Efficient Safety Message Dissemination for Cooperative Collision Warning via Context Modelling

by

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Keywords

Automobile safety, cooperative collisions warning, collisions warning/avoidance, wireless ad-hoc networks, vehicular ad hoc network, VANET, wireless communication protocol, vehicular safety communication, dedicated short-range communication, DSRC, IEEE 802.11p, WAVE, context-aware, multi-hop, multicast, optimisation
Abstract

A Cooperative Collision Warning System (CCWS) is an active safety technology for road vehicles that can potentially reduce traffic accidents. It provides a driver with situational awareness and early warnings of any possible collisions through an on-board unit. CCWS is still under active research, and one of the important technical problems is safety message dissemination. Safety messages are disseminated in a high-speed mobile environment using wireless communication technology such as Dedicated Short Range Communication (DSRC). The wireless communication in CCWS has a limited bandwidth and can become unreliable when used inefficiently, particularly given the dynamic nature of road traffic conditions. Unreliable communication may significantly reduce the performance of CCWS in preventing collisions.

There are two types of safety messages: Routine Safety Messages (RSMs) and Event Safety Messages (ESMs). An RSM contains the up-to-date state of a vehicle, and it must be disseminated repeatedly to its neighbouring vehicles. An ESM is a warning message that must be sent to all the endangered vehicles. Existing RSM and ESM dissemination schemes are inefficient, unscaleable, and unable to give priority to vehicles in the most danger. Thus, this study investigates more efficient and scalable RSM and ESM dissemination schemes that can make use of the context information generated from a particular traffic scenario. Therefore, this study tackles three technical research problems, vehicular traffic scenario modelling and context information generation, context-aware RSM dissemination, and context-aware ESM dissemination.

The most relevant context information in CCWS is the information about possible collisions among vehicles given a current vehicular traffic situation. To generate the context information, this study investigates techniques to model interactions among multiple vehicles based on their up-to-date motion state obtained via RSM. To date, there is no existing model that can represent
interactions among multiple vehicles in a specific region and at a particular time. The major outcome from the first problem is a new interaction graph model that can be used to easily identify the endangered vehicles and their danger severity. By identifying the endangered vehicles, RSM and ESM dissemination can be optimised while improving safety at the same time. The new model enables the development of context-aware RSM and ESM dissemination schemes.

To disseminate RSM efficiently, this study investigates a context-aware dissemination scheme that can optimise the RSM dissemination rate to improve safety in various vehicle densities. The major outcome from the second problem is a context-aware RSM dissemination protocol. The context-aware protocol can adaptively adjust the dissemination rate based on an estimated channel load and danger severity of vehicle interactions given by the interaction graph model. Unlike existing RSM dissemination schemes, the proposed adaptive scheme can reduce channel congestion and improve safety by prioritising vehicles that are most likely to crash with other vehicles. The proposed RSM protocol has been implemented and evaluated by simulation. The simulation results have shown that the proposed RSM protocol outperforms existing protocols in terms of efficiency, scalability and safety.

To disseminate ESM efficiently, this study investigates a context-aware ESM dissemination scheme that can reduce unnecessary transmissions and deliver ESMs to endangered vehicles as fast as possible. The major outcome from the third problem is a context-aware ESM dissemination protocol that uses a multicast routing strategy. Existing ESM protocols use broadcast routing, which is not efficient because ESMs may be sent to a large number of vehicles in the area. Using multicast routing improves efficiency because ESMs are sent only to the endangered vehicles. The endangered vehicles can be identified using the interaction graph model. The proposed ESM protocol has been implemented and evaluated by simulation. The simulation results have shown that the proposed ESM protocol can prevent potential accidents from occurring better than existing ESM protocols.

The context model and the RSM and ESM dissemination protocols can be implemented in any CCWS development to improve the communication and safety performance of CCWS. In effect, the outcomes contribute to the realisation of CCWS that will ultimately improve road safety and save lives.
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## Nomenclature

### Abbreviations

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<tr>
<td>ABS</td>
<td>Anti-lock Braking System</td>
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<tr>
<td>ACC</td>
<td>Adaptive Cruise Control</td>
</tr>
<tr>
<td>ADAS</td>
<td>Advanced Driving Assistance System</td>
</tr>
<tr>
<td>CCH</td>
<td>Control Channel</td>
</tr>
<tr>
<td>CCWS</td>
<td>Cooperative Collision Warning System</td>
</tr>
<tr>
<td>CWS</td>
<td>Collision Warning System</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access with Collision Avoidance</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential GPS</td>
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<tr>
<td>DSRC</td>
<td>Dedicated Short Range Communications</td>
</tr>
<tr>
<td>EEBL</td>
<td>Electronic Emergency Brake Light</td>
</tr>
<tr>
<td>ESC</td>
<td>Electronic Stability Control</td>
</tr>
<tr>
<td>ESM</td>
<td>Event Safety Message</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transportation System</td>
</tr>
<tr>
<td>IV</td>
<td>Intelligent Vehicles</td>
</tr>
<tr>
<td>MAC</td>
<td>Media Access Control</td>
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<tr>
<td>RSM</td>
<td>Routine Safety Message</td>
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<tr>
<td>SAE</td>
<td>Society of Automotive Engineers</td>
</tr>
<tr>
<td>SCH</td>
<td>Service Channel</td>
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<tr>
<td>V2V</td>
<td>Vehicle-to-Vehicle</td>
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<tr>
<td>VANET</td>
<td>Vehicular Ad-hoc NETwork</td>
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<tr>
<td>WAVE</td>
<td>Wireless Access in Vehicular Environments</td>
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<td>Wi-Fi</td>
<td>Wireless Fidelity</td>
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Definitions

Channel congestion: The condition where the channel load generated by the users of the wireless network reaches or exceeds the channel capacity.

Channel load or utilisation: The amount of communication traffic that is being transmitted within a certain period of time.

Communication density: The amount of load on the communication channel (which depends on the number of communication nodes, packet size, packet rate, and nodes) per unit area.

Context information: The information about a local traffic situation that is relevant for the CCWS in determining the interactions between vehicles.

MAC: An abbreviation for the data link layer of the OSI model.

Neighbouring vehicles: Vehicles that are located within certain proximity to a subject vehicle.

PHY: An abbreviation for the physical layer of the OSI model.

Subject vehicle: An arbitrary vehicle that has the current focus in the discussion.

Surrounding environment: Other vehicles and the road situation within certain proximity to a subject vehicle.

Vehicle density: Number of vehicles per a unit area.

Wi-Fi: A range of connectivity technologies including wireless local area network (WLAN) based on the IEEE 802.11 standards.
Statement of Original Authorship

The work contained in this thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature: __________________________
              Alvin Sebastian

Date: __________________________
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Chapter 1

Introduction

This thesis proposes new context-aware methods for improving the performance of vehicular safety communication. The use of vehicular safety communication improves road safety for automobiles and other road vehicles.

This chapter starts by introducing the motivation to this research, followed by the research problems, major contributions, and scope of this research. The structure of this thesis is described in the last part of this chapter.

1.1 Background

Road traffic accidents cause significant fatalities, injuries and financial losses worldwide. Traffic accident casualties are estimated to contribute to around 1.2 million deaths, which is 2.1% of all deaths, and 50 million injuries each year globally [78]. The cost of economic loss was estimated as reaching roughly 2% of Gross National Product (GNP) in high-income countries [78]. The World Health Organization (WHO) conducted a global survey in 2008 that ranked road traffic injuries as the 11th and 9th leading causes of death in the year 2002 and 2004 respectively [75]. Without any improvement in traffic safety, the total number of deaths and injuries is predicted to increase by 65% between 2000 and 2020 [78]. The WHO predicted that road traffic injuries will be the fifth leading cause of death by 2030 [75].

In an effort to reduce traffic accident casualties, a number of safety features have been developed and integrated into our modern automobiles. Such safety technologies consist of passive safety and active safety measures [60]. Passive measures aim to reduce damage and protect the involved person when an
accident occurs. Examples of passive measures are seat belts, airbags, and an improved car frames and body design that can minimise crash impact. Active measures aim to prevent accidents from happening in the first place and minimise the effect of accidents, which can further reduce fatalities, injuries and financial losses. Examples of active measures are hydraulic brake systems, electronic brake systems (e.g. ABS), stability management systems (e.g. ESC) and advanced driving assistance systems (ADAS).

ADAS is an on-board vehicle device that can assess the driving environment and assist a driver by providing warning and enhanced information, or taking over vehicle control [60, 20]. There are several safety-related ADAS applications, such as collision warning and avoidance, vision enhancement, and dangerous spot warning. Special emphasis is given to collision warning systems (CWS) because they can prevent a probable collision caused by, for example, driver inattention. A CWS detects a possible collision and warns the driver accordingly. By realising the critical situation, the driver can perform an evasive action. As most accidents are caused by human errors [95], CWS, or ADAS in general, has the most potential to improve road safety significantly. In addition to safety purposes, there are ADAS applications designed with a focus on comfort and efficiency. Examples of such applications include adaptive cruise control (ACC), parking assistance, and lane keeping assistance. Some of these applications, such as ACC and parking assistance, have been offered on the consumer market since 1995 [112]. While ACC is designed primarily as a comfort or convenience system, several automakers have recently started introducing ACC with an integrated collision warning or avoidance system. However, their availability is generally limited to high-end vehicles because of the associated cost.

ADAS is one of the major outcomes from research in intelligent vehicles (IV), which is part of the larger effort in intelligent transportation systems (ITS). Currently, most ADAS and other IV systems are developed as autonomous systems. Each vehicle independently senses its surrounding environment (e.g. recognising nearby obstacles) by using external sensors such as radar, lidar, sonar, and camera [20]. ADAS processes information obtained from the sensors to be used to assist the driver. Although the sensors can sense various surrounding objects, there are some limitations in their detection range. As most of the sensors require a line-of-sight (LOS) for object detection, they may
not be able to provide sufficient information in complex road traffic situations. Furthermore, such sensors are often associated with high overhead cost, which prevents this technology from being widely adopted.

Rapid evolution of wireless communication technology has advanced the development of cooperative systems in the IV area [102]. Cooperative systems use wireless communication such as dedicated short-range communications (DSRC) to exchange information between vehicles and/or between vehicles and road infrastructure, conceiving what is termed as a vehicular communication network or a vehicular ad-hoc network (VANET). New DSRC standards such as IEEE 802.11p will enable reliable, low latency, wireless networks in the high-speed vehicle environment [46]. Furthermore, advancement in global navigation satellite systems (GNSS) such as Global Positioning Systems (GPS) allows precise localisation with centimetre accuracy. The combination of wireless communication and global navigation technologies may replace or complement the external sensors commonly used in ADAS.

The advantages of cooperative systems over non-cooperative systems have been discussed extensively in literature [15, 21, 60, 97]. In cooperative systems, a vehicle can acquire information about other vehicles that cannot be easily detected by external sensors. For example, vehicles properties such as speed, acceleration, or size can be obtained accurately via communication. Any information can be disseminated over a relatively long distance using a multi-hop scheme. Using radar or cameras to see around corners, behind other vehicles, or over hills is simply infeasible. It is also hard to ensure the reliability of such sensors under bad weather conditions such as heavy rain or fog. Cooperative systems enable better medium-range 360-degree situation awareness at an acceptable cost compared with non-cooperative systems. The production overhead of cooperative systems mainly includes the cost of wireless radio and satellite navigation devices, which is much lower compared to the cost of external sensor devices. The low cost factor may lower the barrier to achieve large market penetration. In addition, the use of communication enables a wide variety of non-safety applications that can further improve efficiency and comfort from the ITS perspective [59].

An important safety application driven by this new trend is a cooperative collision warning system (CCWS). A CCWS extends a typical CWS by incorporating the emerging wireless technologies such as wireless ad hoc networks
and satellite navigation systems. A CCWS employs vehicle-to-vehicle (V2V) communications to realise 360-degrees driver situation awareness and alert the driver of approaching threats without expensive equipment [30]. In such a system, every vehicle tracks the existence and motions of surrounding vehicles by exchanging safety messages using V2V communication. Several CCWS concepts and prototypes have been proposed and developed [65, 117, 97, 30, 89], indicating the technical feasibility of CCWSs given a high rate of market penetration and sufficient wireless spectrum.

While having several advantages over non-cooperative systems, there are some issues with cooperative systems that warrant further research [97]. First, cooperative systems require a high penetration rate, because any vehicle that does not communicate properly cannot be detected by the systems. Second, the accuracy and reliability of the positioning system constitutes the basic integrity of cooperative systems. Third, the reliability and integrity of cooperative systems also depend on the capability and performance of the communication system. This research specifically concentrates on the third issue by investigating and solving problems in the communication system of CCWSs. However, the first and second issues will be briefly discussed for the purpose of completeness.

Safety applications, especially CCWSs, require fast and reliable delivery of information to all relevant vehicles, in a dynamic network environment that is highly unreliable and has limited capacity [36]. Performance evaluations of safety communication using the preliminary IEEE 802.11p standard indicate that safety application requirements can be achieved [99, 119, 28, 123]. However, the technology cannot ensure time-critical message dissemination in dense road traffic conditions. Such a condition implies a high wireless channel load, which means a higher rate of contention and packet collisions among the spatially close vehicles resulting in unreliable communication [119]. To overcome this problem, it is necessary to develop safety communication protocols that can manage channel-load efficiently.

The purpose of this study is to investigate new methods to reduce channel congestion in a CCWS communication system. This is to ensure that the reliability and integrity of the CCWS will not be compromised by an unreliable communication system. The new methods involve the design of a new context-aware system consisting of a vehicle interaction model, efficient safety
message dissemination algorithms, and reliable communication protocols. In general, the objective of this research is to improve the performance of the communication system in the CCWS without compromising safety.

Findings from this research will contribute towards the development of a reliable CCWS that can perform more reliably even in high-density environments, such as traffic jams. It is believed that the CCWS will become one of the important safety features of the automotive industry in the future. In effect, this research will bring the CCWS closer to its reality and to the ultimate goal of improved road safety. Finally, the research contributes to the objective of all safety systems, which is to reduce traffic accident casualties: save lives, prevent injuries, and avoid financial loss.

1.2 Research Problems

Channel congestion is the problem of having unreliable communication performance because of heavy traffic load on the wireless channel. It is a major problem particularly for vehicular safety purposes because safety applications require frequent data exchange with low latency and high reliability. Since a wireless channel has limited capacity [36], heavy traffic load on the channel will cause channel congestion. Especially in dense traffic scenarios, channel congestion will cause high latency or packet loss and will make safety applications, such as a CCWS, defunct [99, 28, 123].

To improve the communication performance of the CCWS, channel congestion must be reduced by designing efficient and reliable higher-level communication protocols. The basic strategy is to optimise the wireless channel utilisation by reducing redundant transmission while still satisfying the safety requirement of CCWS applications. Such optimisation requires contextual information on how vehicles on the road interact with each other. For example, a vehicle should transmit a safety message only to other relevant vehicles that would possibly be endangered. Those endangered vehicles can be determined from the current traffic situation involving the states of nearby vehicles, i.e. a traffic model.

Some terminologies are commonly used in this research. A subject vehicle refers to a vehicle that is currently focused in the discussion. The surrounding environment refers to the other vehicles and the road situation within certain
proximity to the subject vehicle. It is assumed that all vehicles are equipped with a CCWS device that includes positioning and communication systems. There are two types of safety messages relevant to a CCWS that are fundamental for the protocols design [47]:

1. **Routine Safety Messages** (RSMs) are status update messages regularly sent by vehicles, so that every vehicle can realise the state of neighbouring vehicles and warn the driver of any possible collision. RSMs are also known as beacons.

2. **Event Safety Messages** (ESMs) are emergency warning messages triggered by drastic changes in vehicle behaviour or state which are likely to cause an accident (for example, deceleration exceeding a certain threshold, dramatic changes of moving direction, or major mechanical failure).

To achieve the objective, this study investigates the models, algorithms, and protocols of a context-aware communication system separated as three distinctive but closely related research problems:

1. **Vehicular traffic context modelling**
   The research question is about how to model the interactions among a group of vehicles as context information. The context information is used to optimise the communication system of the CCWS. The context model should be able to represent the interactions among vehicles under various traffic scenarios. Given the information about a number of vehicles and their properties (such as position, size, speed, heading, and acceleration) in a specific region and at a point in time, the problem is to develop a model that can represent multiple vehicle interactions. The use case of the model includes a query to determine the possibility of a collision between two vehicles. The model enables context-aware solutions for the following two problems.

2. **Routine safety message dissemination**
   A conventional method for RSM dissemination is to make every vehicle broadcast an RSM periodically at a constant interval or rate. The recommended interval is 100 milliseconds, which equates to a dissemination rate of 10 messages per second [98]. The constant-rate method may perform very well in a sparse road traffic situation, but may cause a
channel congestion problem if the traffic becomes denser. The dynamic nature of road traffic condition means that vehicle density can vary from very sparse to very dense. With a constant rate, the wireless channel utilisation may be underloaded or overloaded depending on the road traffic conditions. High channel utilisation increases the rate of packet loss, leading to unreliability of the CCWS. Therefore, the question is how to optimise the generation rate for different vehicular traffic densities and conditions without causing channel congestion and compromising safety. In addition, messages that impact the most endangered vehicles must be prioritised to improve safety. This problem can be solved by employing a context-aware adaptive rate scheme.

3. Event safety message dissemination
The major problems in ESM dissemination are how to limit the dissemination only to relevant vehicles and how to choose the most efficient relay. In a multi-hop message forwarding scheme, messages may need to be relayed by other vehicles to extend the coverage area. A simple flooding strategy will result in unnecessary transmissions leading to a broadcast storm problem [72]. To reduce unnecessary transmissions, an abnormal vehicle should send the ESMs only to relevant vehicles, rather than to all vehicles. The relevant vehicles are vehicles that are endangered by the abnormal vehicle’s manoeuvre. The relevant vehicles under various complex traffic situations can be determined using the traffic modelling techniques investigated in the first problem. To choose the relay vehicles efficiently, a tree-based multicast routing scheme is used. This problem is addressed by developing a context-aware multicast routing protocol that combines the tree-based routing approach with a contention-based strategy to provide reliability and robustness.

1.3 Major Contributions
The results from this research contribute to the knowledge in the area of intelligent vehicles and ITS safety systems in general, and wireless safety communication in particular. The main outcomes of this research are models, algorithms, and protocols that can improve the performance of the CCWS, particularly its
communication system. This study proposes efficient communication protocols that use optimisation algorithms based on context information to ensure that CCWS applications always perform reliably even in high-density environments, such as traffic jams. The improvement is expected to contribute towards the development of the CCWS.

This thesis presents original contributions to the body of knowledge as follows:

1. A context-aware framework for CCWS safety message dissemination protocols (Chapter 2).
   The framework introduces a new approach to improve both the communication and safety performances of the CCWS by incorporating context information. A context model is maintained by the system to provide feedback to the communication system. The context model is primarily used by the communication protocols for optimisation purposes, and can also possibly be used by the warning system to predict any possible collision. Unlike other existing approaches, this approach proposes a modular design that separates the context enquiries from the content of the protocols itself. To the best of our knowledge, the idea of using vehicular traffic modelling as a means to optimise communication is new in this research area.

2. A context model for CCWS that can represent the context information (Chapter 3).
   The context model represents interactions among multiple vehicles to provide contextual information to CCWS in various traffic scenarios. The new model can be used to easily identify endangered vehicles and their danger severities. Mainly, it enables the context-aware approach that can improve the performance of communication protocols. Additionally, it can be utilised by the warning algorithms to alert the driver. Prior to this study, there was no existing model that could be used to represent and determine the interactions among a group of vehicles. Existing related models only consider a single interaction between a pair of vehicles and cannot be used to determine all of the possible collisions between vehicles.

3. An efficient RSM dissemination protocol (Chapter 4).
   The new RSM protocol uses the context model and a new adaptive
scheme to improve the communication efficiency. The adaptive scheme adjusts the RSM generation rate or interval dynamically depending on the road traffic conditions. Unlike other existing optimisation schemes, the new context-aware scheme considers the interactions between vehicles in determining the generation rate. The new idea is to improve safety by giving priority to vehicles in the most danger. A vehicle in a dangerous situation should send RSMs at a higher rate compared to a vehicle in a rather safe situation. Existing RSM protocols are unable to prioritise a vehicle based on the dangerousness of its traffic situation. Compared to the conventional protocols that use a constant scheme, the new adaptive protocol is more efficient and scalable because it can deliver better performance in situations of either low or high vehicle density. More importantly, it can improve safety by prioritising the most critical messages.

4. An efficient ESM dissemination protocol (Chapter 5).
The new ESM protocol uses the context model and a new multicast scheme to improve the communication efficiency. The multicast scheme finds the most efficient paths to deliver ESMs only to the relevant vehicles, which are the vehicles that may be endangered by the sender. The relevant vehicles can be identified using the context model. In contrast, existing ESM protocols use broadcast schemes that cannot limit the dissemination only to the relevant vehicles, and therefore may send ESMs to a large number of vehicles in the area. The broadcast protocols cannot prioritise the endangered vehicles, which may result in some collisions that could be avoided otherwise. Compared to the existing protocols, the new protocol can reduce the number of unnecessary transmissions and the message reception latency, which reduces the number of vehicle collisions because ESMs are delivered to endangered vehicles as fast as possible. Furthermore, unlike existing protocols that assume ESMs are only disseminated on a highway, the new protocol does not make such an assumption, and therefore can be used in various road traffic scenarios.

5. A simulation platform to evaluate the new protocols (Appendix B).
A new simulator platform was developed by extending the network simulator ns-3 [1]. The evaluation of the new protocols involves simulating
highway traffic scenarios that can generate vehicle collisions or accidents depending on the performance of the protocols. A new mobility module was specifically created for this study because a suitable traffic or vehicular simulator was not available. It enables the simulation of vehicles moving on a highway and vehicle collisions based on the feedback from the communication network. Existing simulators mostly use a collision free traffic model, and therefore cannot simulate vehicle collisions. This simulator may be beneficial to other researchers in the vehicular safety communication area.

1.4 Scope and Limitation

Research on intelligent vehicles can be generalised into four areas: collision warning, driver assistance, collision avoidance and vehicle automation [15]. This study belongs to the area of collision warning, concentrating on the cooperative collision warning applications. The scope of this study can be detailed as follows:

1. The CCWS in this study is assumed to have no automation capability for collision avoidance (i.e. it can only warn the driver).

2. The CCWS is a complex system comprising of several components. This research focuses mainly on the communication component. In addition, some areas in microscopic traffic modelling and vehicular motion predictions are studied for improving the communication schemes. Issues associated with other components of the CCWS such as positioning systems and design of human-machine interfaces (i.e. how to give notification and alert the driver) are beyond the scope of this research.

3. This study addresses the channel congestion problems in vehicular wireless communication at high-level layers of the protocol stacks, mainly the application layer. Problems related to the network, MAC, or PHY layer are outside the scope of this research.

This study is mainly concerned about the performance of a vehicular wireless communication system under heavy load. A large number of vehicles are required in order to evaluate the system in such a condition. Because it is
currently infeasible to conduct real field operational experiments on the road involving many vehicles, the evaluation of this study is based on computer-based simulations. Due to the time limitation and difficulties in developing accident scenarios for every possible road traffic condition, the experiments focus on front-rear crashes in general highway scenarios. However, the theories, concepts, and algorithms are designed by considering a wide range of collision possibilities.

There are two assumptions made related to the other issues in the CCWS:

1. The reliability of the CCWS greatly depends on the accuracy and reliability of positioning or localisation technology. While outside the scope of this study, research on the accuracy and reliability of the positioning system will be discussed in Chapter 2. Based on the results of current positioning technologies [17, 25], it is reasonable to assume that a vehicle can obtain accurate position coordinates relative to other vehicles. Furthermore, a combination of external sensors such as radar, lidar and camera can be added to further improve the accuracy of the positioning system.

2. The experiments performed in this study assume that all vehicles are equipped with a CCWS, i.e. 100% penetration rate. Although the assumption can be considered as unrealistic from a practical point of view, it is sensible for the purpose of this study. It has been shown that with even less than 100% penetration, the use of CCWSs is still beneficial [87, 69]. A quantitative performance evaluation in different penetration rates is beyond the scope of this study. This study is mostly concerned with the communication problems in a high-density network. A very high penetration rate may result in a very high communication density that may cause channel congestion. In the case of less than 100% penetration, the correctness and reliability of the communication protocols will not be compromised because all vehicles without a communication device, or with a malfunctioning device, are considered to be non-existent from the perspective of the communication system.
1.5 Thesis Outline

The remainder of this thesis is organised as follows:

Chapter 2 introduces the concept, design and implementation of a CCWS. The chapter starts with an overview of a CWS in general, followed by the more specific CCWS. The state-of-art in this area is provided by surveying the architecture, components and technologies behind a CCWS, with an emphasis on the communication component. Recent advances in vehicular wireless communication are reviewed to identify the challenges and gaps in this research area. Based on the review, a new design of a context-aware communication scheme for a CCWS is proposed to improve the current system.

Chapter 3 investigates the vehicular dynamics and road traffic models to be used as context information in the CCWS. Different types of existing traffic modelling techniques are reviewed, but identified as unsuitable for the purpose of developing context-aware CCWS communication protocols. A new context modelling technique is proposed by adopting and incorporating some existing methods. A directed weighted graph is used to model the interactions between multiple road vehicles in a specific region and at a specific time. The context model allows for optimisation of the safety message dissemination schemes proposed in Chapter 4 and 5.

Chapter 4 proposes a context-aware adaptive dissemination scheme for routine safety messages. The chapter begins with a review of existing schemes that can improve the routine safety message dissemination. The problem of adaptive repetition rate is identified and described. A new context-aware approach that can solve the problem is discussed. The solution is presented as an adaptive rate protocol that can improve the safety and communication performance of the CCWS. The performance of the context-aware adaptive RSM protocol is compared with constant rate protocols under various traffic situations on a straight road.

Chapter 5 proposes a context-aware multicast dissemination scheme for event-based safety messages. The chapter begins with a review of existing
broadcast schemes related to event-based safety message dissemination. This study proposes a different approach by formulating the multi-hop dissemination as a multicast routing problem. The solution is presented as a multicast protocol and algorithms that employ the context model presented in Chapter 3. The proposed multicast protocol is then evaluated by comparing the performance with other broadcast protocols under some typical highway scenarios.

Chapter 6 concludes this study by providing a summary of the results, highlighting major contributions, and discussing future work and further development.
Chapter 2

Cooperative Collision Warning System

This chapter introduces the background, concept, and technical details of a Cooperative Collision Warning System (CCWS). It starts with an overview followed by a detailed description of the system components. Special emphasis is given to the wireless communication technologies that make the CCWS possible. Current problems in the communication area are identified and discussed by reviewing the state-of-art technologies of the vehicular wireless communication. Following the reviews of existing literature relevant to CCWSs, a context-aware solution to improve CCWS communication capability is presented.

2.1 Overview

A CCWS is an instance of an Intelligent Vehicle (IV) system designed to improve safety in road vehicles, particularly automobiles. IV systems use sensing and intelligent algorithms to understand the environment surrounding the vehicle and to assist the driver by providing an advisory or warning to the driver (collision warning), taking partial control of the vehicle (driver assistance and collision avoidance), or taking full control of the vehicle (vehicle automation) [15]. The ultimate goal of IV systems is to implement a fully automated vehicle, i.e. a self-driving car [103]. However, there are legal liabilities and technical challenges associated with achieving 100% reliability for full autonomy. The
approach taken by the automotive industry is to add pieces of autonomous functionality progressively so that cars will eventually evolve into autonomous robots [20]. Currently, the most prominent implementation of IV systems in commercial automobiles is Advanced Driver Assistance System (ADAS). Examples of ADAS applications include navigation systems, adaptive cruise control (ACC), adaptive light control (ALC), vision enhancement, speed assistance, parking assistance, and collision warning/avoidance. These applications aim to increase comfort, efficiency and safety by assisting the driver in their driving task continuously.

The development of IV systems can be categorised into two concepts: autonomous systems and cooperative systems [15]. In this context, the term "autonomous" means "non-cooperative", in a sense that each vehicle acts independently without communicating with other vehicles. Autonomous IV systems use sensors such as radar, lidar, sonar, and cameras to perceive the surrounding environment of a vehicle. These sensors provide relative-motion information (such as relative positions, velocities, and angles of obstacles) between the sensors and the obstacles. The data obtained from these sensors combined with the data obtained from internal motion sensors are processed by the intelligent algorithms to assist the driver. This concept has been implemented commercially and is available in the heavy-truck, bus and high-class consumer car markets. Cooperative IV systems, in contrast to the autonomous IV systems, depend on the communication between vehicles. Instead of using environment sensors, each vehicle realises the surrounding environment by exchanging information between vehicles and possibly between vehicles and infrastructures built on the roadside. Each vehicle can obtain its own positional information using a global positioning system (GPS) receiver, for example. The relevant information is transmitted to the neighbouring vehicles via a wireless communication system using dedicated short-range communication (DSRC). As an emerging research trend, the development of cooperative IV systems is still in the early stages.

The concept of a CCWS as a cooperative system is preceded by an autonomous Collision Warning System (CWS). The CWS is developed to detect possible oncoming collisions and to provide warning signals to alert the driver. The collision detection relies on the measurement of relative motion information (such as distance) on obstacles surrounding the subject vehicle. As auton-
2.1. Overview

Various IV systems, existing CWSs in the literature produce the measurement by using various sensors such as radar [50], lidar [5], sonar [52], camera [23], or a combination of different sensors [94].

