fig. 5.3. Network context in the Highway Free Flow Scenario**

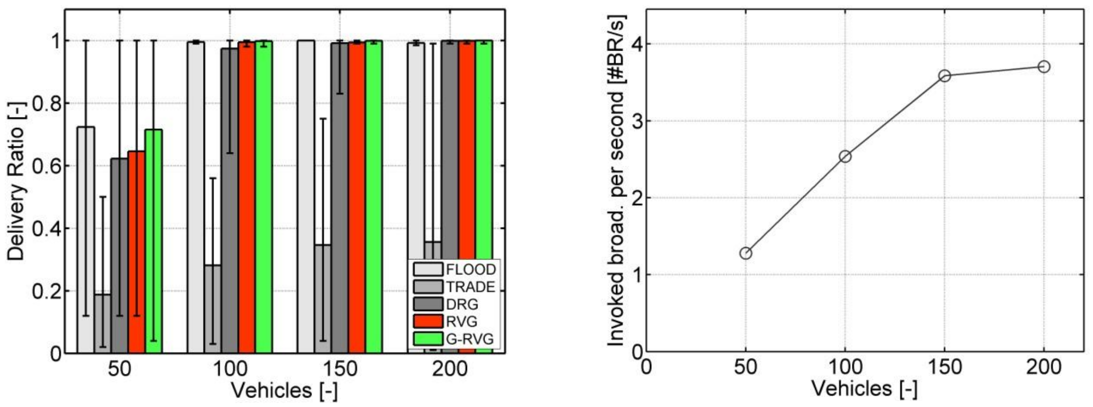
At night time (x = 50 vehicles per scenario, vh/sc, in Fig. 5.4a, Table 5.1) where the network was sparsely connected (in the *broadcast zone*) the Simple Flooding (Flood) protocol reached 72%, TRADE 19%, DRG 62%, RVG 65% and G-RVG 72% delivery ratio and this gradually grew to Flood 99%, TRADE 36%, DRG 100%, RVG 100% and G-RVG 100% delivery ratio in the *broadcast zone* (x = 200vh/sc) in a dense network where the messages were disseminated over approximately 12 hops (Fig. 5.4f). G-RVG achieved a higher number of hops than RVG due to the fact that G-RVG broadcasts in a backwards direction over the traffic jam build up as a consequence of the accident which is a very dense network where many transmissions collide and are not received correctly at MPR nodes and consequently some non-MPR nodes, which were closer to a transmitter, substitute as MPR nodes and rebroadcast. This causes a reduction in the distance between senders and forwarders which increases the number of hops over which the broadcast travels. RVG broadcasts in the accident area as well as in the area opposite to accident which is a significantly less dense network with less collisions and a lower number of MPR substitutions which means that the broadcasts are sent over longer distances which reducing the average hop length over the *broadcast zone*.

All vehicles in the *hazard zone* detected the traffic accident and had to invoke approximately 1 broadcast per second at night time and 4 broadcasts per second at peak time (Fig. 5.4b).

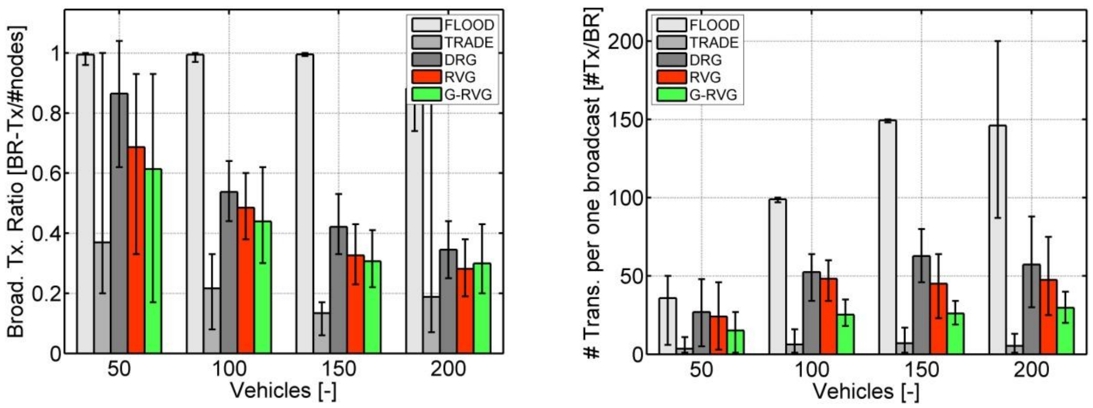
The number of hops affects the end-to-end delay with the number of hops being based on how the forwarding nodes are selected in the case of TRADE, DRG and RVG. TRADE and DRG select forwarders based on distance only with nodes that are furthest from the source being preferred. RVG uses distance as well as motion in selecting its forwarders, which can in some cases mean longer paths (Fig. 5.4f) and consequently it may take marginally longer to transmit a broadcast message to all nodes within the *broadcast zone* i.e. a longer end-to-end delay (Fig. 5.4g). Ignoring TRADE since the broadcast process terminates due to MPR failures; the broadcast process for the Flood and DRG protocols persists significantly longer in the network (End-to-end Busy delay metric, Fig. 5.4h) than RVG as Flood uses all nodes as forwarders and DRG has more repetitions. All protocols under test maintained an end-to-end delay (Fig. 5.4g, h) acceptable for safety messaging as the delay reached a fraction of driver reaction time that is approximately 750ms-2s [31] as well being smaller than the delays demanded by the safety service in Appendix A. But for Safety Services that can tolerate a maximum delay of only 100ms (e.g.Emergency Electronic Brake Lights) the Simple Flood and DRG protocols exceed this delay bound in sparsely connected networks (with 50 vehicles) as they have a high number of broadcasts which results in large delays.

The broadcast transmission ratio (Fig. 5.4c) was kept constant at 100% by the Flood protocol up to 150vh/sc and dropped off to 88% at 200vh/sc as nodes that were outside the *broadcast zone* still received the broadcast but did not forward it. The other protocols reduced the number of transmissions in a well-connected network (x = 200vh/sc) with ratios of: DRG 34%, RVG 28%, G-RVG 30% and TRADE 19%. The ratio had an effect on the number of transmissions per broadcast (Fig. 5.4d) where Flood had to transmit 150, TRADE 7, DRG 60, RVG 48 and G-RVG 30 packets in a well-connected network (x = 200vh/sc). This affected the number of broadcast transmissions per second across all nodes in the *broadcast zone* where Flood transmitted 530, TRADE 20, DRG 210, RVG 180 and G-RVG 105 packets (x = 200vh/sc) per second (Fig. 5.4e). TRADE achieved the lowest number of transmissions as a sender determines only a small subset of neighbours (*multipoint relay set*) and only these neighbours forward the broadcast.

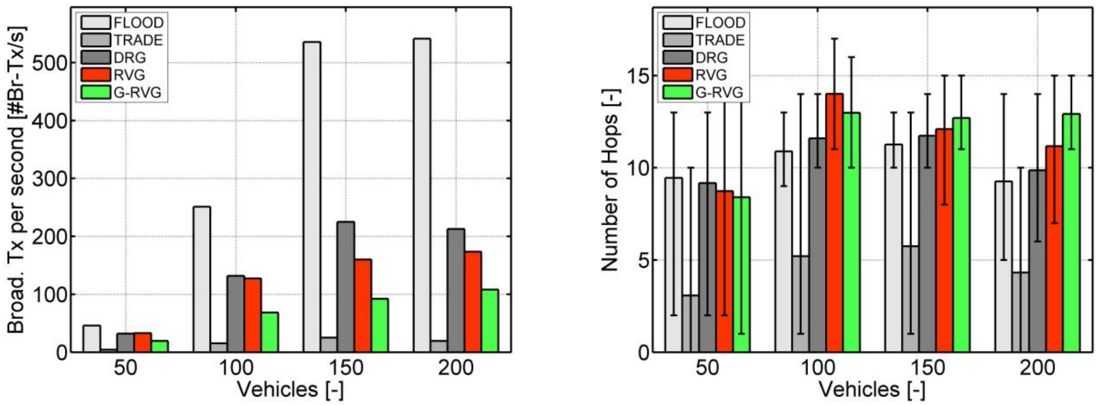
The delivery ratio (Table 5.1) in a sparsely connected network (x = 50vh/sc) up to a distance of 250m (the *proximity zone*) reached values of: Flood 90%, TRADE 60%, DRG 91%, RVG 89% and G-RVG 91%. In sparsely connected networks the average distance between vehicles in the same lane for the Highway Free Flow scenario is 240m (see Table 4.2 in section 4.3.1) which is greater than the stopping distance for vehicles travelling at 120km/h which is approximately 110m under dry conditions and 180m for wet conditions [114]. While the delivery ratio for the sparsely connected network is below 100% in this scenario, vehicles based on the average distance between them have sufficient time to stop even if they do not receive the warning. For a medium dense (x = 100vh/sc) to high density (x = 200vh/sc) network all protocols except TRADE reached 100% delivery. Across all densities, the G-RVG protocol achieved the best delivery ratio for the whole *broadcast zone* as well as for vehicles in close proximity (*proximity zone*). The RVG protocol differs by a maximum of 1% compared with G-RVG from medium to dense networks and RVG improves with increasing vehicle density. The DRG protocol gives a performance similar to G-RVG for delivery ratio in the close *proximity zone* but for the whole *broadcast zone* DRG gives the second worst performance. The poorest protocol performance is attributed to TRADE which gave the lowest delivery ratio. The poor performance of TRADE lies in the fact that only the *multipoint relay set* of neighbours forwards the message which means that in realistic environments, due to interference, some multipoint relay neighbours do not receive the broadcast packet and the broadcast forwarding prematurely terminates. None of the non multipoint relay neighbour nodes rebroadcast which means that no repetitions are attempted for unsuccessful links, unlike RVG, which uses non-MPR nodes to complement the broadcast process.



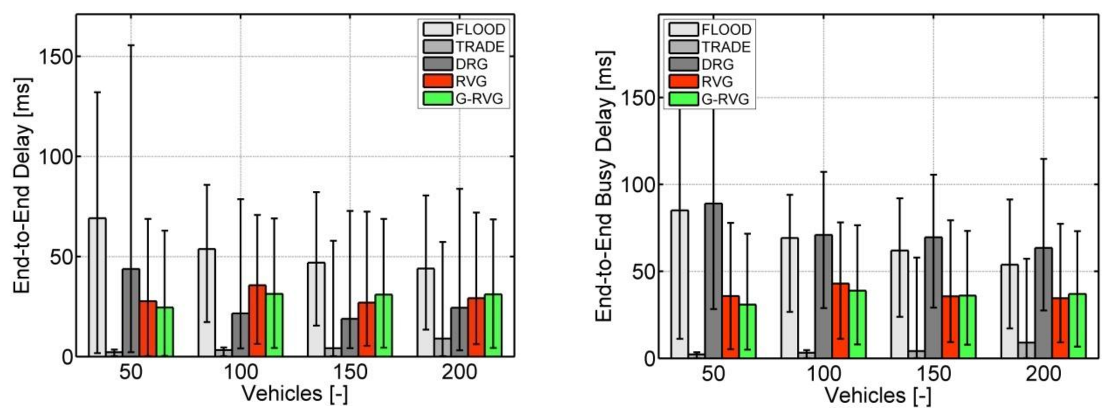
**a) Delivery Ratio in the *Broadcast Zone*** **b) Invoked broadcasts per second (all protocols)**



**c) Broadcast transmission ratio** **d) Transmissions per one broadcast**



**e) Broadcast transmissions per second** **f) Number of hops**



**g) End-to-end delay**

**h) End-to-end Busy delay**

**Fig. 5.4. Broadcast Protocol Performance in the Highway Free Flow Scenario**

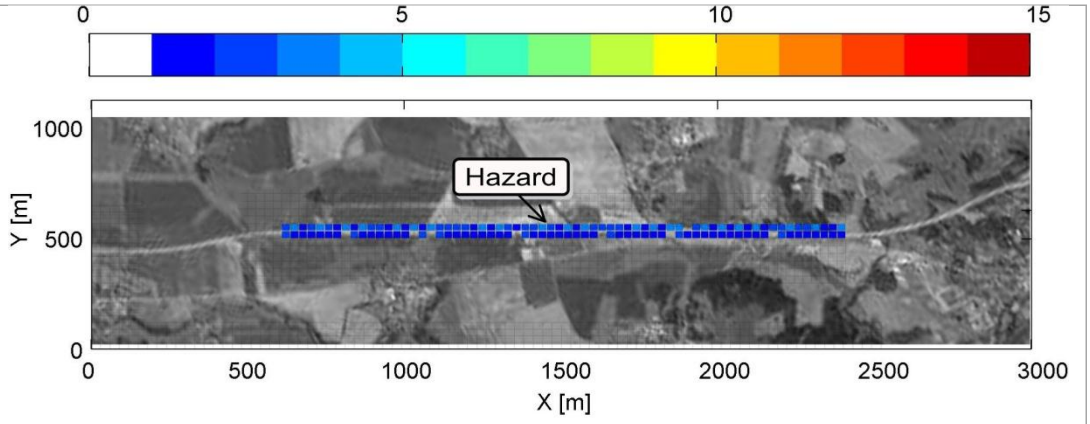
Table 5.1. Delivery ratio (Highway Free Flow Scenario)

| | ***Proximity Zone*** **(250m)** | | | | **500m zone** | | | |
|---|---|---|---|---|---|---|---|---|
| **Veh. density** | **50** | **100** | **150** | **200** | **50** | **100** | **150** | **200** |
| Flood | *0.90* | *1.00* | *1.00* | *0.99* | *0.86* | *1.00* | *1.00* | *0.99* |
| TRADE | *0.60* | *0.75* | *0.78* | *0.72* | *0.36* | *0.50* | *0.57* | *0.55* |
| DRG | *0.91* | *1.00* | *1.00* | *1.00* | *0.78* | *0.99* | *1.00* | *1.00* |
| RVG | *0.89* | *1.00* | *0.99* | *1.00* | *0.78* | *1.00* | *0.99* | *1.00* |
| G-RVG | *0.91* | *1.00* | *1.00* | *1.00* | *0.80* | *1.00* | *1.00* | *1.00* |
| *Achv. [%]* | *1.1* | *0.0* | *0.0* | *1.01* | *-7.0* | *0.0* | *0.0* | *1.0* |

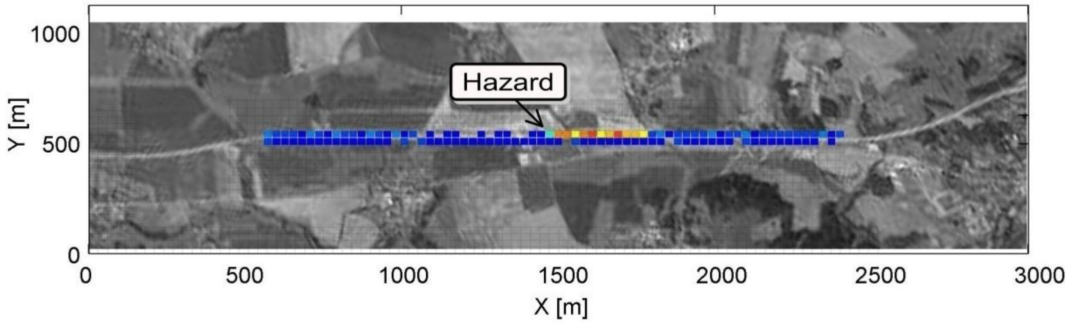
| | **750m zone** | | | | ***Broadcast Zone*** **(1000m)** | | | |
|---|---|---|---|---|---|---|---|---|
| **Veh. density** | **50** | **100** | **150** | **200** | **50** | **100** | **150** | **200** |
| Flood | 0.78 | 1.00 | 1.00 | 0.99 | 0.72 | 1.00 | 1.00 | 0.99 |
| TRADE | 0.25 | 0.36 | 0.43 | 0.43 | 0.19 | 0.28 | 0.35 | 0.36 |
| DRG | 0.70 | 0.98 | 0.99 | 1.00 | 0.62 | 0.97 | 0.99 | 1.00 |
| RVG | 0.71 | 1.00 | 0.99 | 1.00 | 0.65 | 0.99 | 0.99 | 1.00 |
| G-RVG | 0.75 | 1.00 | 1.00 | 1.00 | 0.72 | 1.00 | 1.00 | 1.00 |
| *Achv. [%]* | *-3.9* | *0.0* | *0.0* | *1.0* | *0.0* | *0.0* | *0.0* | *1.0* |

### *5.4.2 Highway Accident Scenario*

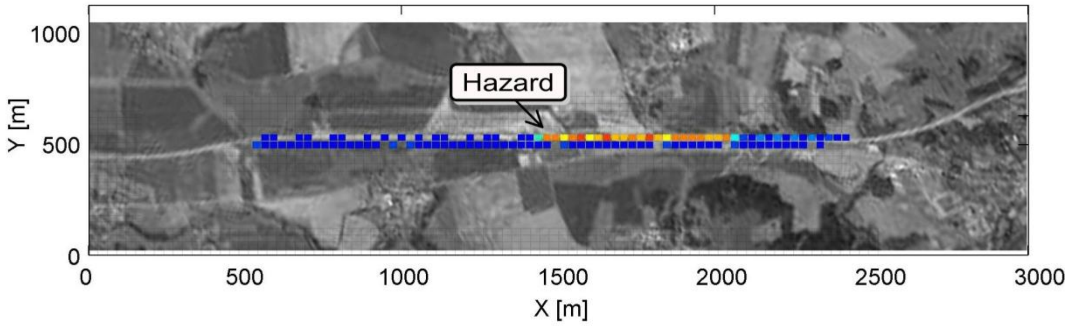
In the Highway Accident Scenario a traffic accident was simulated at peak time (x = 200vh/sc) of the Highway Free Flow Scenario. At the time the accident occurred the traffic jam grew rapidly and vehicles were forced to reduce speed and stop (Fig. 5.5). All vehicles that were in the *hazard zone* (within a radius of 100m from the centre of the accident position) invoked a safety broadcast every 1s, repetition rate is defined based on the safety warning and SOS applications outlined in Appendix A. Vehicles were required to disseminate safety messages in the *broadcast zone* with a radius of 1000m as they entered the *hazard zone*. The time intervals (0s, 70s, 140s and 210s) from the time that the accident occurred were chosen to capture distinct stages of traffic jam development i.e. from the time vehicles began to accumulate at the accident point up to increasing traffic jam length.



