5G-Based Communication System for Future Vehicular Ad-Hoc Network

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Statement of Originality

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Shashank Kumar Gupta

Abstract

With the increasing vehicular traffic volume and congestions on urban roads and highways, the journey time and road accidents are increasing. This has prompted automobile industries and traffic regulatory authorities to develop a new road traffic management architecture using Information and Communication Technology (ICT) systems. With the expected introduction of autonomous vehicles in the next decade, it will be imperative for road traffic authorities to develop strategies to support Vehicle-to-Everything (V2X) communication infrastructure. Intelligent Transport Systems (ITS) provides an excellent framework for integrating information and communication technology with the transport infrastructure. The integrated system could improve vehicular safety, and traffic efficiency by reducing road accidents and traffic congestion. The major issue related to such an advanced system is how to meet the strict latency and robustness requirements of V2X applications in the presence of varying traffic load, high speed vehicles, and different road structure such as city roads and highways. Most of the work has been done to support vehicular networking is currently focused on the IEEE 802.11p and 4G-based-LTE standards. However, due to medium access control rules and limited mobility support of the IEEE 802.11p standard, it is challenging to obtain stringent delay requirements, particularly in a high-density scenario. Due to the centralized architecture, an LTE-based system does not natively support direct V2V connectivity. Instead, it is necessary for messages to be passed through an infrastructure node in the core network. Therefore, the capability of these standard technologies is doubtful to cope with the scalability and the reliability at the radio access level. Recently, the 3GPP has introduced a new LTE standard known as C-V2X to support V2X communications. Compared to the IEEE 802.11p standard, C-V2X is a less studied technology. Due to the coexistence of LTE-D2D communication and normal LTE, it introduces some design

challenges such as resource management among D2D and regular LTE users, efficient and fast D2D peer discovery model, transmission power control to avoid collisions and interference between D2D and regular LTE users.

In this research, a cluster-based C-V2X architecture has been developed and evaluated to support time-critical vehicular safety applications in an efficient and cost-effective manner. Specifically, safety applications require two types of message transmissions; namely, periodic Cooperative Awareness Messages (CAMs) and Decentralized Environment Notification Messages (DENMs). A new D2D peer discovery model and resource distribution technique are proposed to reduce peer discovery delay, control signalling overhead, and to support the higher vehicle densities. The proposed peer discovery model reduces the signaling overhead and end-to-end latency with awareness of proximity (i.e., list of neighboring vehicles in the proximity) utilizing the Global Positioning System (GPS) information. Using the above techniques the vehicles discover each other within the minimum delay requirement for safety message transmissions. Proposed cluster-based round-robin scheduling technique keeps the resource utilization at a minimum level so that conventional mobile networking services can efficiently share the transmission resources.

To efficiently transmit the periodic CAM in a multi-path fading scenario, direct inter-cluster communication adaptive transmission power assignment schemes are proposed. Both schemes are combined to improve the CAM packet success rate for a highway safety message distribution system. A new CAM message structure is also introduced to support the proposed power control algorithm. To efficiently transmit the DENM warning messages, two cluster-based multi-hop communication protocols are proposed. Both protocols use a time slot reservation technique where a separate side link channel time slot will be reserved for the warning message transmission. The proposed protocol is shown to achieve a quicker notification of the warning messages with fewer transmissions as well as a higher reception rate for the safety messages. The performance of proposed protocols is analyzed in both city and highway scenarios. The thesis further proposes a prediction-based protocol to improve the reliability of CAM safety messages transmission in different road structures such as highways with entry and exits roads. The proposed protocol offers a new procedure for trajectory prediction to assist cluster formation and reformation procedures.

In this thesis, the performance of the proposed solutions is examined utilizing an OMNeT++ based simulation models using SimuLTE, SUMO, Veins and OpenCv2x mode 4.

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List of Abbreviations

ACC	Adaptive cruise control
ALUID	Application Layer User ID
BSR	Buffer Status Report
C-ITS	Cooperative Intelligent Transportation Systems
C2C-CC	Car-to-Car Communication Consortium
CAMs	Cooperative Awareness Messages
CCA	Clear Channel Assessment
CCH	Control Channel
CEN	European Committee for Standardization
CMs	cluster Members
CMT	Cluster Member Table
CMT	cluster Member Table
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance mechanism
CW	Contention Window
DCC	Decentralized Congestion Control
DCF	Distributed Coordination Function
DENM	Decentralized Event Notification Messages

DIFS	Distributed Coordination Function
DSRC	Dedicated Short Range Communications
EDCA	Enhanced Distributed Channel Access
eNB	eNodeB
EPUID	EPC ProSe Subscriber ID
ETSI	European Telecommunications Standards Institute
eV2X	Enhance V2X
FCC	Federal Communication Commission
FCD	floating car data
GMLC	Global Mobile Location Centre
HCF	Hybrid Coordination Function
ICT	Information Communication Technologies
ID	Identity
IFS	Inter-Frame Space
ISO	International Organization for Standardization
ITS-S	ITS station
LCS	Location Service Report
LLC	Logical Link Control
LOS	Line-of-Sight
LTE NIC	LTE Network Interface Card
MAC	Medium Access Control
NVL	Neighbouring Vehicle List
NVT	Neighbouring Table

OFDM	Orthogonal Frequency Division Modulation
OSI	Open Systems Interconnection
PCF	Function Point Coordination Function
PCRF	Policy and Charging Rules Function
PDU	Protocol Data Unit
PHY	Physical Layer
PIFS	Point Coordination Function-IFS
RBDS	radio broadcast data system
RDS	Radio Data System
SC	Source cluster
SCH	Semi Cluster Head
SCH	Semi Cluster Head
SCH_A	Source Cluster
SCHs	Service Channels
SE	Selection State
SE	Selection State
SIFS	Short-IFS
SV	Source Vehicle
SV	Source Vehicle
TCM	Temporary Cluster Member
TCP	Transmission Control Protocol
UE	Users Equipment
UPs	User Priorities

V2I	vehicle-to-infrastructure
V2N	Vehicle-to-Network
V2P	vehicle-to-Pedestrian
V2V	vehicle-to-vehicle
V2X	Vehicle-to-Everything
VIR	Vehicle Information Register
WAVE	Wireless Access in Vehicular Environments
WG	Working Group
WLOS	Weak-line-of-Sight
WSMP	WAVE Short Message Protocol

Chapter 1

Introduction

Wireless communication techniques used by vehicles to improve road safety and reduce environmental impact have been investigated well before the rise of the information and communication technologies we are familiar with today. In 1926, Harry Flurscheim invented a radio warning system that permited a road vehicle to signal its presence using electric waves to all other vehicles in its immediate vicinity [19]. In 1984, a first digital infrastructure known as the Radio Data System (RDS) became the first communication protocol for vehicle communication. After few years, it was introduced in the USA as a radio broadcast data system (RBDS) . In 2005, it became a European Standard to provide RDS-Traffic Message Channel (TMC).

However, this standard radio set did not use any networking and remained as a unidirectional system. In early 1990, Philips invented a 5.8 GHz Dedicated Short Range Communications (DSRC) system, which was used for "Intelligent vehicle-highway systems" (IVHS) communications service delivery [19]. After a few years, the concept of networking through infrastructure started to evolve. However, due to some fundamental weaknesses such as expensive and fixed infrastructure, limited bandwidth, and short communication range, the demand for communication development for vehicles has been growing in more recent years.

In early 2000, Ken Labertaus invented the term Vehicular Ad-Hoc Networks (VANETs) which became mostly synonymous with the more generic term Inter-Vehicle Communication (IVC) to refer to Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication based on wireless local area networking technology. One of the known definitions of the VANET is a type of wireless network where each node is a moving vehicle on the road. The vehicles communicate with each other to make the traffic safer and improve traffic flow by avoiding congestion. VANETs and V2X communications have become a popular research area in the past decade. They have attracted many research studies and real field experimental projects, both from academia and automobile ICT industries.