The CWS is an active safety technology that can significantly reduce traffic accidents by preventing vehicle collisions. The technology extends the limited perception of human drivers by providing aid and assistance. Technologies that improve driver performance can have a significant impact on road safety because human error is estimated to be in a factor in 90% of all causes of traffic accidents [95, 78]. While passive safety technologies have made automobiles much safer in the event of a collision, they cannot reduce the chances of a collision. Worldwide statistics show a decreasing trend in number of fatalities in car accidents through the years but an increasing number of accidents [104]. Statistical accident data show that the primary cause for most road accidents is delayed driver reaction to recognise a dangerous situation. For example, 60% of collisions could be avoided if an extra half a second of warning time is provided to a driver, and with one second of warning time this portion increases to 90% [110]. CWSs have been in practical use in commercial heavy-truck fleets [110] and buses [111] in the United States for years with successful results. It is believed that providing some sort of appropriate warning to the driver can help reduce the probability and severity of car accidents.

Typical CWSs can only provide warning signals and do not attempt to take control of the vehicle. Therefore, there are less legal liability issues to deal with compared with other systems that can take control of the vehicle, such as collision avoidance systems. In most countries, as soon as the vehicle takes control there is a shift in the liability for any resulting crash from the driver to the manufacturer [20]. It is also technically harder to ensure the reliability of automated systems in handling the vehicle’s higher and lower level controllers [104]. Therefore, warning systems incur lower technical and non-technical barriers to commercial market adoption compared to other automated systems.

Recent approaches in the development of collision warning are heading toward CCWS. The basic function and goal of a CCWS is similar to a CWS. A CCWS incorporates navigation and wireless technologies, such as GPS and DSRC, instead of environment sensors. CCWS technologies aim to realise the concept of “360-degrees” driver situation awareness without expensive equipment [30]. Based on the benefits and feasibility, the author believes that CCWS
is the most sensible IV system to be widely implemented in the near future.

2.1.1 Definitions

According to Integrated Project PReVENT:

**Collision warning system** is a system that provides information to the driver indicating the need for urgent action to avoid a collision.

**Collision avoidance system** is a system for warning and avoidance of a pending collision.

Therefore, there is a distinction between systems that are able to perform manoeuvres and systems that only warn the driver about dangerous conditions. The capability to perform any avoidance manoeuvre involves a partial automation of vehicle control, which is outside the scope of this study.

In the context of this research, the definitions of CWS and CCWS are given as follows:

**Collision Warning System (CWS)** is a safety technology for road vehicles (automobiles) that can perceive the surrounding environment (roads, other vehicles and objects, etc.) and intelligently assess the situation to warn the driver about current or near-future dangerous situations. The warning is issued well in advance of a dangerous situation (probable collision in the longitudinal or lateral field) to warn the driver of the need to perform emergency braking, lane changing or other emergency manoeuvres in order to avoid a collision.

**Cooperative Collision Warning System (CCWS)** is a type of collision warning system that uses wireless communication technology to share information with other vehicles equipped with the same system. The CCWS collects surrounding vehicles’ location and dynamics and warns the driver when a collision is likely to occur [98]. Each vehicle sends and receives data such as the position, velocity, heading, yaw rate, and acceleration to and from other vehicles in the vicinity. Using this information along with its own position, dynamics, and roadway information

\footnote{Integrated Project PReVENT. http://www.prevent-ip.org}
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(map data), the system determines whether a collision with any vehicle is likely.

2.1.2 Autonomous and Cooperative Collision Warning Systems Comparisons

The most significant difference between autonomous and cooperative IV systems is that cooperative IV systems use wireless communication technologies to enable information exchange between vehicles (or between a vehicle and a roadside infrastructure). Both types of IV systems have their own advantages and disadvantages.

In autonomous IV systems, the capability of environment sensors to realise complex traffic situations is limited. Information fusion of multiple sensors and complex algorithms must be used to obtain results with an acceptable accuracy. Most of the sensors have a limited detection range and require a clear line-of-sight such that they may not recognise objects behind obstacles. It is also very difficult to retrieve some types of information such as other vehicles' type or size. The cost of such sensors is relatively expensive, deterring broad market acceptance of these systems.

In cooperative IV systems, a vehicle can obtain information about other vehicles that cannot be detected by the environment sensors. It is easier to obtain accurate states of the surrounding vehicles, such as speed or acceleration, by using communication. A vehicle has wider coverage of its perceived environment and can detect objects behind obstacles as long as all objects are equipped with communication devices. A further extended coverage range is possible using multi-hop transmissions. In addition, a set of communication and navigation devices incurs a much lower cost compared with the environment sensors. Apart from safety purposes, the wireless networking capability also enables a wide variety of non-safety applications for convenience and entertainment purposes. However, cooperative IV systems have some fundamental engineering limitations that need further research [97]:

1. Cooperative IV systems require a high penetration rate. To be effective, all the vehicles must be equipped with the system. Any obstacle that does not communicate properly can compromise the safety of all surrounding vehicles, for example: unequipped vehicles, road furniture,
vehicles with communication failure, or objects such as a pedestrian.

2. The reliability and integrity of the cooperative IV systems depend on the reliability of the positioning or navigation system of every vehicle. The positioning system needs to be accurate and reliable.

3. The reliability and integrity of the cooperative IV systems also depend on the reliability of the communication system. The communication system must have low latency and high successful reception rate under the dynamic traffic and blockage environment. This is a significant problem because wireless communication is highly unreliable by nature.

The second and third limitations can be considerably addressed by improving the related technologies. The solution to the first problem highly depends on the directions and policies from government and automotive industries. Some possible solutions to the first problem are [97]: 1) Integration of the cooperative and autonomous IV systems to take advantage of both systems; and 2) Achievement of cooperative IV system penetration in that all vehicles and related road infrastructures must be equipped with necessary equipment and devices by formulation and enforcement of governmental regulations and policies. This study focuses on the third limitation, which is about improving the performance of communication systems in a technical manner.

2.1.3 Approaches to Collision Mitigation

Communication requirements for a CCWS are determined by its various safety applications, which generally demand fast and reliable delivery of information. Based on the safety application requirements, the CCWS approaches to prevent collisions can be classified into two different types [21]:

1. Proactive approach

   In a proactive approach, the CCWS uses information from other neighbouring vehicles such as position, velocity, direction, etc. to make a prediction if there is a high probability that a collision may happen within the current situations. Each vehicle regularly transmits status update messages so that each vehicle can realise the location and dynamics of surrounding vehicles. Using this information, the system can predict the
possibility of an impending collision and provide advance warning to the driver so that the collision can be avoided. A proactive approach implies the use of Routine Safety Messages (RSMs) or beacon messages.

2. Reactive approach

In a reactive approach, a vehicle will send emergency warning messages to the relevant neighbouring vehicles in the event of drastic behaviour changes (such as a hard braking, sudden manoeuvre, or mechanical failure) that may lead to a dangerous situation. In some situations when a collision is inevitable or when the proactive approach failed to prevent a collision, using a reactive approach can prevent further collisions that may occur, such as in a case of chain collision accidents. A reactive approach implies the use of Event Safety Messages (ESMs) or emergency warning messages.

The proactive approach aims to prevent the occurrence of dangerous situations in the first place, while the reactive approach aims to prevent the consequences of dangerous situations that have already occurred. To provide reliable and comprehensive road safety, CCWSs should employ both a proactive approach and a reactive approach [21].

2.1.4 Existing Design and Prototypes

Considering the complexity of a CCWS, most of the related work in this area focuses on a particular aspect. However, several studies described the overall system design and proposed a basic concept [65, 45, 35] or a working prototype [43, 97, 89, 22, 66, 83]. Generally, the proposed systems rely on similar key technologies, mainly the GPS and wireless communication devices. Recent CCWS designs assumed the use of DSRC wireless technology [8].

Some of the proposed CCWSs are designed for a particular function or scenario, such as forward/rear-end collision warning [9] or intersection collision warning [65, 71, 42]. For example, an overall CCWS architecture is presented in the work by Miller and Huang [65], but the study is focused on a collision estimation algorithm for a road intersection scenario. Huang and Lin [42] proposed an improved intersection warning algorithm that can be used in the curve environment. Particularly for intersection collision warning, the avail-
ability of roadside infrastructures can provide better communication coverage and additional information such as traffic signals [71].

More general systems [97, 89, 22, 66] are designed to support various warning applications (such as forward collision warning, lane change assistant, and intersection warning) to handle different functions and situations. The prototypes proposed by Tan and Huang [97] and Sengupta et al. [89] use an estimator that fuses measurements from the GPS and the in-vehicle motion sensors to improve their positioning reliability. Gumaste et al. [35] proposed a communication cluster scheme to improve the CCWS communication reliability. To provide existing vehicles with the CCWS capabilities, General Motors has developed a prototype of an add-on transponder device that can be mounted on any existing vehicle [33]. The results from those studies indicated the technical feasibility of CCWS. However, improvement in robustness and reliability is still required for the system to be widely adopted and deployed.

Most of the aforementioned CCWSs prevent collisions by using the proactive approach [65, 45, 43, 97, 35, 89, 83], although some of them imply the use of both the reactive and proactive approaches [22, 66]. Usually, the prior works that use a reactive approach [117, 16] studied only a specific issue in the communication system. Furthermore, almost every existing CCWS is designed based on ad hoc communication, which allows the system to work without any supporting roadside infrastructure or central processing servers. In some cases, such as at intersections [71], having the infrastructure support is highly beneficial.

### 2.2 System Architecture and Components

There are various CCWS architectures proposed in related literature. Some of the system architectures have been built and tested as real-world prototypes [97, 89, 22, 66, 83]. Their high-level designs are similar in principle and thus can be generalised as shown in Figure 2.1. The architecture diagram mostly follows the concept proposed by Sengupta et al. [89], which uses common elements useful to multiple warning applications. The design uses a layered architecture to make improvement and maintenance easier.

Basically, a CCWS unit installed in a vehicle consists of data acquisition devices, communication devices, and an on-board computer. Five functional
blocks constitute the core of the CCWS concept: human machine interface, safety applications, situation awareness system, positioning system, and communication system. A vehicle obtains its own state (position and motion) information using the positioning system. The communication system is responsible for sending the state information to neighbouring vehicles and for receiving the state information sent by neighbouring vehicles. The state information of the subject vehicle and its neighbours is tracked and stored in the situation awareness system. Safety applications calculate and estimate any possible collision using the situation awareness system and send the warning signal to the human machine interface. The interface is then responsible for alerting the driver to any imminent danger.

### 2.2.1 Human Machine Interface

The human machine interface allows the system to interact with the driver. The function of this component includes alerting the driver of an impending collision and displaying the surrounding vehicles map. The user interface
design is important as it directly influences the effectiveness of the safety system. The method of warning must not distract the driver in a critical situation [88]. A CCWS will likely use more than one type of interface, such as audio, visual, and haptic interfaces. For example, an existing audio system in the vehicle can be used for audio warnings and an on-board monitor can be used to display roadmaps and visual warnings [65].

2.2.2 Safety Applications

This component is the layer where various specific collision warning modules are implemented. The modules involve vehicle manoeuvre prediction algorithms to determine the possibility of a collision and warning algorithms to determine the timing and importance of the warning alert. The objective is to avoid the collision by issuing an early warning from which it is still possible for the driver to take necessary preventive actions, without excessive nuisance alerts. The warning modules use the information provided by the situation awareness module, such as the position of surrounding vehicles, and the near-future estimations. This architecture enables a flexibility in which new warning modules can be developed and added on top of the situation awareness system. This simplifies the development of warning modules because each module does not need to individually process raw data obtained from communication systems.

The technical challenge is to make the vehicle prediction more accurate by computing the uncertainties on the road and the delay of wireless communication, so that the lowest rate of false alarm can be achieved. The warning system should minimise the driver’s attention load instead of adding to that load. It should consider the effect of individual driving styles and allow for personal customisation of warning frequency and sensitivity. Each driver has a different driving style, from passive to aggressive. If the system is only designed for the “average” driver, the warning frequency will tend to alienate passive and aggressive drivers [88]. A multi-grade warning concept can be used to offer a gradual response time for the driver [107]. In addition, a warning algorithm based on impact energy can help reduce false alarms [45].

Several examples of warning modules have been summarised from various sources [98, 89]:

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• **Forward Collision Warning (FCW).** A FCW warns the driver when the vehicle is in danger of a collision with another vehicle that is moving in the same direction or stopping in front of it.

• **Intersection Collision Warning (ICW).** An ICW aims to prevent accidents at intersections by warning the driver of any possible threat coming from crossing directions. Intersection collisions account for almost 30% of all crashes, but research in intersection collision warning has produced less significant results compared with forward collision warning [65]. This is because the problem is more complicated and the environment sensors (used in most collision avoidance systems) require a clear line-of-sight to detect the threatening vehicles, which is mostly impossible in intersection cases. In the cooperative approach, non line-of-sight threat detection is possible.

• **Rear Collision Warning (RCW).** A RCW warns the driver of a possible crash from behind. There are other functions defined using the same term, such as a warning sign located at the rear of a vehicle to warn following drivers of impending danger or a system for warning a following vehicle of a potential collision with a leading vehicle. It is also called a Rear Impact Warning.

• **Lane Change Assistant (LCA).** A LCA warns the driver of a possible crash from a vehicle in an adjacent lane when the driver attempts to change lanes.

• **Emergency Electronic Brake Light (EEBL).** An EEBL warns the driver of the following vehicles when the leading vehicle is breaking hard. The leading vehicle sends an emergency message to other vehicles following behind if hard braking is detected. The following vehicles then must determine the relevancy of the received emergency message, and will issue a warning to the driver based on the relevancy. The purpose of this application is to mitigate the chain collision accidents.

• **Post Crash Notification (PCN).** This application is similar to the EEBL, whereas in this case an emergency message will be sent after a vehicle is involved in a collision.
From the example applications, FCW, ICW, RCW, and LCA can be classified as applications that use a proactive approach while EEBL and PCN can be classified as applications that use a reactive approach.

### 2.2.3 Situation Awareness System

This component is the base layer that supports the warning modules in the upper layer. Situation awareness systematically perceives, understands, and anticipates the environment to enhance the driver’s risk perception and reaction \[97\]. Situation awareness can be constructed based on current positions and the future trajectories of all surrounding vehicles. This component is closely related to and enabled by the components below it, which are the positioning system and the communication system.

An example of a concrete implementation of this layer is a neighbouring vehicle map (NVM) \[89\]. The NVM can be viewed as a database that continuously tracks the state of the neighbouring vehicles and the subject vehicle, which realise the 360° awareness of the CCWS. As a common element, the information in the NVM is shared and processed by various collision warning modules. For example, the Forward Collision Warning Module is only interested in the area in front of the vehicle and in the same lane as the vehicle. The Lane Change Assistant Module is only interested in the area behind and in the left or right lane of the subject vehicle. Because the NVM provides 360° situation awareness, other collision warning modules would be added on top of the NVM layer.

### 2.2.4 Positioning System

The positioning system is the component that provides real-time positional information of the subject vehicle. The information is used to estimate any possible collision and is shared with neighbouring vehicles. Most cooperative IV systems rely on the global navigation satellite system (GNSS) technologies to provide absolute position and time information anywhere on earth. As of 2010, the only fully operational GNSS is the USA Global Positioning System (GPS). A GPS receiver is relatively inexpensive and is widely used as an on-board navigation system for vehicles. GNSS-based absolute positioning is currently considered to be the most mature and feasible approach for
cooperative collision warning.

The positioning system must satisfy four requirements: accuracy, latency, reliability, and availability [97]. The analysis of accuracy requirements for CCWS indicates that 1 m accuracy could be marginally acceptable for most CCWS applications, but 50 cm accuracy is recommended [91]. In order to satisfy the accuracy requirement, a more accurate GPS such as differential GPS (DGPS) with a standard deviation between 0.3 m and 0.5 m is required. The recommended accuracy value is within a range that can be achieved today with DGPS in locations that have good sky exposure. There are also other approaches to obtain relative positioning with high accuracy from GPS measurements. For example, neighbouring vehicles can exchange raw GPS data and use the raw data to calculate the accurate relative distance between nearby vehicles [86]. The GNSS positioning accuracy is expected to improve significantly in the future with the continuing improvements in GPS performance and the addition of other satellite constellations such as the European Union’s Galileo and the Russian GLONASS [91].

To further improve the accuracy, reliability and availability, the positioning system also includes an estimator that fuses measurements from the DGPS, the internal motion-sensor suite (such as wheel speed encoders, yaw rate gyro, and steering angle sensor), and other sources. Prior studies with field tests have indicated that such an estimator can provide centimetre-level accuracy under good conditions [97, 89]. Other measurement techniques that can be fused by the estimator to further improve the positioning system include various radio-based ranging techniques [56, 77]. Radio-based ranging techniques work by measuring the signal strength of wireless communication devices and calculating the relative location using a distributed algorithm. By combining various localisation techniques using data fusion techniques, a vehicle can obtain accurate and robust position coordinates relative to other vehicles [17, 25].

The highest level of reliability can be achieved by integrating additional environment sensors as being used in the autonomous IV systems. Low cost sensors, such as radar, sonar, and cameras, can be integrated without penalising the low-cost advantage of cooperative IV systems. The additional sensors can ensure basic function of relative positioning even during GPS outage situations [86].
2.2.5 Communication System

The communication system is the component that handles all the communication-related functions. This component manages the data exchange between vehicles by cooperating with the situation awareness system and the safety applications. The functions performed by this component include:

1. Retrieving the subject vehicle’s state information from the situation awareness system and sending the information as safety messages to the neighbouring vehicles.

2. Receiving the safety messages sent by neighbouring vehicles and storing the relevant content to the situation awareness system.

3. Sending the safety messages as requested by the safety applications. Such a request may be triggered by multiple events.

A vehicle must be able to exchange information with other vehicles within a certain coverage radius. It is achieved by equipping each vehicle with a wireless radio device that is designed for the vehicular environment. As indicated in the literature [89, 66], the de facto chosen technology for the CCWS communication component is a wireless network technology based on the IEEE 802.11 standard, also well known as Wi-Fi. To ensure a reliable operation in the vehicular environment, an amendment has been made to the IEEE 802.11 standard known as the IEEE 802.11p. The IEEE 802.11p is likely to become the wireless standard vehicular communication due to its benefits in terms of hardware costs, bandwidth, latency, reliability, and communication range.

The actual coverage area of the radio transmission depends on the power output and the type of antenna. With the IEEE 802.11p standard, the radio range is expected to achieve up to 1000 m. The type of the antenna determines the shape of the coverage area. A directional antenna is more efficient in using the wireless medium spatially compared to an omni-directional antenna [55]. However, existing CCWS prototypes generally use an omni-directional antenna because of availability and the ease by which it can achieve a 360° coverage area.

Vehicles need to send information such as position, speed, heading, and other data using standard protocols recognisable by all other vehicles [89].
Thus, the communication system component requires the standardisation of the communication protocols, both higher-level and lower-level protocols. The SAE J2735 defines the data packet format or structure, which should be handled by a message dispatcher [81]. The IEEE 802.11p defines the PHY and MAC layer standards and the IEEE 1609 defines the network and transport layer standards. At the network and transport layer, all types of safety messages are handled by the WAVE short message protocol (WSMP) [3]. The higher-level protocols in a CCWS should handle two different kinds of safety messages: RSMs and ESMs. Therefore, a CCWS needs to have both a RSM dissemination protocol and an ESM dissemination protocol. The following Chapter 2.3 provides an overview of the knowledge related to vehicular communication.

2.3 Vehicular Wireless Communication

Vehicular wireless communication generally refers to information exchanges between entities in road transportation systems using wireless communication technology. The wireless communication technology is one of the key elements that constitute the CCWS. Several CCWS prototypes have been built using off-the-shelf wireless devices such as 802.11a, 802.11b, or 802.11g devices. Those prototypes show the feasibility of developing the CCWS using current wireless technology. Some efforts have been made to improve the performance of the technology specifically in a vehicular environment. This section introduces some details of the wireless technology that is used in vehicular communication.

2.3.1 Overview

Vehicular wireless communication may be broadly categorised into vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. In the V2V communications, vehicles communicate directly with each other without support from the infrastructure. In the V2I communications, vehicles communicate with each other with the support of infrastructure such as roadside wireless access points. Vehicles may also communicate with the infrastructure only.

The use of wireless communication in the road transportation system is in-
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introduced by the research in the Intelligent Transportation System (ITS) area. The ITS is an effort to improve the safety and efficiency of existing transportation networks by using advance computer and communications technology. In the ITS, communication can be used for safety or non-safety related purposes. Examples of safety applications are collision warning or avoidance, emergency vehicle notification, road danger warning, and rail-road crossing warning. Examples of non-safety applications include automated toll payment, traffic management and information, enhanced navigation, and infotainment applications such as providing access to the Internet.

The earliest research into vehicular communication was conducted in the 1980s at the Japan Automobile Research Institute [102]. This research considers vehicular communications primarily as traffic and driver information systems incorporated in Advanced Traffic Management Systems (ATMS) / Advanced Traveller Information Systems (ATIS). Japan was the leader in vehicular communications research, beginning before either Europe or the USA. Recently, communications systems for improving automobile traffic safety have generated a great deal of interest in Europe, the USA, and Japan.

Government agencies together with automotive industries have cooperated in promoting the penetration of wireless communications into the transportation system. Significant research activities are conducted worldwide to develop vehicular safety communication technologies. In Japan, the activities include the Advanced Safety Vehicle Program (ASV) and projects supported by the Japan Automobile Research Institute (JARI). In the USA, activities include initiatives such as California’s Partners for Advanced Transit and Highways (PATH), the Department of Transportation’s Intelligent Vehicle Initiative (IVI), and the Vehicle Safety Communication Consortium (VSCC) of the Crash Avoidance Metrics Partnership (CAMP). In the European Union (EU), the activities are conducted through several projects such as Car-to-Car Communications Consortium (C2C-CC), the German FleetNET, CarTalk2000, Network On Wheels (NoW), PReVENT, and Cooperative Vehicles and Infrastructure Systems (CVIS). In Australia, the activities include AusDSRC, an industry-driven national cluster, and projects supported through the Cooperative Research Centre for Advanced Automotive Technology (AutoCRC) program.

There are various wireless technologies that can be considered for vehicu-
lar communication purposes [92], such as 3G Cellular networks, ultra wide band (UWB), IEEE 802.11 (Wi-Fi), IEEE 802.15.1 (Bluetooth), and IEEE 802.16 (WiMAX) [114]. Other technology such as wireless sensor networks (WSNs) can also be used in the ITS [57]. Particularly for vehicular safety communication, the technology must support low latency and high reliability communications in high-speed mobile environments [21].

To satisfy the requirements, a new technology for dedicated short range communications (DSRC) has been standardised by IEEE as 802.11p and 1609 [47]. Furthermore, international standardisation efforts have been conducted by the International Organization for Standardization (ISO) TC 204 Working Group 16. The working group proposed a standard for the Communications Access for Land Mobiles (CALM) concept. CALM specifies a common architecture, network protocols and communication interface definitions for wired and wireless communications using various access technologies including cellular network, satellite, infra-red, microwave, and mobile wireless broadband. Especially for safety communication, the standard defines the CALM M5 access technologies that incorporate the IEEE 802.11p and 1609 standards.

2.3.2 Dedicated Short Range Communications

Dedicated short range communications (DSRC) generally refers to a short to medium range communications service that supports V2V and V2I communications. The term DSRC has been used liberally and may refer to several distinct entities:

1. An earlier standard for short range vehicular communication that operates in the 915 MHz (USA) and 5.8 GHz (Japan and Europe) band. This technology provides wireless communication within a short distance of up to 30 meters [59]. It is currently operational and used primarily by commercial vehicles and electronic toll payment systems.

2. A radio frequency spectrum allocation in the 5.9 GHz band to be used exclusively for vehicular communications.

3. Wireless access technology and its implementations that operate in the 5.9 GHz band and comply with the IEEE 802.11p and IEEE 1609 standards. This technology can provide high speed, low latency, and reliable
vehicular safety communications. The DSRC-related standards are also termed as wireless access in vehicular environments (WAVE) standards. Because this technology is based on the popular Wi-Fi technology, the associated production cost is relatively low. The use of the term DSRC in the rest of this discourse shall refer to this third entity.

The spectrum allocation in the 5.9 GHz band for vehicular communications was first initiated in the USA. In 1999, The USA Federal Communication Commission (FCC) dedicated a 75 MHz spectrum in the 5.9 GHz range (5.875 - 5.925 GHz) for DSRC. The DSRC spectrum is structured into seven 10 MHz channels as shown in Figure 2.2. Channel 178 is assigned as the control channel (CCH), which is a special channel restricted for safety communications and system management purposes only. The two channels at the ends of the spectrum band are reserved for special uses. The rest are service channels (SCHs) that can be used for both safety and non-safety purposes. Other countries may have different DSRC bandwidth allocations. For example, in Europe, the 5.885 GHz to 5.905 GHz spectrum range has been requested to be allocated for critical road safety purposes.

In Australia, the spectrum allocation for DSRC has also been considered [2]. The Australian Communications and Media Authority (ACMA) has proposed a staged plan to release the 5.9 GHz band for DSRC, harmonised with other international arrangements. There are some existing services that may potentially cause interference in the 5.9 band. Such issues must be addressed before the spectrum can be allocated. Similar efforts are occurring in other parts of the world to allocate a radio spectrum band exclusively for vehicular communication.

![Figure 2.2: DSRC 5.9GHz spectrum band and channel allocation in the USA.](image-url)
2.3.3 IEEE 802.11p

The IEEE 802.11p is an amendment to the IEEE 802.11 standard to enhance its operation in vehicular environments. The IEEE 802.11p is based on the IEEE 802.11a adjusted for low overhead operations in the DSRC 5.9 GHz spectrum. The scope of the IEEE 802.11p standard is limited to a MAC and PHY layer that is meant to work within a single logical channel. All necessities related to the DSRC channel plan and operational concept, are handled by the upper layer IEEE 1609 Wireless Access for Vehicular Environment (WAVE) standards. The high-level WAVE architecture is shown in Figure 2.3.

The initial effort at standardising DSRC radio technology was conducted by the American Society for Testing and Materials (ASTM) 2213 working group. In 2002, the ASTM E2213-02 standard was approved and accepted as the basis for the 5.9 GHz American ITS. In 2004, the standardisation effort was transferred to the IEEE 802.11 standard group. The Task Group “p” completed the initial draft in February 2006. The final version was published in July 2010 [4].

The modulation scheme used in the 802.11p PHY is Orthogonal Frequency Division Multiplexing (OFDM). It is a variation of the OFDM from the IEEE 802.11a standard. The 802.11p PHY defines exactly the same signal processing

![Figure 2.3: The WAVE protocol stack.](image-url)
and specification as the 802.11a with the following exceptions:

1. The IEEE 802.11p operates in frequency bands of 5.9 GHz.

2. To increase the tolerance for multi-path propagation effects of signals in the vehicular environment, 10 MHz frequency bandwidth is used instead of 20 MHz. This change in channel width is accomplished through doubling all relevant timing parameters of the IEEE 802.11a PHY. Having a smaller frequency bandwidth reduces the effects of Doppler spread and doubling the guard interval reduces the inter-symbol interference caused by multi-path propagation. As a result of the above, the data rate is halved. The supported data rates range from 3 Mbps to 27 Mbps.

3. In order to support a greater communication range in vehicular environments, four classes of maximum allowable Effective Isotropic Radiated Power (EIRP) up to 44.8 dBm (30W) are defined in IEEE 802.11p. The largest value is reserved for use by approaching emergency vehicles. The power levels specification allows for a communication range from 100 m to 1000 m.

The IEEE 802.11p MAC layer is equivalent to the IEEE 802.11e Enhanced Distributed Channel Access (EDCA) Quality of Service (QoS) extension. The core mechanism uses the IEEE 802.11 Distributed Coordinated Function (DCF), which is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. The DCF supports two access schemes: the basic mode and the request-to-send/clear-to-send (RTS/CTS) mode. For safety communications in CCH, only the basic mode can be used.

The EDCA mechanism provides the QoS support of traffic prioritisation. It includes Listen Before Talk (LBT) and a random back-off. The back-off consists of a fixed and a random waiting time. The fixed waiting time is a number of “slots” given by the parameter AIFS, with an 8µs slot duration. The random waiting time is also a number of slots, but the factor is drawn from a Contention Window (CW). The initial size of the CW is given by the factor $CW_{min}$. Each time a transmission attempt fails, the CW size is doubled until it reaches the size given by the parameter $CW_{max}$.

Prioritisation is provided by using different channel access parameters for each packet priority. There are four available access categories originally
2.3. Vehicular Wireless Communication

Table 2.1: EDCA parameter set.

<table>
<thead>
<tr>
<th>Access Categories</th>
<th>AIFS</th>
<th>CW_{min}</th>
<th>CW_{max}</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC_VO</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>AC_VI</td>
<td>3</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>AC_BE</td>
<td>6</td>
<td>7</td>
<td>15</td>
</tr>
<tr>
<td>AC_BK</td>
<td>9</td>
<td>15</td>
<td>1023</td>
</tr>
</tbody>
</table>

defined for background (AC_BK), best effort (AC_BE), voice (AC_VO) and video (AC_VI) traffic. The parameter set used in IEEE 802.11p is shown in Table 2.1. AC_BK has the lowest priority while AC_VO has the highest priority. In this study, ESMs are assumed to have AC_VO priority (the highest) and RSMs are assumed to have AC_VI priority. There have been further attempts to improve the prioritisation techniques. For example, an adaptive QoS technique that can adjust the contention window size of non-safety queues depending on the channel usage level [123]. If the channel usage level is high, higher priority will be given to the safety queue, so as to minimise the delay for safety messages.

2.3.4 IEEE 1609 Wireless Access in Vehicular Environments

The IEEE 1609 Family of Standards for Wireless Access in Vehicular Environments (WAVE) defines the architecture, communications model, management structure, security mechanisms, and physical access for wireless communications in the vehicular environment. The IEEE 1609 extends the PHY and MAC layers defined in IEEE 802.11p to provide a complete DSRC functionality.

The IEEE 1609 consists of the following standards:

1. IEEE 1609.1 - WAVE Resource Manager
   This standard defines the WAVE Resource Manager to enable interoperability of WAVE applications. It describes major components of the WAVE architecture, and defines command and storage message formats.