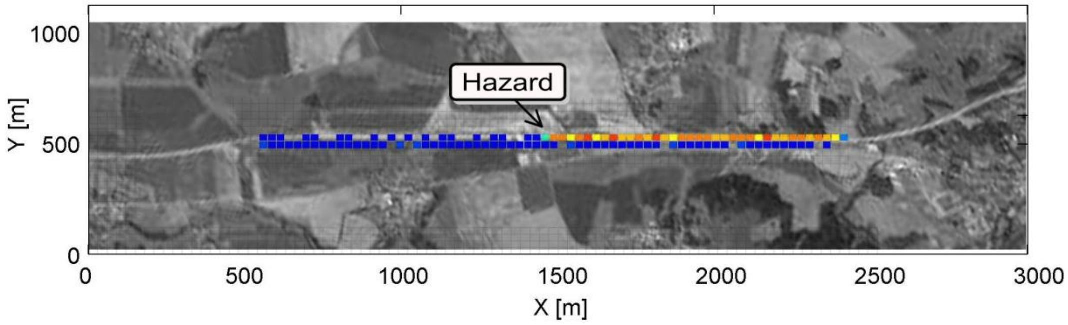
**a) 0s – time of accident**



**b) 70s after the accident occurs**



**c) 140s after the accident occurs**

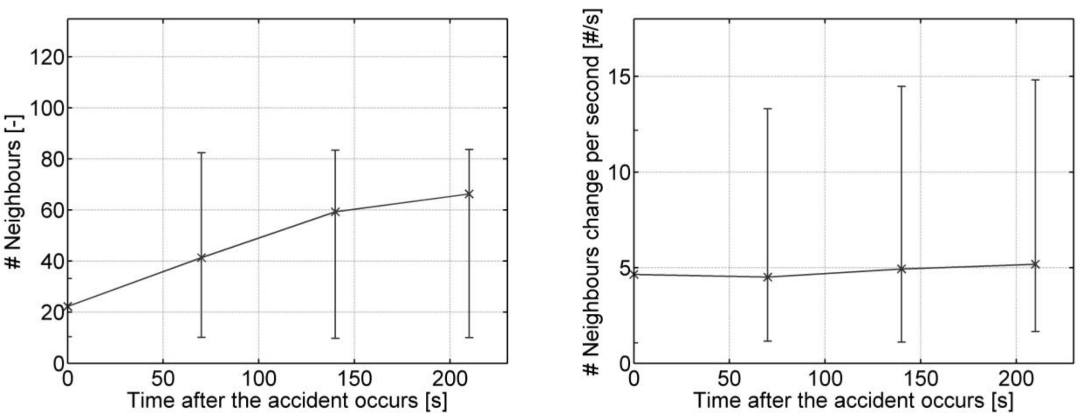


**d) 210s after the accident occurs**

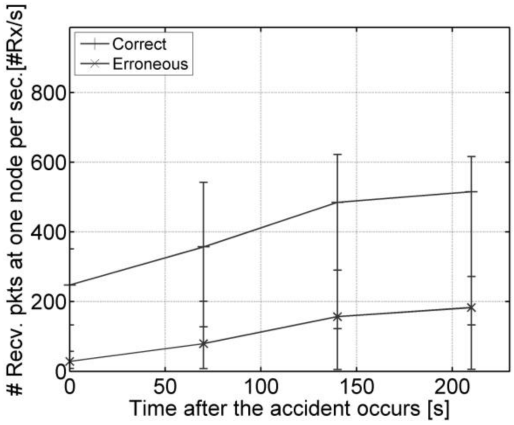
**Fig. 5.5. Highway Accident Scenario is represented by the same stretch of road network as used in the Highway Free Flow Scenario**

Shown in Fig. 5.6 is a contextual description of the network environment that was used to evaluate the broadcast protocols performance. At the beginning of the accident (time x = 0s), the network was well connected with a mean of 20 neighbours per node (Fig. 5.6a) with a rate of approximately 4 changes per second in the *broadcast table* (Fig. 5.6b). This corresponds to over 200 received packets per second with 20 erroneous packets that could not be further processed (Fig. 5.6c). As the traffic jam grew, the network became denser and the number of erroneous packets became higher (Fig. 5.6c) as more packets collided.

At the time the accident occurs (time x = 0s, Fig. 5.7), the network was well-connected and all protocols reached a delivery ratio in the *broadcast zone* (Fig. 5.7a, Table 5.2) of 100% except Flood which reached 99% and TRADE reaching 36%. As the network became more congested with the growing traffic jam, the delivery ratio (at x = 210s after the accident had occurred) slipped to 86% for Flood, 25% for TRADE, 92% for DRG, 98% for RVG and 99% for G-RVG. Furthermore, looking at the errors bars



**a) Number of neighbours** **b) Topological rate of change**



**c) Number of received packets**

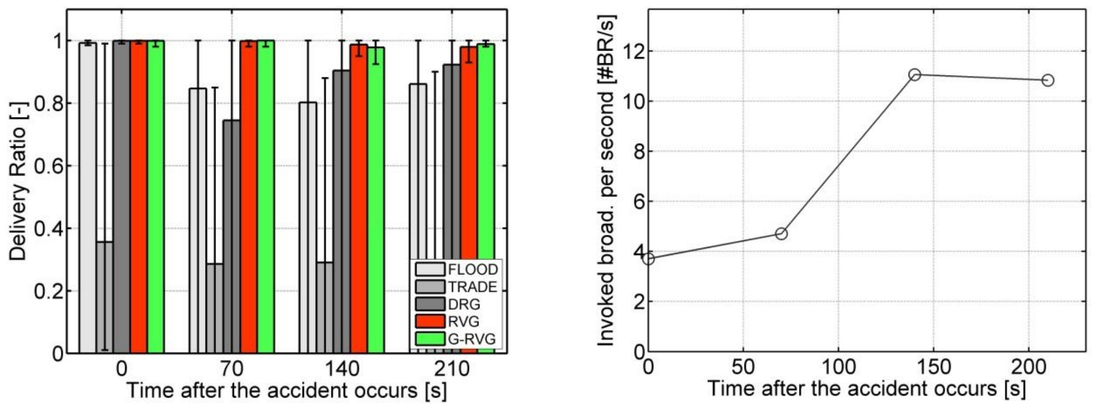
**Fig. 5.6. Network context in the Highway Accident Scenario**

(Fig. 5.7a) for Flood and DRG it can be seen that the values for delivery ratio are dispersed over the complete interval 0%-100% whereas for RVG and G-RVG 95% of the data lies between in the 93%-100% which indicates a much better performance for these protocols. The number of invoked broadcasts per second reached 4 broadcasts per second at the time the accident occurs (time x = 0s) and 11 broadcasts per second in a dense network (at x = 210s, Fig. 5.7b).

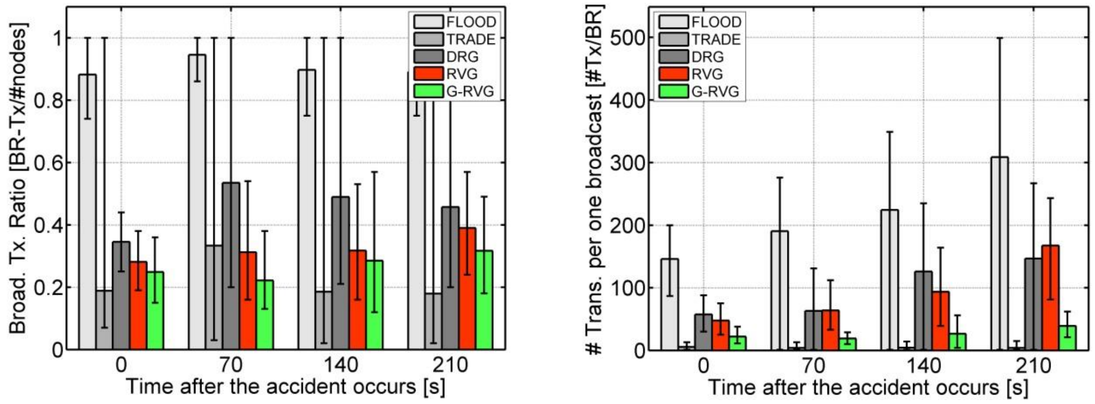
Again, all protocols kept an acceptable end-to-end delay (Fig. 5.7f, g) for services requiring a maximum delay of 1s however for services with maximum delay of 100ms only G-RVG satisfied the requirement across for medium to high density networks. The end-to-end delay (and likewise the end-to-end busy delay) for (G-)RVG in a dense network, as a consequence of traffic build-up due to the accident occurrence, is better than DRG as (G-)RVG uses slots to rebroadcast which lessens collisions and the need for repetitions.

The broadcast transmission ratio (Fig. 5.7c) was kept at around 90% by the Flood protocol while the other protocols reduced the number of transmissions in a dense network (at x = 210s) with values of: DRG 46%, RVG 41%, G-RVG 32% and TRADE 18% (due to *multipoint relaying* which leads to the very poor delivery ratio referred to above and likewise to results referred to below which on the surface appear to be best but again these mask the very meagre delivery ratio). The ratio had an effect on a number of transmissions per broadcast (Fig. 5.7d), where Flood had to transmit 310, TRADE 5, DRG 150, RVG 180 and G-RVG 40 packets in the last stage of the accident (x = 210s). This affects the number of broadcast transmissions per second where Flood transmitted 3400, TRADE 50, DRG 1600, RVG 2350 and G-RVG 400 packets (x = 210s) per second (Fig. 5.7e).

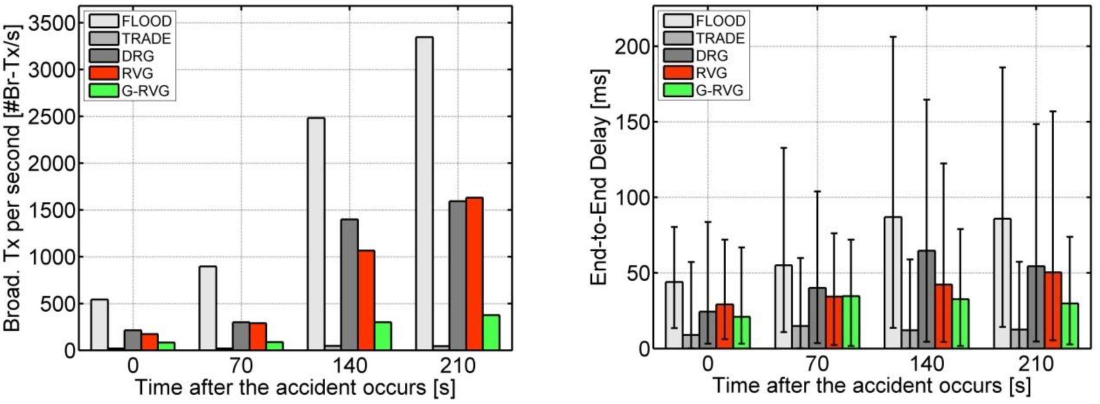
Overall the (G-)RVG protocol gave the best performance in terms of delivery ratio, end-to-end delay and reductions in redundant transmissions. Across the highway traffic jam development, RVG and G-RVG significantly outperform other protocols in terms of delivery ratio with improvements of up to 22% compared with Flood and up to 26% compared with DRG. At the beginning of the accident, RVG and G-RVG kept the delivery ratio at 100% in the *broadcast zone* as well as in *proximity zone*. When the traffic jam reached the maximum simulated length of 1000m, RVG and G-RVG resulted in drop off of only 2% for the maximum possible delivery ratio. In contrast, in the last stage of the accident, the Flood protocol achieved a delivery ratio of 86% and DRG 92%. Over all stages of the accident it is important to have a delivery ratio approaching 100% as in highway environments vehicles will be travelling at speeds likely in excess of 100km/h, so at the time the accident occurs it is important to warn all close proximity vehicles as the average distance between vehicles (see Table 4.2 in section 4.3.1) in the same lane for the Highway Free Flow scenario is 60m at the time of the accident which is much less than the stopping distance for vehicles - 110m at 120km/h under dry conditions and 180m for wet conditions [114].



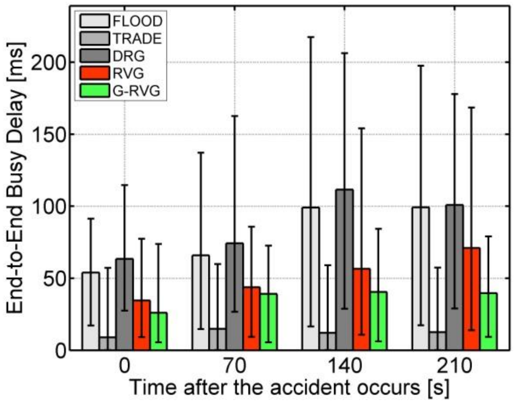
**a) Delivery Ratio in the *Broadcast Zone*** **b) Invoked broadcasts per second (all protocols)**



**c) Broadcast transmission ratio** **d) Transmissions per one broadcast**



**e) Broadcast transmissions per second** **f) End-to-end delay**



**g) End-to-end Busy delay**

**Fig. 5.7. Broadcast Protocol Performance in the Highway Accident Scenario**

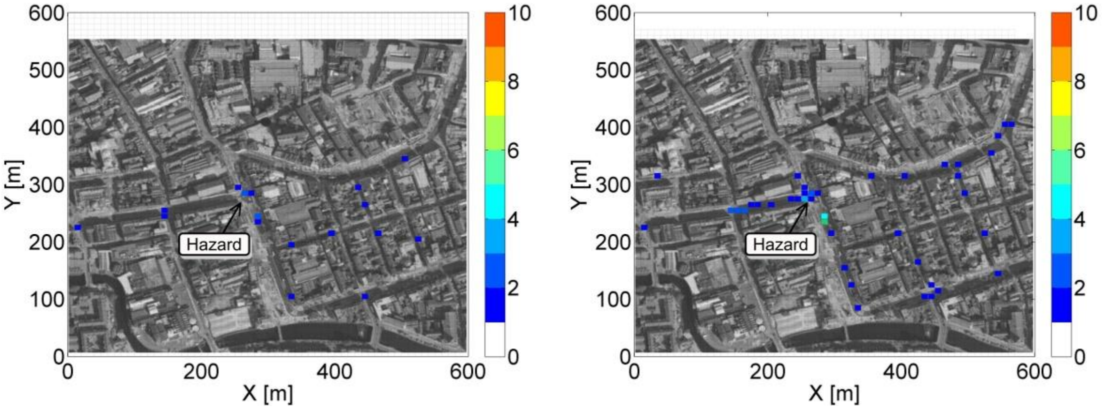
TABLE 5.2. DELIVERY RATIO (HIGHWAY ACCIDENT SCENARIO)

| | ***Proximity Zone* (250m)** | | | | **500m zone** | | | |
|---|---|---|---|---|---|---|---|---|
| **Time** | **0s** | **70s** | **140s** | **210s** | **0s** | **70s** | **140s** | **210s** |
| Flood | 0.99 | 0.85 | 0.83 | 0.88 | 0.99 | 0.84 | 0.81 | 0.87 |
| TRADE | 0.72 | 0.51 | 0.63 | 0.61 | 0.55 | 0.39 | 0.45 | 0.44 |
| DRG | 1.00 | 0.75 | 0.92 | 0.92 | 1.00 | 0.75 | 0.91 | 0.92 |
| RVG | 1.00 | 1.00 | 0.99 | 0.98 | 1.00 | 1.00 | 0.99 | 0.98 |
| G-RVG | 1.00 | 1.00 | 0.98 | 0.99 | 1.00 | 1.00 | 0.98 | 0.99 |
| *Achv. [%]* | *1.0* | *17.6* | *18.1* | *12.5* | *1.0* | *19.1* | *21* | *13.8* |