The aim of traditional VANETs is to improve traffic safety and road efficiency using information and communication technologies among advanced wireless access technology-enabled vehicles. Researchers from industry and academia believe that integrating information and communication technologies with transportation infrastructure and vehicles will revolutionize the way we travel today. In this context, the Cooperative Intelligent Transport System (C-ITS) has been defined as an evolution of the classical transportation system that aims at deploying Vehicle-to-Vehicle (V2V) communication, Vehicle-to-Infrastructure (V2I) communication and Vehicle-to-Network (V2N), and Vehicle-to-Pedestrian (V2P) communications at large scale. Collectively, these wireless transactions are referred to as vehicle-to-Everything (V2X) communication. The C-ITS is considered a new technology domain and requires collaborative research efforts in the interdisciplinary areas of Telecommunication, Transportation, Electronics, and traffic scheduling.

VANETs support a wide variety of safety and non-safety applications. These applications can be categorized into three categories: safety, traffic efficiency, and infotainment [4]. Safety applications are intended to reduce the number of road fatalities. These applications are based on safety messages that are shared among vehicles. These applications rely on periodic and aperiodic transmission of safety messages to the neighboring vehicles or infrastructure (or vice versa). Traffic efficiency applications are intended to reduce travel time and mitigate traffic congestion. For example Foating Car Data (FCD) service [20] where data are collected by vehicles and external sensors, and is periodically transmitted to remote management servers. Infotainment applications consist of traditional internet such as content downloading, file sharing, web browsing, cloud services and other emerging services, such as audio/video streaming, and information and advertisement services.

1.1 Motivation

With the continuous advancements of wireless communication, such as 5G-based wireless communication technology, the autonomous vehicle is becoming a reality. V2X communication has attracted many research studies and real-time field experiments, both from academia and from the automobile industry. The vehicular ad hoc network (VANET) architecture was initially developed using the IEEE 802.11p-based dedicated short-range communication (DSRC) standard [4]. The main objective of the VANET is to support Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication modes. In 1999, the Federal Communications Commission (FCC) allocated a dedicated spectrum for VANET safety applications in the 5.9 GHz band to overcome the interference issue. However, due to the scalability issue, and concerns about possible higher delay in message transmission, lack of infrastructure, and other limiting factors of the IEEE 802.11p standard, many researchers have begun to look for other access technologies.

The cellular Long Term Evolution (LTE) technology has received a lot of attention both from academia and the relevant industries and can possibly meet the requirements of V2X communications. The limitations of the IEEE 802.11p standard, and recent advancements in cellular technologies like D2D communications, has motivated research communities to investigate the LTE-based V2X communications architecture. LTE is a cutting-edge technology that includes some new enhanced networking features, giving the LTE standard an advantage compared to other technologies. An all-IP architecture characterizes the overall LTE system, with a reduced number of network entities and a separation of the control plane and user plane traffic. Due to its flat architecture, the LTE- based network can support Round Trip Times (RTTs) theoretically lower than 10 ms and transfer latency in radio access of up to 100 ms. However, the currently deployed LTE standard in 3GPP Release 13 cannot meet the low-latency and high-speed requirements of safety-critical V2V applications. Also, vehicles in areas with low or no network coverage would be unable to communicate with each other.

Despite these limitations, LTE Release 13 presents some solutions to meet the requirement of some less stringent V2N use cases today. 3GPP recently introduced many vehicular network use cases in the LTE-V2V Release 14 [13] for future vehicular networks. The 3GPP Release 14 LTE standard does include support for cellular-V2X (C-V2X) use cases, such as direct device-to-device communication, to improve latency, support operation at high relative speeds. Also, the ability to leverage existing cellular infrastructure would reduce infrastructure costs, and offer many safety and efficiency benefits for the V2X communication.

With the introduction of 5G technologies, the transportation and ICT industries have refocused their attention towards developing new systems and products mainly relying on Long Term Evolution (LTE)-based technologie. The LTE standard is commonly used as the 4G broadband wireless technology, which is further evolving as one of the significant components of 5G and 6G technologies [21]. To accommodate the needs of vehicular networks, the 3GPP has started to standardize the LTE-V standard to support V2X services, encompassing three modes of communications: V2V, V2I, and vehicle-to-pedestrian (V2P) in Release 14. The standard has developed a new channel architecture using the PC5 interface to support vehicular networking requirements. The standard also supports the conventional Uu interface for different vehicular services. The PC5 interface includes the sidelink, which has Device-to-Device (D2D) communication abilities developed under Release 12 of the LTE standard. Release 12 was mainly developed for public safety applications. The V2X communication services are being enhanced in LTE Release 15 and further enhancements are announced in the recently published Release 16.

The ability for C-V2X to provide a reliable communication channel over a large distance compared to the IEEE 802.11p standard has generated interest in studying these two technologies in combination to create a reliable communication network to improve road traffic efficiency and safety. The C-V2X supports vehicular use cases, specifically targeting higher speed (up to 250 km/hr) and high density (thousands of nodes) communication with few physical (PHY) and medium access control (MAC) layer modifications. The introduction of 5G-based C-V2X networks for V2X communication has opened up new research avenues to improve the performance and to meet the requirements of V2X communication by addressing the drawbacks associated with IEEE 802.11p/DSRC and centralized LTE network architecture.

It is credible that the C-V2X could be a solution to the current challenges with V2X communication and an alternative to the IEEE 802.11p standard for vehicular safety applications. However, the automobile industry is still in debating with the unique advantages of each technology. A number of challenges still need to be investigated and resolved before vehicular communication-based safety systems become a reality. A major challenge in such safety systems is the reliability of wireless communication information exchange mechanisms. Since the safety applications involve human life, a robust communication architecture is needs to be developed.

In addition to the above, advanced and efficient resource allocation mechanisms are needed to meet the resource requirements of both LTE-D2D and conventional LTE communication. This thesis is focused on developing C-V2X-based communication architecture, which can support time-critical vehicular safety applications and other vehicular safety applications efficiently and cost-effectively. The performance of various message dissemination techniques to support safety services in vehicular networks is studied, and novel communication protocols are proposed to ensure the high reliability of safety applications.

1.2 Research Challenges

The VANET architecture provides an excellent framework for the integration of information and communication technology with the transport infrastructure. Road safety is one of the main use cases for vehicular communications since it allows lives to be saved and road accidents to be avoided. For this purpose, the major focus of road safety organisations is on research problems related to the safe access to highways, city roads, or areas with reduced visibility, and research on traffic congestion management. In this thesis, our focus is on safety applications based on the transmission of single-hop and multi-hop safety messages.

There are two types of vehicular safety messages: event-triggered and periodic [3]. Event-triggered messages are generated in the case of hazardous events on the road, and report to other vehicles. Periodic safety messages are called Cooperative Awareness Messages (CAMs) and are also known as beacons. These are short messages containing basic information about the vehicle, such as its location and speed. These messages are generated periodically, and broadcast to neighboring vehicles to increase their awareness of their environment. The reliability of vehicular safety applications depends on successful and timely information exchange between vehicles. The major issue related to such an advanced system is how to meet the strict latency and robustness (i.e, link lifetime, error rate over the link, etc) requirement of different vehicular applications in the presence of varying traffic load or high-load network conditions.

Most of the work done so far to support vehicular networking is focused on the IEEE 802.11p and the LTE standards. The IEEE 802.11p standard has several weaknesses. The IEEE 802.11p network uses a random medium access control protocol know asa Carrier-Sense Multiple Access with collision avoidance (CSMA/CA) to support V2V and V2I services. The IEEE 802.11p network's performance is affected by the network node densities, which could vary on roads depending on the traffic density. Additionally, IEEE 802.11p was designed for the rapid transmission of short-range basic safety messages. It cannot meet the higher bandwidth demands of different V2X applications, such as autonomous driving, multimedia services. The IEEE 802.11p standard also does not have the bandwidth necessary to transmit the raw vehicle sensor data that will become increasingly common in automated vehicles. The main bottlenecks of an IEEE 802.11p vehicular network are the scalability and lack of adequate Quality of Service (QoS) support for a different class of services. The fact that there are a few issues with its performance related to reliability and scalability means that a search for an alternative communication protocol that can either assist or replace the 802.11p standard is needed.

On the other hand, cellular networks have several benefits such as wide-area coverage, high data rate, and guaranteed QoS for multiple services. However, the conventional centralized cellular networks are not always suitable for vehicular networks to use to support some of the services, particularly for distributing time-sensitive broadcast services such as the Cooperative Awareness Message (CAM). In a conventional cellular network, all data communication between devices must go through the eNB, irrespective of whether they are located next to each other or at a long distance. The CAMs are transmitted from each vehicle to its neighbouring vehicles to distribute situational awareness information.