2. IEEE 1609.2 - WAVE Security Services
   This standard describes security services for WAVE management and application messages to prevent attacks such as eavesdropping, spoofing,
alteration, and replay. It covers the format of secure messages and their processing.

3. IEEE 1609.3 - WAVE Networking Services

This standard specifies addressing and routing services within a WAVE system. It defines two parallel protocol stacks on the network and transport layers to support both safety and non-safety applications. The IPv6 together with TCP and UDP are used primarily for non-safety applications. The support of TCP/IP allows the use of any existing internet application. The WAVE short messages protocol (WSMP) is used mainly for safety applications. The WSMP enables the application to send short messages and directly control certain parameters of the radio resource, such as data rate and transmission power level.

4. IEEE 1609.4 - WAVE Multi-Channel Operation

This standard provides enhancements to the IEEE 802.11p MAC to support multichannel operation. Different channels can be used for different types of applications. An example of the available channels is shown in Figure 2.2. Since the design shall allow both single and multi receiver units, the different channels cannot be used simultaneously. Each station continuously alternates between the Control Channel (CCH) and one of the Service Channels (SCHs). A period containing one CCH interval and one SCH interval shall last no more than 100ms. The IEEE 1609.4 resides above 802.11p and supports the operation of higher layers without the need to deal with the physical channel access parameters.

A WAVE system consists of entities called units. Road-Side Units (RSUs) are stationary devices usually installed in roadside infrastructure such as light poles, traffic lights, road signs, and so on. On-Board Units (OBUs) are mobile devices mounted in vehicles. RSUs and OBUs can be either a provider or a user of services and can switch between such modes. By default, WAVE units operate independently. However, they also can organise themselves in small networks called WAVE basic service sets (WBSSs), which are similar in nature to the service sets defined in IEEE 802.11. WBSSs can consist of OBUs only or a mix of OBUs and RSUs.
2.3.5 Vehicular Ad Hoc Network

A vehicular ad hoc network (VANET) is a type of mobile ad hoc network (MANET) operating in vehicular environments that involves V2V and V2I communications. A MANET is a self-configuring, infrastructure-less, computer network that consists of mobile devices interconnected via wireless links. Each communication node in a MANET can move independently, and will therefore change its communication links to other nodes frequently. A VANET is established when a significant number of vehicles are equipped with DSRC devices.

The difference between VANETs and MANETs or other conventional ad hoc wireless networks can be summarised as follows:

- A typical MANET assumes that no infrastructure is available. In a VANET, the assumption is that it is possible to have infrastructure (access points) built along the side of the road.

- The network topology in VANET is assumed to be changed more frequently than in MANET because vehicles can move at high speed. Frequent topology changes imply that a communication link between two vehicles can only be maintained for a very short time. However, the mobility pattern in VANET is predictable to some extent as the movement of a vehicle is constrained by the road.

- Unlike some types of MANETs, in VANETs there are virtually no transmission power or energy constraints. A vehicle can afford significant computing, communication, and sensing capabilities.

- The network densities in VANETs can vary significantly. For example, on freeways or urban areas during rush hour traffic, the network density is expected to be very high, while on rural freeways or during late night hours the network density is expected to be much lower.

- VANETs are expected to handle a wide range of applications ranging from safety to leisure. Consequently, routing and dissemination algorithms should be efficient and should adapt to the characteristics of different applications.
The realisation of VANETs will create opportunities to enhance the applications of ADAS that can improve road safety, increase road capacity, reduce fuel consumption and provide higher comfort level for drivers. This is possible assuming that vehicles have communication capabilities combined with the integration of on-board computers, digital roadmaps, and positioning devices. Based on their purposes, VANET applications can be categorised into safety and non-safety applications. Safety applications such as collision warning/avoidance systems aim to prevent traffic accidents, reduce casualties, and save lives. In addition to safety purposes, the wireless networking capability also enables a wide variety of non-safety applications, such as traffic management and information, electronic payment, and general Internet access. Non-safety applications can provide improved navigation, information and entertainment for the drivers.

Considering the high number of deaths and casualties caused by traffic accidents, special emphasis is given to the development of safety applications. However, the development of non-safety applications may be necessary to encourage wider adaptation of DSRC into the market to achieve higher penetration rate. The stringent performance requirements and dynamic vehicular environment pose new networking challenges. The solutions require network architectures and communication protocols that are customised to VANET.

2.3.6 Communication Challenges in CCWSs

The development of CCWSs has been greatly influenced by recent advances in wireless communication technologies. The benefit and feasibility studies have been performed with positive results, but real-world implementation will depend on the technical improvement in vehicular communication systems. One of the challenges is to ensure the capability and performance of the communication system. Safety applications such as CCWSs impose strict requirements on the communication system for them to be able to function properly. They require frequent data exchanges among vehicles with low latency and high reliability [21] in a network environment that is highly unreliable and has limited capacity [36].

The performance of communication systems that implement preliminary IEEE 802.11p WAVE standard have been evaluated extensively in the litera-
2.3. Vehicular Wireless Communication

The results indicate that the standard achieves promising latency performance compared to safety application requirements. Real field tests on open space and freeway traffic environments showed an adequate degree of communication reliability under both traffic environments [10]. Further examination of the CCWS communication reliability shows the system’s potential in tolerating communication losses and delays [44]. It has been shown that the radio technology of IEEE 802.11p WAVE can provide an adequate signal reception in an environment with high-speed mobility.

However, in dense and high load scenarios, the throughput decreases while the delay increases significantly. The technology cannot ensure time critical message dissemination particularly in dense scenarios [28]. This is due to the packet collision among the spatially close vehicles, which causes frequent back-offs [119]. Simulation studies have shown that under heavy wireless channel usage, more than 10% of the messages would be lost due to packet collisions [113]. The underlying reason is that the radio bandwidth is limited, and can easily be overloaded when multiple neighbouring vehicles try to flood the airwaves with data packets in an uncoordinated manner. This problem is referred to as a channel congestion problem. Channel congestion causes high latency and packet loss, which can make the safety applications defunct.

Channel congestion is a situation that occurs when channel utilisation reaches the channel capacity. Basically, the channel utilisation depends on the combination of data rate, packet size and communication density [47]. Communication density can be defined as the number of carrier sensible events per unit of area and unit of time. Essentially, it is the product of vehicle density, message size, message generation rate, and transmission range. In the vehicular environment, the vehicle density can vary depending on the road traffic conditions. For example, on a quiet rural road, the vehicle density can be very low, while on a busy freeway or traffic jam, the vehicle density can be very high. Because the vehicle density is highly dynamic, the message generation rate or transmission range should be made adaptive to control the communication density and channel congestion.

Congestion control is needed in all layers of the communication protocol stack [123]. In a CCWS, safety message dissemination protocols must include strategies to reduce unnecessary transmissions in order to control congestion and improve reliability. This includes the protocols for RSM and ESM.
dissemination. The proper design of repetition or multi-hop retransmission strategies can ensure the reliability of the communication system in any road conditions. The congestion can be managed by estimating the number of neighbouring nodes, and adjusting the message generation rate or transmission power accordingly [47]. Such an adjustment strategy requires a system that can understand the neighbouring road traffic situation. In addition, channel utilisation should be minimised without compromising safety requirements imposed by the CCWS. Existing message dissemination schemes for both RSM [79, 81, 7, 84] and ESM [13, 117, 16, 76, 101] did not fully consider the road traffic situation, such as the interactions between vehicles.

2.4 Context-Aware Communication System

To address the channel congestion problem in a CCWS, this study proposes a context-aware communication system. The system aims to improve the performance of the CCWS communication system by designing higher-layer communication protocols that can make use of the context information to reduce channel utilisation (e.g. sending fewer messages) without compromising safety. The higher-layer communication protocols mainly consist of RSM protocols and ESM protocols. The protocols are built on top of the WSMP (see Figure 2.3), which is the designated network protocol for safety communication. The design of the context-aware solution is based on an ad hoc or distributed approach that does not assume the availability of centralised servers or computing nodes. The reason for this is to maximise the availability of the CCWS, as the supporting roadside infrastructure may not exist in a majority of roads.

The term “context” is used based on its general definition: “the circumstances that form the setting for an event, statement, or idea, and in terms of which it can be fully understood”\(^2\). In this study, the “context information” specifically refers to the information about a local traffic situation that is relevant to the CCWS in determining the interactions between vehicles. A context model is a model that can represent such information in order to be easily accessible by the safety message protocols. Such a model can be used to optimise and improve the performance of CCWS communication protocols.

For example, to reduce the number of sent messages, a protocol may need to be able to identify a set of endangered vehicles and determine how dangerous the situation is.

Several context-based protocols have been proposed in the literature [27, 29, 53, 26]. Most of the existing protocols provide solutions to routing problems for general purpose applications. In context-assisted routing [27], the destinations must be known initially and context information is used to assist in finding the routing path. Such an approach has a different type of context information and addresses a different set of problems. As for the CCWS, the relevant context information is that which can be used to identify possible dangers arising from the current surrounding traffic situation. For example, the context information can be used to find the relevant destinations, in addition to the routing path. Other context adaptive schemes use the context information to prioritise messages by defining the message benefit [29]. Such generic approaches may not ensure safety for CCWS applications. On the contrary, this research aims to improve communication performance in a CCWS.

In the literature, the problems of efficiently disseminating ESMs and RSMs are mostly addressed independently. The context-aware solution considers the interconnected system of RSM and ESM protocols. It provides an integrated framework for both RSM and ESM protocols to interact with a common module. Each safety message protocol does not need to maintain the context information by itself. Figure 2.4 shows the architecture of the context-aware communication system. The system design is based on the typical system architecture described in Section 2.2. The approach is to extend the existing system by introducing the context model into the situation awareness component. The context model is designed to be primarily used and shared by the RSM and ESM protocols in the communication system. However, it can also be utilised by the safety applications that provide the collision warning to the driver. In fact, since the vehicle kinematics and collision prediction models are the important elements in the CCWS, it would be best to make the context model as a module containing common models and algorithms that can be shared by the safety applications and the communication system.

The proposed design aims to decouple the task of handling the context information from the dissemination algorithms. Any safety message dissemination protocol should directly deal with only the dissemination algorithm.
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Therefore, the context-aware communication system consists of three interconnected separate entities: context model, RSM protocols, and ESM protocols. The implementation details of the context model are discussed in Chapter 3. The design of adaptive and scalable RSM protocols is investigated in Chapter 4. The design of efficient ESM protocols is investigated in Chapter 5.

2.5 Summary

This chapter reviewed recent advances in CCWS development. The CCWSs use inter-vehicular communication to prevent vehicle collisions by providing early warnings to the driver. In such IV systems, each vehicle obtains location information from the GPS, and acquires the location of nearby vehicles by exchanging GPS information via wireless communication. It is an important enhancement to safety technologies to balance the development of vehicle speed and power in the automobile industry. However, there are significant limitations to be considered, namely the penetration of equipped vehicles, the reliability of the positioning system, and the reliability of communication system. The limitation related to the communication system motivates this study to find the technical solution to the problem.

The key elements of CCWSs and their state-of-art were presented. The CCWS architecture can be generalised into five functional components: user interface, safety applications, situation awareness, positioning, and communication. The function of each component and its underlying technologies have been discussed with an emphasis on the communication component. An in-depth survey of the communication area provides the background to wireless
technologies relevant to a CCWS. These include the IEEE 802.11p, DSRC, WAVE, and CALM ISO standards. Prior studies indicated the feasibility of IEEE 802.11p as the wireless technology for a CCWS. However, there is still a problem of communication channel congestion in the case of dense road traffic conditions. Channel congestion is caused by over-utilisation of the wireless channel or medium. It greatly reduces communication reliability in ensuring time-critical message dissemination.

To improve the efficiency and reliability of communication protocols for CCWS, a context-aware communication system is proposed. Using the context information, the communication system can optimise the utilisation of the wireless channel. Communication protocols use intelligent algorithms to adaptively adjust the timing, frequency and number of transmitted messages and to reduce redundant messages. The design of the context-aware solution includes an addition of a context model in the situation awareness component that interacts with both RSM and ESM protocols in the communication component. To the best of our knowledge, this kind of approach has not been proposed previously in the literature. The following chapters (Chapter 3, Chapter 4, and Chapter 5) present the detailed sub-systems of the proposed context-aware solution.
Chapter 3

Context Modelling

Safety message dissemination protocols in Cooperative Collision Warning Systems (CCWSs) must optimise the use of the wireless channel while ensuring safety. Such optimisation requires the availability of context information on how vehicles interact with each other. The context information refers to the interactions between vehicles that show the possible collisions. To date, there is no existing model that can represent the context information. This chapter presents a new model to represent the context information in CCWSs, as part of the context-aware communication system described in Section 2.4. The model can be easily used to identify any possible collision arising from a current vehicular traffic situation. A directed graph is used to model the interactions between multiple vehicles in a specific region and at a specific time. Given a list of vehicles in the vicinity, the interactions between vehicles are computed according to their motion properties such as position, speed, and heading. The model is useful in developing context-aware strategies that can ensure the stability of both communication and safety performance in CCWSs. It has been used in the design of context-aware Routine Safety Message (RSM) and Event Safety Message (ESM) protocols described in Chapter 4 and 5 respectively.

3.1 Introduction

CCWSs can prevent accidents by providing the driver with an early warning of any possible collision. The recognition of any possible collision arising from a current road traffic situation can be regarded as the most important context information from the communication system perspective. The road
traffic situation can change dynamically depending on the road structure such as highways, junctions, or roundabouts as illustrated in Figure 3.1. To ensure reliable communication in such a dynamic traffic situation, safety message dissemination in CCWSs must optimise the wireless channel usage by reducing redundant transmissions without compromising safety. Such optimisation requires the aforementioned context information on how vehicles interact with each other. For example, a vehicle should send ESMs only to other vehicles that may possibly be endangered by its action. Instead of flooding the wireless network, the ESMs can be efficiently disseminated only to the endangered vehicles. To solve this problem, a specific context model that can represent vehicles interactions is needed. Such a context model can be used to identify the endangered vehicles.

The objective of the study in this chapter is to develop the context model that can represent interactions among multiple vehicles. The purpose of the model is for use in context-aware algorithms to easily identify the endangered vehicles. To the best of our knowledge, there is no existing model that can be used for such a purpose. Existing collision models used in the CCWSs [65, 97] only consider a single interaction between a pair of vehicles but do not consider a model of multiple interactions between multiple vehicles. Other related models such as microscopic traffic models used in traffic flow simulations cannot be used to determine all of the possible collisions between vehicles.

The original contribution of the presented work is a new context model for CCWSs that can be used to identify any possible collision arising from a current vehicular traffic situation. The traffic situation is modelled as the interactions between multiple vehicles in a specific region and at a particular time. The interactions are modelled using a directed graph, where a vehicle is represented by a vertex and an interaction between two vehicles is represented by an edge. The interactions between two vehicles are determined by calculating their motion properties.

The context model serves as a foundation for the context-aware communication solution for the CCWS (Section 2.4). The model makes it possible to optimise the communication protocols using context-aware methods. In addition, the collision estimations can be used by the warning algorithms of the safety applications (Subsection 2.2.2).

The following section discusses other work related to vehicular traffic and
3.2 Literature Review

Existing ESM protocols in the literature are mostly designed for straight road or highway scenarios. They assume that all vehicles behind (following) an abnormal vehicle (vehicle in an emergency situation) will be endangered and thus need to be warned [117, 16]. The assumption makes the protocols inefficient in using the wireless channel. In addition, the details regarding how to identify the endangered vehicles have not been addressed. This study tries to address this challenge by providing a method to identify the possibly endangered vehicles that is not limited only to a highway scenario.

Road vehicles, such as cars, trucks or buses, travel together as traffic on a road network. Many factors influence the dynamics of the road traffic, such as driver behaviour, road structures, human regulations, law of physics, and interactions between vehicles. Interactions between vehicles occur when the movement of a vehicle can be influenced by other nearby vehicles. The influence is driven by the possibility of collisions and the principle that every vehicle adapts its movement to avoid any collision with other vehicles. In the context of this study, an interaction between a pair of vehicles is defined as a state of possible collision between the pair given the current vehicle dynamics. In the literature, most of the research relevant to vehicular interactions modelling can be found in the area of traffic flow and vehicular trajectory modelling.

The interactions between vehicles have been studied as traffic flow models in the field of transportation and traffic engineering. Traffic models have been used mainly for traffic flow simulations in an effort to study traffic congestion,
control, and management. Such study is useful for creating an efficient transportation system. For example, it can be used to improve road network design and traffic signalling. The traffic models are also used in VANET simulations to produce realistic node mobility. The mobility has a significant impact on the evaluation of VANET experiments. For example, the performance of a routing protocol can be different depending on the mobility model used.

Traffic models can be classified according to the level of detail: microscopic, submicroscopic, macroscopic, and mesoscopic models [40, 37]. Microscopic models simulate traffic flow in a particular traffic scenario (such as highway, intersection, roundabout, etc.) by modelling the movement of individual vehicles and their interactions. Submicroscopic models are similar to microscopic models, in that they describe the characteristics of individual vehicles, but also model the vehicle substructures and the internal kinematics in detail, such as wheels, gears, engine, etc. Macroscopic models simulate traffic flow of large-scale road networks without distinguishing individual vehicles. The traffic flow is described by cumulative traffic characteristics (such as speed, flow, and density) and their interrelationships. Mesoscopic models combine the properties of both microscopic and macroscopic models. In mesoscopic models, individual vehicles are not traced and the behaviour of individuals is specified in probabilistic terms. Figure 3.2 illustrates the traffic models with different level of detail.

For the purpose of context modelling, the microscopic models have the highest relevancy to this study because they consider the interactions between individual vehicles. The submicroscopic models involve too many parameters that may not be available in the CCWS. The macroscopic and mesoscopic models are not relevant because they do not distinguish each individual vehicle. The microscopic models can be categorised into one of the following groups [19]: cellular automata (discrete space, discrete time), mathematical maps (continuous space, discrete time), and differential equations (continuous space, continuous time) models. From the groups, only the models with continuous space and time can satisfy the accuracy required by the CCWS.

The microscopic models introduced the concept of vehicle interactions [39]. Most of the microscopic models can be categorised as car-following models [18] that describe the interaction between adjacent vehicles in the same lane. The movement of a vehicle depends on the road condition in its desired path. A
vehicle reacts based on the obstacles or other vehicles in front of it. If there are obstacles that can cause a collision, a vehicle must stop or change its course. Otherwise, it can accelerate to its desired speed. The safe distance model [64] defines the minimum distance required between vehicles to avoid a collision given their speeds and deceleration capabilities. The safe distance can be used to determine if a vehicle is influenced by another vehicle. For example, if vehicle $A$ is following another vehicle $B$ and the distance between them is less than a calculated safe distance, it means that vehicle $A$ is influenced by vehicle $B$.

The car-following models provide a way to determine an interaction between a pair of vehicles moving in the same lane and direction. However, there are other situations in which a pair of vehicles are moving in different lanes or directions, such as at junctions or intersections. The car-following models cannot be used to determine the interactions of vehicles in such situations. To address this issue, we will look into vehicular trajectory models used by the CWSs.

In principle, typical CWSs predict a collision by measuring the relative distance between a subject vehicle and neighbouring vehicles. The CCWSs introduce a common component such as a situation awareness framework [97] or a neighbouring vehicle map [89] that maintains the current state and future trajectory of all neighbouring vehicles. Future trajectory is calculated using a single-vehicle dynamics model, but the interactions between vehicles are not modelled. By comparing the predicted future distance between vehicles, a potential collision can be determined. Such approaches are not suitable to determine the severity of a possible collision, which is needed as context information.

Miller and Huang [65] proposed a simple model that calculates route contention to predict a collision between a pair of vehicles with different directions in any position. This method computes the intersection point of the pair's trajectories, and then compares the expected time-to-intersection for each vehicle to determine the possibility of collision. When there are multiple vehicles in the vicinity, each of them will be calculated separately. A similar model can be used to determine the interactions between vehicles with intersecting trajectories. A more accurate collision estimation model is proposed by Shimonaka et al. [90]. The model depends on a predetermined set of mobility situations. It is difficult to match the actual real-world situation with the given set.
The trajectory models cannot be used to anticipate the possibility of changes in the vehicle’s movement that may cause a collision. For example, imagine a car-following scenario with two vehicles moving in the same lane and direction, and at the same speed. Assuming zero acceleration, the trajectory models will estimate no possible collision. However, a collision is imminent if the distance between the two vehicles is less than a safe distance and the leading vehicle suddenly decides to brake. This situation needs to be considered in the context model. Therefore, the context model should adopt, extend, and combine several important concepts from the existing models.

All of the reviewed models provide the methods to find an interaction between two vehicles. However, there is no existing model that defines the aggregation of multiple interactions. A graph structure is the natural construct to model such an aggregation that can be easily used as context information. The use of graph theory to model vehicle interactions and formations has been proposed in the literature [73, 74, 68]. Those models were developed to study the formation and control for different types of vehicles such as unmanned aerial vehicles or robots. The functions of such models are significantly different to the functions required for CCWS context modelling. Nevertheless, the basic idea of using a graph structure is useful and inspiring for the context modelling.

Figure 3.2: The granularity of traffic models.
3.3 Problem Definition

Given a set of vehicles (in this context, the subject vehicle and its neighbours) and their latest state information (such as position, heading, and speed), the objective is to develop a practical model that represents the interactions among multiple vehicles, and corresponding modelling techniques. Using the interaction model, the CCWS can immediately determine vehicles that may be endangered by any specific vehicle and the severity of their critical situation. A vehicle is said to endanger other vehicles if there is a possibility of a collision directly or indirectly caused by the vehicle. The possibility of a collision can be estimated based on the vehicle's motion. A vehicle can endanger and can be endangered by more than one vehicle. The model should be valid for various road scenarios such as straight roads, curved roads, intersections, junctions, and roundabouts, as illustrated in Figure 3.1.

The context modelling problem can be formulated as follows:

**Input:** A set of vehicles \( \mathcal{V} = \{v_1, v_2, \ldots, v_n\} \) and the state of each vehicle represented in a tuple \((x_i, y_i, w_i, l_i, \theta_i, s_i, \alpha_i)\), \(1 \leq i \leq n\), where \(x_i\) and \(y_i\) are the position coordinates, \(w_i\) is the width, \(l_i\) is the length, \(\theta_i\) is the heading, \(s_i\) is the speed, and \(\alpha_i\) is the maximum deceleration of the vehicle.

**Output:** A model to represent the possible interactions among multiple vehicles. Let \(v \in \mathcal{V}\) be a vehicle, \(\mathcal{V}'_v \subseteq \mathcal{V}\) be a set of vehicles possibly endangered by \(v\), and \(\mathcal{W}'_v\) be a set of danger severities of vehicles \(\mathcal{V}'_v\). Given a vehicle \(v\), the set \(\mathcal{V}'_v\) and \(\mathcal{W}'_v\) should be easily identified using the model.

3.4 Vehicle Interaction Graph Model

The context model is implemented as the vehicle interaction graph model. A directed graph structure is used to represent the interactions between multiple vehicles. A vertex represents a vehicle and a directed edge represents an interaction in the graph. An interaction is defined as a state in which two vehicles have an influence upon one another. The possible interaction between two vehicles can be: first vehicle is influenced by second vehicle, vice versa, or
both. The basic concept is to find out all possible interactions for all pairs of vehicles as illustrated in Figure 3.3. Given the interaction graph, it is easy to identify which vehicles are influenced by other vehicles: an arrow from node $v_1$ to node $v_2$ means that $v_2$ is influenced by $v_1$.

A vehicle interacts with another vehicle if there is a possibility of a collision between them. A possible collision is determined by calculating a route contention between a pair of vehicles and an avoidance time based on their motion properties such as trajectory and speed. A space-continuous motion model is used for accuracy reasons. The avoidance time is the maximum available time for a driver to react in order to avoid any possible collision. If the avoidance time is less than a predetermined threshold, an interaction is concluded. The predetermined threshold can be taken from the slowest driver reaction time gathered from statistics. This means that there is no interaction as long as the driver has more than enough time to evade a collision.

### 3.4.1 System Assumptions

The modelling technique is based on the context aware communication system described in Section 2.4. It is assumed that every vehicle is equipped with the positioning and communication systems. A positioning system can provide reasonably accurate relative position, heading, and speed. A wireless communication system is used to exchange the vehicle state using RSMs. Every vehicle maintains an up-to-date table of neighbouring vehicles state, and its own context model. It is assumed that no digital map information is available,
although the model could be extended to include such information.

3.4.2 Graph Definition

The vehicle interaction model is defined as a weighted directed graph $G = (\mathcal{V}, \mathcal{E})$. A set of vertices $\mathcal{V} = \{v_1, v_2, \ldots, v_n\}$ represents the vehicles in a specific area. A set of directed edges $\mathcal{E} \subseteq \{(v_i, v_j) : v_i, v_j \in \mathcal{V}, v_i \neq v_j\}, 1 \leq i, j \leq n$ represents the interactions. A vertex $v$ represents a vehicle and its state defined as a tuple $v = (x, y, w, l, \theta, s, \alpha)$ where $x$ and $y$ are the position coordinates, $w$ is the width, $l$ is the length, $\theta$ is the heading, $s$ is the speed, and $\alpha$ is the maximum deceleration of the vehicle. An edge $e_{ij} = (v_i, v_j)$ represents an interaction between $v_i$ and $v_j$, where $v_i$ is influencing $v_j$. An edge weight $\omega_{ij}, 0 < \omega_{ij} \leq 1$ is a real number that indicates the danger severity or intensity of the interaction $e_{ij} \in \mathcal{E}$. The value of $\omega_{ij} = 1$ indicates an interaction with the highest severity while $\omega_{ij} = 0$ indicates no interaction. The interactions between vehicles are identified using rules detailed in the following subsection.

3.4.3 Graph Generation

An interaction graph $G$ is constructed by defining the set of vertices $\mathcal{V}$ and the set of edges $\mathcal{E}$. The set of vertices $\mathcal{V}$ is the set of neighbouring vehicles tracked by the CCWS and the subject vehicle. Given a set of vehicles $\mathcal{V}$, an interaction graph $G$ is constructed by generating the set of edges $\mathcal{E}$ and its weight $W$ using Algorithm 1. The procedure involves enumerating all pairs of vehicles from $\mathcal{V}$, and for each pair $(v_i, v_j)$ the interactions between $v_i$ and $v_j$ are calculated. Depending on the result, an edge $e_{ij}, e_{ji}$, or both edges, may be added to the set of edges $\mathcal{E}$.

An interaction is determined if an avoidance time $\tau$ is less than or equal to the maximum reaction time $T_{\text{max}}$. The avoidance time $\tau$ is the time available for the driver of the influenced vehicle to react in order to avoid the collision. The maximum reaction time $T_{\text{max}}$ is a parameter that reflects the worst possible reaction time for a driver. The minimum reaction time $T_{\text{min}}$ reflects the best possible reaction time for a driver. The danger severity, represented as an edge weight $\omega$, is determined based on the value of $\tau$ scaled proportionally with $T_{\text{min}}$ and $T_{\text{max}}$. Any interaction with an avoidance time less than $T_{\text{min}}$ will be treated as having the same severity. Based on the statistics [49, 32],
this study assumes the value of $T_{\text{min}} = 0.2s$ and $T_{\text{max}} = 2.5s$. Equations 3.1 and 3.2 are used to calculate the danger severity.

$$\tau = \max (T_{\text{min}}, \tau)$$  \hspace{1cm} (3.1)

$$\omega (\tau) = 1 - \frac{\tau - T_{\text{min}}}{T_{\text{max}} - T_{\text{min}}}$$  \hspace{1cm} (3.2)

Algorithm 1: Generating initial interaction graph.

\begin{itemize}
\item[\textbf{input}]: A set of vehicles $\mathcal{V}$
\item[\textbf{output}]: An interaction graph $\mathcal{G}$
\end{itemize}

1. create a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{E} \leftarrow \emptyset$
2. \textbf{for} each pair of vehicles $(v_i, v_j) \in \mathcal{V}$ \textbf{do}
3. \hspace{1cm} if $v_i$ and $v_j$ are moving in the same direction \textbf{and} have an overlapping path \textbf{then}
4. \hspace{2cm} find the follower $v_F$ and the leader $v_L$
5. \hspace{2cm} calculate actual longitudinal distance $d_a$
6. \hspace{2cm} calculate avoidance time $\tau_1$
7. \hspace{2cm} if $\tau_1 \leq T_{\text{max}}$ \textbf{then}
8. \hspace{3cm} $\mathcal{E} \leftarrow \mathcal{E} \cup \{\langle v_L, v_F \rangle\}$
9. \hspace{3cm} calculate danger severity $\omega_{LF}(\tau_1)$
10. \hspace{2cm} else \textbf{if} $v_i$ and $v_j$ are moving in the opposite direction \textbf{and} have an overlapping path \textbf{then}
11. \hspace{3cm} calculate actual longitudinal distance $d_a$
12. \hspace{3cm} calculate avoidance time $\tau_2$
13. \hspace{3cm} if $\tau_2 \leq T_{\text{max}}$ \textbf{then}
14. \hspace{4cm} $\mathcal{E} \leftarrow \mathcal{E} \cup \{\langle v_i, v_j \rangle, \langle v_j, v_i \rangle\}$
15. \hspace{4cm} calculate danger severity $\omega_{ij}(\tau_2)$
16. \hspace{2cm} else
17. \hspace{3cm} calculate intersection point $P_x$
18. \hspace{3cm} calculate time-to-intersection $t_i$ and $t_j$
19. \hspace{3cm} if $t_i \cap t_j \neq \emptyset$ \textbf{then}
20. \hspace{4cm} calculate avoidance time $\tau_{3i}$ and $\tau_{3j}$
21. \hspace{4cm} if $(\tau_{3A} \leq T_{\text{max}}) \land (\tau_{3B} \leq T_{\text{max}})$ \textbf{then}
22. \hspace{5cm} $\mathcal{E} \leftarrow \mathcal{E} \cup \{\langle v_i, v_j \rangle, \langle v_j, v_i \rangle\}$
23. \hspace{5cm} calculate danger severity $\omega_{ij}(\tau_{3j})$ and $\omega_{ji}(\tau_{3i})$
\end{itemize}

The model considers three distinct cases to determine whether there is any interaction between any pair of vehicles. The first case is Following (line 3),
where both vehicles are travelling in the same direction. Figure 3.4 illustrates this first case. The second case is Opposite (line 10), where the two vehicles are travelling in the opposite direction. Figure 3.5 illustrates this second case. The third case is Intersection (line 16), which covers any other conditions besides the previous two cases. Figure 3.6 illustrates this third case. These three cases can cover all the possible traffic scenarios without road information from a digital map.