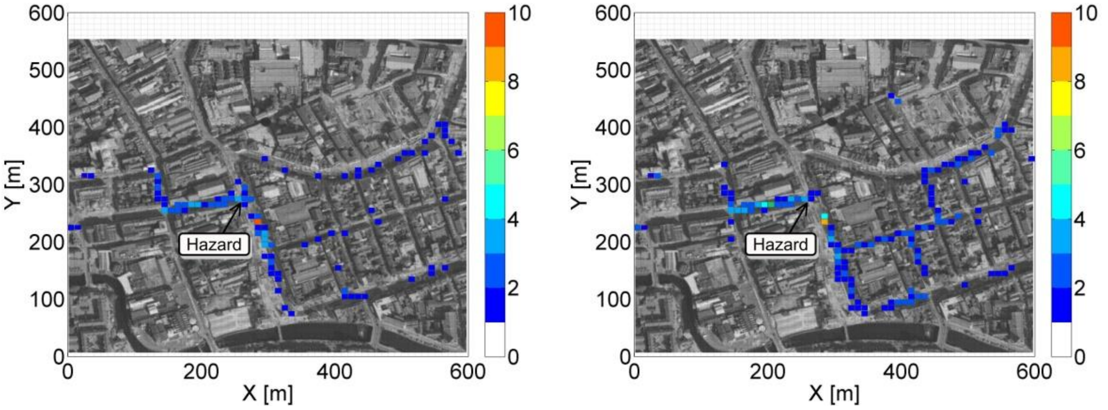
| | **750m zone** | | | | ***Broadcast Zone* (1000m)** | | | |
|---|---|---|---|---|---|---|---|---|
| **Time** | **0s** | **70s** | **140s** | **210s** | **0s** | **70s** | **140s** | **210s** |
| Flood | 0.99 | 0.85 | 0.80 | 0.86 | 0.99 | 0.85 | 0.80 | 0.86 |
| TRADE | 0.43 | 0.32 | 0.35 | 0.32 | 0.36 | 0.28 | 0.29 | 0.25 |
| DRG | 1.00 | 0.75 | 0.91 | 0.92 | 1.00 | 0.74 | 0.90 | 0.92 |
| RVG | 1.00 | 1.00 | 0.99 | 0.98 | 1.00 | 1.00 | 0.99 | 0.98 |
| G-RVG | 1.00 | 1.00 | 0.98 | 0.99 | 1.00 | 1.00 | 0.98 | 0.99 |
| *Achv. [%]* | *1.0* | *17.7* | *22.5* | *15.1* | *1.0* | *17.6* | *22.5* | *15.1* |

### *5.4.3 Urban Free Flow Scenario*

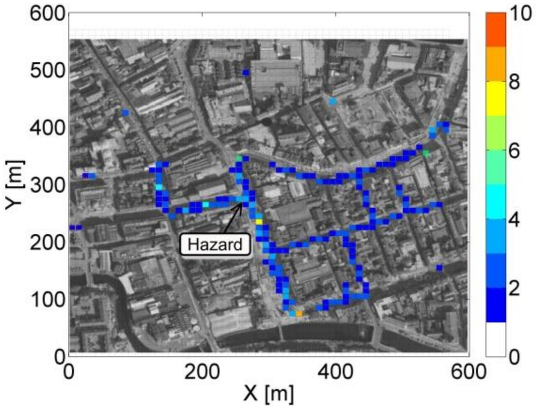
The Urban Free Flow Scenario (Fig. 5.8) represents traffic at night time with approximately 20 vehicles in the network up to a day time peak with 320 vehicles in the network with one *hazard zone* where vehicles within 50m of the hazard invoked a safety broadcast. Broadcasting should cover all nodes in the *broadcast zone* with a radius of 500m.



**a) Night time, approx. 20 vehicle per scenario** **b) Lower medium traffic, approx. 50 vehicles per scenario**

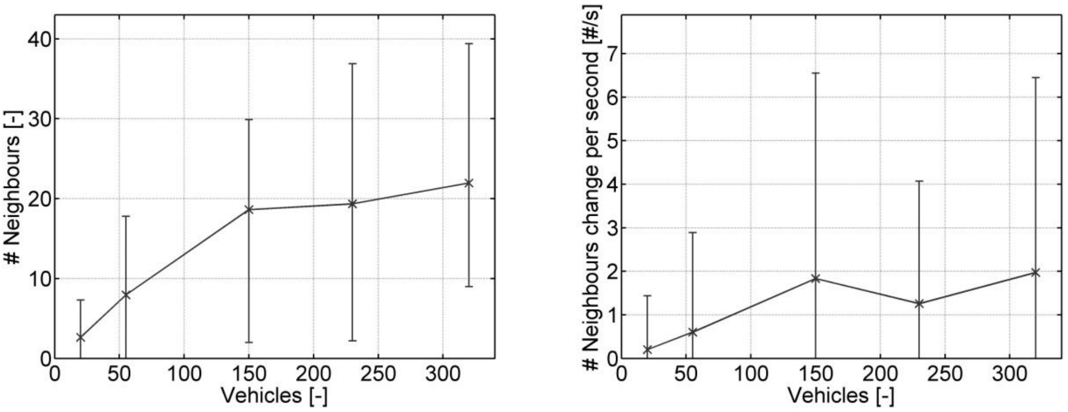


**c) Higher medium traffic, approx. 150 vehicles per scenario** **d) Lower peak time, approx. 230 vehicles per scenario**

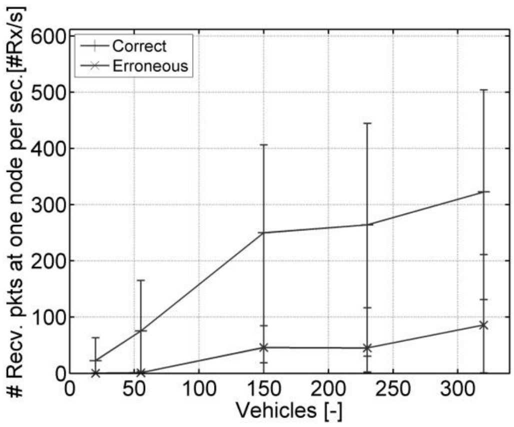


**e) Higher peak time, approx. 320 vehicles per scenario**

**Fig. 5.8. Urban Free Flow Scenario is represented by a real road network in Cork city with an area of 600m x 600m containing a mixture of signalled intersections and stop signs. The colour points in the map represent the number of vehicles in rectangular sections 10m x 10m**



**a) Number of neighbours** **b) Topological rate of change**



**c) Number of received packets**

**Fig. 5.9. Network context in the Urban Free Flow Scenario**

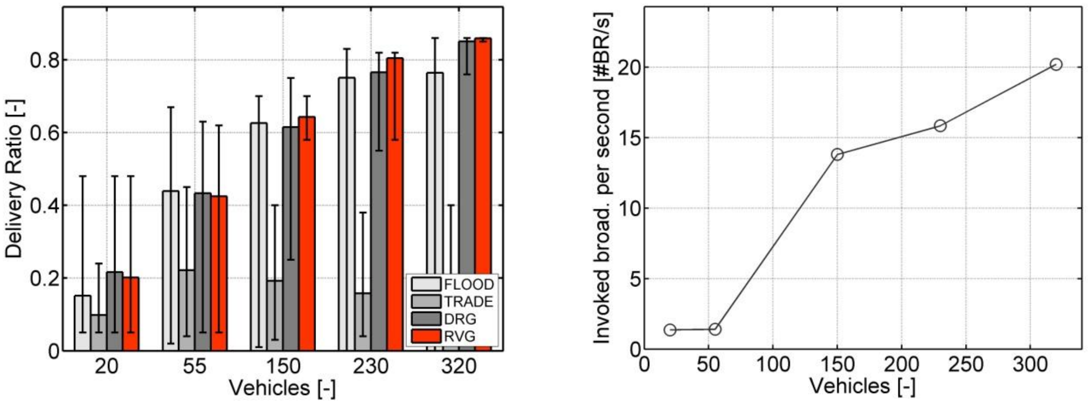
Shown in Fig. 5.9 is a contextual description of the network environment that was used to evaluate the broadcast protocols performance. At night time, the network was sparsely connected with a mean 3 neighbours at per node on average (Fig. 5.9a), with a small rate of change of 0.2 neighbours per second in the *broadcast table* (Fig. 5.9b). This corresponds with only 20 received packets per second with two erroneous packets (Fig. 5.9c). In higher density networks, the network became well connected with increased changes in the *broadcast table* as well as an increase in the number of received and erroneous packets per second.

At night time (x = 20 vehicles per scenario, vh/sc, Fig. 5.10a, Table 5.3) where the network was sparsely connected the delivery ratio (the *broadcast zone*) for the Flood protocol was 15%, TRADE 10%, DRG 22% and RVG 20% and the ratios gradually rose to values of: Flood 76%, TRADE 16%, DRG 85% and RVG 86% delivery in the *broadcast* *zone* (where x = 320vh/sc) in a busy network where the protocols had to disseminate messages over approximately 15 hops (Fig. 5.10f). The number of invoked broadcasts per second (vehicles in the *hazard zone*) reached approximately 1 broadcast per second at night time and 20 broadcasts per second at peak time (Fig. 5.10b).

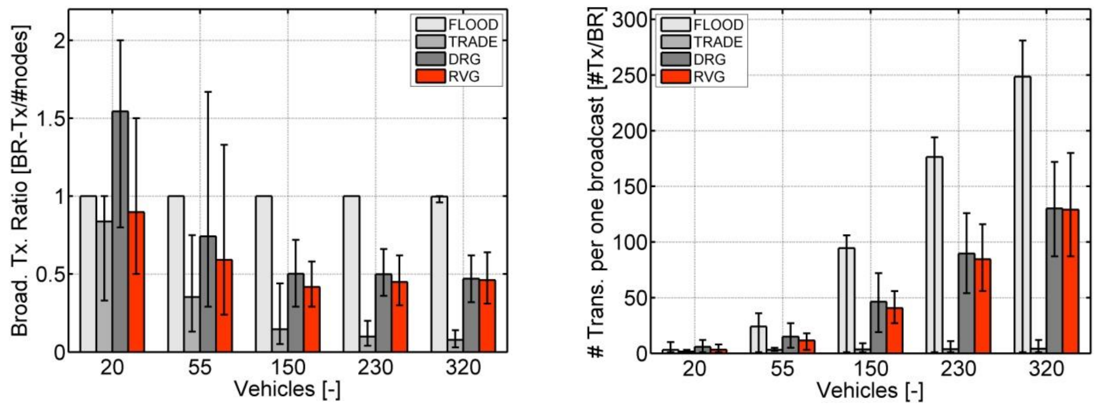
All protocols under test maintained an end-to-end delay (Fig. 5.10g, h) acceptable for safety message applications as the values are a fraction of driver reaction time that is approximately 750ms-2s as well being smaller than the delays demanded by the safety services in Appendix A. The end-to-end (busy) delay performance for both the free flow and accident scenarios in this environment is comparable, with RVG having a better end-to-end (busy) delay in comparison to DRG (again ignoring TRADE). In the Urban scenario the environment is cluttered (buildings, slow moving traffic, traffics signals etc.) irrespective of the traffic density which contributes to shorter transmission distance, increased packet losses and hence the need for repetitions of broadcasts. Because (G-)RVG uses slots to rebroadcast unlike DRG it has improved end-to-end (busy) delay as collisions are less likely.

The broadcast transmission ratio (Fig. 5.10c) was kept constant at 100% by the Flood protocol while the other protocols significantly reduced the number of transmissions in a well-connected network (x = 320vh/sc) with ratios of: DRG 47%, RVG 46% and TRADE 8%. Again TRADE achieved the lowest value because of the *multipoint relaying* scheme. In a low density network (x = 20vh/sc) DRG and RVG reached a higher ratio than Flood due to packet repetitions that helped DRG to reach the highest delivery ratio in the lowest density network. DRG uses a maximum of 5 repetitions at each node while RVG uses a maximum of 2 repetitions only at forwarders (MPR nodes). In the densest network (x = 320vh/sc), the number of broadcast transmissions per second across the network for Flood reached 5000, TRADE 50, DRG 2400 and RVG 2600 packet transmissions per second (Fig. 5.10e) and for the number of transmissions per one broadcast process (Fig. 5.10d) the number of packets that needed to be transmitted were: Flood 250, TRADE 10, DRG 130 and RVG 130 packets.

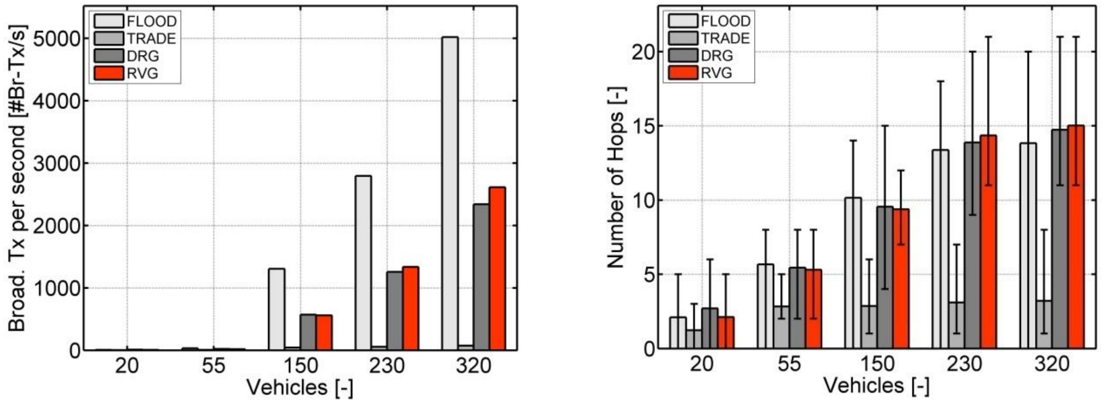
The RVG protocol did not outperform the other protocols in terms of delivery ratio in the lowest density network for the whole *broadcast zone* but on the other hand this result is not crucial from the viewpoint of safety dissemination. For example in low density networks, drivers usually have long distances between each other and have sufficient time to react and avoid an accident. Furthermore in low density networks, broadcasting a message over long distances is not safety critical but more informative as drivers are spread far from the hazard. What is crucial from a safety perspective in low density networks is to warn close proximity drivers (*proximity zone*). From this viewpoint, RVG significantly surpasses the other protocols under test giving improvements of up to 135% compared with Flood. RVG maintained the best delivery ratio in the *proximity zone* across all densities. As the traffic becomes denser, the delivery ratio for the whole *broadcast zone* becomes a more crucial parameter for safety dissemination; here RVG achieved the best delivery ratio for the *broadcast zone* and again outperformed other protocols with achievements of up to 33% compared with Flood.