The CAMs are periodic messages that have a 10 Hz generation frequency with latency restrictions of 100 ms. In the 802.11p-based VANET, the CAM messages are broadcast to the neighbouring vehicles using the CSMA/CA protocol. Generally, conventional cellular networks can support unicast, broadcast, and multicast communications. However, these configurations are not suitable for CAM message transmissions due to high signalling overhead. Also, in dense traffic areas, the heavy load generated by periodic message transmissions from several vehicles strongly challenges the LTE capacity and may penalize the delivery of traditional applications. To accommodate the needs of vehicular networks, the 3GPP has introduced LTE-V or C-V2X standard to support V2X services in Release 14. LTE-V standard improved spectrum utilization efficiency and system capacity in a cellular system. Recent studies [22]show that the LTE-V outperforms the 802.11p based VANET to reduce fatalities and serious injuries on the EU's roads.

However, the use of C-V2X for vehicular safety applications is still under investigation. It introduces some design challenges such as efficient and faster peer discovery to determine the proximity of the communication pairs and set up the link before the communication phase, radio resource management, and power control mechanisms to avoid the collision and interference between D2D and regular LTE users. Peer discovery is one of the significant issues in C-V2X, since before two vehicles can communicate with one another, they must first know (discover) that they are near to each other. Peer discovery is typically time-and radio-resource-consuming, employing beacon signals and sophisticated scanning often involving higher layers and interactions with the end-user. Therefore, it is challenging to make such peer discovery and pairing procedures faster and more efficient in terms of resource consumption.

Although the C-V2X has a large bandwidth and can support high data rates, the amount of resources allocated for the safety applications is limited. This is due to the co-existence of Device-to-Device (D2D) communication and normal LTE. Offering direct D2D or C-V2X communications in a cellular network is challenging due to the two major factors. First, the Base station (BS) suffers from control signalling overhead. This could result in higher peer discovery and message transmission delay. Secondly, D2D enabled vehicles may cause interference to the traditional cellular network enabled users when radio resources are shared between them. As a result, the reliability of single-hop and multi-hop safety messages is degraded. Thus, in such a shared networking environment, resource management becomes difficult where a C-V2X-based system may not meet the requirements of delay-critical safety applications. The other challenge is network load due to the different size of safety message, frequency of safety message generation, and the number of vehicle density. This increase the level of congestion when the network load is greater than the available bandwidth. Thereby, some vehicles have to wait longer to get resources for transmission.

To meet the delay requirements of the safety applications, vehicles need to communicate effectively in sparse network scenarios with light traffic as well as capacity challenging scenarios in a dense traffic condition. Due to the high dynamics, such as the high speed of vehicles, the inter-vehicle distance could vary. As a result, inter-vehicle connectivity is seriously affected. Another challenge in vehicular communication is multi-path fading, which could impact the reception range of the messages beyond the transmission range. Therefore, an adaptive power assignment and an appropriate fading compensation scheme are needed due to the high dynamics and to avoid signal strength fluctuation due to fading in vehicular ad hoc networks.

As compare to the IEEE 802.11p standard, the direct V2V communication using PC-5 interface is a newer and less-studies feature in cellular networks. The centralized control of network resource distribution using C-V2X Mode 3 offers the efficient utilization of the network bandwidth [23]. However, despite the fact that C-V2X shows the improvements compare to the 802.11p standard in high traffic density scenarios, the performance of a C-V2X degrades rapidly [24], particularly for the C-V2X Mode 4. As compare to IEEE 802.11p standard, the C-V2X Mode 4 is also prone to the hidden terminal effect becasue of it's Semi-Persistent Scheduling (SPS) which is sensing-based. C-V2X Mode 4 suffers packet collisions caused by the reselections that are part of the sensing-based SPS scheme and that can occur when several vehicles try to select new sub-channels at the same time when the value reselection Counter is zero.

To overcome above challenges, this thesis investigates the development of a C-V2X architecture for the LTE-A standard to meet the requirements of time-critical vehicular safety application in an efficient and cost-effective manner. The proposed C-V2X communication protocols will improve the QoS of vehicular safety applications as well as to improve the C-V2X network capacity to support higher vehicle densities on the highway as well as on city road scenarios. Each chapter of this thesis discuss the related state of the art literature pertinent to the proposed schemes.

1.3 Thesis Contributions and Organization

The rest of the thesis is organized into five Chapters. Chapter 2 presents a detailed study of the architecture of a vehicular ad-hoc network along with its networking and service requirements. The review of current industrial standards for vehicular communication are discussed followed by the feasibility of each communication standard to meet the requirements of vehicular safety applications. Furthermore, resource allocation/management mechanisms and QoS provision techniques used in C-V2X are reviewed.

Chapter 3 presents our proposed C-V2X-based cluster multicast architecture, referred to as Cluster-Based Cellular Vehicle-to-Vehicle (CBC-V2V) combined with a new sidelink peer discovery model, referred to as Evolved Packet Core Level Sidelink Peer Discovery (ESPD). The proposed peer discovery model that reduces the signalling overhead and end-to-end (E2E) latency with awareness of proximity (i.e., list of neighbour vehicles in proximity) utilizing the Global Positioning System (GPS) information. Thereby, the vehicles discover each other within the minimum delay requirement for safety message transmissions. Proposed cluster based round robin scheduling keep the resource utilization at a minimum level so that conventional mobile networking services can efficiently share the transmission resources.

Chapter 4 presents an advanced LTE Device-to-Device (D2D) cluster communication technique, referred as LTE-DICV2V and a multicast power transmission control technique, referred as CMTPC are also proposed.The proposed architecture reuses the existing LTE control plane procedure to enable a reliable discovery service for V2V communications without introducing a new protocol or consuming additional network resources. Based on the proposed architecture, vehicular communications and related services are further investigated as a specific implementation of ProSe. These algorithms have been proposed for an LTE-based vehicular network, where the algorithms are combined to achieve high QoS for a highway safety message distribution system. A new CAM message structure is also introduced to support the proposed power control algorithm.

Chapter 5 presents the multicast communication architecture to distribute the warning messages using two communication protocols, referred to as the Clustered Multi-hop Multicast Protocol (CMMP) and the Clustered Multi-hop Broadcast and Multicast Protocol (CMBMP). Both protocols use distributed resource allocation techniques in a LTE network. We also propose a time slot reservation technique, where a separate sidelink channel time slot will be reserved for warning message transmission. For both CMMP and CMBMP protocols, the eNodeB's scheduler allocates the reserved time slot to each ON using a time-staggered resource allocation technique for the Warning Message (WM) transmission. The performance of the proposed protocols is analysed in both city and highway scenarios. An extensive performance analysis of the proposed protocols is presented in this chapter. The proposed protocol performances are also compared with the existing IEEE 802.11p/LTE hybrid networks. The performance of the proposed protocols is significantly better than other recently published protocols which support the warning message transmission in hybrid LTE networks.

In Chapter 6, we present a prediction-based protocol to improve the performance of our C-V2X-based cluster architecture at highway roads with entry and exit points. Our approach provides a new procedure for trajectory prediction and collision detection at a road intersection and assists the cluster formation and reformation at road intersection scenarios. The proposed scheme exploits both mobility related metrics such as direction of movement, vehicle speed, inter-vehicle distance and metrics related to communication link quality. We perform the analysis of such metrics under different shadowing and path loss. Moreover, we compare the performance of proposed cluster-based architecture CBC-V2V with IEEE 802.11p and C-V2X Mode 4 considering only periodic safety messages know as CAMs of constant and variable size that are generated following the ETSI standard. Chapter 7 concludes the thesis by providing a summary of the thesis and possible future research directions.

1.4 List of Publications

Following is the published/submitted/ work in book chapter and refereed conference papers.

- **S**. K. Gupta, J. Y. Khan and D. T. Ngo, "A 5G-Based Vehicular Network Architecture to Enhance Road Safety Applications," *Accepted in Vehicular Technology Conference (VTC2021-Fall)*, 2021.