For the sake of simplicity, the absolute position of vehicle $v$ is represented by a Cartesian coordinate $(x_v, y_v)$, referenced as the centre point of the vehicle. Any other coordinate systems such as a geographic coordinate system as measured by the GPS can be used with a proper transformation. The heading of the vehicle $\theta_v$ is in radian where $0 \leq \theta_v < 2\pi$, and $\theta_v = 0$ means heading north. Let $A$ and $B$ be a pair of vehicles to be processed. Depending on the case, the avoidance time $\tau$ is calculated differently based on their vector geometry and kinematic calculations.

Case 1. Following. This is a case where one vehicle is following another vehicle (vehicle $A$ is following $B$ or vice versa). Figure 3.4 shows a general following scenario to illustrate the concept. This case applies if vehicles $A$ and $B$ are moving in the same direction and have overlapping paths. Vehicles $A$ and $B$ are moving in the same direction if their heading angles are almost equal. The equality $\theta_A \approx \theta_B$ can be determined by using a condition $|\theta_A - \theta_B| < \epsilon$, where $\epsilon$ is a parameter to accommodate for a small
difference. To determine if vehicles $A$ and $B$ have overlapping paths, the following procedure is used. Find $d_P$, the distance between point $B$ and $P$, using following equations:

\[
x_{A'} = \sin \theta_A + x_A \quad y_{A'} = \cos \theta_A + y_A
\]

\[
u = \frac{(x_B - x_A)(x_{A'} - x_A) + (y_B - y_A)(y_{A'} - y_A)}{\sqrt{(x_{A'} - x_A)^2 + (y_{A'} - y_A)^2}}
\]

\[
x_P = x_A + u(x_{A'} - x_A) \quad y_P = y_A + u(y_{A'} - y_A)
\]

\[
d_P = \sqrt{(x_P - x_B)^2 + (y_P - y_B)^2}
\]

Equation 3.3 calculates point $A'$ coordinates, where $\overrightarrow{AA'}$ is the normalised vector of direction $\theta_A$. Point $P$ coordinates can be calculated using Equations 3.4 and 3.5. Let $d_P = |\overrightarrow{BP}|$ be the distance between $B$ and $P$ (Equation 3.6). If $d_P < \left(\frac{w_A}{2} + \frac{w_B}{2} + d_{gl}\right)$ then $A$ and $B$ have overlapping paths, where $w_A$ and $w_B$ are the width of vehicles $A$ and $B$ respectively, and $d_{gl}$ is a parameter for the acceptable lateral distance between vehicles.

To find the follower $F$ and the leader $L$, find the angle of vector $\overrightarrow{AP}$. If $\angle \overrightarrow{AP} \approx \theta_A$ then $F = A$ and $L = B$, else $F = B$ and $L = A$. Actual longitudinal distance $d_a$ is calculated using Equation 3.7. The net distance $d_t$ is calculated using Equation 3.8, where $d_{min}$ is a parameter of the expected minimal distance between vehicles, $l_F$ and $l_L$ are the length of vehicles $F$ and $L$.

\[
d_a = \sqrt{(x_P - x_A)^2 + (y_P - y_A)^2}
\]

\[
d_t = d_a - d_{min} - \frac{1}{2}(l_F + l_L)
\]

There are two conditions in this case that can lead to a possible collision. First, the follower is faster than the leader. Second, the distance between them is less than the safety distance. The second condition is used to anticipate an event when the leader brakes abruptly. The conditions are modelled using a different avoidance time $\hat{\tau}_1$ and $\hat{\tau}_2$:

\[
\hat{\tau}_1 = \frac{d_t}{s_F - s_L} - \frac{s_F - s_L}{2\alpha_F} \quad \hat{\tau}_2 = \frac{d_t}{s_F} + \frac{1}{2s_F}\left(\frac{s_L^2}{\alpha_L} - \frac{s_F^2}{\alpha_F}\right)
\]

\[
\alpha = g(f \pm G)
\]
where \( s_F \) and \( s_L \) are the speed of follower and leader vehicles, and \( \delta_F \) and \( \delta_L \) are the maximum deceleration of follower and leader vehicles. A simplified formula to calculate the vehicle maximum deceleration \( \delta \) is given in Equation 3.10 [61], which requires coefficient of friction between tyre and roadway \( f \), road grade \( G \), and gravity constant \( g \). The avoidance time \( \tau_1 \) is calculated using Equation 3.11:

\[
\tau_1 = \begin{cases} 
\bar{\tau}_1 & \text{if } \dot{\tau}_1 < 0 \\
\min (\bar{\tau}_1, \ddot{\tau}_1) & \text{otherwise}
\end{cases}
\] (3.11)

Case 2. **Opposite.** This is a case where a vehicle is heading toward another vehicle and there is a possibility of a collision. Figure 3.5 shows a general opposite scenario to illustrate the concept. This case applies if vehicles \( A \) and \( B \) are moving in the opposite direction and have overlapping paths. Vehicles \( A \) and \( B \) are moving in the opposite direction if their heading angles satisfy \( ||\theta_A - \theta_B - \pi|| < \varepsilon \), where \( \varepsilon \) is a parameter to accommodate for a small difference. To determine if vehicles \( A \) and \( B \) have overlapping paths, the following procedure is used. Find the distance between a point and a line \( d_P \) using Equations 3.6. If \( d_P < \left( \frac{w_A}{2} + \frac{w_B}{2} + d_{gl} \right) \) then check if vehicles \( A \) and \( B \) are approaching each other, instead of receding, by finding the angle of vector \( \overrightarrow{AP} \). If \( \angle \overrightarrow{AP} \approx \theta_A \) then \( A \) and \( B \) have overlapping
paths.

Longitudinal distance $d_a$ and net distance $d_t$ are calculated using Equations 3.7 and 3.8. The avoidance time $\tau_2$ is calculated using Equation 3.12:

$$\tau_2 = \frac{d_t - \frac{s_A^2}{2\alpha_A} - \frac{s_B^2}{2\alpha_B}}{s_A + s_B}$$

Case 3. Intersection. This is a case where two vehicles have intersecting paths and therefore there is a possibility of a collision. Figure 3.6 shows a general intersection scenario to illustrate the concept. This case applies if trajectory lines of vehicles $A$ and $B$ intersect each other. The basic concept of the collision prediction method is adopted from the route contention method proposed by Miller and Huang [65]. Given two non-parallel infinite lines, an intersection point $C(x_C, y_C)$ can be computed using the following formulae:

$$x_C = \frac{(y_B - y_A) - (x_B \cot \theta_B - x_A \cot \theta_A)}{\cot \theta_A - \cot \theta_B}$$

$$y_C = \frac{(x_B - x_A) - (y_B \tan \theta_B - x_A \tan \theta_A)}{\tan \theta_A - \tan \theta_B}$$

Using the intersection point, the expected time-to-intersection for both

Figure 3.6: Two vehicles with intersecting paths.
vehicles can be calculated using the following formulae:

\[ \overrightarrow{AC} = [x_C - x_A, y_C - y_A] \quad \overrightarrow{BC} = [x_C - x_B, y_C - y_B] \]  
(3.15)

\[ d_{AC} = \left| \overrightarrow{AC} \right| - \frac{1}{2} \left( \frac{w_B}{\sin \theta_C} + \frac{w_A}{\tan \theta_C} \right) \]  
(3.16)

\[ d_{BC} = \left| \overrightarrow{BC} \right| - \frac{1}{2} \left( \frac{w_A}{\sin \theta_C} + \frac{w_B}{\tan \theta_C} \right) \]  
(3.17)

\[ t_{AC} = \frac{d_{AC}}{s_A} \text{sign} \left( \overrightarrow{AC} \cdot [\sin \theta_A, \cos \theta_A] \right) \]  
(3.18)

\[ t_{BC} = \frac{d_{BC}}{s_B} \text{sign} \left( \overrightarrow{BC} \cdot [\sin \theta_B, \cos \theta_B] \right) \]  
(3.19)

where \( s_A \) and \( s_B \) are the speed of vehicles \( A \) and \( B \), respectively, \( \overrightarrow{AC} \) is a vector from point \( A \) to point \( C \), \( \overrightarrow{BC} \) is a vector from point \( B \) to point \( C \), and \( \text{sign}() \) is a sign function to identify if a vehicle has passed through the intersection. A route contention exists if both vehicles are expected to arrive at the intersection point around the same time. This can be determined by defining a time frame for each vehicle \( t_A \) and \( t_B \), where \( t_{AC} \leq t_A \leq (t_{AC} + \hat{c}_A) \) and \( t_{BC} \leq t_B \leq (t_{BC} + \hat{c}_B) \), such that \( t_A \cap t_B \neq \emptyset \) signifies a route contention. The contention time windows \( \hat{c}_A \) and \( \hat{c}_B \) are determined by considering the intersection angle \( \theta_C = \angle ACB \) and each vehicle size and speed.

\[ \hat{c}_A = \frac{1}{s_A} \left( \frac{w_B}{\sin \theta_C} + \frac{w_A}{\tan \theta_C} + l_A \right) \]  
(3.20)

\[ \hat{c}_B = \frac{1}{s_B} \left( \frac{w_A}{\sin \theta_C} + \frac{w_B}{\tan \theta_C} + l_B \right) \]  
(3.21)

If there is a route contention then the avoidance times \( \tau_{3A} \) and \( \tau_{3B} \) are calculated using Equation 3.22:

\[ \tau_{3A} = t_{AC} - \frac{s_A}{2 \alpha_A} \quad \tau_{3B} = t_{BC} - \frac{s_B}{2 \alpha_B} \]  
(3.22)

### 3.4.4 Graph Generation Illustration

To illustrate the modelling process, Figure 3.7 shows an example of a traffic situation and the graph generation steps presented in the Algorithm 1. The
input is a set of four vehicles \( V = \{ v_1, v_2, v_3, v_4 \} \) where each vehicle has properties defined as a tuple \( v = (x, y, w, l, s, \theta, \alpha) \) with their values detailed in Table 3.1. All vehicles are assumed to have the same width \( w = 2 \text{ m} \), length \( l = 4 \text{ m} \), and maximum deceleration \( \alpha = 4 \text{ m/s}^2 \). The parameters \( d_{\text{min}} \) and \( d_{\text{gl}} \) are set to 1 m. Figure 3.7(a) illustrates the vehicles formation.

Given the input as described above, the process described in Algorithm 1 will be illustrated as follows. All of the possible pairs from the set of vehicles are processed. Without losing generality, this example begins with a pair \( v_1 \) and \( v_2 \). This pair is an example of two vehicles with intersecting paths. Using the Case 3 procedure results in edges \((v_1, v_2)\) and \((v_2, v_1)\) and their weights \( \omega_{12} = \omega_{21} = 1 \) added to the graph. This step produces a graph as shown in Figure 3.7(b). The next pair is \( v_1 \) and \( v_3 \), which is an example of Case 1. Using the procedure for Case 1 will create an edge \((v_3, v_1)\) as shown in Figure 3.7(c). The next step is shown in Figure 3.7(d), where an edge \((v_4, v_1)\) is added.
3.5 Discussion

The interaction graph models the possible collisions among a group of vehicles given their present state. Since road traffic is a mobile and dynamic environment, the states of vehicles are changing continuously. This requires the graph to be constantly updated to reflect the most current situation, which can be implemented by updating the interaction graph each time a vehicle receives state information from the neighbouring vehicles. Such state information is included in RSMs and ESMs. Each time a vehicle obtains another vehicle’s state $v_i$, the main loop from Algorithm 1 (line 2) is executed for each pair of vehicles $(v_i, v_j), \forall v_j \in V, v_i \neq v_j$. Since the graph always represents the up-to-date situation, any CCWS components can utilise it as valid context information at any time.

The interaction graph is designed to enable a context-aware optimisation method for the CCWS communication protocol. One example is in a case when ESMs need to be sent using multi-hop transmissions. An efficient ESM protocol needs to determine relevant recipients and forwarder nodes, instead of flooding the network by sending ESMs to all vehicles. Sending messages only to relevant recipients can reduce redundant transmissions, and therefore, minimise the wireless channel usage and reduce channel congestion. The interaction graph can be used to identify vehicles that are endangered by a subject vehicle. For example, in Figure 3.3, vehicle $v_8$ only needs to send warning message to $v_9$, $v_6$, and $v_7$. Using the information, a protocol can determine the message recipients and use a context-aware algorithm to select the most effective forwarders. The performance and usefulness of this model will be evaluated together with context-aware protocols presented in Chapter 4 and Chapter 5.

A simple linear motion model is used to determine the interaction between using Case 2 to process the pair $v_1$ and $v_4$. The pair $v_2$ and $v_3$ does not fulfil the conditions given in all of the cases, which means there is no interaction between $v_2$ and $v_3$. Figure 3.7(e) shows the graph after pair $v_2$ and $v_4$ has been processed using the Case 3 procedure. Finally, Figure 3.7(f) shows the completed interaction graph after the pair $v_3$ and $v_4$ is processed using the Case 2 procedure.
a pair of vehicles. The simplicity allows for generalisation to accommodate different types of land vehicles such as automobiles, motorcycles, trains or trams. The reason for using only the most necessary motion parameters (such as position, speed and heading) is to minimise the information that needs to be transmitted and to anticipate the use of this model in portable add-on devices [33]. Such add-on devices may not have access to detailed vehicle motion states such as acceleration, yaw rate or steering angle. To further improve accuracy, a nonlinear model that takes acceleration into consideration can be used to extend the linear model. Other possible improvements include the use of a flexible curved path for trajectory prediction that follows the road geometry and topology obtained from a digital map.

3.6 Summary

The original contribution of this research is a context model implemented as a graph structure to represent multiple vehicle interactions in a specific region and at a specific time. The modelling involves an algorithm to construct the graph and methods to determine the interactions between vehicles. The interaction graph provides context information for CCWSs that can be easily used for various purposes. Mainly, it enables the context-aware approach for the CCWS communication system. Additionally, it can be utilised by the warning algorithms to alert the driver. Based on an extensive literature review, there is no existing model that fits such a purpose and function.

Given a list of vehicles and their state properties, an interaction graph is constructed by considering three different cases. An example is provided to illustrate the graph generation process. The three cases cover all possible route contention occurrences that may cause a collision between a pair of vehicles. The interaction graph can be used to model various road traffic situations such as on highways, at junctions, or intersections. Such a general approach has not received much attention in prior works related to vehicular collision warning or avoidance systems.

The interaction graph can be used by the RSM and ESM dissemination protocols to reduce the number of sent messages without compromising safety. For example, it is useful to determine the target vehicles that are required to receive safety messages in the event of an emergency. The improvement
in communication protocols will generally improve the reliability of CCWSs. The next two chapters propose the context-aware RSM and ESM protocols that utilise the interaction graph.
Chapter 4

Routine Safety Message Dissemination

Routine Safety Messages (RSMs) are disseminated repeatedly and continuously by every vehicle to update their neighbours with their most recent state information, such as position. Proper design of an RSM dissemination strategy is an important factor in preventing the occurrence of a collision. Typical CCWSs assume that RSMs are broadcasted periodically at a constant rate of 10 messages per second. Such a strategy is not scalable as it may lead to channel congestion in a dense road traffic situation, such as when a traffic jam occurs. There are existing strategies that can adaptively adjust the broadcast rate to reduce channel congestion. However, they may not ensure safety because they cannot prioritise vehicles that are most likely to crash with other vehicles. This chapter presents a context-aware RSM dissemination protocol that can adaptively adjust the repetition rate based on the model presented in Chapter 3. The dissemination rate is determined based on an estimated channel load and the danger severities of vehicle interactions. The new method is designed to control channel congestion and prioritise the most endangered vehicles. The performance of the context-aware protocol is compared with those that use a constant rate strategy. Evaluation is done by simulating vehicle collisions caused by inattentive drivers for random straight road scenarios. Experimental results show that the context-aware protocol provides better safety by preventing more collisions under various road traffic densities.
CHAPTER 4. ROUTINE SAFETY MESSAGE DISSEMINATION

4.1 Introduction

Routine Safety Messages (RSMs) are status update messages that are sent repeatedly and continuously by all vehicles equipped with a CCWS. RSMs are most commonly known as beacons, and the term beaconsing refers to the dissemination of RSMs. An RSM contains up-to-date vehicle state information, such as position, speed, heading, and other kinematics or motion information. The purpose of RSMs is so that each vehicle can realise and track the existence of neighbouring vehicles and their most current state information. Using the state information, each vehicle can estimate any possible collision and provide early warnings to its driver accordingly.

The accuracy of the neighbouring vehicle state information that is tracked by each vehicle affects the reliability of the warning system. Relatively inaccurate information tracking will result in inaccurate predictions that may lead to a collision since the driver cannot be alerted in time. The tracking accuracy is measured by the difference between tracked and actual state information. As an illustration, a vehicle that moves with a speed of 100 km/h can travel a distance of 28 m in one second. If an RSM is received only once per second, there could be positional inaccuracy of up to 28 m in the prediction. RSMs must be received more frequently to achieve higher tracking accuracy. Generally, a higher tracking accuracy means a better safety level because a potential collision can be estimated more accurately.

Typical CCWSs assume that a vehicle broadcasts RSMs periodically with the recommended rate or frequency of 10 messages per second (or equivalent to one message for every 100 milliseconds interval) [98]. The constant rate beaconsing strategy is simple and easy to implement, but is not scalable to various road traffic situations. Road traffic is a very dynamic environment, in which its vehicle density, defined as the number of vehicles per a unit area [64], can vary significantly over time. Because wireless channel capacity is limited, using the same constant rate with a different vehicle density will result in a different communication performance, assuming that other factors such as radio range and packet size are constant. For example, a constant rate of 10 Hz in sparse traffic conditions, such as illustrated in Figure 4.1(a), may not generate a significant load on the communication channel. However, using the same rate in denser traffic conditions such as shown in Figure 4.1(b) may result
4.1. Introduction

(a) Low density. 

(b) High density.

Figure 4.1: Illustrations of traffic situations with different vehicle densities.

in channel congestion. The channel congestion leads to a high rate of packet loss that can reduce the safety performance of the CCWSs significantly.

The performance of vehicular safety communications has been evaluated in several studies. The results indicate a need to improve the communication performance (e.g. reception rate) especially in dense traffic conditions such as a traffic jam [119, 28]. Particularly for a CCWS, its beaconing performance has a significant impact on its safety performance, which is measured by the accuracy of the collision prediction [97, 44]. To improve beaconing performance and reduce channel congestion, the beaconing parameters, such as the beaconing rate, should be adjusted dynamically depending on feedback from the traffic situation [121, 105]. There are existing strategies [80, 41] that can adaptively adjust the beaconing rate to improve the communication performance. However, safety performance may not be improved because these strategies cannot prioritise vehicles based on their danger or threat severities.

Reducing the beaconing rate without considering the interactions among vehicles may cause a collision in certain situations. For example, Figure 4.2 shows a simple traffic situation where vehicles $v_1$, $v_2$, and $v_3$ are following each other in unsafe conditions (high speed, small gap) and vehicles $v_4$ and $v_5$ are moving independently. Figure 4.3 shows an assumed interaction graph representing such a traffic situation. Assume that there are many other vehicles in the vicinity that also utilise the same channel. Because of the unsafe conditions, reducing the beaconing rate of vehicle $v_1$ may significantly increase the possibility of collisions with vehicles $v_2$ and $v_3$. In contrast, reducing the beaconing rate of vehicle $v_4$ will not significantly increase the possibility of collisions between $v_4$ and other vehicles. This example shows that the importance of tracking accuracy in preventing a collision relatively depends on the interactions among vehicles. Therefore, vehicles that endanger other vehicles such as $v_1$ and $v_2$ should have a higher beaconing rate compared to vehicles
that have no current interactions with other vehicles, such as $v_4$ and $v_5$. This idea is investigated to design a more efficient RSM dissemination protocol with safety considerations.

The original contribution of the presented work is a new context-aware RSM dissemination protocol that can adaptively adjust the beaconing rate based on the interactions among vehicles. The objective of this research is to optimise the beaconing rate of each vehicle to improve communication and safety performance under various vehicle densities. The beaconing rate is determined based on the estimated channel load and the danger severities of vehicle interactions. The communication performance is improved by controlling channel utilisation to a certain limit to avoid congestion. The safety performance is improved by prioritising the most endangered vehicles using the interaction model proposed in Chapter 3. The performance is evaluated by simulations in ns-3 [1]. The new dissemination scheme is compared with the constant rate schemes. The evaluation involves simulating vehicle collisions caused by inattentive drivers using random straight road scenarios. Experiment results show that the context-aware protocol provides a better safety level by preventing more collisions on average from random scenarios with different vehicle densities. Therefore, the new protocol offers greater scalability without compromising safety.

The rest of this chapter is organised as follows: Section 4.2 introduces the related works in RSM dissemination strategies and identifies the knowledge gap in the literature. Section 4.3 presents a context-aware approach to optimising
4.2 Literature Review

The capacity of a wireless network is limited to the available channel bandwidth and the number of communication nodes that share the channel [36, 58]. When the network becomes denser, the capacity available to each node is reduced. If the channel utilisation at each node exceeds the capacity, it will result in channel congestion, indicated by a drop in communication performance such as high packet loss rate and latency. For safety applications such as CCWSs, a decrease in communication performance can consequently decrease the safety performance. For example, even a 50 milliseconds difference in RSM reception time may determine whether a collision can be prevented [44]. Channel congestion can significantly decrease the reliability of CCWSs.

Channel access in DSRC is performed in a random manner using a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) scheme. All nodes (vehicles) share one channel. There is no centralised coordination to assign a transmission time slot for each node. The CSMA/CA approach is highly challenged when coordinating broadcast transmissions in high vehicular traffic-density scenarios [99]. This is because the channel becomes congested as the channel load reaches the channel capacity. Furthermore, it has been suggested that for efficient channel usage, the load should be between 40% and 60% of the capacity [84]. This implies that the effective capacity, which is the capacity that can be fully utilised without decreasing communication performance, is only 60% of the raw capacity.

The RSM dissemination (beaconing) is an operation that consumes most of the control channel bandwidth. To ensure safety, the control channel must be prevented from being overloaded by the RSMs. Various schemes have been proposed to improve the efficiency and performance of beaconing. The existing schemes can be broadly classified into two categories: schemes that try to maximise or increase the effective capacity, and schemes that try to minimise...
or control the beaconing load.

The effective capacity can be increased by controlling the transmission timing to reduce the possibility of packet collisions, improve reception rate, and ensure fairness of channel access time. Balon and Guo [12] proposed a method to adjust the Contention Window (CW) size dynamically based on the percentage of packet loss. In a CSMA-based communication system, the CW is used in the MAC layer to provide all nodes with equal access to the channel. A node that wants to transmit needs to listen on the desired channel. If the channel is busy (i.e., there is a nearby active transmission), the node waits until transmission stops then waits for a further random contention period based on the CW. In the case of a lower packet reception rate (for example, when the road traffic conditions become denser), all of the involved nodes should increase the CW.

Packet collisions can be avoided by synchronously scheduling packet transmissions into time slots. The basic principle is that two nodes with overlapping transmission areas should not transmit at the same time. Bilstrup et al. [14] proposed the use of a Self-organising Time Division Multiple Access (STDMA) scheme to replace the CSMA/CA scheme. The STDMA scheme is similar to the automatic identification system (AIS) used in the shipping industry. The use of the STDMA scheme for the MAC layer protocol is unlikely to be adopted by the IEEE 802.11p or WAVE standard. However, it is possible to implement a STDMA-like scheme on top of the MAC layer protocol that uses the CSMA/CA scheme. One of such schemes requires the road to be divided into block partitions and the transmission timing to be calculated based on the partitions [82]. Kovacs [34] proposed a GeoMapped beaconing scheme that uses an absolute position reference from the GPS. A vehicle determines the beacon transmission time based on a geographic overlay grid to solve the hidden terminal problem. The scalability issue has not been addressed since both schemes were evaluated only with low vehicle density and communication rate. A concept of reactive beaconing is proposed by van Eenennaam et al. [106]. The idea is that a node should transmit an RSM in reaction to the reception of an RSM from a vehicle in front of it. As yet, there has not been a detailed implementation or evaluation of this concept.

The beaconing load can be minimised or controlled by tuning the various parameters that contribute to the communication density. Communication
density is described as the product of vehicle density, message size, message generation rate, and transmission range [47]. Since vehicle density is given depending on the actual road traffic conditions, only the three other parameters can be controlled directly: message size, message generation rate, and transmission range. The analysis of the beaconing solution space shows that the probability of successful beacon reception mainly depends on those three parameters [105]. Extensive simulations have been conducted to study the effect of these parameters on network performance [85, 121]. The conclusions drawn in those studies emphasised the need for adaptive algorithms to control the channel load by adjusting the parameters dynamically based on the feedback that considers the vehicle's traffic situation. Such approaches aim to maximise the successful message reception rate.

Given a particular PHY data rate, the message size determines the transmission duration. A longer duration increases the channel utilisation. Since the message size is determined by the amount of information as required by the safety applications, there could be only a few viable strategies to reduce the size. One example is the use of a message dispatcher to control all data exchanges between applications and to compose a message selectively based only on required data elements [81]. Many applications require the same data elements (such as position or speed) to be sent repeatedly at different frequencies. The message dispatcher schedules and combines the same data elements required by different applications, preventing the same elements from being transmitted multiple times by different applications. Further reduction in channel load can be achieved by using a predictive coding scheme, in which a data element will be sent only when the estimation error of its actual value is larger than a specified threshold.

The transmission range can be dynamically adjusted to minimise interference and maximise the number of simultaneous transmissions. The basic idea is to reduce the range when the vehicle density on the road increases. Generally, the transmission range is determined by the transmission power. The IEEE 802.11p/WAVE standard allows packet-level power control, which means each RSM can be transmitted with a different transmission power. Torrent-Moreno et al. [100] proposed a Distributed Fair Power Adjustment for Vehicular networks (D-FPAV) scheme to control the beaconing load. The scheme formulates the power control problem as a max-min problem and uses a distributed algo-
rithm to solve the problem. Its objective is to determine a power assignment such that the minimum of transmission power for all nodes is maximised and the beaconing load remains below a predefined threshold. Mittag et al. [67] proposed an improved scheme that uses a distributed vehicle density estimation to lower the overhead of D-FPAV. Yang et al. [115] proposed a scheme that periodically increases or decreases the power level depending on the average reception rate, which is calculated by monitoring the sequence number of the received messages. Huang et al. [41] proposed an adaptive scheme that controls both the message generation rate and the transmission range. The transmission range is adjusted linearly based on the average observed channel occupancy.

The message generation rate (beaconing rate) should be minimised without reducing tracking accuracy and compromising safety. In contrast to the other two parameters, the beaconing rate directly affects the safety performance of CCWSs in addition to the communication performance. Existing studies of adaptive beaconing rate schemes use the metric of tracking accuracy to measure the safety performance. Their goal is to reduce or control beaconing rate while maintaining a sufficient level of tracking accuracy. Rezaei et al. [79, 80] presented a scheme to adapt the beaconing rate depending on a position prediction error. Since the movement of a vehicle is predictable to some degree, an RSM needs to be sent only when the prediction error is greater than a specified error threshold. For example, a prediction error can be caused by a relatively noticeable change of course such as acceleration or a change of direction. Armaghan et al. [7] further improved the idea by dynamically adapting the error threshold and the number of estimation steps based on safety distance. Each vehicle estimates its location ahead for several intervals and sends the information along with its actual current position. While the estimated information is available, there is no new transmission unless any estimation errors are detected. Note that those schemes only predict the position, but not other states such as speed. Both of the existing schemes do not consider the effect of different node densities and actual channel load. The rate is not adapted based on actual channel load and the defined maximum error can be exceeded due to message loss. It is possible that even the reduced beaconing rate is still relatively high and enough to cause channel congestion. For example, on a wide highway with many lanes, a traffic jam will cause frequent
occurrences of a sudden change of movement (stop and go situation) that will result in many RSMs being sent frequently. Huang et al. [41] proposed an adaptive scheme that can reduce the rate when the actual channel load is too high. A transmission probability is calculated based on the estimated tracking error. The tracking error is stochastically decided depending on the estimated channel load. The approach had been shown to be more scalable to various vehicle densities. Schmidt et al. [84] presented the overview of a situation-adaptive beaconing rate scheme that considers the vehicle’s own movement and also the neighbouring vehicles’ movement.

None of the aforementioned adaptive beaconing rate schemes are able to prioritise the vehicles that are in a more dangerous situation than vehicles in a relatively safer situation. The use of tracking accuracy as a metric to measure the safety performance of CCWSs is rather unreliable because the tracking accuracy required in preventing a collision is relative, depending on interactions among vehicles. The next section proposes a new scheme that can improve the safety performance, which is measured by simulating the number of possible collisions. The scheme uses the vehicle interaction graph to prioritise vehicles in the most danger and can improve both the communication and safety performance.

4.3 Context-Aware Adaptive Generation Rate

In general, RSM dissemination works as follows. Every vehicle repeatedly sends an RSM to all other vehicles with an interval $I$ between two consecutive RSM transmissions. The beaconing interval $I$ directly determines the beaconing rate, which is the number of RSMs sent per second. The interval $I$ can be predetermined as a constant for all time or can be determined dynamically in real time.