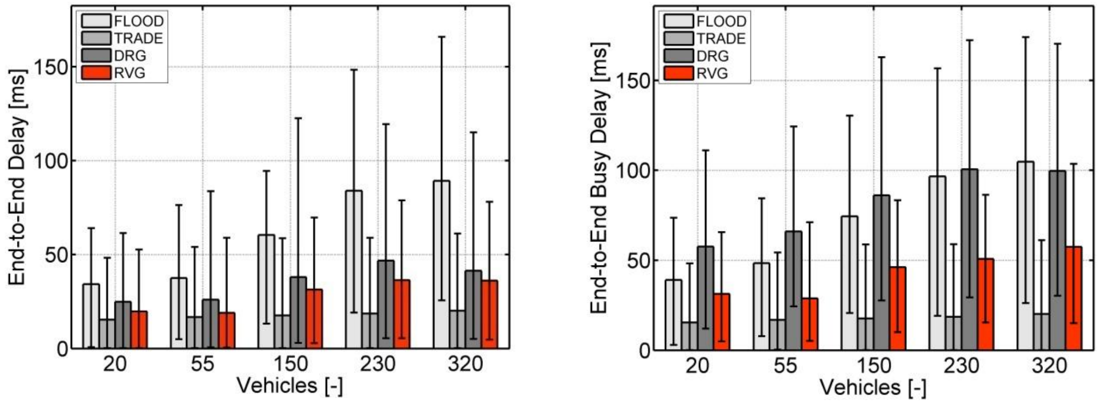
**a) Delivery Ratio in the *Broadcast Zone*** **b) Invoked broadcasts per second (all protocols)**



**c) Broadcast transmission ratio** **d) Transmissions per one broadcast**



**e) Broadcast transmissions per second** **f) Number of hops**



**g) End-to-end delay** **h) End-to-end Busy delay**

Fig. 5.10. Broadcast Protocol Performance in the Urban Free Flow Scenario

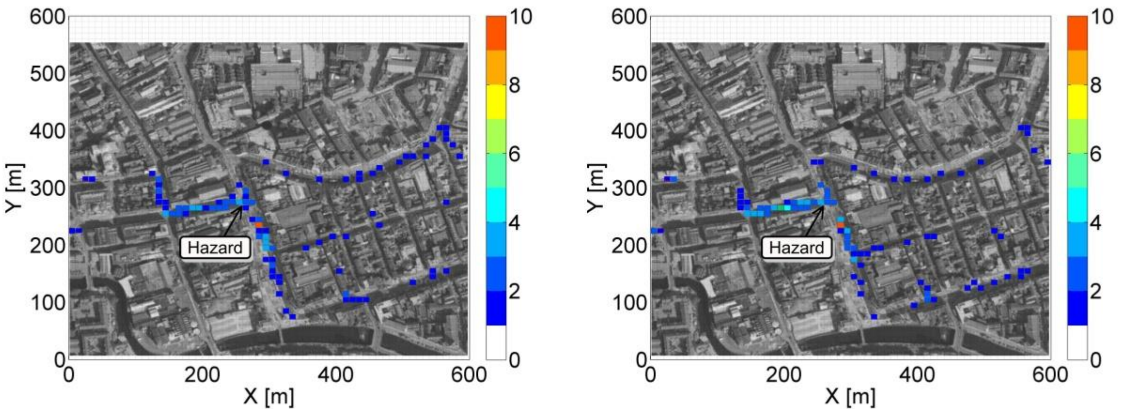
TABLE 5.3. DELIVERY RATIO (URBAN FREE FLOW SCENARIO)

| | ***Proximity Zone*** **(125m)** | | | | | **250m zone** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Veh. density** | **20** | **55** | **150** | **230** | **320** | **20** | **55** | **150** | **230** | **320** |
| Flood | 0.17 | 0.49 | 0.92 | 0.92 | 0.89 | 0.15 | 0.44 | 0.80 | 0.90 | 0.89 |
| TRADE | 0.11 | 0.24 | 0.43 | 0.21 | 0.21 | 0.10 | 0.22 | 0.25 | 0.16 | 0.16 |
| DRG | 0.24 | 0.48 | 0.90 | 0.92 | 0.99 | 0.22 | 0.43 | 0.78 | 0.77 | 0.85 |
| RVG | 0.40 | 0.74 | 0.95 | 0.99 | 1.00 | 0.22 | 0.47 | 0.82 | 0.96 | 1.00 |
| *Achv. [%]* | *135* | *51.0* | *3.3* | *7.6* | *12.4* | *46.7* | *6.8* | *2.5* | *6.7* | *12.4* |

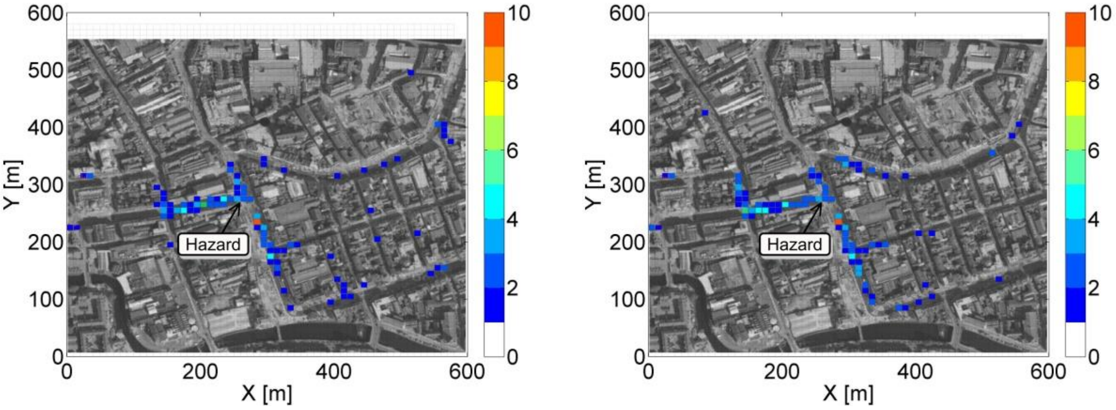
| | **375m zone** | | | | | ***Broadcast Zone*** **(500m)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Veh. density** | **20** | **55** | **150** | **230** | **320** | **20** | **55** | **150** | **230** | **320** |
| Flood | 0.15 | 0.44 | 0.63 | 0.75 | 0.76 | 0.15 | 0.44 | 0.63 | 0.75 | 0.76 |
| TRADE | 0.10 | 0.22 | 0.19 | 0.16 | 0.16 | 0.10 | 0.22 | 0.19 | 0.16 | 0.16 |
| DRG | 0.22 | 0.43 | 0.62 | 0.77 | 0.85 | 0.22 | 0.43 | 0.62 | 0.77 | 0.85 |
| RVG | 0.20 | 0.43 | 0.64 | 0.80 | 0.86 | 0.20 | 0.43 | 0.64 | 0.80 | 0.86 |
| *Achv. [%]* | *33.3* | *-2.3* | *1.6* | *6.7* | *13.2* | *33.3* | *-2.3* | *1.6* | *6.7* | *13.1* |

### 5.4.4 Urban Accident Scenario

In this scenario a traffic jam built up is considered as a consequence of a traffic accident occurring at a crossroads in a medium busy road network (x = 150vh/sc) that stopped all traffic. At the time the accident occurred the traffic jam grew rapidly and vehicles were forced to reduce their speed and stop (Fig. 5.11). All vehicles that were in the *hazard zone* (as in the Highway Accident Scenario) invoked safety broadcast every 1s. The broadcast protocols were required to disseminate safety messages over a *broadcast zone* with a radius of 500m as the vehicles enter the *hazard zone*, defined as being within a radius of 50m of the hazard.

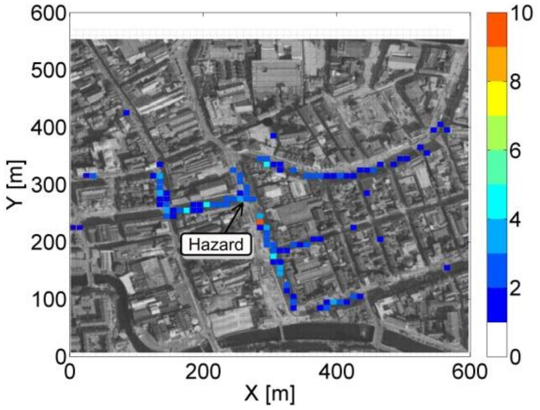


**a) 0s – time of accident** **b) 30s after the accident occurs**



c) 60s after the accident occurs

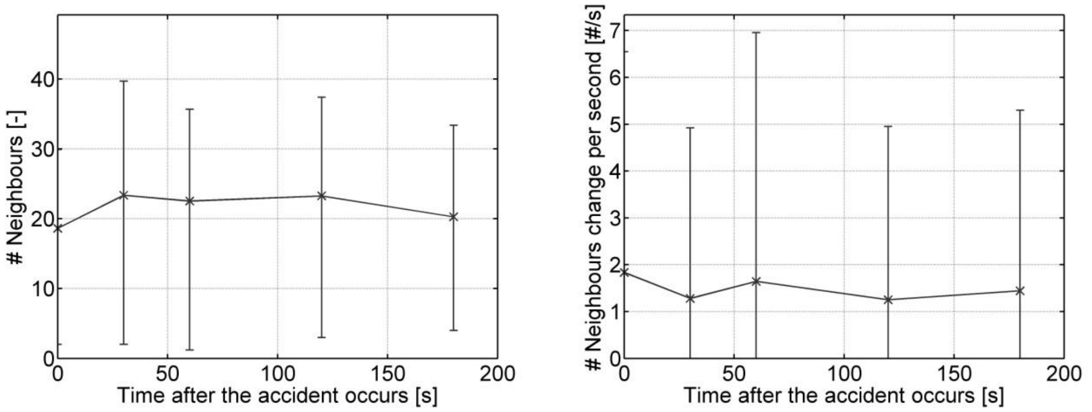
d) 120s after the accident occurs



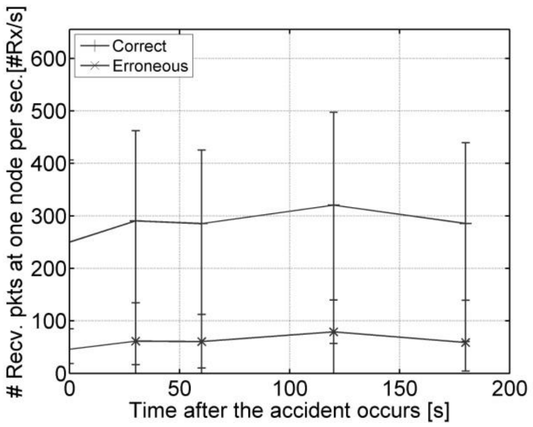
e) 180s after the accident occurs

**Fig. 5.11. Urban Accident Scenario is represented by the same stretch of road network as used in the Urban Free Flow Scenario**

Shown in Fig. 5.12 is a contextual description of the network environment that was used to evaluate the broadcast protocols performance. At the time an accident occurs, the network was well connected with a mean of 19 neighbours per node (Fig. 5.12a), with a rate of ca. 1.5 changes per a second in the *broadcast table* (Fig. 5.12b). A mean of 250 packets per second were correctly received while 50 packets were received erroneous and could not be further processed (Fig. 5.12c). In all stages of the accident development (traffic build-up as a consequence of the accident occurring), the networks were well connected with a similar number of neighbours, changes in the *broadcast table* and the numbers of received and erroneous packets.



**a) Number of neighbours** **b) Topological rate of change**



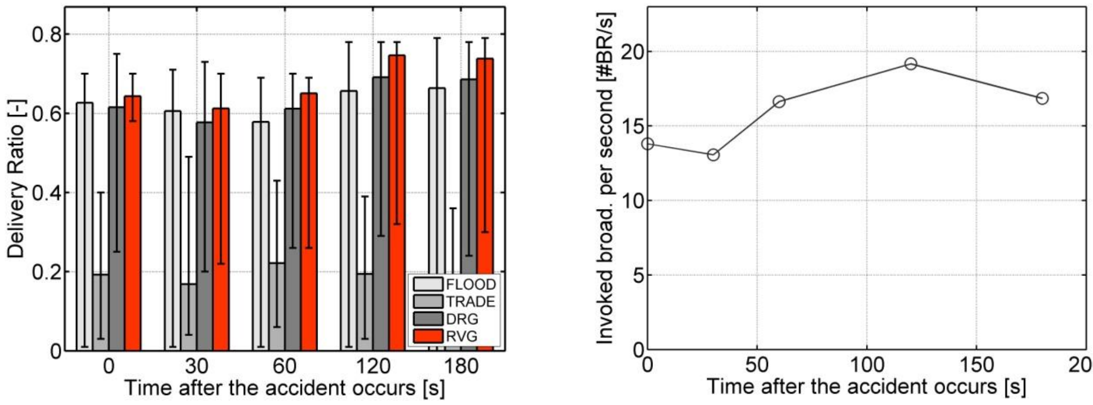
**c) Number of received packets**

**Fig. 5.12. Network context in the Urban Accident Scenario**

At the beginning of the accident (time x = 0s Fig. 5.13a, Table 5.4) where the network was well-connected the delivery ratio (in the *broadcast zone*) of the Flood protocol reached 63%, TRADE 19%, DRG 62% and RVG 64%; this grew to values of: Flood 66%, TRADE 17%, DRG 69% and RVG 74% delivery at the end of simulated time (x = 180s, time after the accident occurs). Delivery ratio in the *proximity zone* (up to 125m distance, Table 5.4) reached values of: Flood 86%, TRADE 45%, DRG 94% and RVG 98% in the last stage of the accident (x = 180s). The number of invoked broadcasts per second was kept in the region of 13-20 broadcasts per second (Fig. 5.13b).

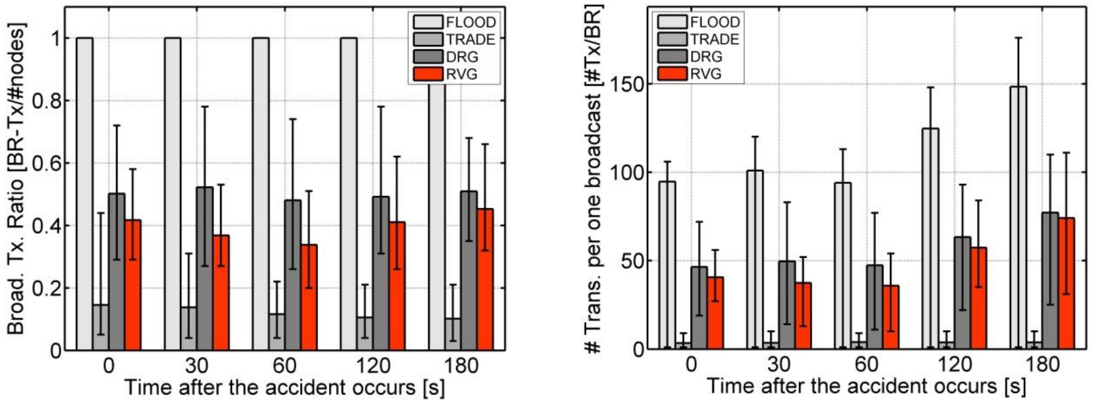
Similar to the previous scenarios, all protocols under test kept end-to-end delay (Fig. 5.13f, g) acceptable for safety data dissemination as the values are a fraction of driver reaction time that is approximately 750ms-2s as well being smaller than the delays demanded by the safety services in Appendix A. The broadcast transmission ratio (Fig. 5.13c) was kept constant at 100% by the Flood protocol while the other protocols reduced the number of transmissions e.g. with ratios of: DRG 51%, RVG 45% and TRADE 10% in the last stage of the accident (x = 180s). The ratio had an effect on the number of transmissions per broadcast (Fig. 5.13d) where Flood had to transmit 150, TRADE 5, DRG 75 and RVG 72 packets (x = 180s). This affects the number of broadcast transmissions per second where Flood transmitted 2500, TRADE 50, DRG 1350 and RVG 1300 packets (x = 180s) per second (Fig. 5.13e).

The RVG protocol outperforms other protocols by keeping the best delivery ratio across the urban jam scenario with improvements of up to 14% compared with Flood. When the accident occurred (x = 0s), RVG was able to deliver packets to 95% of nodes in the *proximity zone* (Flood 92%, DRG 90%) and to 64% of nodes in the *broadcast zone* (Flood 63%, DRG 62%). Across the urban traffic jam scenario, RVG kept the end-to-end delay to approximately 50% of the Flood protocol and in the region of 10%-40% below that of DRG, highlighting RVG as the more suitable dissemination mechanism for the most demanding safety services described in Appendix A (e.g. Emergency Electronic Brake Lights, Wrong Way Driver Warning).

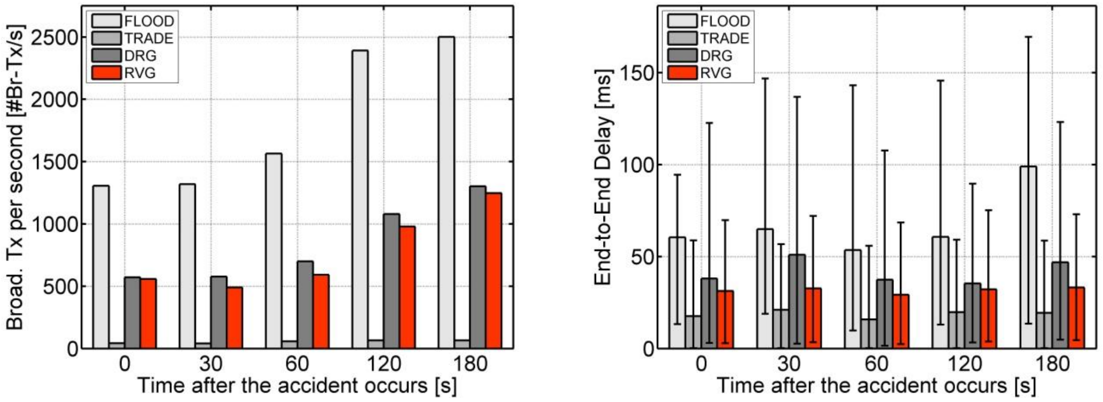


**a) Delivery Ratio in the *Broadcast Zone***

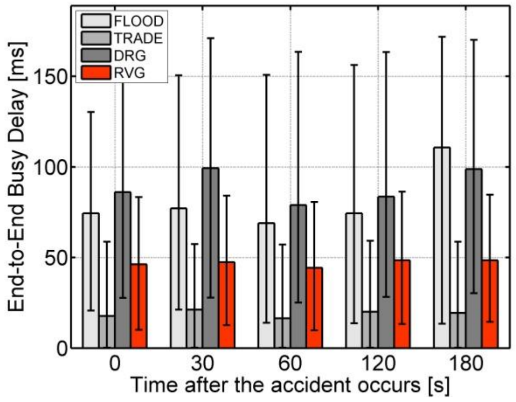
**b) Invoked broadcasts per second (all protocols)**



**c) Broadcast transmission ratio** **d) Transmissions per one broadcast**



**e) Broadcast transmissions per second** **f) End-to-end delay**



**g) End-to-end Busy delay**

**Fig. 5.13. Broadcast Protocol Performance in the Urban Accident Scenario**

TABLE 5.4. DELIVERY RATIO (URBAN ACCIDENT SCENARIO)

| | *Proximity Zone* (125m) | | | | | 250m zone | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time** | **0s** | **30s** | **60s** | **120s** | **180s** | **0s** | **30s** | **60s** | **120s** | **180s** |
| Flood | 0.92 | 0.86 | 0.81 | 0.86 | 0.86 | 0.80 | 0.78 | 0.74 | 0.84 | 0.84 |
| TRADE | 0.43 | 0.39 | 0.51 | 0.47 | 0.45 | 0.25 | 0.22 | 0.28 | 0.25 | 0.22 |
| DRG | 0.90 | 0.85 | 0.89 | 0.94 | 0.94 | 0.78 | 0.74 | 0.78 | 0.88 | 0.87 |
| RVG | 0.95 | 0.88 | 0.92 | 0.98 | 0.98 | 0.82 | 0.79 | 0.83 | 0.95 | 0.93 |
| *Achv. [%]* | *3.3* | *2.3* | *13.6* | *14.0* | *14.0* | *2.5* | *1.3* | *12.2* | *13.1* | *10.7* |

| | 375m zone | | | | | *Broadcast Zone* (500m) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time** | **0s** | **30s** | **60s** | **120s** | **180s** | **0s** | **30s** | **60s** | **120s** | **180s** |
| Flood | 0.63 | 0.61 | 0.58 | 0.66 | 0.66 | 0.63 | 0.61 | 0.58 | 0.66 | 0.66 |
| TRADE | 0.19 | 0.17 | 0.22 | 0.19 | 0.17 | 0.19 | 0.17 | 0.22 | 0.19 | 0.17 |
| DRG | 0.62 | 0.58 | 0.61 | 0.69 | 0.69 | 0.62 | 0.58 | 0.61 | 0.69 | 0.69 |
| RVG | 0.64 | 0.61 | 0.65 | 0.75 | 0.74 | 0.64 | 0.61 | 0.65 | 0.75 | 0.74 |
| *Achv. [%]* | *1.6* | *0.0* | *12.1* | *13.6* | *12.1* | *1.6* | *0.0* | *12.1* | *13.6* | *12.1* |

### 5.4.5 Summary of Highway & Urban Scenario Performance Evaluations

Highlighted in Table 5.5, Table 5.6 and Table 5.7 are the primary metrics from the viewpoint of safety data dissemination where the results demonstrate the performance achievement and reflect on how RVG (G-RVG) compares against the baseline protocol – the Simple Flood protocol. The percentage achievements can mean that RVG performs better or worse as the case may be.