- **S**hashank Kumar Gupta, Jamil Yusuf Khan and Duy Trong Ngo (May 26th 2020). An LTE-Direct-Based Communication System for Safety Services in Vehicular Networks [Online First], IntechOpen, DOI: 10.5772/intechopen.91948. Available from: https://www.intechopen.com/online-first/an-lte-direct-based-communication-system-for-safety-services-in-vehicular-networks.

- **S**. K. Gupta, J. Y. Khan, and D. T. Ngo, "Clustered Multicast Protocols for Warning Message Transmissions in a VANET" in *Proc. IEEE Vehicular Networking Conference (VNC)*, pp. 1-8, 2019.

- **S**. K. Gupta, J. Y. Khan, and D. T. Ngo, "A D2D multicast network architecture for vehicular communications," in *Proc. IEEE 89th Vehicular Technology Conference (VTC2019-Spring)*, pp. 1–6. 2019

- **S**. K. Gupta, J. Y. Khan, and D. T. Ngo, "Cluster-based D2D architecture for safety services in vehicular ad hoc networks," in *Proc. IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, pp.43–48, 2018.

Chapter 2

Vehicular Ad Hoc Networks - Overview and Modeling

This chapter presents an in-depth introduction to vehicular ad hoc networks, their design considerations, and key algorithms used to develop the vehicular networks with particular focus on safety applications. With this goal in mind, this chapter is organized as follows: Section 2.1 briefly introduces vehicular ad hoc network architectures, their role in an Cooperative Intelligent Transportation Systems (C-ITS), applications and associated data traffic requirements. Section 2.2 discusses current communication standards and their limitations. Section 2.3 presents the next generation communication standards to support V2X communications in VANETs. Section 2.4 presents a review of existing communication protocols used to improve the performance of safety message transmission in VANETs and Section 2.5 presents the simulation framework used in the rest of the thesis. Finally, Section 2.6 concludes the chapter.

2.1 Vehicular ad hoc network

VANET is a wireless ad hoc network where vehicles on roads communicate using advanced wireless communication technologies to make the traffic safer and improve traffic flow by avoiding congestion. VANETs have become a popular research area over the last two decades. Many research studies and real field experimental projects have been initiated by academia, transport and Information Communication Technologies (ICT) industries. The integration of VANET with information and communication technologies will transform today's transportation systems. In this direction, Cooperative Intelligent Transportation Systems (C-ITS) have been defined as an evolution of the classical transportation system that aim at deploying Vehicle-to-Vehicle (V2V) communication, Vehicle-to-Infrastructure (V2I) communication, vehicle-to-Network (V2N), and Vehicle-to-Pedestrian (V2P) communication, referred to as Vehicle-to-Everything (V2X) communication at large scale. The C-ITS are considered a new domain and require collaborative research efforts in the interdisciplinary areas of Telecommunication, Transportation, Electronics, and traffic scheduling areas.

2.1.1 Cooperative Intelligent Transport System (C-ITS)

ITS stations communicate and share information in cooperative intelligent transport systems to provide road users with better road safety, traffic efficiency, comfort, improved mobility, and sustainability. In Europe, stakeholders who are belonging to the Car-to-Car Communication Consortium (C2C-CC), signed a Memorandum of Understanding (MoU) on join deployment of C-ITS applications [25]. They signed the MoU with following three objectives given below:

- Improve road safety through vehicle's on-board communication systems to provide road users with an increased awareness of the surrounding traffic to avoid collision and provide road operators the possibility to warn drivers about road hazards.

- To reduce travel time, fuel consumption, and air pollution by optimizing the transportation and traffic management applications in VANETs.
- Through the expansion of Internet connectivity everywhere on the road and vehicles, C-ITS would open new market perspectives to promote many new additional services, including infotainment services for increased road users comfort and a better road travel experience.

2.1.1.1 C-ITS Reference Architectures

In order to ensure interoperability among vehicles made by different manufacturers to communicate with each other and with road infrastructure systems, a common ITS station (ITS-S) communication architectures have been developed by the government and industrial organizations in Europe and the United States [26]. Many consortia such as Car-to-Car Communication Consortium (C2C-CC) [25], Vehicle Safety Communications Consortium (CAMP), and standardization groups such as European Telecommunications Standards Institute (ETSI), and projects such as Secure Cooperative Autonomous project (SCA) and SCOOP [27] have contributed to the standardization activities in the C-ITS domain. In Europe, European Committee for Standardization (CEN) and ETSI capitalized on the standards for car-to-car communication or intelligent transport systems. These standards follow a general architecture, specified in ETSI EN 302 665 [26] and International Organization for Standardization (ISO) 21 217 [28]. In the United States, the IEEE 1609 working group (WG) developed a set of standards know as Wireless Access in Vehicular Environments (WAVE) [2].

2.1.1.2 ETSI ITS-S Communication Architecture

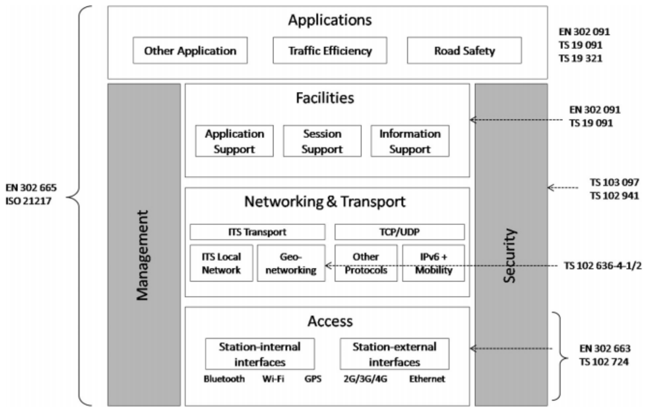


Figure 2.1: ITS-Station Reference Architecture and Main standards [1]

The European standard for vehicular communication has been defined by the technical committee on Intelligent Transport Systems (ITS) established by ETSI. Fig 2.1 present the ITS-S layered communication architecture presented in the ETSI EN 302 665 standard [1]. To support the ITS applications, it follows the principles of the OSI model [29]. Each layer of ETSI's communication architecture provides the following functionalities [30]:

- Access Layer: this represent OSI (Open Systems Interconnection) layers 1 and 2 which integrate multiple communication technologies such as IEEE 802.11p, Cellular and wireless LAN at the MAC and PHY layers. It primarily uses a specific set of IEEE 802.11 options [31], which is ITS-G5 (where G5 stands for the 5 GHz frequency band).

- Networking and transport layer: offer data transport between ITS stations. To achieve this task, ETSI considers the following communication profiles: BTP [32] over GeoNet [33], TCP/UDP over IPv6 and TCP/UDP over IPv6 over GeoNet [34].

- Facilities layer: support ITS applications by providing three types of services [35]:
  - Application support: offer common features and services for the management of CAMs and DENMs.
  - Information support: it provides common data and database management functionalities for application execution.
  - Session/communication support: offer services for communication support such as addressing mode, geocasting support and session support.
- Applications layer: support and runs different vehicular applications.
- Management cross layer: it manages the access, networking and transport, and facilities, depending on the application layer requirement.
- Security cross layer: offer secure services to all communication layers of communication architecture.

2.1.1.3 IEEE Wireless Access in Vehicular Environments (WAVE) Communication Architecture

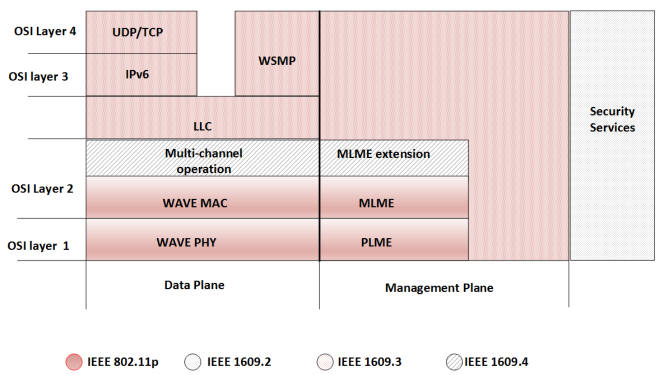


Figure 2.2: IEEE WAVE architecture [2]

In the United States, the IEEE 1609 working group (WG) developed a standard for Wireless Access in Vehicular Environments (WAVE) [2]. As shown in the Fig 2.2, the major focus of the WAVE architectures is on the IEEE 802.11 access technology. Physical and WAVE MAC layers construct the lower layer of the WAVE model. The IEEE 802.11p handles the MAC and PHY layer functionality. The IEEE 802.11p is an extension of 802.11a (Wi-Fi), and was standardised by the IEEE in 2009. The MAC and PHY layers of legacy IEEE 802.11 protocol stack have been enhanced to cope with a highly mobile environment characterized by the quickly varying network topologies and propagation conditions to meet the requirements of vehicular applications. The detailed description of the IEEE 802.11p is presented in Section 2.2.1.