A vehicle $v_1$ that receives an RSM sent by other vehicle $v_2$ at time $t_1$ knows the state of vehicle $v_2$ at time $t_1$. Tracking accuracy is defined as differences between a state of vehicle $v_2$ at time $t_1$ as recorded by vehicle $v_1$ and the actual state $v_2$ at current time $t_{\text{now}} = t_1 + \Delta t$. The most relevant metric for tracking accuracy is positional distance error [80, 41], which measures the distance between the tracked position and the actual position. Generally, the tracking accuracy is higher if the duration $\Delta t$ is shorter, which can be achieved
by increasing the reception rate of beacon messages. Since the communication channel capacity is limited, the reception rate cannot be increased indefinitely by increasing the beaconing rate, which limits the achievable tracking accuracy.

Higher tracking accuracy will result in a more accurate collision warning prediction [97, 44]. As an inaccurate warning prediction may lead to a collision since the driver cannot be alerted in time, tracking accuracy has been used as an indicator to assess the safety performance of beaconing schemes. However, the safety level also depends on the danger severity of a vehicle’s traffic situation. For example, a vehicle in a very safe situation has a very small possibility of being involved in a collision. Such a vehicle does not need the warning and tracking accuracy to be as high as required by another vehicle that is in an unsafe situation. This study introduces the concept of safety level that implies different tracking accuracy for different danger severity. One vehicle at a particular time does not always need the same tracking accuracy as another vehicle to maintain the same safety level.

Danger severity is determined from a time duration $\tau$ that is available to perform an evasive action before a collision becomes unavoidable, given a particular interaction between vehicles. A longer duration $\tau$ provides a driver more time and opportunity to react and evade a possible collision. Figure 4.4 plots examples of possible trajectories of two vehicles following each other: vehicle $F$ (follower) is following vehicle $L$ (leader). Figure 4.4(a) shows a situation where the avoidance time $\tau$ is only 0.5 s. If a collision warning is given at time 0, the driver of vehicle $F$ will only have at most 0.5 seconds time to react. In Figure 4.4(b) (longer gap between $F$ and $L$) and Figure 4.4(c) (the speed of $F$ is lower), the driver of vehicle $F$ will have the avoidance time

Figure 4.4: An example of car-following situations with different safety levels.
4.3. Context-Aware Adaptive Generation Rate

\(\tau\) of 1.5 s and 2.5 s, respectively. This example shows that a vehicle with lower danger severity has a greater chance to successfully avoid a possible collision.

To optimise channel usage without compromising safety, the beaconing interval \(I\) must be made adaptive based on an estimated load and the danger severity. The danger severity can be obtained using an interaction graph detailed in Chapter 3. The beaconing interval \(I\) of a vehicle can be proportionally adjusted based on the ratio between danger severity of itself and danger severity of its neighbouring vehicles. The basic principle is to give the highest priority (shortest interval \(I\)) to vehicles in the most danger to avoid any possible collisions, and at the same time control the channel load.

4.3.1 Problem Definition

Let \(v_s\) be a subject vehicle that has a CCWS installed, and \(\mathcal{V}'\) be a set of vehicles within one-hop communication range of \(v_s\). The identity and state (such as position, speed, heading, and any other properties) of each vehicle \(v_n \in \mathcal{V}'\) are obtained from a received RSM. The state of the subject vehicle \(v_s\) is obtained from the positioning system of the CCWS, as described in 2.2.4. A set of vehicles, \(\mathcal{V} = \{v_s\} \cup \mathcal{V}'\), consists of a subject vehicle \(v_s\) and its neighbouring vehicles \(\mathcal{V}'\). The set \(\mathcal{V}\) and an interaction graph \(\mathcal{G} = (\mathcal{V}, \mathcal{E})\) is maintained locally by every subject vehicle \(v_s\). The interaction graph \(\mathcal{G}\) is generated using the state information of each vehicle \(v \in \mathcal{V}\).

Given a constant message size \(S\) and the physical data rate of wireless communication \(R\), transmission duration for a single message \(T = \frac{S}{R}\) can be calculated. The duration \(T\) excludes the extra time taken by PHY or MAC protocol overhead. As mentioned in Chapter 2, IEEE 802.11p supports the use of data rates from 3 Mbps up to 27 Mbps. For example, a single transmission of a message with a size of 500 bytes using a data rate of 6 Mbps will occupy the communication channel for 0.6 milliseconds. Channel load \(\lambda\) can be estimated based on the number of nodes in the transmission range of each other \(n\), the message generation rate of each node \(f_i\), and the transmission duration \(T\):

\[
\lambda = \sum_{i=1}^{n} f_i \cdot T
\]  

(4.1)

For example, given the number of nodes \(n = 50\), the same generation rate
for each node $f = 10$ Hz, and transmission duration $T = 0.0006$ s, the channel load will be: $\lambda = 50 \times 10 \times 0.0006 = 0.3$. A channel load $\lambda > 1$ means that the channel is overloaded. In practice, the actual IEEE 802.11 based wireless channel load can hardly reach $\lambda = 1$. The channel becomes more congested when $\lambda$ approaches 1.

Therefore, to control the channel load consumed by beaconing, the beaconing rate $f$ for each vehicle must be adjusted dynamically. The beaconing rate should not be the same for all vehicles because each vehicle may have a different neighbouring vehicle density and a different danger severity. This problem of determining beaconing interval can be formalised as follows:

**Input:** An up-to-date interaction graph $G = (V, E)$, a transmission duration of a single RSM $T$, and a maximum beaconing load $\lambda_{\text{max}}$ as a parameter to control channel utilisation.

**Output:** The beaconing interval $I$ or rate $f = \frac{1}{I}$ for each subject vehicle such that the maximum beaconing load $\lambda_{\text{max}}$ is not exceeded and the most endangered vehicles are assigned with the shortest interval.

### 4.3.2 Determining danger severity using interaction graph

Since a vehicle can endanger more than one other vehicle, the beaconing interval should be adjusted according to the interaction that has the highest danger severity. Given the interaction graph $G = (V, E)$, the maximum danger severity of a vehicle $v_i \in V$ can be obtained from the interaction graph by finding the highest weight $\omega$ from all of the outgoing edges of $v_i$:

$$\omega_{\text{max}} (v_i) = \max_{(v_i, v_j) \in E} \omega_{ij} \quad (4.2)$$

Each subject vehicle can calculate the sum of maximum weight $\tilde{\omega}$:

$$\tilde{\omega} = \sum_{v \in V} \omega_{\text{max}} (v) \quad (4.3)$$

The sum of maximum weight $\tilde{\omega}$ reflects a temporary local knowledge of the beaconing load within the communication range of the subject vehicle. If a vehicle knows the sum $\tilde{\omega}$ in its neighbouring area, it can estimate the beaconing rate of other neighbouring vehicles, which is equivalent to the beaconing load.
The sum of maximum weight $\tilde{\omega}$ of each subject vehicle is included in every RSM sent by it. Hence, each vehicle can obtain the sum $\tilde{\omega}$ for all its neighbouring vehicles, defined as $\tilde{\omega}_v, v \in \mathcal{V}$. The total sum of danger severity $\tilde{\omega}_{\text{max}}$ in its neighbouring area is calculated by finding the highest $\tilde{\omega}_v$:

$$\tilde{\omega}_{\text{max}} = \max_{v \in \mathcal{V}} (\tilde{\omega}_v)$$  \hspace{1cm} (4.4)

### 4.3.3 Context-Aware RSM Protocol

#### Algorithm 2: Pseudo-code of the CARD protocol.

```plaintext
function CalculateInterval()
  if |\mathcal{V}| = 1 then
    Calculate default interval $\mathcal{I}_s$ using Equation 4.5
    return $\mathcal{I}_s$
  
  Calculate interval $\mathcal{I}$ using Equation 4.6
  if $\mathcal{I} < \mathcal{I}_{\text{min}}$ then $\mathcal{I} \leftarrow \mathcal{I}_{\text{min}}$
  else if $\mathcal{I} > \mathcal{I}_{\text{max}}$ then $\mathcal{I} \leftarrow \mathcal{I}_{\text{max}}$
  return $\mathcal{I}$

procedure SendMessage()

  Get the vehicle self state from the positioning system
  Update the context model $\mathcal{G}$ with the current self state
  Create a new RSM $m$ that contains the current self state
  Transmit $m$ using WSMP
  $t_{\text{prev}} \leftarrow t_{\text{now}}$
  $\mathcal{I}_{\text{new}} \leftarrow \text{CalculateInterval()}$
  Execute SendMessage() after interval $\mathcal{I}_{\text{new}}$

procedure ReceiveMessage($m$)

  Retrieve the vehicle state from $m$
  Update the context model $\mathcal{G}$ with the received state
  if $t_{\text{prev}}$ is defined then
    Cancel any scheduled transmission
    $\mathcal{I}_{\text{new}} \leftarrow \text{CalculateInterval()}$
    $\mathcal{I}_{\text{now}} \leftarrow t_{\text{now}} - t_{\text{prev}}$
    if $\mathcal{I}_{\text{now}} < \mathcal{I}_{\text{new}}$ then
      Execute SendMessage() after interval $(\mathcal{I}_{\text{new}} - \mathcal{I}_{\text{now}})$
    else
      SendMessage()
```

The concept of rate adaptation with safety consideration has been de-
developed as a Context-aware Adaptive rate RSM Dissemination (CARD) protocol. The CARD protocol consists of one function and two main procedures: CalculateInterval, SendMessage, and ReceiveMessage. Algorithm 2 describes the pseudo-code of the protocol. In principle, the protocol works as follows:

1. When a vehicle receives an RSM from another vehicle, information from the RSM is used to update the interaction graph, which is locally maintained by the vehicle. Two different vehicles may not have the same information in their interaction graphs. However, closely spaced vehicles will have similar information.

2. A vehicle sends an RSM repeatedly with a dynamic interval, which is calculated using a function that utilises the interaction graph. Whenever the interaction graph is updated or modified, the interval is also re-adjusted.

There are several common terms, variables and constants used throughout the protocol. The minimum interval $I_{\text{min}}$ is the lower bound that is used to limit the beaconing interval to the smallest reasonable value. For example, a vehicle at speed 126 km/h (35 m/s) can travel 1.75 m within an interval of 50 ms. This means that the 50 ms interval is small enough to give a reasonable distance error of less than two meters. The maximum interval $I_{\text{max}}$ is the upper bound that is used to limit the interval to the largest reasonable value. For example, the $I_{\text{max}}$ parameter can be set to one second to ensure that an RSM is always sent at least one every second. Time $t_{\text{now}}$ is the present or most current time given by the system clock. The system clock is assumed to be globally synchronised through the GPS.

The CalculateInterval function calculates the beaconing interval based on the danger severity of the current road traffic situation. If a vehicle has no neighbouring vehicle, which means that there are no other vehicles within its communication range, this function returns a default interval $I_s$. The default interval $I_s$ is calculated based on the vehicle speed using Equation 4.5:

$$I_s = \begin{cases} \frac{e_s}{s} & \text{if } s > 0 \text{ and } \frac{e_s}{s} < I_{\text{max}} \\ I_{\text{min}} & \text{if } \frac{e_s}{s} < I_{\text{min}} \\ I_{\text{max}} & \text{otherwise} \end{cases}$$

(4.5)
where \( s \) is vehicle current speed and \( e_t \) is an error tolerance threshold. A higher speed will result in a smaller interval to keep a possible distance error less than the threshold \( e_t \). The threshold \( e_t \) is a parameter that can be set based on an assumption of acceptable position or distance error in CCWSs. If a vehicle has one or more neighbouring vehicles, this function returns the interval \( I \) calculated using Equation 4.6:

\[
I = \frac{1}{I_{\text{max}}} + \frac{\omega_{\text{max}}}{\lambda_{\text{max}}} \left( \frac{|V|}{I_{\text{max}}} - \frac{|V|}{I_{\text{max}}} \right)
\]  

(4.6)

The formula calculates an interval proportionally based on a vehicle’s danger severity \( \omega_{\text{max}} \) (Equation 4.2) and the sum of neighbouring vehicles’ danger severity \( \tilde{\omega}_{\text{max}} \) (Equation 4.4), in which the resulting channel load is restricted to the maximum beaconing load \( \lambda_{\text{max}} \). The resulting interval \( I \) is bounded to the minimum and maximum interval such that \( I_{\text{min}} \leq I \leq I_{\text{max}} \).

A vehicle \( v_s \) may start sending RSMs after its engine has been started by executing the Send\text{Message} procedure. First, current vehicle self state, such as position, speed, and heading, is acquired from the positioning system. The state information of vehicle \( v_s \) is used to update its interaction graph \( G \) by processing each pair of vehicles \( (v_s, v) \), \( \forall v \in \mathcal{V}, v_s \neq v \). A new data packet that encodes the state information is created and transmitted using WAVE Short Message Protocol (WSMP) as defined in the IEEE 1609.3 standard [3]. The time of transmission is kept in \( t_{\text{prev}} \). The next RSM transmission is then scheduled by executing the Send\text{Message} procedure after an interval calculated by the Calculate\text{Interval} function.

The Receive\text{Message} procedure is called when a vehicle \( v_s \) receives an RSM \( m \) from another vehicle \( v_n \). The procedure decodes the state of vehicle \( v \) from \( m \) and updates the interaction graph \( G \) of vehicle \( v_s \) with the new information. The interaction graph \( G \) of vehicle \( v_s \) is updated by processing each pair of vehicles \( (v_n, v) \), \( \forall v \in \mathcal{V}, v_n \neq v \). Every time an RSM is received, it is likely that the interactions among neighbouring vehicles have changed. Therefore, any scheduled RSM transmission is cancelled to reschedule the next transmission with a new interval. The new interval \( I_{\text{new}} \) is calculated using the Calculate\text{Interval} function. The actual current interval \( I_{\text{now}} \) is the duration elapsed since the last transmission time \( t_{\text{prev}} \) until the current time \( t_{\text{now}} \). If the new interval is longer than the actual current interval, the next RSM
transmission is then scheduled at time $I_{new} - I_{now}$. Otherwise, an RSM must be sent immediately by calling the `SendMessage` procedure.

### 4.4 Evaluation

The performance of the CARD protocol is evaluated by simulation. The simulation involves simulating a wireless network, vehicles moving on a straight road with multiple lanes, and collisions between vehicles caused by unsafe situations. The simulation program was implemented by extending the ns-3 network simulator (version 3.8) [1]. The evaluation compares the performance of the CARD protocol and the Constant Rate (CR) protocols. CR protocols implement a constant rate scheme in which RSMs are periodically sent at a constant interval. Four CR protocols with different intervals were compared: CR-50 (50 ms interval), CR-100 (100 ms interval), CR-200 (200 ms interval), and CR-500 (500 ms interval).

#### 4.4.1 Performance Metrics

The performance is measured in terms of safety and communication issues. The CCWS aims to improve road safety by trying to prevent vehicle collisions caused by the error or limited perception of human drivers. Therefore, this evaluation uses the vehicle collisions as the metric to assess safety performance. A protocol can be said to have a better safety performance if using the protocol results in a smaller number of potential vehicle collisions. The number of potential vehicle collisions can be measured by simulating an accident scenario on a typical highway. To study the effect of different RSM protocols on the number of potential collisions, the simulation is designed in a way such that a collision will occur only if an RSM is not received in time. Assumptions made in the simulation are detailed in Subsection 4.4.2.

The communication performance involves the metrics of dissemination latency or delay, actual channel usage, and probability of message reception. The latency is the duration between the time when an RSM is sent to the MAC layer and the time when it is received by other vehicles. The latency consists mostly of MAC queueing time and channel access time. A lower latency gives a better chance for a vehicle to avoid a collision. The actual
channel usage is measured by averaging channel busy time from all nodes during the simulation time. As such, the measured usage includes the PHY and MAC protocol overhead. Higher channel usage increases the possibility of channel congestion. The probability of message reception is the probability that an RSM is successfully received by a node located at a particular distance from a sender node. Higher probability of message reception indicates fewer packet collisions. The communication performance metrics are used to measure the efficiency of the protocol.

A good overall performance is indicated by both safety and communication performance. This means that a good protocol must achieve a low number of collisions, low latency, low channel usage, and high probability of message reception. However, since the ultimate goal of the CCWS is to improve safety, this research emphasises the number of potential collisions metric.

4.4.2 Simulation Design and Setup

4.4.2.1 Wireless Communication

In the simulation, all vehicles are equipped with a CCWS. Each vehicle continuously and repeatedly sends RSMs during the simulation duration at an interval determined by the RSM protocols. For example, the CR-100 protocol sends an RSM every 100 milliseconds. The size of an RSM is set to a constant value of 500 bytes, excluding the MAC layer protocol specific header. A constant message size is used to provide a consistent comparison result. The transmission power is configured to 19 dBm. The probabilistic Nakagami distribution is selected for the radio propagation loss model, as field tests on highways showed that the Nakagami distribution is suitable to be used on vehicular communication in highway scenarios [101]. The parameter of $m = 1$ is set to simulate severe fading conditions; therefore, demonstrating the protocols’ performance in the worst case scenario.

Lower layer protocol (PHY and MAC) parameters are set according to the IEEE 802.11p draft standard, which operates at 5.9 GHz on a 10 MHz control channel (CCH). The PHY data rate is configured to 6 Mbps, which is the optimal value for safety communication [48]. The channel switching scheme is currently not implemented, which means the whole 10 MHz CCH bandwidth can be used by the CCWS application. The MAC layer is configured to ad hoc
Table 4.1: Common configuration parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHY and MAC protocol</td>
<td>802.11p</td>
</tr>
<tr>
<td>802.11p data rate</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>Propagation loss model 1</td>
<td>Three log distance</td>
</tr>
<tr>
<td>Propagation loss model 2</td>
<td>Nakagami $m = 1$</td>
</tr>
<tr>
<td>Transmission power</td>
<td>19 dBm</td>
</tr>
<tr>
<td>RSM size</td>
<td>500 bytes</td>
</tr>
<tr>
<td>RSM Priority level</td>
<td>AC_VI</td>
</tr>
<tr>
<td>CARD parameter $I_{\text{min}}$</td>
<td>50 ms</td>
</tr>
<tr>
<td>CARD parameter $I_{\text{max}}$</td>
<td>1000 ms</td>
</tr>
</tbody>
</table>

mode with QoS support using the EDCA mechanism as described in IEEE 802.11e. The priority for RSMs is set to AC_VI (second highest). All the RSM protocols are simulated as extensions to the IEEE 1609 WAVE Short Message Protocol (WSMP) [3]. They are directly implemented on top of the MAC layer. Common configuration parameters related to communication are summarised in Table 4.1.

### 4.4.2.2 Road Traffic and Accident Scenario

The simulation of vehicles moving on a road is based on a typical multi-lane highway scenario as illustrated in Figure 4.5. To demonstrate the scalability of the CARD protocol, five scenarios with different average vehicle densities are evaluated: VD-30, VD-60, VD-90, VD-120, and VD-150. The vehicle density starts from 30 vehicles/km (VD-30) up to 150 vehicles/km (VD-150). The length of the road is always set to 2 km. Therefore, each scenario is designed with different numbers of vehicles and lanes to create a realistic situation with a desired density. Table 4.2 shows the parameters of the scenarios. Each lane has a random number of vehicles and vehicles on each lane travel at slightly different speeds, which are also randomised. The vehicle density determines the average inter-vehicle distance and vehicle speed in each lane. The distance between two consecutive vehicles $d_{i,j}$ is random, but is always greater than the required safety distance. This is to ensure that a collision is always avoidable provided that an RSM is received on time. For each scenario, simulations with different random seeds were performed 50 times. Each simulation instance uses a random road traffic situation (random speed and inter-vehicle distance).
4.4. Evaluation

![Diagram of vehicle moving direction and lane illustration](image)

Figure 4.5: Illustration of the highway scenarios used in the simulation.

Table 4.2: Specific parameters for scenarios with different vehicle density.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of vehicles</th>
<th>Number of lanes</th>
<th>Average speed (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VD-30</td>
<td>60</td>
<td>2</td>
<td>25-30</td>
</tr>
<tr>
<td>VD-60</td>
<td>120</td>
<td>3</td>
<td>15-25</td>
</tr>
<tr>
<td>VD-90</td>
<td>180</td>
<td>3</td>
<td>10-15</td>
</tr>
<tr>
<td>VD-120</td>
<td>240</td>
<td>6</td>
<td>15-25</td>
</tr>
<tr>
<td>VD-150</td>
<td>300</td>
<td>6</td>
<td>10-15</td>
</tr>
</tbody>
</table>

Results from the simulation are averaged from the 50 runs.

The simulation implements a main function of the CCWS, which is to predict a potential collision based on the state information obtained via RSMs. If a collision is likely to occur, the CCWS warns the driver. Based on the warning, the driver then performs necessary actions to avoid the collision. To evaluate the safety performance of the CCWS, collisions between vehicles are simulated by assuming that some drivers become distracted or inattentive. A distracted driver cannot promptly react to avoid a collision with a leading vehicle, unless they are warned by the CCWS. To prevent the collision, the CCWS must warn the driver at the right time, which is calculated based on the tracked state of neighbouring vehicles obtained from RSMs. If RSMs cannot be promptly received, the warning calculation will be inaccurate, and a collision may occur accordingly. For example, when a vehicle L starts braking, its direct

Table 4.3: Common parameters for the highway scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver’s reaction time</td>
<td>1.5 s</td>
</tr>
<tr>
<td>Vehicle length</td>
<td>4 m</td>
</tr>
<tr>
<td>Min. inter-vehicle gap</td>
<td>2 m</td>
</tr>
<tr>
<td>Vehicle deceleration</td>
<td>4.9 m/s²</td>
</tr>
<tr>
<td>Highway length</td>
<td>2000 m</td>
</tr>
</tbody>
</table>
follower vehicle $F$ must also brake accordingly in order to avoid a collision with $L$. Let us assume that the driver of vehicle $F$ is distracted. Vehicle $F$ will not start braking until its driver is warned by the CCWS. If a prompt warning is given to the driver, vehicle $F$ will brake accordingly to avoid a collision. Otherwise, vehicle $F$ will collide with vehicle $L$. If vehicle $F$ always fails to receive an RSM from vehicle $L$, it will result in a collision. If an up-to-date RSM is not received on-time, it may result in a collision. Therefore, the safety performance of different RSM protocols can be evaluated based on the number of potential collisions that cannot be prevented.

The number of distracted or inattentive drivers in each simulation instance is determined using a parameter, which is the percentage of the total number of vehicles in each scenario. The performance of the RSM protocols can be fully demonstrated by using a worst case scenario that assumes all the drivers are inattentive. However, using such an assumption would be considered very unrealistic. To make the simulation more realistic, the number of inattentive drivers is set to 15 percent of the total vehicles in each scenario. The percentage is obtained from statistics of driver inattention in the US [95], which are based on the analysis of five years of data from the Crashworthiness Data System (CDS).

The simulation models a situation when vehicles stop at a red traffic light. Each vehicle at the front end of each lane $v_{laneId,1}$ will start decelerating normally at $4.9 \text{m/s}^2$ when approaching the end of the road, until it stops completely right at the end of the road. To avoid a collision, a following vehicle must decelerate at the right time depending on the relative position and speed of its leading vehicle. A normal vehicle will start decelerating based on the calculation using the actual position and speed of its leading vehicle. A vehicle with a distracted driver will start decelerating only after its warning system predicts a collision based on the known (tracked) position and speed of its leading vehicle, instead of the actual position and speed. Inaccurate position and speed prediction may result in some collisions depending on the interaction between vehicles.

Common parameters related to the vehicles are given in Table 4.3. Driver’s reaction time is set to a constant value of 1.5 s. The length of all vehicles is assumed to be the same, which is set to 4 m. A minimum inter-vehicle gap is assumed to be 2 m. The minimum gap is used as a tolerance buffer in the
calculation of collision prediction. The error tolerance threshold $e_t$ assumes
the same value as the minimum gap. The simulation duration for each run of
the scenario is different. A simulation instance finishes when all vehicles stop
moving, which can last from 60 to 200 seconds.

4.4.3 Simulation Results

The CARD protocol is expected to perform differently given a different value
of the maximum beaconing load $\lambda_{max}$. To evaluate the performance of the
CARD protocol with different $\lambda_{max}$, 10 sets of simulations are performed with
$\lambda_{max}$ starting from 0.1 up to 1.0 with an increment of 0.1. Figure 4.6 shows
the results of the simulations averaged from all scenarios with different vehicle
densities. The parameter $\lambda_{max} = 1.0$ results in the least average number of
collisions as shown in Figure 4.6(a). Better safety performance is indicated
by the fewer number of collisions. Note that there is no significant difference
in the average number of collisions with $\lambda_{max} \geq 0.6$, in which all the average
values are below 0.2.

Figure 4.6(b) shows the average distance error, which is the metric for
tracking accuracy. The average distance error is measured by accumulating
the distance error of each tracked position for every 100 ms and averaging the
result. The distance error is the distance between the tracked position and
the actual position of a vehicle at a certain time. A smaller distance error
implies a shorter beaconing interval, which results in a higher actual channel
usage, which is shown in Figure 4.6(c). Figure 4.6(d) shows the probability
of message reception, which is a popular metric to measure communication
reliability. As expected in a wireless network that uses the CSMA MAC pro-
tocol, the overall probability of message reception decreases as the channel
usage increases. Although the CARD protocol with $\lambda_{max} = 1.0$ has the lowest
reception probability, it has the fewest number of collisions. The results con-
firmed the proposition that safety performance cannot be measured solely by
the tracking accuracy metric or by the communication performance.

The performance of the CARD protocol with $\lambda_{max} = 1.0$ is then compared
to other CR protocols. The average number of collisions for each protocol in
each scenario is shown in Figure 4.7 with the exact values provided in Table 4.4.
From a safety perspective, the CR-50 protocol has the worst performance in
Figure 4.6: Performance of the CARD protocol given different values of maximum beaconing load $\lambda$ parameter, averaged from all scenarios.
4.4. Evaluation

Table 4.4: Number of vehicle collisions in different scenarios and the total average.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CR-50</th>
<th>CR-100</th>
<th>CR-200</th>
<th>CR-500</th>
<th>CARD</th>
</tr>
</thead>
<tbody>
<tr>
<td>VD-30</td>
<td>0</td>
<td>0.10</td>
<td>0.34</td>
<td>3.16</td>
<td>0.02</td>
</tr>
<tr>
<td>VD-60</td>
<td>0.20</td>
<td>0.16</td>
<td>0.74</td>
<td>4.34</td>
<td>0</td>
</tr>
<tr>
<td>VD-90</td>
<td>0.24</td>
<td>0.04</td>
<td>0.34</td>
<td>2.38</td>
<td>0</td>
</tr>
<tr>
<td>VD-120</td>
<td>3.04</td>
<td>1.50</td>
<td>1.78</td>
<td>9.78</td>
<td>0.20</td>
</tr>
<tr>
<td>VD-150</td>
<td>25.34</td>
<td>1.22</td>
<td>1.68</td>
<td>8.44</td>
<td>0.22</td>
</tr>
<tr>
<td>Total average</td>
<td>5.764</td>
<td>0.604</td>
<td>0.976</td>
<td>5.620</td>
<td>0.088</td>
</tr>
</tbody>
</table>

the scenario with the highest vehicle density (VD-150). Such a result indicates severe channel congestion because the channel capacity is overloaded. The CR-500 protocol has the worst performance in all other scenarios (VD-30 to VD-120), which indicates that the beaconing rate of 2 messages per second is too low for most situations to ensure safety. The CARD protocol can prevent all potential collisions in the VD-60 and VD-90 scenarios and has the lowest number of collisions in the VD-120 and VD-150 scenarios. Overall safety performance can be compared by looking at the total average of the result from all scenarios, which is shown in the last row of Table 4.4. The total average shows that the CARD protocol has the best safety performance, followed by the CR-100, CR-200, CR-500, and CR-50 protocols. The average number of collisions for the CARD protocol in every scenario is always less than 0.3, which demonstrates that it can ensure safety in various traffic situations with different vehicle densities.

The average latency of one hop transmissions is shown in Figure 4.8. The latency for the CR-50 protocol in VD-120 and VD-150 scenarios is not fully plotted in the graph because the scale is much higher than for the other protocols. It is more than 16 ms in the VD-120 scenario, and more than 400 ms in the VD-150 scenario. The latencies for the other protocols are all below 5 ms, which make their differences relatively insignificant.

Average channel usage during the simulation duration is shown in Figure 4.9. It demonstrates the efficiency of the CARD protocol compared to CR-50, CR-100, and CR-200 protocols in most scenarios. The CR-500 protocol has the lowest channel usage compared to the other protocols; however, it cannot ensure safety as indicated by the high number of collisions. The CARD protocol is more scalable because it can maintain channel usage below 70% even in high density scenarios.
Figure 4.7: Number of vehicle collisions in different scenarios.

Figure 4.8: Latency of one hop transmissions experienced by RSMs in different scenarios.
4.4. Evaluation

To evaluate the communication reliability of the protocols, Figure 4.10 compares the probability of message reception between the CR-100 and CARD protocols. The probability is plotted with respect to the distance between a receiver and a sender. The CR-100 protocol is chosen for the comparison because it has the least number of vehicle collisions compared to the CR-50, CR-200, and CR-500 protocols. Figure 4.10(a) shows that the reliability of the CR-100 protocol decreases significantly when the vehicle density increases. In contrast, Figure 4.10(b) shows that the reliability of the CARD protocol does not change significantly with different vehicle densities. In the VD-30 scenario, the overall probabilities of message reception of the CR-100 and CARD protocols are relatively similar. However, the resulting number of collisions in the same scenario for the CARD protocol is smaller than for the CR-100 because the CARD protocol can prioritise vehicles in the most danger.