TABLE 5.5. DELIVERY RATIO IN THE *BROADCAST ZONE*

| **High. Scen.** | **Free Flow** | | | | **Accident** | | | |
|---|---|---|---|---|---|---|---|---|
| **Time (veh. density)** | **- (50)** | **- (100)** | **- (150)** | **- (200)** | **0s (200)** | **70s (300)** | **140s (400)** | **210s (500)** |
| Flood | 0.72 | 1.00 | 1.00 | 0.99 | 0.99 | 0.85 | 0.80 | 0.86 |
| TRADE | 0.19 | 0.28 | 0.35 | 0.36 | 0.36 | 0.28 | 0.29 | 0.25 |
| DRG | 0.62 | 0.97 | 0.99 | 1.00 | 1.00 | 0.74 | 0.90 | 0.92 |
| RVG | 0.65 | 0.99 | 0.99 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| G-RVG | 0.72 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.99 |
| *Achv. [%]* | *0* | *0* | *0* | *1* | *1* | *18* | *22* | *15* |

| **Urban Scen.** | **Free Flow** | | | | | **Accident** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time (veh. density)** | **- (20)** | **- (55)** | **- (150)** | **- (230)** | **- (320)** | **0s (150)** | **30s (160)** | **60s (170)** | **120s (190)** | **180s (220)** |
| Flood | 0.15 | 0.44 | 0.63 | 0.75 | 0.76 | 0.63 | 0.61 | 0.58 | 0.66 | 0.66 |
| TRADE | 0.10 | 0.22 | 0.19 | 0.16 | 0.16 | 0.19 | 0.17 | 0.22 | 0.19 | 0.17 |
| DRG | 0.22 | 0.43 | 0.62 | 0.77 | 0.85 | 0.62 | 0.58 | 0.61 | 0.69 | 0.69 |
| RVG | 0.20 | 0.43 | 0.64 | 0.80 | 0.86 | 0.64 | 0.61 | 0.65 | 0.75 | 0.74 |
| *Achv. [%]* | *33* | *-2* | *2* | *7* | *13* | *2* | *0* | *12* | *14* | *12* |

TABLE 5.6. DELIVERY RATIO IN THE *PROXIMITY ZONE*

| **High. Scen. zone = 250m** | **Free Flow** | | | | **Accident** | | | |
|---|---|---|---|---|---|---|---|---|
| **Time (veh. density)** | **- (50)** | **- (100)** | **- (150)** | **- (200)** | **0s (200)** | **70s (300)** | **140s (400)** | **210s (500)** |
| Flood | 0.90 | 1.00 | 1.00 | 0.99 | 0.99 | 0.85 | 0.83 | 0.88 |
| TRADE | 0.60 | 0.75 | 0.78 | 0.72 | 0.72 | 0.51 | 0.63 | 0.61 |
| DRG | 0.91 | 1.00 | 1.00 | 1.00 | 1.00 | 0.75 | 0.92 | 0.92 |
| RVG | 0.89 | 1.00 | 0.99 | 1.00 | 1.00 | 1.00 | 0.99 | 0.98 |
| G-RVG | 0.91 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 0.98 | 0.99 |
| *Achv. [%]* | *1* | *0* | *0* | *1* | *1* | *18* | *18* | *13* |

| **Urban Scen. zone = 125m** | **Free Flow** | | | | | **Accident** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time (veh. density)** | **- (20)** | **- (55)** | **- (150)** | **- (230)** | **- (320)** | **0s (150)** | **30s (160)** | **60s (170)** | **120s (190)** | **180s (220)** |
| Flood | 0.17 | 0.49 | 0.92 | 0.92 | 0.89 | 0.92 | 0.86 | 0.81 | 0.86 | 0.86 |
| TRADE | 0.11 | 0.24 | 0.43 | 0.21 | 0.21 | 0.43 | 0.39 | 0.51 | 0.47 | 0.45 |
| DRG | 0.24 | 0.48 | 0.90 | 0.92 | 0.99 | 0.90 | 0.85 | 0.89 | 0.94 | 0.94 |
| RVG | 0.40 | 0.74 | 0.95 | 0.99 | 1.00 | 0.95 | 0.88 | 0.92 | 0.98 | 0.98 |
| *Achv. [%]* | *135* | *51* | *3* | *8* | *12* | *3* | *2* | *14* | *14* | *14* |

TABLE 5.7. END-TO-END DELAY [MS]

| **High. Scen.** | **Free Flow** | | | | **Accident** | | | |
|---|---|---|---|---|---|---|---|---|
| **Time (veh. density)** | **- (50)** | **- (100)** | **- (150)** | **- (200)** | **0s (200)** | **70s (300)** | **140s (400)** | **210s (500)** |
| Flood | 78.50 | 53.69 | 46.92 | 43.94 | 43.94 | 55.08 | 86.94 | 85.92 |
| DRG | 42.55 | 21.50 | 18.80 | 24.37 | 24.37 | 40.14 | 64.73 | 54.40 |
| RVG | 24.60 | 35.61 | 26.96 | 29.18 | 29.18 | 34.35 | 42.35 | 50.29 |
| G-RVG | 26.15 | 31.34 | 30.89 | 31.09 | 20.87 | 34.58 | 32.67 | 29.99 |
| *Achv. [%]* | *66* | *41* | *34* | *29* | *52* | *37* | *62* | *65* |

| **Urban Scen.** | **Free Flow** | | | | | **Accident** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Time (veh. density)** | **- (20)** | **- (55)** | **- (150)** | **- (230)** | **- (320)** | **0s (150)** | **30s (160)** | **60s (170)** | **120s (190)** | **180s (220)** |
| Flood | 34.2 | 37.5 | 60.4 | 83.9 | 89.2 | 60.4 | 64.9 | 53.6 | 60.7 | 99.0 |
| DRG | 24.8 | 26.0 | 38.0 | 46.8 | 41.3 | 38.0 | 51.0 | 37.4 | 35.4 | 46.9 |
| RVG | 19.8 | 18.9 | 31.3 | 36.3 | 36.1 | 31.3 | 32.7 | 29.2 | 32.1 | 33.1 |
| *Achv. [%]* | *42* | *49* | *48* | *56* | *59* | *48* | *49* | *45* | *47* | *66* |

A high delivery ratio over the whole geographic target area is not always a crucial parameter from the perspective of safety dissemination. For example in low density networks, drivers usually have long distances between each other and have sufficient time to react and avoid an accident. Furthermore in low density networks, broadcasting a message over long distances is not safety critical but more informative as drivers are spread far from the hazard. What is crucial from a safety perspective in low density networks is the first stage of traffic accident where it is essential that close proximity vehicles (*proximity zone*) are warned. RVG and G-RVG (geo-cast RVG) protocols outperform the other protocols tested, giving the best delivery ratio for close proximity vehicles in all networks, scenarios and environments. The performance difference between RVG (G-RVG) and e.g. the Simple Flood protocol reached up to 135% in urban and 18% in highway scenarios.

As the traffic becomes denser or traffic jams get longer the delivery ratio for the *broadcast zone* becomes a more crucial parameter for safety dissemination. Consider the example of a highway where an accident occurs and a traffic jam grows. Vehicles in the traffic jam have come to a stop but vehicles approaching the edge of the traffic jam must be warned so that they can start decelerating their vehicles. It is essential to deliver warnings to these vehicles on the edge of the traffic jam. From this analysis perspective, RVG and G-RVG gave the best delivery ratio across all stages of the traffic jam in highway and urban environments as they were able to deliver the warnings to the edge of the jam with high reliability. The performance difference between RVG (G-RVG) and the other protocols considered increased with traffic jam build up, with the largest difference reaching 33% in urban and 22% in highway scenarios between RVG (G-RVG) and the Simple Flood protocol.

The next crucial parameter from the viewpoint of safety dissemination is end-to-end delay. From the results presented it can be concluded that all protocols reached acceptable end-to-end delay for services that require a maximum delay of 1s (e.g. SOS Services). The end-to-end delay for all protocols (except (G-)RVG which uses slots) was positively impacted through the use of the $T_{WL}$ wait interval which was used to further randomise channel access times with a view to supporting collision free transmissions thereby maintaining low end-to-end delays for broadcast processes. However, the Simple Flood protocol experienced the longest delay in all scenarios and was approximately two times that of the proposed (G-)RVG protocol. The DRG protocol achieved a shorter delay than Simple Flood but generally had a longer delay (except in the Highway Free Flow Scenario) than the (G-)RVG protocol with a deterioration reaching tens of percent. For most scenarios RVG maintained the shortest delay which satisfies the most delay demanding safety services described in Appendix A (e.g. Emergency Electronic Brake Lights, Wrong Way Driver Warning ) with a maximum allowed delay of 100ms. The deviation of the end-to-end delay and delivery ratio statistics across all scenarios is much smaller for the proposed RVG and G-RVG protocols compared to the DRG, Flood and TRADE protocols. The 95% quantile of the sampled statistics for RVG and G-RVG lie much closer around the mean value than for the other three protocols as (G-)RVG uses slotted access which supports collision free transmissions and keeps end-to-end delays similar for each broadcast process

1) **Simple Flood** - While the Simple Flood protocol is effective in guaranteeing a high delivery ratio in medium density networks for low and high density networks it has a significantly worse delivery ratio compared with the other protocols. Simple Flooding does not contain an algorithm for repeating transmissions for those broadcasts that are unsuccessful over unstable and unreliable links. Consequently in low density, sparsely connected networks where nodes attempt to communicate over distant links the dissemination prematurely ends and packet delivery drops. For example in the urban environment the results showed that the delivery ratio in the *broadcast zone* for Simple Flood fell by 30% and in the *proximity zone* it fell by 57% compared with RVG. In high density networks, Simple Flooding does not contain an algorithm for reducing redundant transmissions which causes the protocol to over saturate the physical medium with a high number of transmissions. As the network is oversaturated, transmissions collide and dissemination terminates prematurely. Results showed that in all high density networks that the Simple Flood protocol has a significantly worse delivery ratio compared with RVG with a difference of up to 22%.
2) **TRADE** - The TRADE protocol resulted in the poorest delivery ratio across all scenarios and is unacceptable for safety application dissemination.
3) **DRG** - In contrast to Simple Flooding, DRG does repeat unsuccessful transmissions and also reduces redundancy. The results showed that DRG

achieved the highest delivery ratio in a low density urban scenario but on the other hand DRG achieved the worst delivery ratio in the low density highway scenario. In highway scenarios DRG achieved a poorer delivery ratio than the Simple Flood and RVG protocols with differences of up to 14% for Simple Flood and 16% for RVG. Results indicate that the DRG protocol does not perform well in highly dynamic environments where nodes move fast.

With the rollout of V2V systems the penetration of vehicles equipped with On Board Units (OBU) with wireless interface(s) will be low initially. From this perspective the wireless network will be sparsely connected although in reality the traffic can be dense. Let us consider that the busy traffic networks shown in Fig. 5.2d (Highway, 200 vehicles) and Fig. 5.8e (Urban, 320 vehicles) contain a low penetration of vehicles with OBUs and the wireless networks are then similar to those in Fig. 5.2a (Highway, 50 vehicles) and Fig. 5.8a (Urban, 20 vehicles) i.e. sparsely connected. Consider for example that the penetration of vehicles with OBUs is 25% (50 vehicles with OBUs, 150 vehicles without OBUs) in the highway scenario. For the urban environment the penetration of vehicles with OBUs is then only 6% (20 vehicles with OBUs, 300 vehicles without OBUs). In networks such as these, i.e. dense traffic with a low number of OBU equipped vehicles the RVG protocol can still deliver a performance that satisfies safety application demands. But what is the performance like at the edge of a long traffic jam? In the highway environment G-RVG reached the highest delivery ratio for the *broadcast zone*. The delivery ratio is obviously smaller than in high penetration networks as fewer vehicles can be used as hops for dissemination but still 72% of vehicles with OBUs received the message. In urban environments RVG did not reach the best delivery ratio but when the ESSMD scheme (see section 5.4.8) is used with RVG then it outperformed the other protocols in terms of delivery ratio with a value of 28% in comparison to: Flood 15% and DRG 22%. From the perspective of very low penetration of OBUs in vehicles, the RVG (G-RVG) protocol satisfies safety requirements and outperforms the other protocols under test.

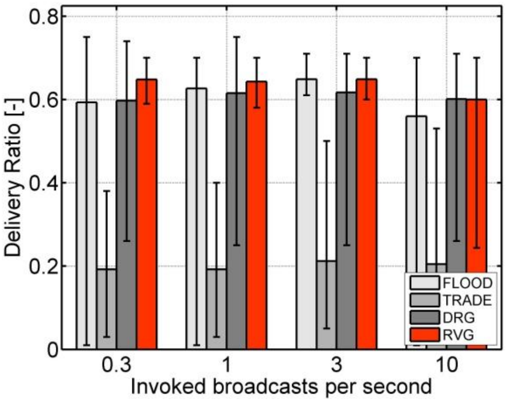
### *5.4.6 Effect of Broadcast Repetition Rates on Broadcast Performance*

The effect of broadcast repetition rates on broadcast performance was investigated to examine the network load. For evaluation purposes a local event was considered with different broadcast repetition rates and the broadcast performance was investigated. A local event in this case is contained to a specific region i.e. a traffic accident. The results presented are measured in the Urban Accident Scenario (section 5.4.4) with approximately 150 vehicles.

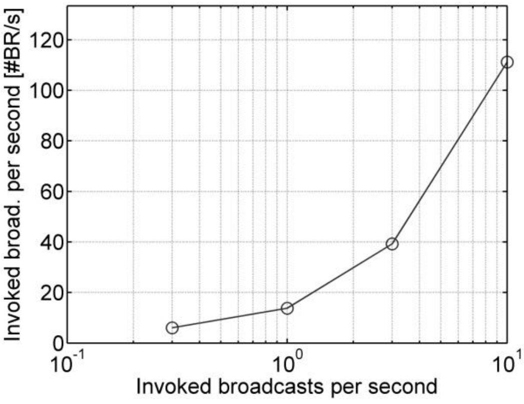
All vehicles in the *hazard zone* detected the traffic accident and had to invoke a safety broadcast with a rate of 1 packet every 3 seconds up to 10 packets per second (Fig. 5.14b). The scenario is comparable with the scenario described in section 5.4.4. From very low data traffic (x = 0.3 invoked broadcasts per second, Br/s) up to medium busy data traffic (x = 3Br/s) all protocols kept a relatively constant delivery ratio in the *broadcast zone*, where Flood reached 65%, TRADE 21%, DRG 62% and RVG 65% delivery ratio but RVG with the lowest dispersion of the ratio . With increasing data traffic, the physical medium became more saturated and delivery ratio dropped to 56% for Flood, 20% for TRADE, 60% for DRG and RVG (x = 10Br/s) with RVG reaching the highest performance across all data traffic (Fig. 5.14a, Table 5.8).

The Broadcast transmission ratio (Fig. 5.14c) was kept relatively constant by all protocols up to medium busy traffic. The End-to-End delay (Fig. 5.14f, g) is acceptable for safety message applications.