As shown in the Fig 2.2, at the upper layers, traditional Internet protocols (IPv6, TCP, UDP) supports non-safety applications, and the WAVE Short Message Protocol (WSMP) supports the fast single-hop reliable broadcasting of safety messages [4]. In the wave model,the IEEE 1609 standard handles the upper layers' functionality [18]. IEEE 1609.4 standard complements the MAC sub-layer, allowing the support of multi-channel wireless connectivity [36]. The WAVE Short Messages (WSM) associated with security applications has the higher priority and travel through the CCH.

The IEEE 1609.3 is the WAVE network layer and it can be distinguish between data plane and management plane services [18]. It offers the data services of a Logical Link Control (LLC) sub-layer and IPv6 and higher layers as User Datagram Protocol (UDP) and Transmission Control Protocol (TCP) and WSMP [37]. Security algorithms and mechanisms for secure data transfer between WAVE units are defined in the IEEE 1609:2 standard [38].

2.1.2 C-ITS communication architecture and its applications

The C-ITS communication architecture is shown in Fig 2.3. It consists of two main communication entities: the On-Board Unit (OBU) and Road-Side Unit (RSU). An OBU is mounted to the vehicle and supported by a wireless transceiver, whereas a RSU deployed at road side. Vehicles' OBU and roadside unit (RSU) are also called ITS-Station (ITS-S). ITS-S communicate with each other according to four different modes of V2X communications: Vehicle-to -Vehicle communication (V2V), Vehicle to Infrastructure communication/ Infrastructure-to-vehicle communication (V2I/I2V), Vehicle-to-Pedestrian (V2P) and Vehicle-to-Network (V2N). These links are bidirectional.

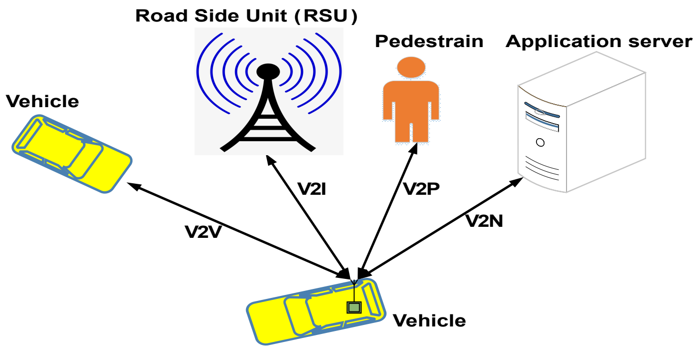


Figure 2.3: C-ITS communication architecture

2.1.3 The Deployment of C-ITS Applications

For the initial deployment of standards, the C-ITS has offered the different applications using V2X communication. ETSI has categorized them into three main categories: road safety, traffic management, and user infotainment as shown in Table 2.1 [39]. Major applications listed in the Table 2.1 are discussed in the following subsections.

Table 2.1: Application and Selected Use Cases [18]

Application class	Use cases	Message type	Max. Delay
Active road safety	Forward collision warning	CAM (V2V)	0.1s
	Lane change warning	CAM (V2V)	0.1s
	Intersection collision avoidance	CAM (V2V)	0.1s
	Left-turn collision warning	CAM (V2V)	0.1s
	Emergency brake light	DENM (V2V	0.02s
	Post-crash warning notification	DENM (V2V)	0.5s
	Approaching emergency vehicle	DENM (V2V)	0.5s
	Emergency multimedia	DENM (V2V)	20s-60s
Cooperative traffic management	Enhanced route guidance	CAM (V2I)	1s
	Optimal traffic signal timing	CAM (V2I)	1s
	Traffic signal violation warning	CAM (V2I).	1s
User infotainment	Downloading music	DENM (V21)	1s-5s
	Multi-player games	DENM (V2I)	0.1s-1s
	Media streaming	DENM (V2V)	1s-5s
	Electric Vehicle Charging	DENM (V2V)/(V2I)	1s-5s
	Restaurant booking	DENM (V2I)	1s-5s

2.1.3.1 Safety Applications

The design aim of safety applications is to assist road users with up-to-date information of the surrounding traffic to avoid dangerous situations or accidents. As the aim of VANETs is to improve road user safety, these applications impose strict delay requirements as shown in table 2.1. There are two types of vehicular safety messages: periodic messages and event-triggered [3]. The periodic safety messages are called Cooperative Awareness Messages (CAMs) and are also known as beacons. These are short messages containing the basic information about the vehicle, such as its location and speed. These messages are generated periodically to neighbouring vehicles to increase their awareness of their environment. As can be seen from Table 2.1, forward collision, lane change, intersection collision and left-turn collision warning applications require the periodic exchange of safety messages.

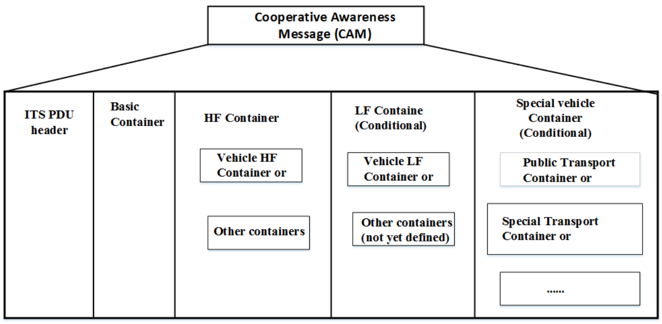


Figure 2.4: General CAM structure [3]

Fig 2.4 illustrates the structure of a CAM as specified by ETSI EN 302 637 [3]. A CAM consists of one common ITS Protocol Data Unit (PDU) header and multiple containers. The ITS PDU header is a common header that includes the information from the protocol version, the message type and the ITS-S Identity (ID) of the originating ITS-S [30]. A CAM contains multiple container such as one basic container, one high frequency container, and also include one low frequency container. The basic container contains the basic information and the high frequency container contains highly dynamic information about the originating ITS-S respectively. The low frequency container contains static and slightly dynamic information about the originating ITS-S [30] [3].

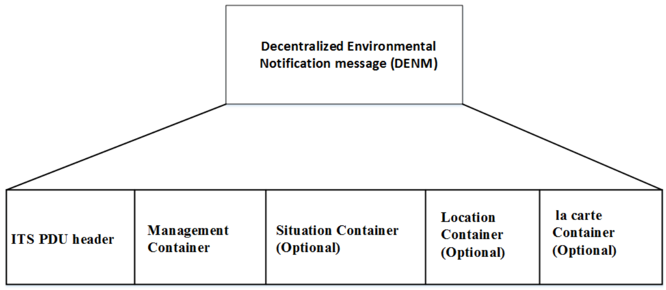


Figure 2.5: General DENM structure [3]

Event-triggered messages called Decentralized Event Notification Messages (DENM) are generated in the case of hazardous events on the road, and report to other vehicles. Fig 2.5 illustrates the structure of a DENM as specified by ETSI EN 302 637 [3]. For example, if a vehicle on the road, suddenly applied the brake, an emergency warning message also know event-driven safety message or DENM is instantly generated and need to propagated to alert other neighbouring vehicles within the proximity. Depending on the vehicular application type, a DENM message may also need to transmit over long distances by multi-hops communication [18].

2.1.3.2 Traffic Management Applications

The design aim of the traffic efficiency applications to reduce travel time, fuel consumption and air pollution and traffic congestion. Similar to infotainment applications, the traffic efficiency applications have fewer delay requirements. However, higher delay and packet loss can affect the performance of traffic efficiency applications [40]. For example, floating car data (FCD) service [20] where data are collected by vehicles and external sensors, and are periodically transmitted to remote management servers.