The results of communication performance show that, in general, a higher channel usage causes a higher latency and a lower probability of message reception. The CARD protocol can limit its channel usage and keep the probability of message reception within acceptable levels in any scenario with different vehicle densities. Although the CARD protocol cannot achieve a very high
probability of message reception, its safety performance is the best among the other CR protocols.

4.5 Discussion

Simulation results demonstrate the efficiency, safety, and scalability of the proposed CARD scheme. In all scenarios, the CARD scheme can maintain its actual channel usage between 45% and 65% of the capacity. It is better than the CR-50 and CR-100 schemes that can utilise more than 80% of channel capacity in some scenarios but without significant improvement in safety. Although the CR-200 and CR-500 schemes consume the least channel capacity, their safety performance is lower than the CR-100 and CARD schemes. Safety performance of the CR-50 scheme is the lowest in the VD-150 scenario because it has the highest channel usage of all the schemes. This indicates that the CR-50 scheme causes channel congestion that significantly reduces safety particularly when road traffic becomes denser such as in a traffic jam.

The CR-100 scheme has the best overall performance among the constant rate schemes (CR-50, CR-200, and CR-500). It seems that the popular assumption of using an interval of 100 milliseconds for beaconing [98, 101, 21] may not be without grounds. Communication performance of the CARD scheme is more scalable than the CR-100 scheme in all tested scenarios, as indicated by their latency and probability of message reception. Figure 4.8 shows that the latency for the CARD scheme is kept at below 3 ms in all scenarios while the latency for the CR-100 scheme can exceed 3 ms in some scenarios. The CARD scheme can ensure a more stable and relatively high probability of message reception (Figure 4.10(b)) compared to the CR-100 scheme (Figure 4.10(a)).

In general, the CARD scheme constantly performs better than the other schemes for all tested scenarios with different vehicle densities, as indicated by the average of the results from different densities. The CARD scheme comes with the smallest average number of collisions of 0.088, followed by the CR-100 scheme with an average number of collisions of 0.604, which is more than six times larger than the CARD’s result. The result demonstrates the scalability of the CARD scheme to ensure the communication and safety performance of CCWSs under road traffic situations with different vehicle densities.

It is expected that the maximum beaconing load parameter $\lambda_{max}$ cannot
4.5. Discussion

Figure 4.10: Probability of message reception with respect to the distance from the sender in scenarios with different vehicle densities.

(a) CR-100 protocol.

(b) CARD protocol with $\lambda_{\text{max}} = 1.0$. 
control the channel usage precisely because each vehicle only relies on its own local one-hop knowledge. For $\lambda_{\text{max}} \leq 0.3$, the actual channel usage is slightly more than the specified limit $\lambda_{\text{max}}$. For $\lambda_{\text{max}} > 0.3$, the actual channel usage is getting much lower than the specified parameter $\lambda_{\text{max}}$ as the value of $\lambda_{\text{max}}$ increases. The discrepancy is sensible because the parameter $\lambda_{\text{max}}$ is used as a maximum limit of the channel usage estimation. Since the beaconing interval is bounded between 50 ms and 1000 ms, the maximum limit may not be reached in some situations, such as when vehicles are not moving. The aim of the CARD scheme is not to precisely control the actual channel usage, but to improve the communication and safety performance.

A real-world implementation of the RSM protocol should incorporate all the existing schemes to further improve the performance and reliability. It is possible to use the proposed CARD method with other schemes, such as the scheme proposed by Rezaei et al. [80] that only sends an RSM if there is a significant and unpredictable change of movement. For example, the adaptive interval calculated by the CARD method can be treated as the minimum interval allowed, and an RSM can actually be sent with a longer interval if the movement is still predictable. An aggregation or piggybacking scheme such as the one proposed by Yang et al. [116] can be used to improve the probability of message reception.

### 4.6 Summary

This chapter has presented a new context-aware approach to optimising the RSM dissemination rate in CCWSs. The original contribution of this research is a Context-aware Adaptive rate RSM Dissemination (CARD) protocol that is developed using the new context-aware approach. This new protocol adjusts the repetition interval or rate dynamically based on an estimated channel load and danger severity. To improve safety, priority is given to vehicles facing the highest risk of collision. The RSMs are sent at a shorter interval for these vehicles to avoid a possible collision. The proposed approach requires estimating the danger severity of each vehicle using an interaction graph presented in Chapter 3. The performance of the CARD protocol has been evaluated by conducting simulation experiments in ns-3. The CARD protocol has been compared with constant rate protocols by simulating accident scenarios on a
multiple lane straight road. Safety performance is measured as the average number of collisions that occurred within the experiment. Simulation results have demonstrated the safety, efficiency, and scalability of the CARD protocol. It is able to outperform the constant rate protocols by reducing the collision rate significantly, and therefore improve safety. It has lower channel usage compared to other protocols that have a similar safety performance. The safety and communication performance of the CARD protocol can be maintained consistently across various scenarios with different vehicle densities.
Chapter 5

Event Safety Message Dissemination

In the event of an accident, event safety messages (ESMs) must be disseminated to all of the endangered vehicles. Existing methods to disseminate ESMs can be categorised as scoped broadcasts. Broadcast routing is not efficient as it may send ESMs to a large number of vehicles in the area, rather than only the endangered vehicles, which may lead to communication channel congestion. It also cannot prioritise the receivers based on their critical time to avoid a collision, which may result in some collisions that could be avoided otherwise. This chapter presents a context-aware multicast protocol that can overcome the aforementioned problems. The protocol is designed based on a more efficient context-aware approach by utilising the model presented in Chapter 3. The performance of the multicast protocol is compared with existing ESM protocols for some typical highway scenarios. The performance is measured by the number of vehicle collisions occurring in a simulated chain collision scenario, which is a typical road accident. Experiment results show that using the new multicast protocol can save more vehicles from collisions in some scenarios. In addition, the use of this multicast protocol is not restricted only to highway scenarios unlike the existing protocols.
5.1 Introduction

ESMs, or emergency warning messages, are notification messages sent by a vehicle when certain safety events occur. Any event that can cause a dangerous situation (such as an occurred or imminent accident) can trigger ESMs. ESMs may also be triggered by any drastic changes in the vehicle behaviour or state that are likely to cause an accident, such as deceleration exceeding a certain threshold, dramatic changes in moving direction, or major mechanical failure. When a vehicle detects such a dangerous situation, the vehicle becomes an abnormal vehicle and therefore needs to send ESMs to other endangered vehicles in a timely manner with the highest priority. Upon receiving an ESM, a vehicle informs its driver of the possible dangerous situation through on-board interfaces (audio, visual, etc.). Being made aware of the dangerous situation, the driver should perform evasive action.

The purpose of ESMs is to warn upcoming vehicles of imminent hazards in traffic. Such a purpose is more directed toward eliminating or limiting the consequences of dangerous situations that have already occurred. ESMs are especially useful to mitigate multi-vehicle chain collisions because they can propagate faster than visual indicators such as tail brake lights [16]. An example of safety applications designed to prevent such accidents by using ESMs is known as Electronic Emergency Brake Light (EEBL) [98, 123]. An EEBL application will trigger ESM dissemination if a vehicle brakes too hard. ESMs may need to be propagated along a roadway beyond the coverage area of the original sender. This can be done by using a multi-hop scheme, in which ESMs are relayed by other vehicles. Figure 5.1 illustrates a multi-hop scheme in which vehicles \( b \) and \( e \) relay the ESMs sent by vehicle \( a \) to vehicle \( c \).

Several ESM dissemination protocols have been proposed in the literature [16, 31, 122, 118]. Most of them can be categorised into a scoped-broadcast scheme in which ESM dissemination is limited to a specific area and direction. They are not efficient as they may still send ESMs to vehicles that are not endangered and they cannot prioritise the receivers based on their critical time to avoid collision. They are designed for a simple road traffic situation, specifically for a straight road segment such as a highway, where only two directions are considered: forward or backward. Most of the existing protocols assume no prior knowledge about the receivers and their states. In a complete
5.1. Introduction

CCWS, such knowledge can be obtained through the use of RSMs.

The original contribution of the presented work is a new context-aware ESM dissemination protocol that uses a multicast routing strategy to disseminate ESMs efficiently. The objective of the new protocol is to deliver ESMs to endangered vehicles as fast as possible to minimise the number of vehicle collisions. The multicast routing strategy combines a tree-based routing method with a contention-based method. The strategy incorporates methods to obtain the required context information, such as the global network topology; a sender node, which is an abnormal vehicle; and the receiver nodes, which are the vehicles that may be endangered by the abnormal vehicle. Such information can be obtained as each vehicle also exchanges RSMs to track the state of its neighbouring vehicles. Using the context information, the routing method finds the most efficient routes from a sender node to all the receiver nodes as a multicast tree. The problem of finding the multicast tree can be formulated as a minimum delay tree problem, which can be solved using Dijkstra's shortest path algorithm [24]. By using the tree-based routing method, the protocol can reduce unnecessary transmissions and therefore can minimise the message reception latency as imposed by safety applications. To the best of our knowledge, this multicast concept for an ESM protocol has never been proposed previously in the literature.

The performance of the multicast protocol is evaluated by simulation in ns-3 [1] and compared with existing broadcast protocols. The main evaluation metric is the number of vehicle collisions that can be prevented. For that purpose, a highway mobility model that can simulate chain collisions has been developed on top of the network simulator. The simulation results show that using the multicast protocol resulted in fewer vehicles collisions in some scenarios compared to other protocols.

The rest of this chapter is organised as follows: Section 5.2 introduces existing works related to ESM dissemination protocols and identifies their weaknesses. Section 5.3 presents a more efficient multi-hop ESM dissemination scheme using a multicast approach. A formal definition, methods to obtain the input values from context information, and a new context-aware multicast protocol are elaborated in this section. The performance of the proposed method is evaluated in Section 5.4. Section 5.5 analyses the simulation results and the advantages of the new multicast protocol. Finally, Section 5.6
summarises the results and contributions of this chapter.

5.2 Literature Review

Communication protocols for ESM dissemination aim to propagate hazard warnings along a roadway in a timely manner. By using multi-hop communication, safety messages can be forwarded to any vehicle beyond the radio range of an original sender. The ESM dissemination problem is related to routing problems in wireless networks. In general computer networks, there are three basic types of routing schemes: unicast, broadcast, and multicast. Unicast routing is used to deliver a message to a specified node. Broadcast routing is used to deliver a message to all nodes in the network. Multicast routing is used to deliver a message to a group of nodes that have expressed interest in receiving the message.

In wireless networks, the characteristics of the wireless medium imply the use of broadcast routing for single-hop communication at a physical level. However, for multi-hop communication, there are higher level protocols that use unicast, multicast, and broadcast routing schemes [21]. All routing schemes for wireless networks involve finding and selecting a node or nodes to relay a message to any destination node that cannot be reached from a sender node via single-hop communication.

In VANET, which is a specialised wireless ad hoc network, existing routing schemes can be broadly categorised into general purpose and safety purpose routing. General purpose routing is used to disseminate any type of data such as traffic information or multimedia streams. In principle, it requires finding and establishing a route from a sender to a receiver, and using the established route to deliver the data, which may contain many messages. There are two basic approaches to finding the route: 1) A reactive approach finds the route on-demand by broadcasting a hello message to all communication nodes (e.g.
vehicles) at the time a message needs to be sent; 2) A proactive approach maintains up-to-date network information and uses the information to find the route when needed. Safety purpose routing is used to disseminate data important for road safety, such as ESMs. Safety purpose routing requires lower latency and higher reliability compared with general purpose routing. Most existing routing schemes, for safety purposes, use a similar approach to the reactive approach with one significant difference. Given the size of a safety message is relatively small, there is no need to find and establish the route before sending the actual message. Instead, the safety message is broadcasted as the hello message itself.

The basic method to disseminate an ESM in a multi-hop manner is by using a plain broadcast scheme such as flooding. In the flooding scheme, messages are disseminated to all nodes by having all the nodes retransmit or relay received messages. A flooding scheme is highly inefficient and may cause a broadcast storm problem [72]. A broadcast storm can overload the limited channel capacity, causing channel congestion that reduces communication reliability. Therefore, various scoped broadcast routing schemes that can improve the efficiency of multi-hop safety communication have been proposed in the literature. The scoped broadcast schemes use various techniques to limit the number of transmissions. The main concerns of those schemes are how to reduce unnecessary transmissions and improve reliability. It has been suggested that the multi-hop routing scheme should be handled by application level protocols, which have contextual knowledge such as the state of neighbouring vehicles [47].

Yang et al. [117] introduced the concept of an abnormal vehicle and the state transition mechanism to limit the forwarding distance and reduce redundant messages. A vehicle becomes an abnormal vehicle when an emergency event is happening to the vehicle itself or when the vehicle is reacting to other abnormal vehicles nearby. As long as a vehicle is marked as an abnormal vehicle, it repeatedly broadcasts the Emergency Warning Message (EWM), which is just another term for ESM. Such an approach can be viewed as the method to select a forwarder or relay node. Once an abnormal vehicle resumes its regular movement, the vehicle is no longer an abnormal vehicle and it returns back to its normal state. Details on implementation of the state transition policy based on traffic conditions have not been properly addressed. The use
of repetitive transmissions to increase the successful reception rate may result in unnecessary transmissions.

There are several techniques commonly used in the literature to improve the efficiency of ESM dissemination. Most of them are based on an approach in which a vehicle that receives an ESM decides whether to forward, ignore, or use the received ESM. To reduce the number of retransmissions, the number of hops can be minimised by selecting the optimal forwarder. Implicit acknowledgement is another technique to limit the number of repetitions that are required to ensure reliability. It introduces a contention duration before rebroadcasting the same message; therefore, allowing a vehicle to detect if other vehicles had already rebroadcasted the same message. When a vehicle detects that same message, it will abort the rebroadcast attempt.

The methods used to select a relay (rebroadcast policy) and calculate the contention duration can be based on distance only [13, 31], distance with dedicated back-off procedure [122, 118], distance with random contention window [76], distance with probability factor [109], direction with random duration [16], or predefined area [62]. One of the position-based methods also considers the angle between vehicles [118]. Most of the protocols for ESMs in the literature do not consider the use of RSMs. They assume that the information about the receivers and their location is not available. In such a case, the scoped broadcast strategies are the most suitable option. Torrent-Moreno et al. [101] proposed a scheme that makes use of information obtained from the RSM. In that scheme, a specific forwarder is nominated for every transmission to minimise the delay caused by the contention duration. They also proposed a more efficient RSM dissemination scheme that dynamically controls the transmission power and evaluated it in combination with their ESM protocol.

One of the key techniques used by existing schemes is to limit the ESM dissemination into a specific area or direction. The intended receivers (i.e. the endangered vehicles) are assumed to be all the vehicles that are inside a region behind the sender [117, 16, 122, 76, 101], behind the sender but moving in the same direction [118], or inside a predefined risk zone [13, 62]. Most of the existing schemes are designed mainly for a highway or straight road scenario and only consider two directions: forwards or backwards. Since interactions among vehicles were not considered, ESMs can be disseminated to irrelevant vehicles and vehicles cannot be prioritised based on their critical time to avoid
5.3 Context-Aware Multicast Approach

ESMs may need to be propagated along a roadway using a multi-hop scheme to extend the original sender’s transmission coverage. For example, in a highway platoon scenario, a vehicle that encounters an emergency situation becomes an abnormal vehicle. The emergency situation can be defined as a rapid change of motion that exceeds a certain threshold. An example for this is a rapid deceleration that may be caused by an abrupt braking or even a collision. Assume that an abnormal vehicle must send ESMs to all vehicles in the platoon to prevent multi-vehicle chain collisions. If the length of the platoon is greater...
than the sender’s radio transmission range, multi-hop message forwarding is required. To reduce unnecessary transmissions, an abnormal vehicle should send the ESMs only to relevant vehicles instead of all vehicles. The relevant vehicles are vehicles that are endangered by the abnormal vehicle’s manoeuvre. Given the state of neighbouring vehicles in various complex scenarios, the relevant vehicles can be identified by using the multi-vehicle interaction graph proposed in Chapter 3.

From the perspective of communication, the abnormal vehicle is the sender node and the relevant vehicles are the receiver nodes, which can be considered as a multicast group. ESMs must be delivered from the sender to each receiver within a specific time depending on each receiver’s situation. The communication can be single-hop or multi-hop, and may involve relay nodes other than the receivers. For example, in a scenario shown in Figure 5.1, assume that vehicle \( a \) performs a sudden movement at time \( t \) that endangers vehicles \( b \), \( c \), and \( g \). Therefore, vehicle \( a \) sends ESMs to vehicles \( b \), \( c \), and \( g \) at time \( t \). Vehicle \( a \) does not need to send the ESMs to vehicles \( d \), \( f \), and \( h \) because they are not in immediate danger. Although vehicle \( h \) is in the same lane as vehicle \( g \), vehicle \( h \) may not be endangered if its speed is slower than of vehicle \( g \) and the distance between them is large enough. A vehicle that is not in danger can receive and relay the ESMs. In this example, vehicle \( e \) is the relay node to forward the ESMs to vehicle \( c \).

This study assumes that a driver may or may not overreact to the alert given by a CCWS. Therefore, a vehicle that receives an ESM may react by braking abruptly (very high deceleration) or by braking sensibly (convenience deceleration) to achieve a safety distance from the leading vehicle. In a case when a receiving vehicle brakes abruptly, it will become another abnormal vehicle. To ensure safety, the new abnormal vehicle will send a new ESM to a new up-to-date set of endangered vehicles. In the previous example, vehicle \( g \) receives an ESM from vehicle \( a \) at time \( t \). Vehicle \( g \) will start braking at time \( t' = t + t_r \), where \( t_r \) is the driver’s reaction time. If vehicle \( g \) brakes abruptly, it becomes a new abnormal vehicle. It will first determine the endangered vehicles by generating or updating its own interaction graph that reflects the current situation. If, for example, vehicle \( h \) becomes endangered by the action of vehicle \( g \) at time \( t' \), vehicle \( g \) will send a new ESM to vehicle \( h \). If there are no endangered vehicles, vehicle \( g \) does not need to send a new ESM.
5.3. Context-Aware Multicast Approach

The ESM is only useful if it is received within a specific time. For example, assume that vehicle $b$ must receive the ESM within $\Delta$ seconds after $t$. If vehicle $b$ received the ESM after $\Delta$ seconds, there would not be enough time for vehicle $b$ to brake so that it could stop before crashing with vehicle $a$. In order to minimise the number of vehicle collisions, the relay node must be selected in such a way so that the end-to-end delay from the sender node to every receiver node is minimised.

In tree-based multicast routing, a sender computes a multicast tree before sending the ESM. The multicast tree represents routing paths from the sender to every receiver. The wireless network is modelled as a weighted directed graph, where the weight of an edge represents an estimated one-hop transmission delay. Given the network graph, a sender, and a group of receivers, a minimum delay tree is computed using Dijkstra’s shortest path algorithm [24]. The minimum delay tree provides routing paths with the least end-to-end delay, which can be used to disseminate ESMs.

5.3.1 Problem Definition

The communication network is modelled as a weighted directed graph $G = (V, E)$ where $V$ is a set of communication nodes representing the vehicles and $E$ is a set of directed edges representing the communication links between the nodes. A directed edge $e = (u, v) \in E$ if and only if node $v$ can receive packets from node $u$, where $u, v \in V$ and $u \neq v$. A non-negative real-valued function is associated with each node $v \in V : \delta(v) : V \rightarrow \mathbb{R}^+$, which represents the estimated one-hop delay for every packet relayed through node $v$. Let $s \in V$ be the initial sender of an ESM, and let $R \subseteq V - \{s\}$ be the set of receivers. Nodes belonging to $V \setminus (R \cup \{s\})$ may become relay nodes, i.e. they are involved in forwarding the ESM, or they may remain isolated without receiving or transmitting any signal. A multicast tree $T(s, R) = (V_T, E_T)$, where $V_T \subseteq V$ and $E_T \subseteq E$, is a tree rooted at $s$ connecting all receiver nodes in $R$.

Let $P_T(s, r)$ be a unique path in the tree $T$ from the sender node $s$ to a receiver node $r \in R$. The set of nodes on the path $P_T(s, r)$ is defined as $U(P_T(s, r))$. The total end-to-end delay from sender node $s$ to node $r \in R$ is
defined as the sum of the delay of nodes in $U(P_T(s, r)) \setminus \{ r \}$, that is:

$$
\delta(P_T(s, r)) = \sum_{v \in (U(P_T(s, r)) \setminus \{ r \})} \delta(v)
$$

(5.1)

The maximum total end-to-end delay of the tree $\delta(P_T(s, R))$ is defined as:

$$
\delta(P_T(s, R)) = \max_{r \in R} \delta(P_T(s, r))
$$

(5.2)

Based on the previous definition, the minimum delay multicast tree $T(s, R)$ can be defined as a tree that has:

$$
\min \delta(P_T(s, R))
$$

5.3.2 Context Information

The minimum delay tree problem requires the availability of several input parameters and functions that depend directly or indirectly on the context information. Context information is defined as the road traffic and communication network situation perceived by the abnormal vehicle at the time an ESM needs to be sent. In particular, the context information includes the network topology, end-to-end communication delay, the sender node, and the receiver nodes.

A vehicle generates or updates the context information just before it sends an ESM by processing the tracked state information of the neighbouring vehicles such as position, speed, heading and one-hop delay. Such information is obtained by listening to the RSMs (beacons) sent by other vehicles. Depending on the vehicle density and the safety concerns, knowledge about up to $n$-hop neighbouring vehicles may be needed. To obtain the knowledge of more than one-hop neighbours, there are several possible techniques that can be used. To avoid flooding, for example, the $n$-hop information can be aggregated and piggybacked into an extended RSM [51, 101]. The number of hops $n$ can be a predetermined constant or a variable dynamically set at real-time. This study assumes a constant $n = 4$, which approximately corresponds to a coverage of two kilometres in each direction on a highway.
5.3. Context-Aware Multicast Approach

5.3.2.1 Network modelling

In a wireless networking environment, a receiver can successfully receive a message if the receiver is located within the sender’s coverage area. For simplicity, the coverage area is modelled as a planar circle where its radius is the transmission range of the sender, as illustrated in Figure 5.3. The state of the network connections, represented by the network graph $G$, is estimated using the position and the maximum transmission range of each node. Such information is available in the CCWS since it is shared between vehicles via the RSMs. The maximum transmission range is the estimated communication range that can be achieved using the maximum transmission power.

Let $d_{uv} = d_{vu}$ be the distance between node $u \in V$ and node $v \in V$, and $R_{tx}^u$ and $R_{tx}^v$ be the maximum transmission range of node $u$ and $v$, respectively. The distance between node $u$ and node $v$ with Cartesian coordinates $(x_u, y_u)$ and $(x_v, y_v)$ respectively is:

$$d_{uv} = \sqrt{(x_u - x_v)^2 + (y_u - y_v)^2} \quad (5.3)$$

There exists a communication link represented by directed edge $(u, v) \in E$ between node $u$ and node $v$ if $d_{uv} \leq R_{tx}^u$, which means that node $v$ can receive a message from node $u$. Given the set of nodes $V$, the set of edges $E$ can be generated by enumerating all the pairs of nodes in $V$. Algorithm 3 describes the procedure to generate the network graph.

Figure 5.3: Illustration of the network modelling.
Algorithm 3: Generating the network graph.

**Input**: $V$ - the set of nodes (vehicles)  
\[d_{uv}, \forall u, v \in V\]  
- the distance between $u$ and $v$  
\[R^t_u, \forall u \in V\]  
- the maximum transmission range  

**Output**: $E$ - the set of edges

1. $E \leftarrow \emptyset$
2. for each pair of nodes $(u, v)$ in $V$ do
3. \quad if $d_{uv} \leq R^t_u$ then $E \leftarrow E \cup \{(u, v)\}$
4. \quad if $d_{uv} \leq R^t_v$ then $E \leftarrow E \cup \{(v, u)\}$

5.3.2.2 Delay function

The total end-to-end delay experienced by a packet sent from a sender node to any receiver is the sum of the delay at each node between the sender (inclusive) and the receiver (exclusive). It depends on the number of intermediary nodes between them and the delay experienced at each intermediary node (one-hop delay). To measure the one-hop delay, the implementation uses an estimation method adopted from existing work in MANET QoS routing [70]. The one-hop delay is estimated by measuring the value of actual delays experienced by the RSMs. All of the nodes are assumed to have synchronised clocks via the GPS. Each RSM includes its creation time, and when a neighbouring node receives the message, the one-hop delay can be measured by calculating the difference between the creation time and the received time. The measured one-hop delay mostly consists of the MAC queueing and transmission delay. Propagation delay can be neglected because the value is very small. Note that the priority of RSMs is assumed to be lower than the priority of ESMs. Therefore, the actual delay experienced by an ESM is expected to be less than the estimated delay.

5.3.2.3 Identifying the sender node

The sender node is an abnormal vehicle that initiates the dissemination of the ESM. There are two cases where a vehicle needs to send an ESM:

1. A sudden change of vehicle state or unexpected circumstances experienced by the vehicle. A sudden change of vehicle state can be defined as a change in motion that exceeds a certain threshold, such as hard braking or turning the steering wheel abruptly. Unexpected circumstances
are other dangerous factors that may cause an accident, such as engine breakdown, braking failure, or any other vehicle malfunction.

2. An inevitable collision with any other vehicle based on the current state of vehicles. It is possible that a collision may happen without any sudden manoeuvre. For example, in a car following scenario, if the leading vehicle moves slower than the following vehicle, they will eventually collide. This kind of accident is most likely to be caused by inattentive drivers. Using the interaction graph, the CCWS can keep track of the predicted critical interactions between vehicles and react accordingly.

### 5.3.2.4 Identifying receiver nodes

**Algorithm 4:** Using BFS to identify receiver nodes given an interaction graph.

```
input : the interaction graph \( \mathcal{G} = (\mathcal{V}, \mathcal{E}) \) and the sender node \( s \)
output: the set of receiver nodes \( R \)
1 Unmark all nodes in \( \mathcal{V} \)
2 \( R \leftarrow \emptyset \)
3 Create an empty queue \( Q \)
4 Mark \( s \)
5 Enqueue \((Q,s)\) // Enqueue \( s \) into \( Q \)
6 while \( Q \) is not empty do
7 \( i \leftarrow \text{Dequeue}(Q) \)
   // For each adjacent node \( j \) of \( i \)
8 for \( \langle i,j \rangle \in \mathcal{E} \) do
9    if \( j \) is unmarked then
10       Mark \( j \)
11       \( R \leftarrow R \cup \{j\} \)
12       Enqueue \((Q,j)\) // Enqueue \( j \) into \( Q \)
```

The receiver nodes are vehicles that will be endangered by the course of an abnormal vehicle or the sender node. To identify the receiver nodes, a sender needs to know the relevant or endangered vehicles based on the current road traffic situation. The endangered vehicles can be determined by generating or updating an interaction graph at the time of an abnormal event. Given the interaction graph \( \mathcal{G} \) (as proposed in Chapter 3) and the sender node \( s \), a set of receiver nodes \( R \) can be obtained by performing a breadth-first search (BFS)
Algorithm from node $s$. Algorithm 4 shows the pseudo-code for identifying the receiver nodes. As an example, given an interaction graph as shown in Figure 5.2 and node $a$ as the sender, the resulting receivers will be nodes $b$, $c$, and $g$.

5.3.3 Context-Aware Multicast Protocol

A Context-aware Multicast routing for ESM dissemination (CMED) protocol has been developed based on the minimum delay multicast tree. To deal with the inherent nature of unreliability in wireless transmission, the tree-based multicasting protocol is complemented and combined with contention-based relaying and implicit acknowledgement. The CMED protocol consists of three main procedures: SendInitialMessage, SendMessage, and ReceiveMessage. Algorithm 5 describes the pseudo-code of the CMED protocol.

An abnormal vehicle becomes a sender node that initiates the first ESM by invoking the SendInitialMessage procedure. In this procedure, a multicast tree is computed using Dijkstra’s shortest path algorithm [24]. The input values or parameters required by Dijkstra’s algorithm are obtained from the context information:

1. The sender node $s$ is the abnormal vehicle that can be determined using methods described in Section 5.3.2.3.
2. The network graph $G = (V, E)$ is generated using Algorithm 3.
3. The receiver nodes are the endangered vehicles. The set of receiver nodes $R$ is generated using Algorithm 4, as detailed in Section 5.3.2.4.
4. The delay $\delta(v)$ for each node $v \in V$, that can be obtained using methods described in Section 5.3.2.2.

The output of the algorithm is the multicast tree $T(s, R)$, which is used as the routing paths to disseminate the ESMs. A new ESM is created and the tree $T(s, R)$ is then encoded to the ESM. The ESM also contains an originId, which is the address of the initial sender node (abnormal vehicle), and an eventId, which is a unique identifier for each emergency event initiated by a node. The pair of originId and eventId represents a unique messageId, which is used for uniquely identifying an emergency event. After that, the SendMessage procedure is invoked to send the ESM.
Algorithm 5: Pseudo-code of the CMED protocol.