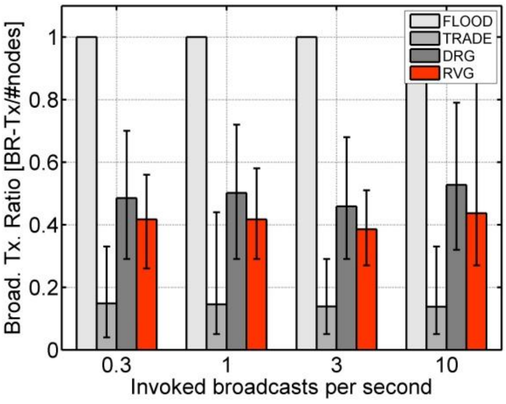
Irrespective of the broadcast transmission rate the protocol performances remain similar to performances observed in the previous section, i.e. RVG in general outperforms the other protocols under test.



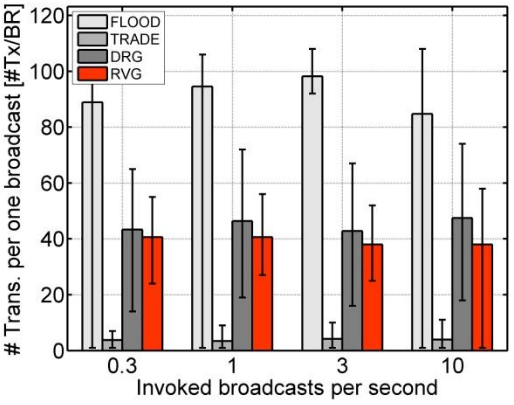
**a) Delivery Ratio in the *Broadcast Zone***



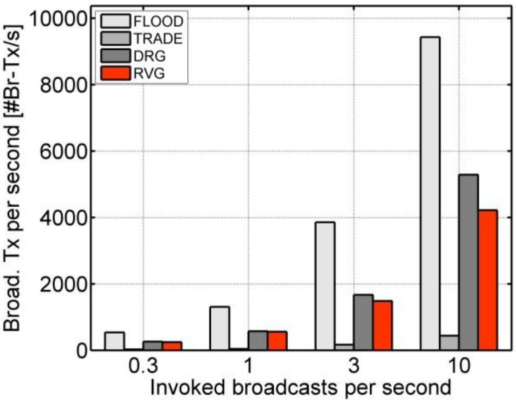
**b) Invoked broadcasts per second (all protocols)**



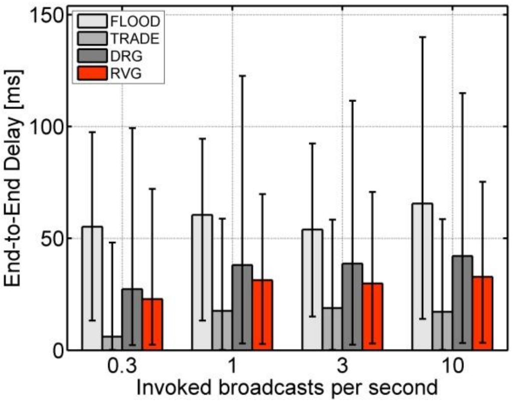
**c) Broadcast transmission ratio**



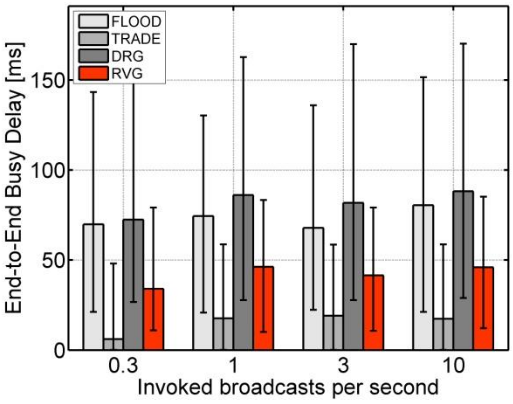
**d) Transmissions per one broadcast**



**e) Broadcast transmissions per second**



**f) End-to-end delay**



**g) End-to-end Busy delay**

Fig. 5.14. Broadcast Protocol Throughput Performance in the Urban Free Flow Scenario (150 vehicles)

TABLE 5.8. DELIVERY RATIO (LOCAL EVENT)

| | ***Proximity Zone* (125m)** | | | | **250m zone** | | | |
|---|---|---|---|---|---|---|---|---|
| **Br. Rt. [pkt/s]** | **0.3** | **1** | **3.3** | **10** | **0.3** | **1** | **3.3** | **10** |
| Flood | 0.86 | 0.92 | 0.94 | 0.83 | 0.76 | 0.80 | 0.82 | 0.71 |
| TRADE | 0.45 | 0.43 | 0.47 | 0.45 | 0.25 | 0.25 | 0.27 | 0.26 |
| DRG | 0.89 | 0.90 | 0.91 | 0.90 | 0.76 | 0.78 | 0.78 | 0.76 |
| RVG | 0.94 | 0.95 | 0.95 | 0.89 | 0.83 | 0.82 | 0.82 | 0.76 |
| *Achv. [%]* | *9.3* | *3.3* | *1.1* | *7.2* | *9.2* | *2.5* | *0.0* | *7.0* |

| | **375m zone** | | | | ***Broadcast Zone* (500m)** | | | |
|---|---|---|---|---|---|---|---|---|
| **Br. Rt. [pkt/s]** | **0.3** | **1** | **3.3** | **10** | **0.3** | **1** | **3.3** | **10** |
| Flood | 0.59 | 0.63 | 0.65 | 0.56 | 0.59 | 0.63 | 0.65 | 0.56 |
| TRADE | 0.19 | 0.19 | 0.21 | 0.20 | 0.19 | 0.19 | 0.21 | 0.20 |
| DRG | 0.60 | 0.62 | 0.62 | 0.60 | 0.60 | 0.62 | 0.62 | 0.60 |
| RVG | 0.65 | 0.64 | 0.65 | 0.60 | 0.65 | 0.64 | 0.65 | 0.60 |
| *Achv. [%]* | *10.2* | *1.6* | *0.0* | *7.1* | *10.2* | *1.6* | *0.0* | *7.1* |

### *5.4.7 Reliability Methods – Performance Evaluation*

The *Pseudo Acknowledgment* (PACK) scheme is a general scheme that can be applied to any broadcast protocol for increasing reliability. The PACK scheme was developed as an extension to the SRMB scheme and together they are collectively referred to as the RVG (SRMB+PACK) and RVG is used in the figures below (Fig. 5.15). For a consistent comparison of reliability methods, SRMB (chapter 3.6) was used as the underlying dissemination protocol for all the reliability schemes that were tested including SRMB+RR-ALOHA referred to as RR-ALOHA (chapter 2.4.2.b) and SRMB+SFR referred to as SFR (chapter 2.4.2.c).

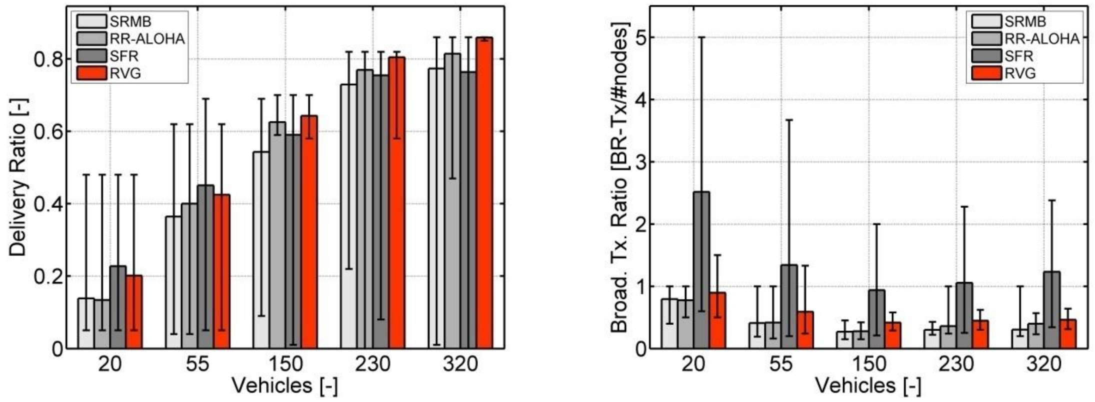
The results from schemes under tests are taken from the same Urban Free Flow Scenario as was presented in section 5.4.3 and the results recorded are comparable with those achieved in Fig. 5.10. The urban environment was chosen due to its complexity resulting from a highly varying vehicle density over a complex urban road network. The PACK scheme incorporated in RVG (SRMB+PACK) was compared with SRMB, RR-ALOHA and SFR where safety messages had to be disseminated in a *broadcast zone* with radius of 500m as vehicles passed a *hazard zone*.

At night time (x = 20 vehicles per scenario, vh/sc, Fig. 5.15) where the network was sparsely connected, the delivery ratio in the *broadcast zone* (Fig. 5.15a, Table 5.9) for the SRMB scheme was 14%, RR-ALOHA 13%, SFR 23% and RVG 20%. The ratio gradually rose to SRMB 77%, RR-ALOHA 81%, SFR 76% and RVG 86% in a busy network (x = 320vh/sc). RR-ALOHA has a good performance in busy networks (x = 320vh/sc) due to minimum collisions as a consequence of slotted transmissions while the SFR scheme is the reverse – it achieved the highest delivery ratio in low density networks (x = 20vh/sc) but weak improvements in high density networks (x = 320vh/sc) due to a high number of retransmissions. The RVG scheme reached the second best result in low density networks and the best results in high density networks. Similar results were reached for the delivery ratio in the *proximity* zone (Table 5.9).

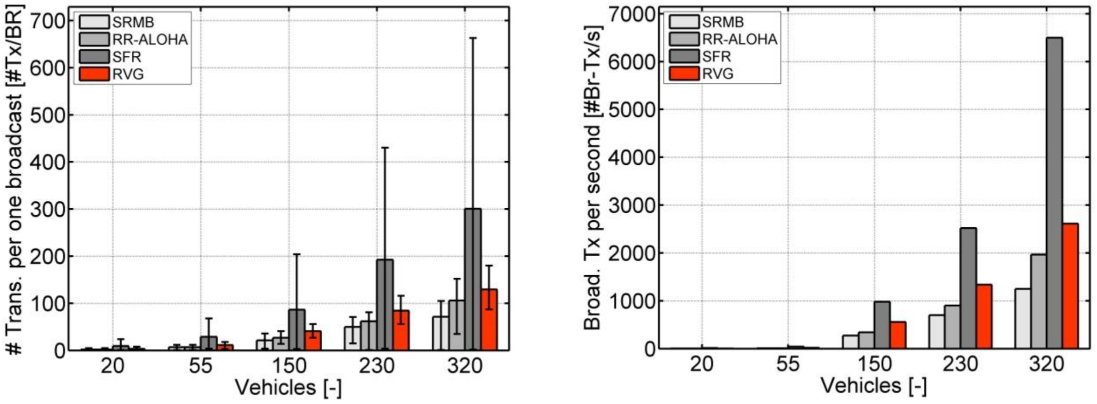
All schemes maintained acceptable end-to-end delay (Table 5.10) for safety message applications (as the values are a fraction of driver reaction time that is approximately 750ms-2s as well being smaller than the delays demanded by the safety services in Appendix A) except the RR-ALOHA scheme which reached a value of 2s in a busy network (x = 320vh/sc), a value not acceptable for the delay requirements of safety messages. The broadcast transmission ratio (Fig. 5.15b) was kept constant by the Flood protocol, reduced by RR-ALOHA and RVG and increased by SFR. The ratio had an effect on the number of transmissions per broadcast (Fig. 5.15c) where SRMB had to transmit 80, RR-ALOHA 110, SFR 300 and RVG 130 packets in a well-connected network (x = 200vh/sc). This affected the number of broadcast transmissions per second (Fig. 5.15d) where SRMB transmitted 1150, RR-ALOHA 2000, SFR 6500 and RVG

2800 packets (x = 200vh/sc) per second across the network. From the results presented in Fig. 5.15 and Table 5.9 the following conclusions can be drawn:

1) **SFR** - repeating broadcasts leads to a very marginal improvement in the delivery ratio in low density networks and vice versa, a deterioration in delivery ratio in high density networks due to a high number of redundant transmissions which easily saturate the network under higher loads. The redundancy incurred as a consequence of repetitions can lead to flooding making this scheme unsuitable for VANETs.
2) **RR-ALOHA** - using small time slots for broadcasts leads to increased delivery ratio due to minimum collisions in higher density networks, while in low density networks it does not have a significant effect. RR-ALOHA rapidly increased the end-to-end delay as broadcast transmissions must be transmitted in a set slot interval at successive rebroadcast nodes. Consequently, the delay for RR-ALOHA reaches large values that cannot be tolerated for safety-related data dissemination.
3) **RVG** - repeating overheard packets by PACK leads to an increase in delivery ratio which results in RVG achieving the second best delivery ratio in low density networks and the best in higher density networks. From the experimental results presented the PACK mechanism increases the reliability of multi-hop broadcasting and is suitable for safety-related data dissemination.



**a) Delivery Ratio in the *Broadcast Zone*** **b) Broadcast transmission ratio**



**c) Transmissions per one broadcast** **d) Broadcast transmissions per second**

**Fig. 5.15. Reliability Schemes Performance in the Urban Free Flow Scenario**

TABLE 5.9. DELIVERY RATIO (RELIABILITY SCHEMES)

| | ***Proximity Zone*** **(125m)** | | | | | **250m zone** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Veh. density** | **20** | **55** | **150** | **230** | **320** | **20** | **55** | **150** | **230** | **320** |
| SRMB | 0.28 | 0.65 | 0.83 | 0.93 | 0.92 | 0.15 | 0.41 | 0.69 | 0.88 | 0.90 |
| RR-ALOHA | 0.27 | 0.70 | 0.92 | 0.96 | 0.98 | 0.15 | 0.44 | 0.79 | 0.92 | 0.95 |
| SFR | 0.45 | 0.75 | 0.88 | 0.94 | 0.90 | 0.25 | 0.50 | 0.75 | 0.91 | 0.89 |
| RVG | 0.40 | 0.74 | 0.95 | 0.99 | 1.00 | 0.22 | 0.47 | 0.82 | 0.96 | 1.00 |
| *Achv. [%]* | *42.9* | *13.9* | *14.5* | *6.5* | *8.7* | *46.7* | *14.6* | *18.8* | *9.1* | *11.1* |

| | **375m zone** | | | | | ***Broadcast Zone*** **(500m)** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Veh. density** | **20** | **55** | **150** | **230** | **320** | **20** | **55** | **150** | **230** | **320** |
| SRMB | 0.14 | 0.36 | 0.54 | 0.73 | 0.77 | 0.14 | 0.36 | 0.54 | 0.73 | 0.77 |
| RR-ALOHA | 0.14 | 0.40 | 0.63 | 0.77 | 0.81 | 0.13 | 0.40 | 0.63 | 0.77 | 0.81 |
| SFR | 0.23 | 0.45 | 0.59 | 0.75 | 0.76 | 0.23 | 0.45 | 0.59 | 0.75 | 0.76 |
| RVG | 0.20 | 0.43 | 0.64 | 0.80 | 0.86 | 0.20 | 0.43 | 0.64 | 0.80 | 0.86 |
| *Achv. [%]* | *42.7* | *19.4* | *18.5* | *9.6* | *11.7* | *42.7* | *19.4* | *18.5* | *9.6* | *11.7* |

TABLE 5.10. END-TO-END DELAY [MS] (RELIABILITY SCHEMES)

| | ***Broadcast Zone* (500m)** | | | | |
|---|---|---|---|---|---|
| **Veh. density** | **20** | **55** | **150** | **230** | **320** |
| SRMB | 16 | 16 | 25 | 31 | 30 |
| RR-ALOHA | 118 | 287 | 588 | 1072 | 2007 |
| SFR | 24 | 27 | 33 | 46 | 83 |
| RVG | 16 | 21 | 31 | 36 | 36 |
| *Achv. [%]* | *5* | *29* | *24* | *19* | *19* |

### 5.4.8 Aggregation & Suppression Methods – Performance Evaluation

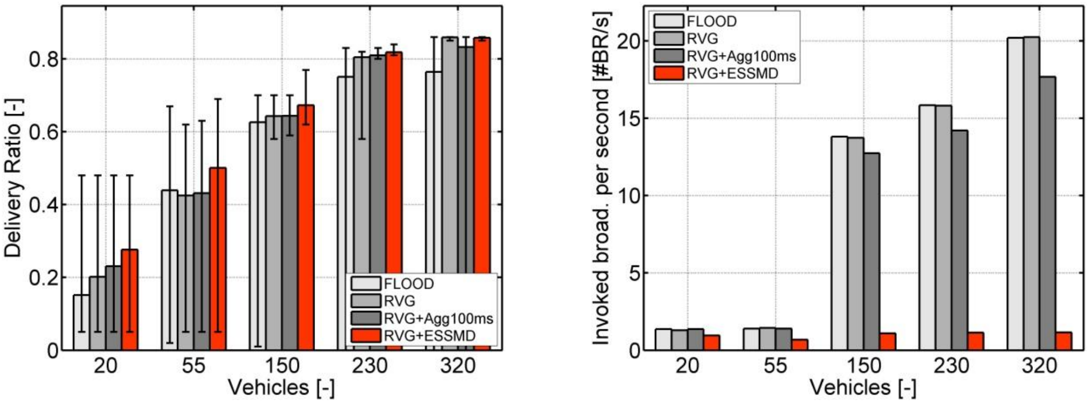
The *Event Suppression for Safety Message Dissemination* (ESSMD) scheme is a general scheme that can be applied to any broadcast protocol in order to reduce the number of reporting source nodes. Because ESSMD was developed as an extension to the RVG protocol it is implemented over RVG and is referred to as RVG+ESSMD in Fig. 5.16. The performance of RVG+ESSMD is compared to the Simple Flood protocol as the baseline protocol, and an aggregation method is implemented using RVG as the broadcast protocol; this is labelled as RVG+Agg100ms. At each node the RVG+Agg100ms aggregates all the packets that arrive in a 100ms interval into one packet; over multiple hops this would lead to delays that are beyond the delay bounds for safety applications. Consequently to investigate aggregation it was decided to aggregate packets at the first hop only (the largest concentration of nodes detecting the hazard is within this area) in order to maintain an acceptable delay over the complete path. The results are recorded for the Urban Free Flow Scenario shown in section 5.4.3. As in this previous scenario, vehicles are required to disseminate safety messages in a *broadcast zone* with a radius of 500m as vehicles pass a *hazard zone*.