2.1.3.3 User Infotainment and Other Applications

The infotainment applications listed in Table 2.1 have fewer delay requirements and offer higher latency in the order of few seconds [18]. However, depending on the infotainment applications, such as YouTube watching, music download and live media streaming [41] the amount data to be shared is large and require a low maximum latency of 0:1s to 1s [42]. For some infotainment applications such as electric vehicle charging, new movies, product promotions, the RSUs need to be installed at suitable places at the road to maximum delay requirements.

Fig. 2.6 shows the different stages of the C-ITS application deployment. Phase 1 application includes a sustainable set of use cases specified to operate under low market penetration with a manageable level of complexity to support traffic warning/efficiency applications without automated tasks. These applications include both V2V and V2I exchange of basic safety and traffic efficiency warnings.

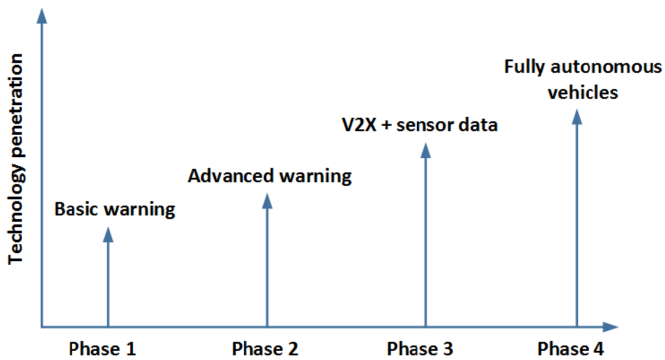


Figure 2.6: Deployment Stages of C-ITS Applications

In phase 2, the complexity of C-ITS applications will increase with the higher penetration of equipped vehicles and the larger roadside infrastructure coverage to include advanced warnings for crash avoidance and hard safety services.

In phase 3, successive transitions will ultimately lead to C-ITS applications to converging towards the platooning structure. Platooning is a cooperative driving pattern for a group of vehicles with a common path, in which a following vehicle maintains a small and nearly constant distance to the preceding one [43]. In classic platooning applications, an Adaptive Cruise Control (ACC) system uses on-board sensors (e.g., radars or lasers) to detect the distance from the preceding vehicle and autonomously adjust the speed.

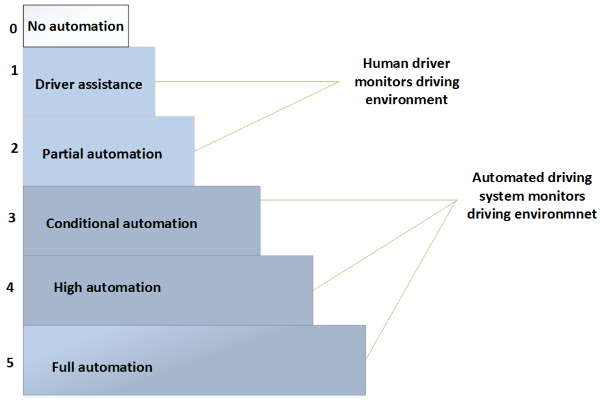


Figure 2.7: Level of Automated Driving [4]

In phase 4, the automated driving application has emerged as a technology evolution of vehicles and attract many researcher in industry and academia. Work is already under progress in ETSI to enhance the basic versions and develop the next package (Release 2) of C-ITS standards. Automated driving does not necessarily mean that the vehicle becomes-human driverless; instead, different levels of automation can be distinguished [44]. As illustrated in Fig. 2.7, human assistance is still needed to monitor the surroundings up to level 2. It is assisted in some of the driving tasks (level 1) or the automated driving system executes some driving tasks, such as steering, acceleration/deceleration (level 2). In fact, to achieve automation at levels 1 and 2, the use cases of V2X communication in Release 1 play an important role. At higher automation levels, two vehicular applications can be considered such as dissemination of sensor data message which carry information of the vehicle such as current speed, positions, topology and status information of road segment and cooperative maneuvering where safety margin need to add into planned trajectory by automated vehicle's control system, due to uncertain behaviour of neighboring vehicles.

2.1.4 Future Vehicular Network Requirements

Traffic management systems are constantly evolving to improve road traffic services and the safety of road users. Recently, the 3GPP introduced a number of vehicular network use cases, Release 14 [45] for future vehicular networks. The study showed that vehicular network requirements have evolved over time. Previously, vehicular networks were developed mainly to support safer vehicle movements and reduce traffic congestion. However, future vehicular networks are being planned to support a range of basic and enhanced services. Some of the future suggested services are listed below. The following list shows that future vehicular network requirements have been extended to include several smart city services such as parking management services, pedestrian services and vulnerable road user safety. Some of the service characteristics are briefly summarized in Table 2.2.

- Forward collision warning (FCW)
- Control loss warning (CLW)
- Emergency vehicle warning
- V2V emergency stop
- Cooperative adaptive cruise control (CACC)
- V2I emergency stop case
- Queue warning
- Road safety services

Table 2.2: Application and Selected Use Cases

Service	Main purpose	Communication Mode	Service Requirements
Forward collision warning	The FCW service has been proposed to warn the driver of a Host vehicle (HV) about an impending rear end collision with a Remote Vehicle (RV) or vehicles. The FCW service can help reduce collisions.	HV and RV communicate using V2V transmission mode.	Periodic broadcast CAM message, support high mobility, early warning message.
Control loss warning	The CLW service enables an HV to broadcast self-generated loss of control message to RVs. Upon receiving the message RVs warn drivers for appropriate action(s).	HV and RV communication using V2V services.	Communicate messages over a distance to generate warning message with ample time to respond. Event based broadcast message.
Emergency vehicle warning	This service enables all vehicles to acquire location, speed and direction information of surrounding emergency vehicle(s) to assist smooth movement of emergency vehicles.	V2V communication using LTE-D2D	Event based CAM message broadcast to cars within 300-500 meters.
Cooperative Adaptive Cruise Control (CACC)	The CACC service provides convenience and safety benefits to group of vehicles in close vicinity. Can be used for platooning structure.	Mainly V2V services, but V2X communication can also be used to obtain forward traffic flow information	The service can support a maximum latency of 1sec and a maximum frequency of one message per second.
Queue Warning	This service allows vehicles to receive forward road queue warning messages. Road user safety can be significantly increased by using this service.	V2V and V2I communication services.	Able to transmit and receive V2I messages with a maximum relative velocity of 160 km/h. Support an appropriate communication range necessary for early warning.
Road safety services	Using this service, V2X messages are delivered from a UE to other UEs via an installed RSU (Road Side Unit).	V2X and V2I services.	A V2X message should be delivered within 100 ms via an RSU with low delivery loss. An RSU should be able to transmit V2X messages at a maximum frequency of 10 Hz.
Curve speed warning	This application sends alert messages to the driver to manage possible blind spot or the curve at an appropriate speed. An RSU is placed before a curve to transmit information such curve location, recommended speed, curvature, road surface conditions.	RSU-based I2V and V2I services.	I2V message transmission with a maximum latency of 1 sec and maximum frequency of 1 message per second.
Vulnerable road user safety	This service should alert drivers about presence of other road users such as pedestrians, cyclists and other vulnerable road users.	This service can be supported by using V2X and V2P services.	Should support variable size CAMs. Maximum latency support of 100 ms

- Automated parking system (APS)
- Wrong way driving warning (WDW)
- V2X message transfer
- Pre-crash sensing warning
- V2X services in areas outside network coverage
- V2X road safety services via infrastructure
- V2N traffic flow optimisation
- Curve speed warning
- Warning to pedestrian messaging
- Vulnerable Road User (VRU) safety

The above table shows that communication needs and service requirements of future vehicular networks are quite diverse with variable QoS requirements. It is expected that over time, the service categories will grow and their requirements will evolve.

2.2 Current Communication Standards and Their Limitations in C-ITS

Despite the fact that researchers have achieved significant progress on the VANETs study, there are still some challenges to overcome and problems to examine further. More and more vehicles are connected to the Internet and to each other, driving new technological transformation in a multidisciplinary way. Although the main high-speed wireless access technologies and standards have been proposed for use in

C- ITS deployment phases	Representative use cases	Main enabling standard technologies
Phase 1	1- Emergency vehicle warning 2- Traffic jam ahead warning	IEEE 802.11p
Phase 2	Crash notification	IEEE 802.11p
Phase 3	Platooning	IEEE 802.11p, LTE, LTE-A, 5G-C-V2X
Phase 4	Autonomous Driving	

Figure 2.8: Main communication technologies and standard supporting C-ITS applications

VANET connectivity, delivering appropriate levels of service remains a challenge in term of low latency, higher throughput, and increased reliability. The evolutionary path of communication technologies and standards is in supporting the requirements of C-ITS applications as shown in Fig. 2.8. However, it is open to question that which communication standard is capable of meeting the requirement of different applications.