1. **procedure** SendInitialMessage()
   2. \[\text{Compute multicast tree } T(s,R)\]
   3. \[\text{Create a new ESM } m \text{ and add } T(s,R) \text{ to the header}\]
   4. \[\text{sentMessages} \leftarrow 0\]
   5. \[\text{SendMessage}(m)\]

6. **procedure** SendMessage(m)
   7. Transmit \( m \) using WSMP
   8. \[\text{sentMessages} \leftarrow \text{sentMessages} + 1\]
   9. **if** \( \text{sentMessages} < \text{maxRepeatCount} \) **then**
      \[\text{Execute SendMessage}(m) \text{ after waiting time of } \text{repeatInterval}\]

11. **procedure** ReceiveMessage(m)
   12. Retrieve multicast tree \( T \) from the header of \( m \)
   13. **if** \( T \) contains \( \text{myId} \) **then**
      14. **if** first time reception of this message **then**
         15. **if** receiving vehicle is endangered by this event **then**
            \[\text{Warn driver to brake}\]
            \[\text{Mark messageId as received}\]
            \[\text{countMessages} \leftarrow 0\]
            **if** receiver is a relay node **then**
            \[\text{// Relay message}\]
            \[\text{SendMessage}(m)\]
      **else**
      \[\text{Calculate contention time } t_c\]
      **if** \( t > 0 \) **then**
      \[\text{// Start contention}\]
      \[\text{isContending} \leftarrow \text{true}\]
      \[\text{Execute SendMessage}(m) \text{ after waiting time of } t_c\]
      **else**
      \[\text{// The same message } m \text{ has been received previously}\]
      \[\text{countMessages} \leftarrow \text{countMessages} + 1\]
      **if** \( \text{isContending OR (countMessages} \geq \text{maxMessages}) \)
      **then**
      \[\text{Cancel contention}\]
To send an ESM, a node invokes the `SendMessage` procedure. This procedure transmits a message using the WAVE Short Message Protocol (WSMP) as defined in the IEEE 1609.3 standard [3]. A node keeps track of the number of messages sent for each unique emergency event. To improve reliability, a sender will send the same message repeatedly with a constant interval of `repeatInterval`. The repetition is terminated if the same message is received from another node that belongs to the same multicast tree. In addition, a maximum number of repetitions is introduced to further reduce channel load. The message will not be transmitted more than `maxRepeatCount` times.

The `ReceiveMessage` procedure is invoked when a node receives an ESM. The multicast tree is first retrieved from the message and the receiving node checks if the tree contains the node’s unique identifier `myId` (such as MAC address). The message will only be processed if the tree contains the receiver’s id. If the same message has been received previously, it is then considered as an implicit acknowledgement, and any scheduled transmission for the same message will be cancelled. If the message is received for the first time, then the CCWS will warn the driver to perform evasive manoeuvre, and record the received `messageId`. If the receiver node is a relay node, as identified from the multicast tree, the node will relay the message immediately. It is possible that a designated relay node may not receive the ESM or may not receive it in time. To ensure reliability, a contention-based method similar to other protocols [122, 118, 101] is used. Another receiver node may relay the message as a substitute to a failed relay node. If the receiver node is not a relay node, it will schedule to send the message after a specific contention time, which will be cancelled if it receives another message with the same `messageId`. The contention time is calculated based on its distance to the sender node:

\[ t_c = maxContentionTime \times \left( 1 - \frac{d_{sr}}{d_{max}} \right) \]

where `maxContentionTime` is a parameter of the maximum contention time, \(d_{sr}\) is the distance between the sender and the receiver, and \(d_{max}\) is the approximate transmission range.
5.4 Evaluation

The performance of the CMED protocol was evaluated by simulation. The simulation was implemented in the network simulator ns-3 (version 3.8) [1]. The performance of the CMED protocol was compared with the following ESM protocols:

1. Intelligent Broadcast with Implicit Acknowledgement (IBIA) protocol [16]: This protocol represents a simple approach to ESM dissemination in which the rebroadcasting strategy is based on random contention and vehicle direction.

2. Emergency Message Dissemination for Vehicular environment (EMDV) protocol [101]: This protocol employs a distance-based contention strategy complemented with the selection of a next hop forwarder made at transmission time to minimise the delay.

All of the protocols were implemented at a higher level layer on top of the MAC layer in ns-3.

5.4.1 Performance Metrics

The performance is measured in terms of the safety and communication issues. A protocol is better in terms of safety if using the protocol results in the smallest number of vehicle collisions. The communication issues involve the metrics of dissemination latency (or delay) and number of sent messages. The maximum dissemination latency is the time required to disseminate an ESM to all of the intended receivers. A lower dissemination time gives a better chance for a vehicle to avoid a collision. The number of sent messages reflects the efficiency of the protocol. A smaller number of sent messages indicates a more efficient protocol.

A vehicle collision is mainly caused by vehicles that do not receive the ESM in time or do not receive the ESM at all. This means that safety performance is mostly influenced by the dissemination latency and the reliability of the communications. The reliability of a protocol is indirectly measured from the number of vehicle collisions. As a reference, the evaluation includes the results from a theoretical optimal protocol in which ESMs can be disseminated to all relevant vehicles with zero delay or latency.
In order to measure those metrics, a vehicle-following logic similar to the work proposed by Biswas et al. [16] has been developed. This was done by extending the ns-3 mobility model and developing a highway scenario module that can simulate road accidents, particularly a chain or multiple collisions on a highway. A chain collision situation is started by triggering an emergency event, in which a vehicle is forced to rapidly decelerate at $8\text{ m/s}^2$. Such a vehicle becomes an abnormal vehicle. The high deceleration rate models an unexpected collision scenario in which a vehicle can stop within a short distance. Immediately after decelerating, the abnormal vehicle will start sending the ESMs. A vehicle that receives an ESM will start braking with a normal deceleration of $4.9\text{ m/s}^2$ after a 1.5 s reaction time. A vehicle is not allowed to change lanes. Existing protocols for ESM dissemination were designed specifically for highway scenarios. Therefore, highway scenarios are chosen to allow a comparison with existing protocols.

### 5.4.2 Simulation Design and Setup

To provide a fair comparison, this study tries to follow the simulation setup and environment used by the authors of IBIA and EMDV [16, 101] as closely as possible. In the simulation, all vehicles are equipped with a CCWS. Each vehicle generates RSMs (beacon messages) at a rate of 10 messages per second. Before sending the first RSM, each vehicle calculates a random number from 0 to 100 ms, and uses that number as the time to send the first RSM. The next RSM is then scheduled to be sent periodically every 100 ms. The message size of both ESMs and RSMs is set to 500 bytes, including the application protocol specific headers. A constant message size is used to provide a consistent comparison result. The transmission power is configured to 19 dBm, which corresponds to 1000 m transmission range with around 20% message reception probability and 500 m transmission range with 90% message reception probability. The probabilistic Nakagami distribution is selected as the radio propagation loss model [101]. Real-world tests on highways showed that the Nakagami distribution is suitable to be used on vehicular communication in highway scenarios. The parameter of $m = 1$ is set to simulate severe fading conditions; therefore, demonstrating the protocols' performance in the worst case scenario.
The lower layer protocol (PHY and MAC) parameters are set according to the IEEE 802.11p draft standard, which operates at 5.9 GHz on a 10 MHz control channel (CCH). The PHY data rate is configured to 6 Mbps, which is the optimal value for safety communication [48]. The channel switching scheme is currently not implemented, which means the whole 10 MHz CCH bandwidth can be used by the CCWS application. The MAC layer is configured to ad hoc mode with QoS support using the EDCA mechanism as described in IEEE 802.11e. The priority for ESMs is set to AC_VO (highest), and the priority for RSMs is set to AC_VI (second highest). Both the ESM and RSM protocols are simulated as extensions of the IEEE 1609 WAVE Short Message Protocol (WSMP) [3]. They are directly implemented on top of the MAC layer.

The common configuration details related to lower layer protocols are summarised in Table 5.1. The specific parameters to the IBIA and EMDV protocols are configured by following the given value in the original paper. A minor modification is made to the IBIA protocol by setting a maximum number of repetitions. The specific parameters for the IBIA, EMDV, and CMED protocols are detailed in Table 5.2.

Two typical cases of highway scenarios are used to evaluate the performance of the ESM protocols. The first case is a simple highway scenario that represents a typical road traffic scenario with relatively low communication traffic. The second case represents a typical road traffic scenario with high communication traffic density. In the second case, the distance between vehicles is randomised at each simulation run to test how the protocols perform in different highway traffic situations.

5.4.2.1 A Simple Highway Scenario

This scenario models a one-lane highway with \( n \) vehicles moving in the same direction with the same speed, similar to the scenario used to evaluate the IBIA protocol [16]. The platoon was formed with uniform inter-vehicle spacing \( s \), as visualised in Figure 5.4(a). To demonstrate the protocols' performance with different vehicle densities, the simulation is conducted with different numbers of vehicles \( n \) ranging from 40 to 200. The distance between the vehicles at the first \( (v_0) \) and last \( (v_n) \) positions is fixed to 2000 meters, so a higher number of vehicles would mean a shorter inter-vehicle spacing. An emergency event was initiated by the abnormal vehicle at the front of the platoon \( (v_0) \). Without a
## Chapter 5. Event Safety Message Dissemination

### Table 5.1: Common configuration parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHY and MAC protocol</td>
<td>802.11p</td>
</tr>
<tr>
<td>802.11p data rate</td>
<td>6 Mbps</td>
</tr>
<tr>
<td>Propagation loss model 1</td>
<td>Three log distance</td>
</tr>
<tr>
<td>Propagation loss model 2</td>
<td>Nakagami $m = 1$</td>
</tr>
<tr>
<td>Transmission power</td>
<td>19 dBm</td>
</tr>
<tr>
<td>Safety message size</td>
<td>500 bytes</td>
</tr>
<tr>
<td>RSMs (beacons) generation rate</td>
<td>10 packets/s</td>
</tr>
<tr>
<td>Priority level:</td>
<td></td>
</tr>
<tr>
<td>ESMs</td>
<td>AC_VO</td>
</tr>
<tr>
<td>RSMs (beacon messages)</td>
<td>AC_VI</td>
</tr>
</tbody>
</table>

### Table 5.2: Specific protocol parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBIA messagePeriod</td>
<td>100 ms</td>
</tr>
<tr>
<td>IBIA randomWaitTime</td>
<td>[0-10] ms</td>
</tr>
<tr>
<td>IBIA maxRepeatCount</td>
<td>10</td>
</tr>
<tr>
<td>EMDV disseminationAreaLength</td>
<td>2000 m</td>
</tr>
<tr>
<td>EMDV forwardingRange</td>
<td>500 m</td>
</tr>
<tr>
<td>EMDV maxMessages</td>
<td>3</td>
</tr>
<tr>
<td>EMDV maxContentionTime</td>
<td>100 ms</td>
</tr>
<tr>
<td>EMDV maxChannelAccessTime</td>
<td>10 ms</td>
</tr>
<tr>
<td>CMEDmaxContentionTime</td>
<td>10 ms</td>
</tr>
<tr>
<td>CMED$d_{max}$</td>
<td>500 m</td>
</tr>
<tr>
<td>CMEDmaxRepeatCount</td>
<td>10</td>
</tr>
<tr>
<td>CMEDrepeatInterval</td>
<td>100 ms</td>
</tr>
<tr>
<td>CMEDmaxMessages</td>
<td>3</td>
</tr>
</tbody>
</table>

### Table 5.3: Common parameters for the highway scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver’s reaction time</td>
<td>1.5 s</td>
</tr>
<tr>
<td>Vehicle length</td>
<td>4 m</td>
</tr>
<tr>
<td>Vehicle speed</td>
<td>32 m/s</td>
</tr>
<tr>
<td>Vehicle emergency deceleration</td>
<td>8.0 m/s$^2$</td>
</tr>
<tr>
<td>Vehicle normal deceleration</td>
<td>4.9 m/s$^2$</td>
</tr>
</tbody>
</table>
5.4. Evaluation

(a) Simple highway scenario.

(b) Random highway scenario

Figure 5.4: Illustration of highway scenarios used in the simulation.

Table 5.4: Parameters specific to the simple highway scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highway length</td>
<td>2000 m</td>
</tr>
<tr>
<td>Number of vehicles</td>
<td>[40-200]</td>
</tr>
<tr>
<td>Number of abnormal vehicles</td>
<td>1</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>1</td>
</tr>
<tr>
<td>Inter-vehicle spacing</td>
<td>[10-50] m</td>
</tr>
</tbody>
</table>

CCWS, all of the vehicles behind vehicle $v_0$ would be involved in chain collisions. This scenario is useful to evaluate the performance of ESM protocols in a low density environment with deterministic node topology and mobility. Each simulation was repeated 100 times with a random seed for each run to obtain a statistically significant result. Table 5.4 indicates the specific parameters used in this scenario.

5.4.2.2 A Random Highway Scenario

The aim of this scenario is to simulate a typical real-world two-way highway environment. Figure 5.4(b) illustrates this scenario. The highway consists of 6 lanes with 3 lanes for each direction. The total number of vehicles is 600, and each lane contains 100 vehicles. The starting distance between vehicles was randomised for every simulation run, with a value between 9 to 50 m. $N$ number of abnormal vehicles (initial sender) were randomly selected, which means $N$ emergency events were initiated in the course of the simulation. Those events were triggered at around the same simulation time, separated by 1 millisecond each. Experiments are conducted for different values of $N$ ranging from 1 to 6. Each time, the simulation is repeated with a random seed.
Table 5.5: Parameters specific to the random highway scenario.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of vehicles</td>
<td>600</td>
</tr>
<tr>
<td>Number of abnormal vehicles</td>
<td>[1-6]</td>
</tr>
<tr>
<td>Number of lanes</td>
<td>6</td>
</tr>
<tr>
<td>Inter-vehicle spacing</td>
<td>[9-50] m</td>
</tr>
</tbody>
</table>

Table 5.6: Number of vehicle collisions in the simple highway scenario.

<table>
<thead>
<tr>
<th># vehicles</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>100</th>
<th>120</th>
<th>140</th>
<th>160</th>
<th>180</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>IBIA</td>
<td>1.2</td>
<td>3.24</td>
<td>4.03</td>
<td>5.38</td>
<td>6.7</td>
<td>9.25</td>
<td>11.52</td>
<td>13.49</td>
<td>15.97</td>
</tr>
<tr>
<td>EMDV</td>
<td>1.03</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6.21</td>
<td>8</td>
<td>10.01</td>
<td>12.01</td>
<td>14.14</td>
</tr>
<tr>
<td>CMED</td>
<td>1</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6.21</td>
<td>8.01</td>
<td>10</td>
<td>12.01</td>
<td>14.11</td>
</tr>
</tbody>
</table>

100 times to obtain a statistically significant result. Table 5.5 indicates the specific parameters used in this scenario.

5.4.3 Simulation Results

5.4.3.1 A Simple Highway Scenario

From 100 simulation runs, the average of maximum dissemination latency for scenarios of 40 to 200 vehicles is calculated and plotted in Figure 5.5. The result shows that a higher number of vehicles (higher density) leads to a higher latency. In all of the cases, the CMED protocol can deliver ESMs faster than the IBIA and EMDV protocols. In terms of efficiency, the number of sent messages is plotted in Figure 5.6. It shows that the number of sent messages for the CMED protocol is just slightly lower than for the EMDV protocol. Both the CMED and EMDV protocols send significantly fewer messages compared to the IBIA protocol. In this scenario, all of the protocols can achieve an optimal number of vehicle collisions in most cases. Table 5.6 shows that there is no significant difference in the numbers of collisions resulting from this scenario between the three protocols. For example, in a case with 200 vehicles, the total number of collisions averaged from 100 simulation instances was 15.97 for IBIA, 14.14 for EMDV and 14.11 for CMED. As a reference, the smallest number of collisions that can possibly be achieved was 14. The higher number of collisions for IBIA means that in some instances of the simulation, the protocol has failed to ensure 100% message delivery to all endangered vehicles.
5.4. Evaluation

Figure 5.5: Average of maximum dissemination latency in the simple highway scenario.

Figure 5.6: Total number of ESMs sent by all vehicles in the simple highway scenario.
5.4.3.2 A Random Highway Scenario

Each simulation instance produces a unique highway scenario that results in different number of vehicle collisions for each run. The lowest possible number of collisions for each unique scenario, which is the optimal result, is obtained by simulating a dummy protocol that can transmit ESMs to all relevant vehicles instantaneously just after an emergency event occurred. The resulting number of vehicle collisions for the other protocols was normalised to the optimal result in order to clearly show the differences between the evaluated protocols.

Figure 5.7 shows the number of excess vehicle collisions for different numbers of concurrent events (from 1 to 6). When there is more than one concurrent event, the CMED protocol delivered a lower number of collisions compared to both the IBIA and EMDV protocols. Given only one concurrent event, the CMED protocol delivered an equal number of collisions to the EMDV protocol, but lower than for the IBIA protocol.

The number of sent messages for the CMED protocol is the lowest for all of the cases, as shown in Figure 5.8. The overall number was obtained by adding up the number of messages sent by all vehicles from 100 simulation instances.

Figure 5.9 shows the maximum dissemination time required for an ESM to reach all relevant vehicles. The maximum dissemination time was averaged from 100 simulation instances. It shows that, generally, the CMED protocol is always able to disseminate the ESMs faster than both the IBIA and EMDV protocols.

5.5 Discussion

This section discusses the simulation results of the CMED protocol in comparison to the IBIA and EMDV protocols. The simulation results demonstrate the advantages of the proposed CMED protocol. In the first scenario, the IBIA protocol results in lower latency, but a higher number of vehicle collisions, compared to the EMDV protocol. In some simulation instances, the IBIA protocol has failed to deliver warning messages to some endangered vehicles, which means that the IBIA protocol is less reliable compared to the EMDV and CMED protocols. Although the number of collisions for the CMED protocol is not much different compared to the EMDV protocol, the CMED protocol
Figure 5.7: Number of excess vehicle collisions (normalised to the optimal result) from 100 instances of the random highway scenario.

Figure 5.8: Total number of ESMs sent by all vehicles from 100 instances of the random highway scenario.
stillshowssomeadvantagesintermsofthenumberofsentmessageandthemaximumdisseminationtime.

The random highway scenario demonstrates the performance of a multicast protocol in a typical highway environment with high communication traffic density. From 100 random simulation runs, the CMED protocol results in fewer collisions compared to both the IBIA and EMDV protocols. This means that using the CMED protocol can generally improve the safety aspect of the CCWS. The results from this scenario have also shown that the CMED protocol is more scalable than the other protocols. A higher number of concurrent events means higher communication traffic density. Figure 5.7 shows that the difference in number of collisions becomes more significant as the number of concurrent events increases. In both the simple and random scenarios, the number of sent messages and the maximum dissemination time clearly show that the CMED protocol is more efficient compared to both the IBIA and EMDV protocols. The CMED protocol is also more reliable because it can improve safety indicated by a lower number of collisions.

In addition to the advantages in a highway scenario shown by the simulation results, another advantage of the CMED protocol is the applicability in various
cases of traffic accidents. To prevent accidents, ESMs must be delivered to all relevant vehicles. The position and direction of the relevant vehicles depend on the traffic scenario and road topology, which have extensive possibilities and variations. Existing ESM protocols only consider a straight road scenario such as a highway and assume that the receivers are those vehicles located within the region behind or in front of the abnormal vehicle that are moving towards the abnormal vehicle. However, some accidents may occur in a more complex road traffic situation such as at a junction, on a curved road or a roundabout. Another weakness of prior ESM protocols is that for each transmission, only one relay can be selected based on the contention method, resulting in a single dissemination direction.

Figure 5.10 shows one example of a junction road topology where the endangered vehicles or broadcast region cannot be determined based on the forward or backward direction of the sender. In this example, assume that vehicle $a$ is the abnormal vehicle and vehicles $b$, $c$, $d$, $e$, $f$ and $g$ are the endangered vehicles. Figure 5.10(a) shows an example of ESM dissemination using the prior approaches. Vehicle $a$ broadcasts the ESM, which is received by vehicle $b$, $c$, and $e$. Vehicle $e$ ignores the received ESM because of its different direction. Vehicle $c$ is chosen as the relay based on the contention rules (e.g. farthest distance from the sender) and forwards the ESM to vehicle $d$. Vehicle $f$ ignores the received ESM for the same reason as vehicle $e$. This results in endangered vehicles $e$, $f$ and $g$ not receiving the ESM.

The context-aware strategy aims to decouple the task of determining the endangered vehicles from the routing algorithm. The interaction graph, which is used to identify the endangered vehicles, can be considered as a separate module from the routing algorithm. Given the set of endangered vehicles as the input parameter, the routing algorithm can find the best possible paths to all of the endangered vehicles. Figure 5.10(b) shows the example of ESM dissemination using the CMED approach. Using this approach, vehicle $e$ and $f$ can recognise themselves as endangered vehicles, and vehicle $f$ is informed to forward the ESM to vehicle $g$. A protocol designed with this approach will be able to deliver the warning messages effectively in various road traffic scenarios.
CHAPTER 5. EVENT SAFETY MESSAGE DISSEMINATION

5.6 Summary

This chapter has presented a context-aware multicast protocol for ESM dissemination in a CCWS. The new protocol is designed based on the assumption that the CCWS will use both reactive and proactive approaches, as represented by RSMs and ESMs. Differing from other existing approaches, the proposed multicast approach uses a precomputed routing tree based on the estimated delay, and utilises the vehicle interaction graph to identify receiver nodes. The multicast tree is the minimum delay tree from a sender to the receivers, computed using Dijkstra’s shortest path algorithm with transmission delay as the cost function. The multicast protocol incorporates the contention-based forwarding techniques to improve reliability. Using this approach, the wireless bandwidth can be used more efficiently by reducing the number of sent messages, which can improve the packet reception rate and reduce the packet collision rate and latency. All of these will directly contribute to the main objective of reducing the number of accidents or crashed vehicles.

The performance of the proposed protocol has been evaluated by experiments conducted using the network simulator ns-3. It has been compared with broadcast protocols in highway traffic scenarios, with a constant beaconing load. Road accident scenarios are simulated by extending ns-3 with a new highway mobility model. The experimental results have shown that the multicast protocol outperforms the broadcast protocols in terms of efficiency and reliability. Moreover, the multicast protocol is able to reduce accident casualties significantly in some scenarios. A case study is used to demonstrate an additional advantage of the multicast approach over other scoped broadcast
approaches. The multicast approach can disseminate ESMs in any direction depending on the multicast tree, and therefore can support various road traffic scenarios.
Chapter 6

Conclusion and Future Research

This chapter summarises the findings and the original contributions of the research presented in this thesis. It also discusses additional issues to be considered as possible future works.

6.1 Summary

The use of a Cooperative Collision Warning System (CCWS) can improve road safety as it can prevent vehicle collisions. The CCWS differs from the non-cooperative CWS in two main ways: 1) Every vehicle obtains its own state information, such as position, speed, heading, etc, using positioning or localisation technology; and 2) Every vehicle disseminates its own state information to its neighbouring vehicles using wireless communication technology, which is based on the IEEE 802.11p DSRC/WAVE standard. To anticipate and prevent a collision from occurring in the first place, Routine Safety Messages (RSMs) that contain vehicle status updates are disseminated repeatedly among neighbouring vehicles. To prevent multiple collisions that may be caused by an emergency event, Event Safety Messages (ESMs) are disseminated to warn vehicles that may be endangered because of the event. The effectiveness of the CCWS critically relies on each endangered vehicle receiving accurate and relevant information in a timely manner to warn its driver of the danger. Current positioning or localisation technology allows a vehicle to calculate its own relative position with a centimetre accuracy. However, the current communication technology is unable to ensure the reliability of vehicular safety communication in a road traffic environment with high vehicle density. This is because of the
inefficient use of a wireless channel that has limited bandwidth.

This thesis investigated new efficient strategies for safety message dissemination in the CCWS. A new context-aware communication system was proposed to improve the performance of vehicular safety communication, and therefore ensure that the CCWS can function as intended. The proposed approach focuses on two components of the CCWS: the situation awareness system; and the communication system. A new context model is introduced into the situation awareness system to provide context information to both the RSM and ESM protocols in the communication system. A multi-vehicle interaction graph was proposed as the context model. Efficient RSM and ESM protocols that utilise the interaction graph were developed to complete the context-aware communication system. The protocols were evaluated by simulating several accident scenarios, in which some collisions could be avoided if safety messages were successfully received on time by the relevant vehicles. For that, a combined vehicular-network simulation platform was developed by extending ns-3, a well-known and respected network simulation tool. Extensive simulations were conducted in a typical straight road scenario under various traffic situations with different vehicle densities. The experimental results demonstrated the efficiency and scalability of the new protocols in preventing vehicle collisions. The new protocols can consistently reduce the overall number of collisions compared to existing protocols.

To develop the context model, Chapter 3 investigated the problem of modelling context information, which is the interactions among multiple vehicles, where an interaction between vehicles is defined as a possible collision between them. Given a list of vehicles in a vicinity and their latest state information, the challenge is to develop a model that can represent the interactions among multiple vehicles under various road traffic situations and be easily used to identify vehicles that may be endangered by any other vehicle and the severity of their critical situation. A multi-vehicle interaction graph, which is a weighted directed graph, was proposed to model the interactions among multiple vehicles in a specific region and at a specific time. The interaction graph can be generated by considering three different cases to calculate the possible collision based on the vehicles kinematics. It has been implemented as part of the context-aware communication system, enabling the development of efficient RSM and ESM protocols.
In designing the efficient RSM protocol, Chapter 4 investigated the problem of reducing the RSM repetition rate without compromising safety. RSMs must be disseminated repeatedly by every vehicle. The repetition rate or interval significantly affects the safety performance of the CCWS. To improve the efficiency, scalability, and safety, a challenging problem of adapting the repetition interval dynamically and distributively was identified. Increases in efficiency and scalability result in communication that is more reliable. Safety performance can be improved by having reliable communication and also by giving priority to vehicles in the most danger. The problem was addressed using a scheme that can adjust the repetition interval adaptively based on an estimated channel load and the danger severity of the vehicle interactions. The danger severity is obtained from the interaction graph model. The proposed solution was implemented as a context-aware adaptive rate protocol. Performance evaluation was conducted by comparing the proposed adaptive protocol with conventional constant rate protocols. Safety performance was evaluated by simulating vehicle collisions caused by inattentive drivers on a multi-lane straight road. The simulation results showed that the adaptive protocol provides better efficiency, scalability, and safety compared to the constant rate protocols.

In designing the efficient ESM protocol, Chapter 5 investigated the problem of efficiently propagating ESMs to endangered vehicles as fast as possible, which may require multi-hop transmissions. Efficiency can be achieved by reducing unnecessary transmissions, which can be done by limiting the dissemination only to relevant vehicles. Dissemination time or latency can be reduced by routing the ESMs through the paths (or relays) that give the least delay. The problem was formulated as a minimum delay tree routing problem. It was addressed using a multicast scheme that utilises the interaction graph to identify the relevant vehicles and computes the minimum delay tree using Dijkstra's shortest path algorithm. The proposed solution was implemented as a context-aware multicast protocol that adopts the implicit acknowledgement and contention-based forwarding techniques. Performance evaluation was conducted by simulating chain collision scenarios and comparing the number of vehicle collisions with those using existing broadcast protocols. The simulation results showed the new multicast protocol outperforms other broadcast protocols in terms of efficiency, latency, and safety.
CHAPTER 6. CONCLUSION AND FUTURE RESEARCH

All of the simulations in this research were performed using the network simulator tool ns-3. The simulator has been used and cited in several high quality publications, which indicates its reputation in the research community. The accuracy of the simulation results generated by ns-3 has been validated [34, 11]. Particularly important to this research is the validation of the IEEE 802.11 models. A validation study of the ns-3 model of the IEEE 802.11 MAC was performed in a variety of scenarios by comparing the results obtained from the simulator with the measurements obtained from experiments using real networking devices [11]. The results show that, in general, there is a good qualitative agreement between the simulator and the real devices. Therefore, the evaluation results presented in this thesis reasonably represent the performance of the proposed protocols in the real environment.

6.2 Major Contributions

Generally, this research contributes to an improvement in intelligent vehicle safety systems, particularly on CCWSs. Although research on CCWSs has attracted more attention recently, some particular areas still need further improvement in order to make the system more robust and reliable. A CCWS can significantly reduce traffic accidents and their casualties, but it needs more research before it can be widely introduced in future cars. The proposed context-aware communication system has the potential to contribute towards the realisation of the CCWS.

Specifically, this research is focused on improving the performance of the wireless communication system of the CCWS. The performance can be improved by using communication protocols that can optimise the use of a wireless channel based on the road traffic situations (i.e. context information). The optimisation aims to reduce channel congestion, which is the main problem in the area of wireless communication. This will ensure that the CCWS can still ensure its safety function even in high-density environments, such as traffic jams.

The major contributions to CCWS development are discussed in detail as follows:

1. A context-aware communication system architecture for a CCWS.
   The context-aware communication system is a new design that extends
6.2. Major Contributions

the typical system architecture of an existing CCWS by incorporating context information. The new design implements the idea of using vehicular traffic modelling as a means to optimise communication and to improve safety altogether, which has never been proposed previously. Existing ESM and RSM dissemination schemes do not consider the use of context information to minimise the number of transmissions while not compromising safety. Existing context-aware approaches can only be used for non-safety purpose routing, where the routing destinations are known and safety requirements are not the concern. In a typical existing CCWS architecture, the situation awareness system stores and tracks the state information of neighbouring vehicles obtained from the communication system, but the situation awareness system is unable to give feedback regarding the tracked traffic situation to the communication system. In the context-aware communication system, a context model is maintained by the situation awareness system to provide feedback to both the RSM and ESM protocols in the communication system. The feedback can be used to optimise communication and to improve safety altogether. The context-aware architecture improves the design of existing RSM and ESM protocols by proposing a loosely coupled design that separates any context enquiry (such as “is a sender vehicle in front of the receiving vehicle?”) from the protocol implementation.

2. A multi-vehicle interaction graph model.

The interaction graph is a new context model for the CCWS that can be used to easily identify endangered vehicles and their danger severities. It is the first model that uses a weighted directed graph to represent interactions among multiple vehicles in a specific region and at a specific time. Existing collision models used in the CCWSs only consider a single interaction between a pair of vehicles. Other related models such as microscopic traffic models used in traffic flow simulations cannot be used to determine all of the possible collisions between vehicles. The new modelling techniques include an algorithm to construct the graph and methods to determine the interactions between vehicles. A vehicle is modelled as a vertex and an interaction between a pair of vehicles is modelled as an edge. The danger severity of an interaction is mod-
eled as the weight of the edge. An interaction and its danger severity are determined based on a calculation of a possible collision between a pair of vehicles by considering the driver's reaction time. Three different cases are considered to calculate all possible occurrences of trajectory contention that may cause a collision between a pair of vehicles. The three cases accommodate various road traffic situations, such as in highways, junctions, or intersections, without any road topology information. Such a general approach has not been addressed in prior works related to CCWSs. The interaction graph is primarily used to reduce channel utilisation without compromising safety. For example, it can be used to determine the relevant vehicles that are required to receive safety messages in the event of an emergency. Additionally, it can also possibly be used by the warning system to predict any possible collision.