At night time (x = 20 vehicles per scenario, vh/sc, in Fig. 5.16a, Table 5.11) where the network was sparsely connected the delivery ratio (the *broadcast zone*) for the Flood protocol was 15%, RVG 20% RVG+Agg100ms 23% and RVG+ESSMD 28% and the ratio gradually increased to 76% for Flood, 83% for RVG+Agg100ms and 86% for RVG and RVG+ESSMD (for the highest number of vehicles x = 320vh/sc). In a busy network (x = 320vh/sc) RVG+ESSMD outperformed the other protocols by achieving the highest delivery ratio, sparing the physical medium from a high number of transmissions.

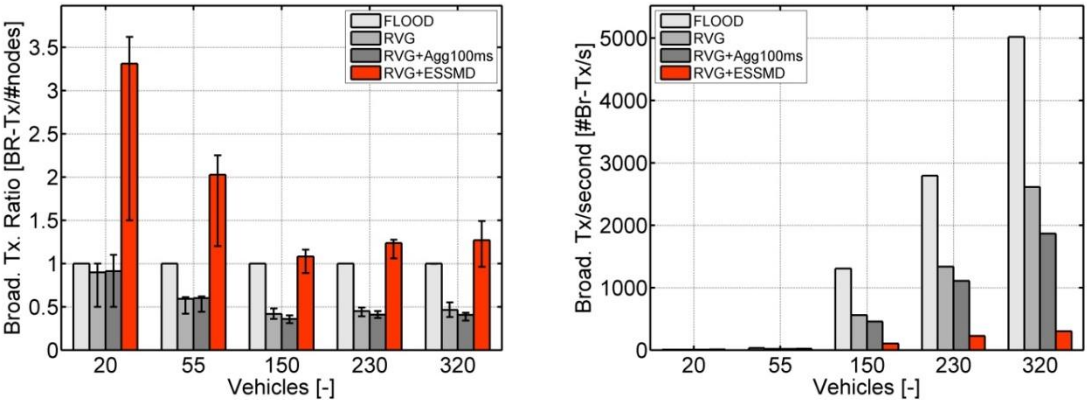
All protocols again maintained an acceptable end-to-end delay (Fig. 5.16f, g) for safety message applications. The number of invoked broadcasts (Fig. 5.16b) rapidly grew with increasing density of nodes with 21 invoked for Flood, 21 for RVG and 18 broadcasts invoked per second for the RVG+Agg100ms protocol (x = 320vh/sc). The RVG+ESSMD scheme kept an almost constant number of invoked broadcasts across all densities with a value of 1.1 (see Fig. 5.16b) broadcasts invoked per second in a busy network (x = 320vh/sc). The broadcast transmission ratio (Fig. 5.16c) was one for Flood, below one for the RVG and RVG+Aggr100ms protocols and above one for RVG+ESSMD due to the additional repetitions with the ESSMD schemes (these are in addition to the repetitions for RVG). RVG+ESSMD generated a significantly lower number of broadcast transmissions per second (Fig. 5.16d) with 300 transmissions for RVG+ESSMD, 5020 for Flood, 2614 for RVG and 1900 transmissions per second for RVG+Agg100ms in the high density network (x = 320vh/sc), with RVG+ESSMD reducing the number of transmissions by 93% against Flood.

The results presented below (Fig. 5.16, Table 5.11, Table 5.12) show that RVG+ESSMD improved broadcast performance since in low density networks it significantly increased the delivery ratio in the *broadcast zone* where Flood achieved a packet delivery of only 15% with RVG+ESSMD attaining 28% showing a significant difference of 87%. RVG+ESSMD achieved the highest delivery ratio for the *broadcast zone* with a significant reduction in the number of transmissions which falls from 5020 transmissions by Flood to 302 by RVG+ESSMD giving a difference of 93%. Overall the performance of ESSMD can be summarised as follows:

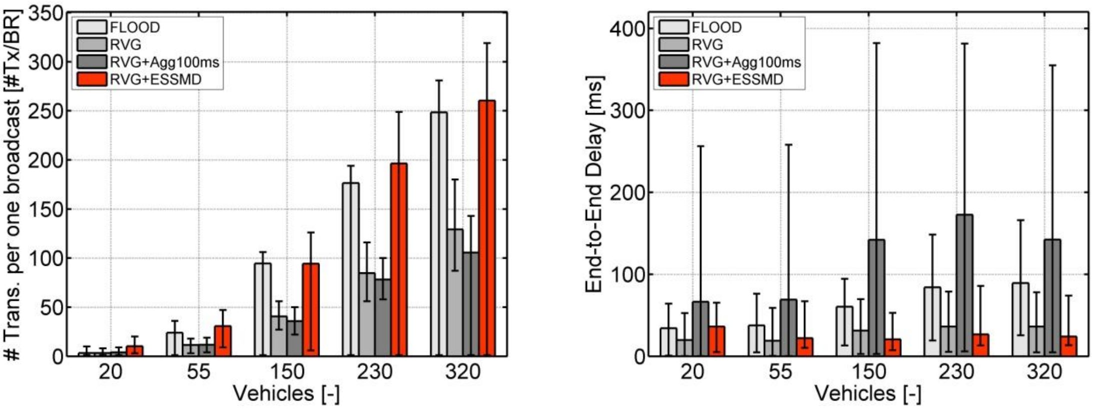
1) It dramatically decreases the number of transmissions thereby sparing the physical medium
2) As it does not overload the physical medium, less broadcast transmissions fail which improves the delivery ratio for ESSMD
3) Across all densities ESSMD maintains the lowest end-to-end delay



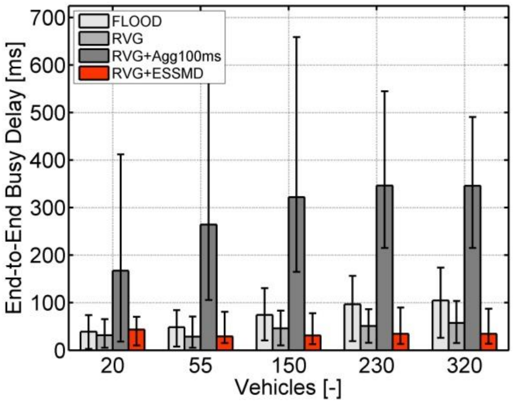
**a) Delivery Ratio in the *Broadcast Zone*** **b) Invoked broadcasts per second**



**c) Broadcast transmission ratio** **d) Broadcast transmissions per second**



**e) Transmissions per one broadcast** **f) End-to-end delay**



**g) End-to-end Busy delay**

**Fig. 5.16. Aggregation & Suppression Schemes Performance in the Urban Free Flow Scenario**

TABLE 5.11. DELIVERY RATIO (SUPPRESSION SCHEMES)

| | ***Broadcast Zone* (500m)** | | | | |
|---|---|---|---|---|---|
| **Veh. density** | **20** | **55** | **150** | **230** | **320** |
| Flood | 0.15 | 0.44 | 0.63 | 0.75 | 0.76 |
| RVG | 0.20 | 0.43 | 0.64 | 0.80 | 0.86 |
| RVG+Agg100ms | 0.23 | 0.43 | 0.64 | 0.81 | 0.83 |
| RVG+ESSMD | 0.28 | 0.50 | 0.67 | 0.82 | 0.86 |
| *Achv. [%]* | *86.7* | *13.6* | *6.0* | *8.5* | *11.1* |

TABLE 5.12. BROADCAST TRANS. PER SECOND (SUPPRESSION SCHEMES)

| | ***Broadcast Zone* (500m)** | | | | |
|---|---|---|---|---|---|
| **Veh. density** | **20** | **55** | **150** | **230** | **320** |
| Flood | 4 | 34 | 1306 | 2794 | 5020 |
| RVG | 5 | 16 | 557 | 1337 | 2614 |
| RVG+Agg100ms | 6 | 16 | 456 | 1108 | 1867 |
| RVG+ESSMD | 10 | 21 | 104 | 224 | 302 |
| *Achv. [%]* | *-29* | *38* | *92* | *91* | *93* |

## 5.5 Conclusion

This chapter presented a theoretical analysis and an experimental evaluation using the CALMnet simulation environment of the proposed RVG protocol.

A comparison of the theoretical performance of the end-to-end delay for the RVG and Simple Flooding protocols was used to underpin the validity of the results obtained from simulations. In the case of Simple Flooding, results showed that the end-to-end delay significantly increases with growing number of hops (see end-to-end delay e.g. from the Urban Free Flow Scenario in Table 5.7) and can easily reach a value that is the same as the length of the CCH Time Slot, causing the broadcast process to be split over two CCH TS intervals. For the RVG protocol, the end-to-end delay is not strongly correlated with the number of hops but rather it is more dependent on the network load as repetitions are used. Simulation evaluation (e.g. Table 5.7) confirmed that with growing number of hops the end-to-end delay slightly increases as the network become denser. The results showed that the Flood protocol reached approximately a delay two times longer than the RVG protocol. As was shown in section 5.2, the RVG protocol reached the shortest end-to-end delay for broadcasting over long multi-hop paths (> 6 hops).

Simulation evaluations of the proposed safety dissemination framework: namely RVG, PACK and ESSMD were presented in this chapter. In sections 5.4.1-5.4.6, the RVG protocol was evaluated against Simple Flooding, DRG and TRADE protocols in urban and highway environments including free flow traffic and a traffic accident scenario. The effectiveness of the broadcast protocols in warning surrounding vehicles was examined mainly from the viewpoint of satisfying safety data dissemination with high packet delivery, low end-to-end delay and minimal overhead. The findings that can be drawn from the simulations showed that the RVG protocol satisfied the requirements and outperformed the Simple Flooding, DRG and TRADE protocols. While RVG in some cases had a performance similar to DRG, namely the high density free flow scenario, RVG is more suited than DRG as a general purpose dissemination mechanism for a range of safety applications over diverse vehicular environments as its performance over the test networks demonstrated. Flooding is unsuitable due to excessive network saturation and likewise TRADE as it has markedly low delivery ratios across all test networks.

In section 5.4.7 the PACK scheme was tested against RR-ALOHA and SFR reliability schemes in the Urban Free Flow Scenario. The evaluation results showed that PACK outperformed other schemes by increasing the delivery ratio with minimal overhead with a very marginal increase in delay. In section 5.4.8, the ESSMD scheme was tested against general aggregation methods. The evaluation results presented showed that

ESSMD outperformed the others by dramatically decreasing the transmission overhead, increasing the delivery ratio and maintaining a low end-to-end delay.

# Chapter 6 Conclusions & Outlook

Since the 1950s when the first automobile safety systems were introduced to the automobile marketplace, vehicle safety has rapidly evolved. Nowadays vehicles include a wide range of systems that protect the driver/passengers during crashes such as airbags, seatbelts, robust vehicle structure, brakes, suspension etc. and although these systems help to provide protection and to lessen fatalities, they do not assist in preventing road traffic accidents. Over recent years ambitious plans to create a system that would assist in the prevention of accidents were introduced. These systems are known as Active safety systems and rely on wirelessly disseminating safety messages among vehicles in vehicular ad hoc networks. V2V communication links are very unreliable as the physical medium is shared, bandwidth is limited and wireless signals fade. These constraints impose strong requirements on vehicular communication protocols in terms of delay and delivery reliability. Most importantly, for active safety applications the reception of safety message and the warning of drivers in advance of or immediately after road traffic incidents can lead to reduced fatalities. Consequently, for active safety systems the underlying dissemination protocol must be extremely reliable with low delay and work in a range of environments with diverse vehicle speeds, densities and road topologies.

## 6.1 Discussion

The results presented in this thesis have compounded the need for reliable broadcasting for safety data dissemination in vehicular networks. A review of dissemination protocols in Chapter 2 showed that several dissemination protocols have been proposed for VANET environments with each protocol exhibiting varying performance characteristics over sample network environments. Vehicular Ad hoc network configurations can differ greatly depending upon the topology, traffic flows, mobility rates and node densities resulting in some protocols outperforming others depending on the particular network scenario. As Vehicular ad hoc networks exhibit time varying characteristics, the broadcast protocol efficiency can have an irregular performance profile. Current approaches fail to satisfy the stringent reliability requirements (delay, high delivery success and low overhead) for vehicular safety applications over a wide range of use case environments. In contrast, the *Reliable Vehicular Geo-broadcast* - RVG protocol presented in this thesis has been demonstrated to overcome these drawbacks. RVG is a robust broadcast protocol for safety data dissemination in targeted geographical areas that satisfies safety data dissemination requirements with high packet delivery, low delay and low overhead. The RVG protocol consists of two schemes namely the *Slotted Restricted Mobility Based* (SRMB) method and the *Pseudo-Acknowledgements* (PACK) mechanism. These schemes can work individually but together they are referred to as the RVG protocol. Optionally, RVG can be used with the ESSMD extension that has been designed for reducing redundant transmissions for broadcast protocols.

The RVG broadcast protocol is a reliable network protocol that is built to be compliant with the IEEE 1609 standards and generally, RVG can be used to disseminate any type of application data but it has been optimised for the dissemination of safety related messages with high reliability and low delay. The RVG protocol is designed for vehicular ad hoc networks with populations spanning tens to hundreds of vehicles per km on a road (not all vehicles are required to be equipped with On Board Units). While RVG has proven itself to be a reliable broadcast protocol for safety data dissemination across a range of vehicular networks it does however have some limitations. In low density networks (and/or low technology penetration in terms of On Board Units being available within vehicles) RVG reaches its technical limits (as is common with other dissemination mechanisms), in terms of vehicle-to-vehicle communication when the VANET network is sparsely connected RVG is not able to perform reliably over the targeted geographic area. Practical examples of highly disconnected networks are rural environments where vehicles typically have long distances between each other or another instance is at night times in urban or highway environments where the numbers of vehicles using the roads is low. In urban and highway environments with moderate to high density vehicle numbers, RVG has been shown to achieve high packet delivery with low delay and minimal overhead is incurred. RVG must maintain an accurate knowledge of 1-hop neighbours' geographical position (within meters precession limits) however it is only required by RVG to keep high precision of relative position to determine distances between nodes. For example in the case of city canons where GPS does not work well and localization precision is very poor this can make selecting forwarders (MPR nodes) difficult making advanced methods for precise pseudo-position localisation neccessary such as Differential GPS (DGPS), Wide Area Augmentation System (WAAS) or use the mobility information of the vehicle such as speed and heading to help estimate an accurate position. The RVG protocol is a complex protocol that requires higher computing power when compared with other protocols as it includes a series of algorithms for operation. RVG relies primarily on *Neighbour Elimination* to restrict redundant transmissions and the *Multipoint Relay* algorithm to select forwarders and both these algorithms have higher requirements for computing power, but the computing technologies within vehicles are more than adequate to support the processing requirements of the RVG protocol.

## 6.2 Review of Contributions

This section summarises the contributions that the work presented in this thesis has made while also reviewing the findings and conclusions that can be drawn from the evaluations undertaken.

### *6.2.1 Reliable Vehicular Geo-Broadcast Protocol*

The Reliable Vehicular Geo-broadcast (RVG) protocol combines multipoint relaying to reduce the number of transmissions and neighbour elimination to increase reliability. RVG was evaluated against the Simple Flood (section 2.3.1.a), DRG (section 2.3.3.b) and TRADE (section 2.3.4.a) protocols in urban and highway environments including free flow traffic and a traffic accident scenario where the effectiveness of the broadcast protocols in warning surrounding vehicles was examined. The findings that can be drawn from this are:

1) Delivery ratio over the whole geographic target area is not always a crucial parameter from the viewpoint of safety dissemination. For example in low density networks, drivers usually have long distances between each other and have sufficient time to react and avoid an accident. Furthermore in low density networks, broadcasting a message over long distances is not safety critical but more informative as drivers are spread far from the hazard. What is crucial from a safety perspective in low density networks is the first stage of the traffic accident where it is essential that close proximity vehicles are warned. RVG and G-RVG (geo-cast RVG) protocols outperform the other protocols tested, giving the best delivery ratio for close proximity vehicles in all networks, scenarios and environments. The performance difference between (G-)RVG and e.g. Simple Flood protocol reached up to 135% in urban and 18% in highway scenarios.