2.2.1 IEEE 802.11p

The traditional IEEE 802.11 has been extended to cope with a highly mobile environment such as quickly varying network topologies [46]. In 2012, 802.11p was included in the overall IEEE 802.11 standard. Several field operational tests were conducted to demonstrate suitability of IEEE 802.11p as a wireless access technology for vehicular communication in real traffic scenarios [31] [47] [48]. The IEEE 802.11p standard is responsible for the functionality of the PHY and MAC layers of the protocol stack. The operation of the PHY and MAC layers of IEEE 802.11p is briefly presented in following sections:

2.2.1.1 PHY Layer

In order to cope with the specificities of the vehicular environment, the 802.11p PHY layer uses Orthogonal Frequency Division Modulation (OFDM) with 52 subcarriers and 10-MHz-wide channels to cope with the doppler spread and the inter-symbol interference caused by multi-path fading [5]. The main features of 802.11p PHY layer are discussed below [49].

2.2.1.2 Channelization and Power Constraints

A band named ITS-G5 of 50 MHz around the frequency of 5.9 GHz is reserved [49] for the vehicular applications in Europe. ITS-G5A is a 30 MHz-wide band intended to support safety applications. The remaining band of 20 MHz, ITS-G5B, includes the frequencies from 5.855 to 5.875 GHz and is dedicated to non-safety applications.

In the USA, in 1999 the Federal Communication Commission (FCC) reserved a band of 75 MHz from 5.850 to 5.925 GHz for the Dedicated Short Range Communications (DSRC) based vehicular communication. There are seven 10 MHz-wide communication channels are available (numbered with even numbers from 172 to 184) in the spectrum: one Control Channel (CCH) and six Service Channels (SCHs). There is also a guard-band of 5 MHz is introduced in the lower portion of the DSRC band [49].

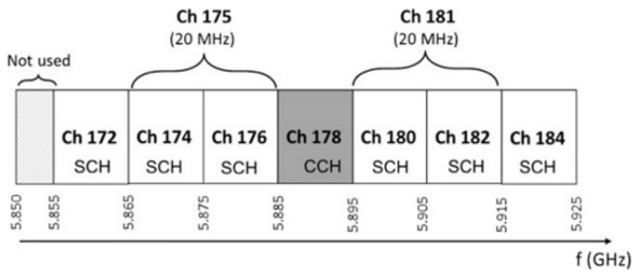


Figure 2.9: IEEE 802.11p/DSRC channel allocation [5]

The channel allocation for DSRC communication is shown in Fig. 2.9. For each channel a transmission power 33 dBm limit is fixed. However in order to overcome interference problem at long distances, some vehicular applications might need to limit the transmission power to within a range from 10 to 20 dBm. Channel 178 is used as a Control Channel for the transmission of safety information and advertisements about the services provided on the SCHs. The SCHs 174, 176, 180, and 182 are utilize for user infotainment, and traffic management applications. The channels 172 and 184 were intended for public safety applications. It is possible to join two adjacent 10 MHz Service Channels in order to operate on 20 MHz-wide channels.

After several years, the FCC issued new rules for the use of SCHs in 2006 [46]. According to the FCC, Channel 172 is designated for vehicle-to-vehicle safety communication, which involves vehicles exchanging messages in order to avoid road accidents. Channel 184 will be used for public safety applications and will be broadcast at a higher power (up to 40 dBm) to cover longer distances.

2.2.1.3 MAC layer

The MAC layer [6] standard provides two QoS mechanisms to meet the strict delay requirements and improve the reliability of real-time applications [6].

- The first mechanism is called Enhanced Distributed Channel Access (EDCA). The EDCA is a distributed mechanism which transmits traffic according to user priorities (User Priorities) (UPs) .
- The second mechanism is centralized and is designated as a Hybrid Coordination Function Controlled Channel Access (HCCA). It allows the reservation of permissions transmission (Transmission Opportunities (TXOPs)) [6].

To maintain necessary QoS in consistently changing network resource requirements and dynamic propagation conditions, the MAC layer provides two types of

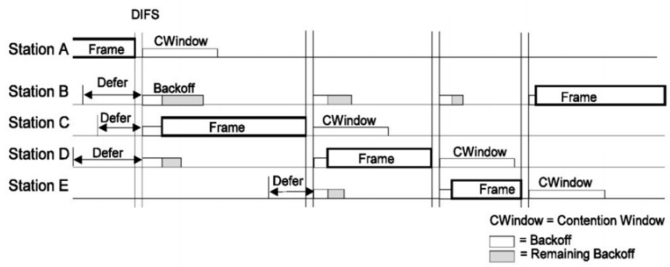


Figure 2.10: Mechanism DCF [6]

function: the function Point Coordination Function (PCF) and the Hybrid Coordination Function (HCF) through the Distributed Coordination Function (DCF). The DCF is described in the following section.

2.2.1.4 CSMA/CA in 802.11p

Distributed Coordination Function (DCF) as shown in Fig. 2.10 is based on Carrier Sense Multiple Access with Collision Avoidance mechanism (CSMA/CA). Each station is required to access contention before accessing the channel. This contention process is repeated for all waiting frames in the queue at the MAC layer. According to the EDCA [6] process, application messages are classified into one of four queues based on their priority level. Each queue accesses the transmission medium using the traditional CSMA/CA mechanism, but the CSMA/CA parameters (backoff, etc.) vary from queue to queue in order to support frames with high priority.

A Clear Channel Assessment (CCA) scheme works for CSMA/CA. The CCA is depends on the MAC protocol and the terminal settings. The CCA mechanism ensures that the minimal distance between concurrent transmitters. If the receiver is beyond the transmitter's radio range, there would be limited interference at the receiver. It also restricts the number of concurrent transmitters, and the number of frames that can be transmitted per second. As a result, the spatial reuse imposed by the CCA mechanism and network capability are inextricably linked.

In Fig 2.10 [6], a wireless station or vehicle intending to transmit data performs channel sensing to ensure that the channel is idle [46]. The medium access priority is controlled by the use of time slots Inter-Frame Space (IFS) which separate the frames transmissions. Three IFS intervals are specified in the standard: Short-IFS (SIFS), Point Coordination Function-IFS (PIFS) and Distributed Coordination Function (DIFS).

When the station detects that the channel is free, it transmits a data frame. When the data frame is transmitted, the frame duration field is used to notify the other stations of the time during which the medium is busy. When the station detects that the channel is busy, it waits until the channel is free during DIFS. Then, it select the random backoff integer value Contention Window (CW). This period of backoff is decremented at each time slot as the channel is free for the Contention Window CW period:

- If the channel becomes busy during the process the backoff is suspended.
- If the backoff value reaches zero, the station transmits the data frame.
- If two stations have a backoff period equal to zero simultaneously, a collision then occurs. Each station should generate a new backoff time.
- If the channel becomes busy and backoff time has not reached zero, the station freezes the backoff time.
- Contention window size is intially set to CW_{min}
- After failed transmission, the size of the contention window is increased by 2(CW+1) until it reaches CW_{max}
- After every successful transmission, the contention window size is reset to CW_{min}

2.2.1.5 Limitations of IEEE 802.11p Supporting C-ITS

The enhancement at the PHY and MAC layers enables 802.11p cope with a highly mobile vehicular environment and deal with harsh propagation conditions. However the decentralized nature of IEEE 802.11p imposes limitations on the reliability and scalability of the standard.