3. A context-aware adaptive rate protocol for RSM dissemination.

This research has designed, developed and implemented a new protocol for RSM dissemination that can improve safety to a greater degree than other conventional protocols. The new protocol employs a new adaptive scheme to adjust the RSM repetition rate or interval dynamically depending on the road traffic conditions. This work addresses the new issue of optimising and allocating the repetition interval based on the estimated channel load and the priority given to each vehicle. The priority is calculated based on the danger severity of a vehicle's interactions with its neighbouring vehicles. The danger severity is determined using the interaction graph. The new idea is to allocate a shorter interval for vehicles in a more dangerous situation, and a longer interval for vehicles in a safer situation. Such an idea has never before been proposed in the literature. Existing adaptive schemes are unable to prioritise vehicles based on the danger severity. Previous studies in this area use tracking accuracy as a metric to measure the safety performance, which is rather imprecise. The tracking accuracy required to prevent a collision is relative depending on interactions among vehicles. In this study, a new method was proposed to measure the safety performance of the RSM protocol. The method involves simulating vehicle collisions caused by inattentive drivers that depend on the CCWS notifying them to brake.
The new protocol was evaluated by comparing its performance with conventional protocols that implement a constant rate scheme. The detailed findings from the evaluation are as follows:

(a) A significant safety improvement was demonstrated by having the least number of vehicle collisions in overall compared to the constant rate protocols.

(b) Efficiency was demonstrated by the lower channel usage compared to other protocols that have a similar safety performance.

(c) Scalability was demonstrated by the consistency of safety and communication performance across various scenarios with different vehicle densities.


This research has designed, developed and implemented a new protocol for ESM dissemination that can improve safety to a greater degree than some other broadcast protocols. The new protocol employs a new multicast scheme that combines a tree-based routing method with a contention-based method. This work addressed the issues of modelling vehicles as nodes in a network graph, identifying an abnormal vehicle as a sender node, identifying the endangered vehicles as receiver nodes, estimating the transmission delay, and finding the minimum delay tree. The endangered vehicles are identified using the interaction graph. Unnecessary transmissions are reduced by sending ESMs only to the endangered vehicles. A minimum delay tree is used as the multicast tree to provide the fastest dissemination time. Given the sender node, receiver nodes, and delay estimation, the minimum delay tree can be generated using Dijkstra’s algorithm. This kind of multicast scheme for the ESM protocol has never been proposed in the literature. Existing ESM protocols are generally designed based on a broadcast scheme. They are not able to determine the endangered vehicles, and therefore may send ESMs to a large number of vehicles in the vicinity. They also cannot prioritise the endangered vehicles, which may result in some collisions that could be avoided otherwise. Previous ESM dissemination schemes mostly assume that ESMs are only disseminated on a highway or a segment of
straight road. The interaction graph eliminates the need for such an assumption and enables the development of a generalised ESM dissemination scheme that can support various road traffic scenarios. Safety performance is measured by the number of vehicle collisions caused by a simulated chain collision accident. In such an accident, a collision may be avoided if an ESM is received promptly. The new protocol was evaluated by comparing its performance with existing broadcast protocols. The detailed findings from the evaluation are as follows:

(a) In highway scenarios with random inter-vehicle spacing, using the new multicast protocol improves safety significantly as shown by the least number of vehicle collisions compared to the broadcast protocols.

(b) The new multicast protocol is able to disseminate ESMs faster than the broadcast protocols. Experiment results showed that a lower dissemination time or latency will mostly result in a fewer collisions. The reason is that the drivers of the vehicles moving toward the accident place will have more time to react and perform an evasive action.

(c) The efficiency of the new multicast protocol was demonstrated by a lower number of sent messages compared to other broadcast protocols. Reducing the number of sent messages improves packet reception rate and lower the number of packet collisions and packet latency.

5. A simulation platform for conducting performance evaluations of the RSM and ESM protocols.

A new simulator platform was developed to evaluate the RSM and ESM protocols. The simulator was implemented by extending the network simulator ns-3. The most significant extension is a new mobility module that can simulate road traffic situations on a highway and collisions between vehicles. The module was specifically created for this study because a suitable traffic or vehicular simulator was not available. The evaluation of this research requires a vehicular traffic simulator that can simulate vehicle collisions and interact with the network simulator. A col-
6.3 Future Research

The work presented in this thesis can be regarded as an initial research on context-aware communication approaches for CCWSs. Although this research in principle has shown the benefits of the context-aware approach and a significant improvement in the safety performance of a CCWS, there is still much work to be done to ensure the reliability of a CCWS in a real driving environment. More efforts are needed to gain the confidence of the market and encourage worldwide deployment. To further improve the CCWS in general, and the proposed context-aware communication system in particular, some ideas for future work originating from this research are discussed in this section.

The accuracy and reliability of the context model in determining the endangered vehicles depends on the assumptions used in estimating the possible collisions. Currently, the context modelling problem does not consider some exceptional, but possible, types of vehicle motion such as drift, rollovers, jumps or other movements beyond the normal direction of the vehicle. The question that needs to be answered first is whether it is necessary to consider the possibility of such exceptional movements. There are many improvements that can be made to the current model while keeping its main function, which is to allow easy identification of any possible collision. To further improve the accuracy, the motion model, which is used in the interaction calculation, can be extended. A nonlinear model that considers acceleration can be used to extend the linear model. A nonlinear or curved path can be used for the estimation of trajectory contention by considering the road geometry and topology obtained.
from a digital map. The trajectory estimation also depends on the vehicle type. It is possible to generalise the model to support railroad vehicles, such as train and trams. This is very useful for transportation networks that have many railway crossings with no safety gates or warning signals, where there are possible collisions between road vehicles and railway vehicles. Extensive field tests are needed to obtain various real movement traces to calibrate and validate the accuracy and reliability of the context model.

The context-aware RSM protocol can be extended by incorporating existing ideas and concepts to further improve the performance. A state prediction scheme can be used to further reduce the RSM repetition rate and to eliminate the need to send information that has not changed since it was previously sent. An aggregation or piggybacking scheme can improve the reliability of RSM dissemination. Such extensions need to be implemented and evaluated to validate the benefits of a combined system. In addition, the proposed protocol focuses only on the dissemination repetition interval or rate adaptation. To further improve the efficiency of the protocol, the next step would be to investigate an extended scheme that adaptively adjusts both the repetition interval and the transmission power.

The context-aware ESM protocol uses a multicast scheme that requires context information about neighbouring vehicles within more than 1-hop communication range. The required number of hops should be dynamic depending on the safety distance and the vehicle density. Further research is needed to investigate an intelligent and efficient method to obtain the $n$-hop context information. It is also possible to extend and modify the multicast scheme to work with only 1-hop information by investigating more distributed approaches. Other possible future works include prioritisation of relevant receivers based on their individual danger severity, investigation of a transmission power adaptation scheme, and comprehensive comparisons with additional existing protocols.

Due to time and resource limitations, some interesting experiments and evaluation strategies had to be left for future investigations. The proposed ESM protocol was only evaluated together with a conventional RSM protocol in order to conduct a fair comparison with other ESM protocols. It is expected that overall safety and communication performance can be further improved when both the proposed ESM and RSM protocols are used jointly. However,
solid evidence is needed to demonstrate the improvement and to ensure that there would be no unforeseen problems. Therefore, experiments are needed to validate and evaluate the integration of the proposed RSM and ESM protocols.

Both the proposed RSM and ESM protocols need to be extensively evaluated in other complex traffic scenarios, such as intersections, junctions or roundabouts. The evaluation should include various test cases that cover different situations that lead to different types of collisions. It is also important to conduct more realistic experiments that involve real driving situations. While it is still feasible to conduct field tests using several real motor vehicles (e.g. cars), which represent a very sparse traffic scenario, it requires enormous resources to conduct similar tests that can represent a very dense traffic scenario. The most feasible solution would be to develop a combination of a driving simulator, traffic simulator, and wireless network simulator that can simulate real driving situations as closely as possible. The simulator must enable analysis of safety performance based on the occurrence of collisions. Realistic collisions can be emulated by using a real person to drive a virtual vehicle in the simulator. However, high density experiments would require a large number of both driving simulator hardware devices and test drivers. A compromise can be made by simulating a vehicle’s action based on human driver behaviour.
Appendix A

Supplemental Mathematical Derivations

A.1 Calculation of Avoidance Time (Chapter 3)

All the trajectory contention calculations presented in Chapter 3 are derived based on the following basic equations of motion:

\[ d = s \cdot \Delta t \]  \hspace{1cm} (A.1)

\[ s = a \cdot \Delta t \]  \hspace{1cm} (A.2)

\[ d = s \cdot \Delta t + \frac{1}{2} a \cdot (\Delta t)^2 \]  \hspace{1cm} (A.3)

where \( d \) is the distance, \( s \) is speed, \( a \) is acceleration (or deceleration), and \( \Delta t \) is time interval.

The braking distance of a vehicle is the distance travelled while it speed reduces from \( s \) to \( s' \) with a deceleration \( \alpha \geq 0 \), which can be calculated by a formula derived using Equation (A.3):

\[ d_{brake} = \frac{(s - s')^2}{2\alpha} \]  \hspace{1cm} (A.4)

The braking distance needed for a vehicle to reach a full stop, which is when its final speed \( s' = 0 \), is therefore:

\[ d_{brake} = \frac{s^2}{2\alpha} \]  \hspace{1cm} (A.5)
In general, the avoidance time $\tau$ is calculated by finding the time that is needed for a vehicle to travel an avoidance distance $d_{\text{avoid}}$, which is the distance from a vehicle’s current position to its estimated trajectory contention point minus the braking distance:

\[
d_{\text{avoid}} = d_t - d_{\text{brake}} \tag{A.6}
\]

\[
\tau = \frac{d_{\text{avoid}}}{s} \tag{A.7}
\]

For the following case, the avoidance time is the smallest non-negative value from $\dot{\tau}_1$ and $\ddot{\tau}_1$. In the case that the follower $F$ is faster than the leader $L$, the avoidance time $\dot{\tau}_1$ is the reaction time available for the follower $F$ to avoid a collision:

\[
\dot{\tau}_1 = \frac{d_t - d_{\text{brake}_\text{FL}}}{s_{FL}} = \frac{d_t - \frac{(s_F - s_L)^2}{2\alpha_F}}{s_F - s_L} = \frac{d_t}{s_F - s_L} - \frac{s_F - s_L}{2\alpha_F} \tag{A.8}
\]

where $d_{\text{brake}_\text{FL}}$ is the braking distance required to reduce the speed $s_F$ to $s_L$, and $s_{FL}$ is the relative speed between vehicle $F$ and $L$. The avoidance time $\ddot{\tau}_1$ is the reaction time available for the follower $F$ to avoid the collision in the case when the leader $L$ brakes abruptly:

\[
\ddot{\tau}_1 = \frac{d_t + \dot{d}_{\text{brake}_F} - \dot{d}_{\text{brake}_L}}{s_F} = \frac{d_t - \frac{1}{2} \left( \frac{s_F^2}{s_F} - \frac{s_L^2}{s_L} \right)}{s_F} = \frac{d_t}{s_F} + \frac{1}{2s_F} \left( \frac{s_L^2}{\alpha_L} - \frac{s_F^2}{\alpha_F} \right) \tag{A.9}
\]

For the opposite case, the avoidance time $\tau_2$ is the reaction time available for both vehicles $A$ and $B$ to avoid a head-on collision:

\[
\tau_2 = \frac{d_t - \left( \dot{d}_{\text{brake}_A} + \dot{d}_{\text{brake}_B} \right)}{s_{AB}} = \frac{d_t - \frac{s_A^2}{2\alpha_A} - \frac{s_B^2}{2\alpha_B}}{s_A + s_B} \tag{A.10}
\]

where $s_{AB}$ is the relative speed between vehicle $A$ and $B$.

For the intersection case, the avoidance times $\tau_{3A}$ for vehicle $A$ and $\tau_{3B}$ for vehicle $B$ are calculated by subtracting the distance-to-intersection $d_{AC}$ and $d_{BC}$ with their braking distance and dividing the distance by their speed:

\[
\tau_{3A} = \frac{d_{AC} - \dot{d}_{\text{brake}_A}}{s_A} = \frac{d_{AC} - \frac{s_A^2}{2\alpha_A}}{s_A} = \theta_{AC} - \frac{s_A}{2\alpha_A} \tag{A.11}
\]

\[
\tau_{3B} = \frac{d_{BC} - \dot{d}_{\text{brake}_B}}{s_B} = \frac{d_{BC} - \frac{s_B^2}{2\alpha_B}}{s_B} = \theta_{BC} - \frac{s_B}{2\alpha_B}
\]
The interval $I$ for each vehicle is determined proportionally according to a priority ratio $p$ given to each vehicle. The priority ratio is determined based on the maximum danger severity of a vehicle $\omega_{\text{max}}$ (Equation (4.2)) and the total of maximum danger severities of all vehicles within a particular communication range $\bar{\omega}_{\text{max}}$, as shown by the following:

$$p = \frac{\omega_{\text{max}}}{\bar{\omega}_{\text{max}}}, \quad 0 \leq p \leq 1$$

(A.13)

Given a maximum channel load $\lambda_{\text{max}}$, the theoretical message generation rate that can produce the given load can be found to be:

$$\lambda_{\text{max}} = \sum_{i=1}^{n} f_i \cdot T$$

(A.14)

$$\sum_{i=1}^{n} f_i = \frac{\lambda_{\text{max}}}{T}$$

(A.15)

where the rate $f_i$ consists of a constant minimum rate $f_{\text{min}}$ and a variable rate $f_i'$:

$$f_i = f_{\text{min}} + f_i'$$

(A.16)

Since all vehicles use the resource at least at a minimum rate, thus:

$$\sum_{i=1}^{n} f_i' = \frac{\lambda_{\text{max}}}{T} - \sum_{i=1}^{n} f_{\text{min}}$$

$$= \frac{\lambda_{\text{max}}}{T} - n \cdot f_{\text{min}}$$

(A.17)

(A.18)

If all vehicles are to be assigned with the same minimum rate $f_{\text{min}}$, the extra rate $f_i'$ can be found by dividing the left hand side of equation A.17 by
\[ f'_i = \frac{1}{n} \left( \frac{\lambda_{\text{max}}}{T} - n \cdot f_{\text{min}} \right) \]

As a vehicle should be prioritised based on its danger severity, the extra rate \( f'_i \) for each vehicle \( i \) should be in proportion to the priority ratio \( p \):

\[ f'_i = p \left( \frac{\lambda_{\text{max}}}{T} - n \cdot f_{\text{min}} \right) \quad \text{(A.19)} \]
\[ = \frac{\omega_{\text{max}}}{\omega_{\text{max}}} \left( \frac{\lambda_{\text{max}}}{T} - n \cdot f_{\text{min}} \right) \quad \text{(A.20)} \]

Assume that \( n \) is the number of vehicles in the set \( \mathcal{V} \), \( n = |\mathcal{V}| \). The repetition rate \( f \) for each vehicle can be found by substituting \( f'_i \) in equation A.16 with equation A.19:

\[ f = f_{\text{min}} + \frac{\omega_{\text{max}}}{\omega_{\text{max}}} \left( \frac{\lambda_{\text{max}}}{T} - |\mathcal{V}| \cdot f_{\text{min}} \right) \quad \text{(A.21)} \]

The interval of a rate \( f \) is calculated using \( \mathcal{I} = \frac{1}{f} \). Substituting \( f \) with Equation A.21 gives the Equation 4.6 as described in Chapter 4:

\[ \mathcal{I} = \frac{1}{\frac{1}{\mathcal{I}_{\text{max}}} + \frac{\omega_{\text{max}}}{\omega_{\text{max}}} \left( \frac{\lambda_{\text{max}}}{T} - \frac{|\mathcal{V}|}{\mathcal{I}_{\text{max}}} \right)} \]

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Appendix B

Implementation Notes

All experiments in this study were performed using the ns-3 network simulator. All the RSM and ESM protocols were implemented in ns-3. The highway traffic and accidents were simulated by developing highway scenario and vehicle mobility models that extend the ns-3 models. An extra effort in developing a simulator platform is needed because there is no publicly available simulator that can simulate accidents. Existing VANET simulators that were reviewed in several surveys and comparative studies [93, 38, 63] are unable to generate vehicle collisions. A highway traffic simulator that extends ns-3 exists [6], but it is also unable to simulate vehicle collisions. Most of the simulators use a collision-free traffic model for the traffic simulation. There are some simulators that can generate vehicle collisions mentioned in the literature, such as a ns-2 based hybrid simulator [16] and HiTSim [120], but they are not publicly available and the author was not able to obtain access to those simulators.

The ns-3 network simulator is a discrete-event network simulator targeted primarily for research and educational use. It is free and open source software licensed under the GNU GPLv2 license, and is publicly available for research, development, and use. It has been used in several recent studies on communication\(^\dagger\). Ns-3 is the next generation of the well-known and respected ns-2 network simulator. The ns-3 architecture was redesigned from scratch and is not an extension of ns-2. In ns-2, some components are written in C++ and others in OTcl. In ns-3, the simulator is written entirely in C++, with optional Python bindings. The new single language approach together with a

APPENDIX B. IMPLEMENTATION NOTES

clean object-oriented design and the use of modern C++ features make development and debugging on ns-3 easier than on ns-2. In addition, ns-3 has more detailed IEEE 802.11 models, which is an important aspect in studies related to IEEE 802.11-based wireless communication.

The decision to use ns-3 in this research was made after considering the ease of use and extensibility, feature set, and performance of several existing network simulation tools. The performance of ns-3 has been compared with other open source network simulation tools [108], namely ns-2, OMNeT++, JiST and SimPy. The performance comparison shows that ns-3 has the best overall performance in terms of both simulation run-time and memory usage.

The ns-3 source code and and all documentation can be downloaded from the ns-3 website [1]. The releases of ns-3 are based on date-driven schedules rather than feature-based with a typical interval of 3-4 months. All the simulations in this thesis was performed using version 3.8 (ns-3.8).

B.1 The ns-3 Network Simulator

In ns-3, the abstraction of a basic computing device is called the node. This abstraction is represented in C++ by the class Node. The Node class provides methods for managing the representations of computing devices in simulations. An instance of any class that models an application, a protocol stack or a peripheral card with its associated driver can be added to the Node by using the object aggregation technique. To create one or more nodes in the simulation, the NodeContainer::Create() method is invoked. An instance of a simulation run in ns-3 is executed by calling the Simulator::Run() method. The following simple example illustrates the basic use of the ns-3:

```cpp
#include "ns3/core-module.h"
#include "ns3/helper-module.h"
#include "ns3/node-module.h"
#include "ns3/simulator-module.h"

using namespace ns3;

static void someActions () {
    // Do something here
```
To evaluate the performance of the proposed RSM and ESM protocols, a new module was developed as an extension to ns-3 by following the object-oriented paradigm. The aim is to design a flexible, extensible, and easy to use simulation program to conduct all the experiments. The conceptual, simplified, UML class diagram of the extension module is shown in Figure B.1. Using the module, a particular experiment can be conducted by specifying any particular scenario and protocols to be tested. The following section describes the lower layer settings used in the experiments. Sections B.3 and B.4 describe the main models that are contained in the extension module.
Figure B.1: High-level class diagram of the simulator platform.

B.2 Wireless Simulation Setup

All simulations are performed using the same settings and parameters of the wireless device and the lower layer protocols. The ns-3 provides a set of helper classes to ease the task of installing required components (devices, protocols or applications) to all the nodes. For the PHY and MAC layer components, this setup uses WifiHelper, YansWifiChannelHelper, YansWifiPhyHelper, and QosWifiMacHelper.

B.2.1 Propagation Models

The wireless signal propagation is modelled in terms of the propagation delay and the propagation loss, which are defined in two generic interfaces, namely PropagationDelayModel and PropagationLossModel, respectively. For the propagation delay, this setup uses the ConstantSpeedPropagationDelayModel which by default models the delay of signals that propagate at the speed of light. For the propagation delay, this setup uses the ThreeLogDistancePropa-
B.2. Wireless Simulation Setup

gationLossModel and the NakagamiPropagationLossModel in combination to better reflect the real conditions. The $m_0$, $m_1$, and $m_2$ parameters for the NakagamiPropagationLossModel are set to 1.0 to model the severe fading conditions, which is the worst case scenario. The propagation models are applied by using the following code:

```cpp
YansWifiChannelHelper wch;

wch.SetPropagationDelay("ns3::ConstantSpeedPropagationDelayModel");

wch.AddPropagationLoss("ns3::ThreeLogDistancePropagationLossModel");

wch.AddPropagationLoss("ns3::NakagamiPropagationLossModel",
    "m0", DoubleValue(1.0),
    "m1", DoubleValue(1.0),
    "m2", DoubleValue(1.0));

YansWifiPhyHelper wph = YansWifiPhyHelper::Default();

wph.SetChannel( wch.Create() );
```

The effect of using the specified Nakagami and log-distance propagation models on the probability of message reception is shown in Figure B.2. The measurement was done using a simple setup that has only two nodes spaced at a certain distance, one is the sender and one is the receiver. For each sampled distance $d$, the sender transmits one hundred 500-bytes packets with 19 dBm transmission power. The probability of message reception $p$ at distance $d$ is calculated by counting the number of messages successfully received by the receiver. The results from using two different PHY data rates are compared: 3 Mbps and 6 Mbps.

B.2.2 PHY and MAC Models

The transmission power was set to a constant value of 19 dBm by the following lines:

```cpp
Config::SetDefault("ns3::YansWifiPhy::TxPowerStart", DoubleValue(19));
Config::SetDefault("ns3::YansWifiPhy::TxPowerEnd", DoubleValue(19));
```

This setup used a constant data rate of 6 Mbps in a 10 MHz channel. The following codes were used to set all the required physical parameters according
Figure B.2: The effect of Nakagami and log-distance propagation loss models on the probability of message reception with respect to distance in a collision-free channel (a sender and a receiver at each distance).

to the IEEE 802.11p standard:

```cpp
std::string phyMode = "wifi-6mbps-10Mhz";
WifiHelper wh = WifiHelper::Default();
wh.SetStandard(WIFI_PHY_STANDARD_80211p_CCH);
wh.SetRemoteStationManager("ns3::ConstantRateWifiManager",
    "DataMode", StringValue(phyMode),
    "ControlMode", StringValue(phyMode));
```

The MAC layer operates in an ad hoc mode with QoS support:

```cpp
QosWifiMacHelper wnh = QosWifiMacHelper::Default();
wnh.SetType("ns3::QahocWifiMac");
```

To install the wireless devices (including the PHY and MAC protocols) that have been setup properly:

```cpp
NetDeviceContainer devices = wifiHelper.Install(wh, wnh, nodes);
```
B.3 Highway Traffic Simulation

Wireless network simulation in ns-3 requires the MobilityModel interface to determine the position of each node. The position is needed to calculate the distance between a sender and a receiver that is used in the calculation of signal propagation loss and interference. The position of a node is implemented as a 3d vector $\vec{p} = [x, y, z]$ in the Cartesian coordinates.

To simulate the movement of a vehicle, a new VehicleMobilityModel class that implements the MobilityModel interface was developed. A vehicle is modelled as a rectangular object with length $l$ and width $w$. The centre of the rectangle is the reference point for the absolute position of the vehicle. The vehicle movement is modelled based on the simple dynamics of an object moving along a path. The vehicle path was modelled and abstracted as a LanePath interface. A path has a finite length $O$. A vehicle’s relative position on the path is termed as an offset $o$, where $0 \leq o \leq O$. The path can be used to represent a lane segment on the road. The absolute position of a vehicle (node) in the simulation depends on its offset on the path and the absolute position of the path. Any concrete implementation of LanePath must implement its CalculatePoint method that accepts the offset as the parameter and returns the absolute position $\vec{p}$.

A StraightLanePath class that extends LanePath was implemented to model the vehicle path on a highway. A straight path is modelled by two vectors, a starting point $\vec{p}_s$ and an ending point $\vec{p}_e$. An object travels along a straight line from $\vec{p}_s$ to $\vec{p}_e$, which has a constant direction $\vec{d} = \frac{\vec{p}_e - \vec{p}_s}{||\vec{p}_e - \vec{p}_s||}$. To calculate the absolute position of a vehicle with a specific offset $o$ on the path, the CalculatePoint method implements the following function:

$$\text{CalculatePoint} (o) = \vec{p}_s + l\vec{d} \quad (B.1)$$

The position $\vec{p}$ of every vehicle is updated for every given time interval $\Delta t$ based on its current speed $s$ and acceleration $a$:

$$o = o + \left( s \cdot \Delta t + \frac{1}{2}a (\Delta t)^2 \right) \quad (B.2)$$

$$\vec{p} = \text{CalculatePoint} (o) \quad (B.3)$$
The speed $s$ should also be updated:

$$s = s + a \cdot \Delta t$$  \hspace{1cm} (B.4)

If the updated speed is less than 0 then the speed and the acceleration are set to 0.

A new `RoadTrafficScenario` class was developed to generalise a simulation of vehicular traffic regardless of the road topology. An instance of this class controls the behaviour of each vehicle in the simulation. The class is responsible for creating the node objects that represent vehicles, setting up a new `VehicleMobilityModel` for each node object, setting up the initial state of each vehicle, updating the vehicle's position and speed periodically, and controlling the vehicle's acceleration. The vehicle's position and speed are updated based on its current dynamics (equations (B.3) and (B.4)). A collision is detected if the distance between a leading vehicle $L$ and a following vehicle $F$ is less than or equal to 0, that is:

$$o_L - o_F - \frac{l_L}{2} - \frac{l_F}{2} \leq 0$$  \hspace{1cm} (B.5)

The vehicle's acceleration can be changed based on a predetermined (scheduled) event or a driver's behaviour. The predetermined event allows us to schedule a change to the acceleration of any vehicle. It is useful to set up a scenario where we can trigger emergency braking on a particular vehicle at a certain time. The driver's behaviour is abstracted as a `DriverModel` interface. An implementation of `DriverModel` is responsible for adjusting the acceleration of a vehicle based on the feedback from the system. For example, the `ConstantSpeedWithBrakingDriverModel` class models a simple driver behaviour that tries to avoid a collision by calculating the trajectory contention and braking accordingly.

To simulate vehicular traffic on a highway, a `HighwayScenario` class that extends `RoadTrafficScenario` was introduced. The class models a highway with an arbitrary number of lanes. Each lane is represented by the `StraightLanePath` object, which is positioned and arranged accordingly. The initial speed and acceleration for each vehicle and the initial inter-vehicle spacing can be randomised or set the same uniformly. The highway scenario is set up based on several common parameters or constants defined in Table B.1.
Table B.1: Common parameters used in highway simulations.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>vehicle_min_gap</td>
<td>2 m</td>
</tr>
<tr>
<td>vehicle_length</td>
<td>4 m</td>
</tr>
<tr>
<td>vehicle_width</td>
<td>2 m</td>
</tr>
<tr>
<td>vehicle_normal_deceleration</td>
<td>4.9 m/s²</td>
</tr>
<tr>
<td>vehicle_emergency_deceleration</td>
<td>8 m/s²</td>
</tr>
<tr>
<td>highway_lane_width</td>
<td>4 m</td>
</tr>
<tr>
<td>driver_reaction_time</td>
<td>1.5 s</td>
</tr>
<tr>
<td>movement_update_period</td>
<td>50 ms</td>
</tr>
</tbody>
</table>

B.4 Safety Message Dissemination Protocols

The Wave Short Message Protocol (WSMP) was implemented in the WsmProtocol class. An instance of WsmProtocol must be installed on each node. The WSMP directly interacts with the MAC layer within a node via two main methods: ReceivePacket and BroadcastPacket. The ReceivePacket method is used to handle any received message or packet that was sent using the WSMP. The received packet is first handled by the PHY and MAC layers. To invoke the ReceivePacket method when a relevant packet is received, a callback must be registered on each node:

```cpp
node->RegisterProtocolHandler(MakeCallback(&WsmProtocol::ReceivePacket, this),
                               m_protocolNumber, 0);
```

The BroadcastPacket method is used to broadcast a WSMP packet. The method directly sends any given packet to the MAC layer by invoking the WifiNetDevice::Send() method:

```cpp
// Obtain a WifiNetDevice of a node
m_wifiNetDevice = node->GetDevice(0)->GetObject<WifiNetDevice>();

// Make a node to send a packet through its WifiNetDevice
m_wifiNetDevice->Send(packet, m_wifiNetDevice->GetBroadcast(), m_protocolNumber);
```

All common functions for the RSM and ESM protocols were implemented in the RsmProtocol and EsmProtocol classes, respectively. Both of the classes are derived from the WsmProtocol class. Different RSM and ESM protocols were implemented by creating subclasses of the RsmProtocol and EsmProtocol classes.
classes, respectively. When a packet is received, it is the responsibility of the subclasses to filter the relevant packet and process the packet accordingly by overriding the `ReceivePacket` method of the parent class. The content structure of the packet sent by the `RsmProtocol` or `EsmProtocol` is modelled as the packet header. The packet header of each protocol was implemented in classes that are derived from the `Header` class. Each protocol has a particular method that must be invoked to send a packet. The method creates a new header, adds it to a newly created packet, and sends the packet using the `WsmProtocol::BroadcastPacket` method.

The interaction graph that is used by the RSM and ESM protocols was implemented as an adjacency list in the `ContextMap` class. Each time a new vehicle state information is received by the `RsmProtocol`, the information is used to update the interaction graph in the `ContextMap`. 
Appendix C

List of Publications

Some of the material from this thesis has appeared previously in the following peer-reviewed publications:


Bibliography


BIBLIOGRAPHY