2) As the traffic becomes denser or traffic jams get longer, the delivery ratio for a targeted geographic area becomes a more crucial parameter for safety dissemination. Consider the example of a highway where an accident occurs and a traffic jam grows. Vehicles in the traffic jam have come to a stop but vehicles approaching the edge of the traffic jam must be warned so that they can start immediately decelerating the vehicle. It is essential to deliver warnings to these vehicles on the edge of traffic jam. From this analysis perspective, RVG and G-RVG gave the best delivery ratio across all stages of the traffic jam in highway and urban environments as they were able to deliver the warnings to the edge of the jam with high reliability. The performance difference between RVG (G-RVG) and the other protocols considered increased with traffic jam build up, with the largest difference reaching 14% in urban scenarios and 15% in highway scenarios between RVG (G-RVG) and the Simple Flood protocol.

3) The next crucial parameter from the perspective of safety dissemination is end-to-end delay. From the results presented it can be concluded that all protocols

(Simple Flood, DRG, TRADE and (G-)RVG) maintained an end-to-end delay acceptable for safety messaging as the delay reached a fraction of driver reaction time as well being smaller than the delays demanded by the safety services requiring a maximum delay of 1s (e.g. SOS Services). To ensure a reasonable performance in terms of end-to-end delay (delay values below 1s) for the test protocols (Simple Flood, DRG and TRADE) considered in the evaluation, these protocols were tuned using the $T_{WL}$ window length parameter (chapter 5.2) to achieve minimum delay with acceptable reliability and a low number of collisions. But for safety services that can tolerate a maximum delay of only 100ms (e.g. Intersection Collision Warning) the Simple Flood and DRG do not satisfy the requirements as a high number of broadcasts exceed the delay. In contrast, in the majority of scenarios the (G-)RVG protocol maintained the shortest delay which satisfies the most delay demanding safety services described in Appendix A (e.g. Intersection Collision Warning, Wrong Way Driver Warning) with a maximum allowed delay of 100ms. The next advantage of (G-)RVG is that broadcast transmissions have a statistically narrow spread in time (low standard deviation) over the complete data set with all values being close to the statistical mean  unlike the other test protocols (see busy end-to-end delay statistics). This results in restricting the broadcast transmissions to shorter intervals over the physical medium which leaves more bandwidth for another services on the medium.

4) While the Simple Flood protocol is effective in guaranteeing a high delivery ratio in medium density networks, its delivery ratio performance is significantly worse in low and high density networks when compared to other protocols. Simple Flooding does not contain an algorithm for the repeating of broadcasts for unsuccessful transmissions over unstable and unreliable links. As a result of this, low density and sparsely connected networks where nodes are connected over distant links suffer from the dissemination prematurely ending and packet delivery drops. For example, in urban environments the performance difference

showed that the delivery ratio over the *broadcast zone* for Simple Flood fell by 30% and the delivery ratio in the *proximity zone* fell by 57% compared with RVG. In high density networks, Simple Flooding does not contain an algorithm for reducing redundant transmissions and the protocol over saturates the physical medium with a high number of transmissions. As the network is oversaturated, transmissions collide and dissemination ends precipitately. Results showed that in all high density networks the delivery ratio for Simple Flood significantly worsens when compared with RVG with a difference of up to 22%.

5) The TRADE protocol achieved a significantly worse and unacceptable delivery ratio in comparison to all protocols that were tested and has highlighted the inappropriateness of the TRADE protocol as a dissemination mechanism for safety related applications.

6) In contrast to the Simple Flooding, DRG contains algorithms to repeat unsuccessful transmissions and reduces redundancy. The results showed that DRG achieved the highest delivery ratio in low density urban scenarios but on the other hand DRG achieved the worst delivery ratio in the low density highway scenario. In highway scenarios DRG achieved a worse delivery ratio compared to the Simple Flood and RVG protocols with a difference of 14% for Simple Flood and 16% for RVG. The evaluation results indicate that DRG protocol does not perform well in highly dynamic environment where nodes move fast making it unsuitable as a VANET safety application dissemination mechanism.

7) The results showed that with increasing the load, the throughput ratio dropped across all protocols. The Simple Flooding protocol showed a decreased throughput due to the overloading of the network with many redundant transmissions and DRG showed a decreased throughput due to many repetitions. The RVG protocol in low to highly loaded networks gave a better performance than the Simple Flood and DRG protocols. The advantages of the RVG protocol are further highlighted when safety application are required to

report with a higher rate (<1s, see services in Appendix A) as it can maintain a high delivery ratio for moderate to high density networks (e.g. Emergency Electronic Brake Lights).

### 6.2.2 Pseudo-Acknowledgements Scheme

The *Pseudo Acknowledgment* (PACK) scheme is an acknowledging method used to increase delivery reliability and was tested against the RR-ALOHA (section2.4.2.b) and SFR (section2.4.2.c) schemes where all these methods were implemented over the SRMB broadcast protocol. In order to minimise the number of retransmissions and repetitions of transmissions, PACK relies on nodes overhearing rebroadcasts and interprets these as pseudo-acknowledgements. The evaluation results presented in chapters 5.4.7 show that:

1) SFR: repeating broadcasts leads to an improvement in delivery ratio in low density networks while causing a deterioration in the delivery ratio in high density networks due to the high number of redundant transmissions which can easily saturate the network under higher loads. The redundancy incurred as a consequence of repetitions which can lead to flooding makes this scheme unsuitable for VANETs.

2) RR-ALOHA: using small time slots for broadcasts leads to an increase in the delivery ratio due to minimum collisions for busy networks but RR-ALOHA rapidly increased end-to-end delay as broadcast packets wait to be placed in time slots at each successive rebroadcast node. This causes large delay times that cannot be tolerated for safety-related data dissemination.

3) PACK (RVG): repeating overheard packets by PACK increases the delivery ratio with minimal overhead when compared against existing methods. From the experimental results the PACK mechanism increased the reliability of multi-hop broadcasting and is suitable for safety-related data dissemination, with only a very marginal increase in delay and it improved packet delivery again at a cost of slightly increasing broadcast overhead.

### 6.2.3 Event Suppression for Safety Message Dissemination Scheme

The *Event Suppression for Safety Message Dissemination* (ESSMD) scheme restricts the number of source nodes that report on the same event and was tested against general aggregation methods (section2.5) using RVG as the underlying broadcast protocol. The evaluation results presented showed that:

1) ESSMD dramatically decreases the number of transmissions thereby sparing the physical medium from redundant traffic. In the busiest urban test network RVG+ESSMD transmitted only 300 packets per second versus over 5000 packets per second when compared against the Simple Flood protocol.
2) As ESSMD does not saturate the physical medium, fewer transmissions fail and subsequently the delivery ratio improves.
3) Due to the repetition mechanism in ESSMD, it achieved significantly higher packet delivery in low density networks than other protocols.
4) Across all densities ESSMD maintains a low end-to-end delay.

### 6.2.4 CALMnet Simulation Environment

CALMnet is a simulation tool primarily implemented for the examination of lower layer protocol performance in the CALM ITS environment. Accurate environmental modelling is therefore vital. The CALMnet simulation environment was developed in conjunction with the work presented within this thesis. Creating a realistic test bed for Intelligent Transport System (ITS) is a difficult and complex task that requires the implementation of the necessary elements such as accurate modelling of radio propagation, vehicle mobility and networking with IEEE 802.11p and IEEE 1609 standards

The evaluation results presented in Chapter 5 were simulated in CALMnet, a network-centric simulation model for CALM-based ITS systems using the OPNET modeler simulation tool. Considering vehicle mobility, channel behaviour, application characteristics and CALM management entities, a complete CALM simulation environment is implemented. Using a heterogeneous mix of complementary radio technologies, vehicles have continuous coverage, fostering a large set of potential services in the ITS domain.

## 6.3 Outlook

As V2V communications grows in popularity, technology will become standard in cars and this will lead to specifically defined requirements for safety applications which will enable the specification of a set of suitable configuration parameters for RVG. Parameters such as the frequency at which broadcasts are invoked based on hazard sensing and *minimum broadcast distance* will need to be tuned according to application requirements (Appendix A); the number of allowable repetitions of a broadcast will need be tuned with reference to the load placed on the medium and must be sufficient to not overload the communications medium with redundant transmissions and on the other hand must adequately maintain the high reliability achievable with RVG. The theoretical transmission distance will need to be determined based on precise realistic channel models of the environment of interest. Furthermore, in this thesis the packet processing time on different hardware platforms (more, less powerful) was not considered. To fine tune the delay/wait intervals referred to by equations (3.2)-(3.5) their parameters should consider hardware specific processing times, this will decrease the probability of simultaneous transmissions in one time slot. Without including the hardware processing time in physical rollouts of the RVG protocol the reliability of RVG will be comprised as delays/wait intervals will not be calculated accurately.

Although the RVG protocol has been primarily designed in order to disseminate safety data in vehicular ad hoc networks, in general RVG could be used as a data dissemination mechanism for a range of applications that require high packet delivery and low delay in vehicular ad hoc networks. The RVG protocol is suitable for use in route discovery for reactive routing protocols in VANETs. From the route discovery perspective routes would be built based on delay, bandwidth consumption and mobility of nodes in the source-destination path. Nodes with similar mobility behaviour (speed, motion vector) would be selected as intermediate hops as this supports the generation of stable routes and reduces route maintenance overhead.

The RVG protocol does not perform well in low density sparsely connected networks such as those typical of rural environments. In order to improve the packet reception rate among nodes, the RVG protocol could be extended to store a broadcast message until a new link is discovered. However this store & forward mechanism would lead to an increased delivery delay. In order to circumvent this support for communication amongst vehicles, roadside units and infrastructure should be considered to increase connectivity. Having backend connectivity to an infrastructure provides the capability for vehicles to update their geographic location which can be used to manage traffic flow.

The typical performance of broadcast protocols is that the probability of the successful reception of data decreases with growing distance from the sender. Bearing this in mind it is not efficient to let a broadcast protocol disseminate data over large distances as this would flood the medium with high number of redundant transmissions that are not likely to reach distant nodes. From this perspective, infrastructure deployment would be necessary and the RVG protocol could be extended to carry compulsory information in order to disseminate data through infrastructure and ad-hoc networks when certain hop limit thresholds are exceeded for example.

Within wireless networks in general the current trend is towards autonomic management and configuration. As networks are becoming increasingly complex, a desirable trait is that they can self-configure and adapt to changing network conditions in terms of topology, traffic flows, connectivity and such like. For a system to support autonomy, network strategies must be implemented in a distributed manner, be capable of observing changes in the network and adapting to the current conditions. The proposed RVG protocol relies on local observations with one hop neighbour information exchange and can be viewed as an initial step towards developing an autonomic dissemination framework that aims to furnish nodes with the ability to adapt to local topology conditions to continually satisfy application demands. As VANET environments are inherently distributed systems the RVG protocol presented in this thesis does not make use of system-wide knowledge but relies on individual nodes having only local network perceptions.

For VANET evaluations it is common with most research that VANETs are assessed over closed simulated environments. Uniform network conditions are experienced over the available simulation space, with node density, node mobility rates and traffic flows remaining constant for the simulation duration. Such an approach does allow for the testing, evaluation and comparison of protocols under the same conditions but it is not an accurate reflection of realistic environments over which vehicular ad hoc would be deployed. Real world scenarios will not conform to a uniform space with similar conditions being experienced throughout the operating area. While the availability of traffic simulators support realistic mobility and traffic flows the need for tightly coupled traffic generators and network centric simulators is needed for comprehensive protocol evaluation. The CALMnet simulator developed as part of this research is one such example for an integrated simulation environment.

Presently, the testing and evaluation of VANET routing performance is implemented subjectively. Although, throughout the available research literature common network parameters, such as throughput, delay, and control traffic overhead, are used to evaluate network performance, the tests used are dependent on the researcher’s design and parameter selection. This is prohibitive to comparing protocol performance across several proposed techniques. To realise a suite of tests that will facilitate the evaluation of different techniques benchmark testing is necessary. The use of benchmark testing will provide a performance basis for estimating the capabilities and limitations of VANET protocols. A relevant benchmark test suite must be suitable for assessing, contrasting and comparing different routing methods. The MANET working group [38] has suggested metrics such as control overhead, end-to-end delay and throughput among others as being suitable evaluation metrics for quantifying the performance of protocols. While MANET and VANET routing and dissemination protocol standardisation is underway there is no such move towards developing benchmark performance evaluation tests. Vehicular networks are attracting avid research attention, but due to the lack of benchmark evaluation it is difficult if not impossible to compare and contrast works as evaluation tests along with performance indices are, as previously stated, subjectively defined. To quantifiably assess and compare protocols there is an urgent necessity to define a benchmark suite of tests for VANET protocol performance evaluation. In conjunction with this and the metrics suggested by the MANET working group this would provide a standard set of performance appraisal metrics and test suite. Such a combination of standardised benchmark testing and metrics will lead to a coherent research effort with quantifiable evaluation results.

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# Appendix A: Safety Services defined for 5GHz Medium

This section provides a list of services that are likely to be considered as safety services for multi-hop V2X communications, this is extracted from the list of services in [88,89] and only multi-hop services over with a dissemination distance in excessive of 200m are considered.

| Update (Rep.) Rate | Min. broadcast distance | Delay | Service | Detail |
|---|---|---|---|---|
| 1Hz | 200m | 1s | Road Condition Warning | Road condition warning is used to provide warning messages to nearby vehicles when the road surface is icy, or when traction is otherwise reduced. |
| | 300m | 0.5s | Post-Crash Warning | This in-vehicle application warns approaching traffic of a disabled vehicle (disabled due to an accident or mechanical breakdown) that is stuck in or near traffic lanes, as determined using map information and GPS. |
| | 300m | 1s | Work Zone Warning | Work zone safety warning refers to the detection of a vehicle in an active work zone area and the indication of a warning to its driver |
| | 300m | 1s | Highway/Rail Collision Warning | Railroad collision avoidance aids in preventing collisions between vehicles and trains on intersecting paths |
| | 300m | 1s | Low Bridge Warning | Low bridge warning is used to provide warning messages especially to commercial vehicles when they are approaching a bridge of low height. |
| | 400m | 1s | SOS Services | This in-vehicle application will send SOS messages after airbags are deployed, a rollover is sensed, or the vehicle otherwise senses a life-threatening emergency. |
| | 1000m | 1s | Approaching Emergency Vehicle Warning | This application provides the driver a warning to yield the right of way to an approaching emergency vehicle |
| | 1000m | 1s | Emergency Vehicle Signal Pre-emption | This application allows an emergency vehicle to request right of way from traffic signals in its direction of travel (update rate not available) |
| 2Hz | 250m | 100ms | Visibility Enhancer | This application senses poor visibility situations (fog, glare, heavy rain, white-out, night, quick light-to-dark transitions) either automatically or via user command. |
| | 400m | 0.5s | Vehicle-Based Road Condition Warning | This in-vehicle application will detect marginal road conditions using on-board systems and sensors (e.g. stability control, ABS), and transmit a road condition warning, if required, to other vehicles via broadcast. |
| | 400m | 0.5s | Vehicle-To-Vehicle Road Feature Notification | This in-vehicle application senses the road features such as grade, curve, etc. that exceed pre-set limits and transmits the information to other vehicles via broadcast. |
| 10Hz | 250m | 100ms | Traffic Signal Violation Warning | Traffic signal violation warning uses infrastructure-to-vehicle communication to warn the driver to stop at the legally prescribed location if the traffic signal indicates a stop and it is predicted that the driver will be in violation |

| | | | |
|---|---|---|---|
| 250m | 100ms | Stop Sign Violation Warning | Stop sign violation warning uses infrastructure-to-vehicle communication to warn the driver if the distance to the legally prescribed stopping location and the speed of the vehicle indicate that a relatively high level of braking is required for a complete stop. |
| 250m | 100ms | Highway Merge Assistant | This application warns a vehicle on a highway on-ramp if another vehicle is in its merge path (and possibly in its blind spot). |
| 300m | 100ms | Left Turn Assistant | The Left Turn Assistant application provides information to drivers about oncoming traffic to help them make a left turn at a signalized intersection without a phasing left turn arrow. |
| 300m | 100ms | Stop Sign Movement Assistance | This application provides a warning to a vehicle that is about to cross through an intersection after having stopped at a stop sign. |
| 300m | 100ms | Intersection Collision Warning | This application warns drivers when a collision at an intersection is probable. |
| 300m | 100ms | Emergency Electronic Brake Lights | When a vehicle brakes hard, the Emergency Electronic Brake light application sends a message to other vehicles following behind. |
| 500m | 100ms | Wrong Way Driver Warning | This application warns drivers that a vehicle is driving or about to drive against the flow<br>of traffic |