1. **Reliability:**

   The use of reliable routeing protocols for communication are needed for reliable communication among communication stations. Reliability is define as the capacity of routeing protocol to be robust enough for the frequent path distribution caused by vehicle mobility and deliver improved throughput and better packet delivery ratio. Decentralized channel-access mechanisms and communication over the varying channel conditions affect the reliability of the IEEE 802.11p standard. In [50], the authors discuss the problem of spectrum access to deal with channel dynamics due to highly mobile nodes. A CSMA/CA design to support concurrent transmissions by allocating the channel for every beacon interval, However proposed technique is inadequate for fast-fading VANET environments. A MAC based on opportunistic spectrum access, which selects a channel for each transmission, is unable to provide a fair share of spectrum among devices.

1. **Scalability:**

   Furthermore, scalability is identified as one the major problems for the use of 802.11p in vehicular communications. Design of the road and traffic safety applications has to take into account the limitation of IEEE 802.11p. The limitation is mainly comes from the the 802.11p Mac layer (CSMA/CA) rules to access the medium. As channels are shared, communication nodes, sufficiently far from each other, can emit at the same time. This limits the capacity of IEEE 802.11p to meet the requirements of road and traffic safety applications in high density scenarios. The capacity is defined here as the maximum number of frames per second that the network is able to send.

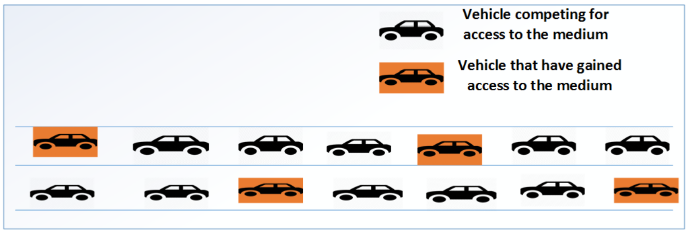


Figure 2.11: Example of concurrent transmissions: Only orange vehicles are allowed to transmit frames at the same time

Fig. 2.13 presents an example where all vehicles intend to transmit their data frame. However according to the MAC layer rules of the 802.11p standard, vehicles (coloured in orange in the figure) will be allowed to transmit their frames in such a way that distances between concurrent transmitters are large enough to avoid interference. The capacity of system is related to these distances as they limit the number of simultaneous transmitters. Thus, even though the 802.11p standard performs well in low density scenario, it doesn't have the capacity to accommodate a large number of users when the traffic density increases.

As stated, the 802.11p standard can be a very good candidate for vehicular communication; however, due to its limitation related to reliability and scalability, a search for an alternative communication protocol which can either assist or replace 802.11p would be useful for the development of future vehicular and ITS networks.

2.2.2 LTE/LTE-Advance Standard

In Release 8-9, the 3GPP introduced the Long Term Evolution (LTE) standard that enhanced the performance of the IP domain of the networks. The LTE standard

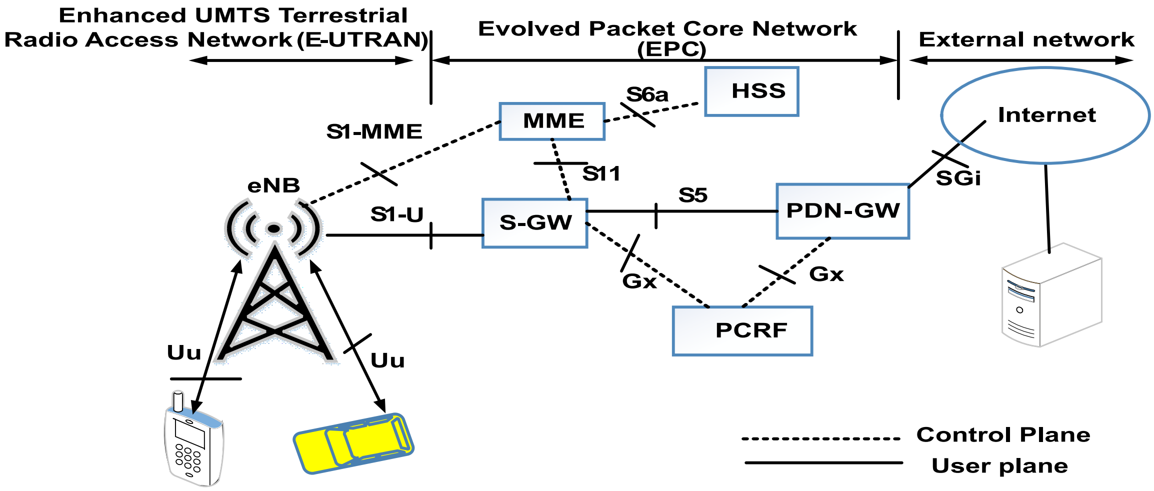


Figure 2.12: LTE network architecture

provides new features such as variable bandwidth per carrier and carrier aggregation to design radio network. In Release 10, the 3GPP introduced a new version of LTE called LTE-Advance. In this section, we give a brief briefly overview the the LTE architecture and present the new features that have been available in LTE-Advance.

Fig. 2.12 shows that the overall LTE architecture consists of two parts: the evolved UMTS terrestrial radio access network (E-UTRAN), which is the radio access part of LTE, and the Evolved Packet Core (EPC) which encompasses all core network entities. The radio access network is consists of Users Equipment (UE) and base stations which are called evolved NodeBs (eNBs). The LTE-Advance is used the OFDMA (Orthogonal Frequency Division Multiple Access) technology in downlink, and the space-division–time-division multiple access (SD-TDMA) in uplink to support multipath fading scenarios.

On other hand, the LTE core network, EPC, is composed of three main entities: the Mobility Management Entity (MME), the Serving Gateway (S-GW), and the Packet Data Network Gateway (PDN-GW). The major task of the MME are: mobility management, paging, location update and authentication of users using Home Subscriber Server (HSS). The S-GW act as a router and is responsible for data forwarding between eNBs and PDN-GW and is also responsible for charging by working with the Policy and Charging Rules Function (PCRF). The PDN-GW is the gateway that allows communication with outside data networks such as internet, IP Multi-Media Subsystems (IMS) and third party application servers. In cellular networks, Evolved Multimedia Broadcast Multicast Services (eMBMS) supports different transmission modes such as multicast and broadcast transmissions over the LTE licensed spectrum [51].

2.2.2.1 Protocol Architecture

Fig. 2.13 illustrates the LTE protocol stack between eNodeB and UE [8]. The protocol stack is composed of three layers, commonly called layers 1, 2 and 3 presented below:

1. **Physical layer:**

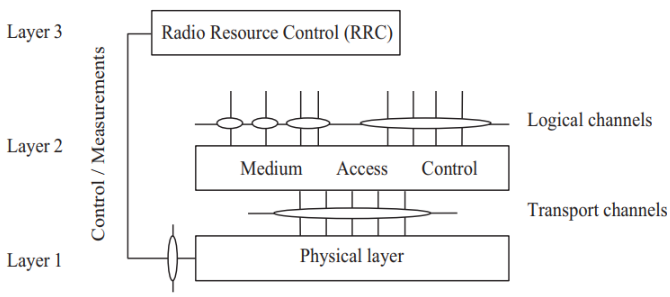


Figure 2.13: Protocol architecture around the LTE PHY layer [7] [8]

The LTE physical layer design supports two types of frame. The type 1 frame is used for Frequency Division Duplex (FDD) mode, presented in Fig. 2.14. Fig. 2.15 shows the type 2 structure used for Time Division Duplex (TDD) mode. The duration of the LTE frame is 10 ms, equivalent to 10 subframes (each 1 ms long). In FDD mode, each subframe consists of two concatenated slots of 0.5 ms long. In TDD mode, the radio frame with total length of 10 ms divided into two half-frames of 5 ms. Similarly, the FDD, each subframe of the type 2 frame structure also consists of two slots of 0.5 ms in length. As shown in the Fig 2.15, the special subframe are included in the half-frame. Each special subframes are used for switching from downlink to uplink and includes three field: DwPTS (Downlink Pilot Time Slot), GP (Guard Period) and UpPTS (Uplink Pilot Time Slot).

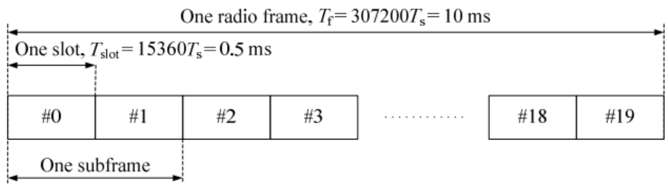


Figure 2.14: Frame structure type 1 [9] [8]

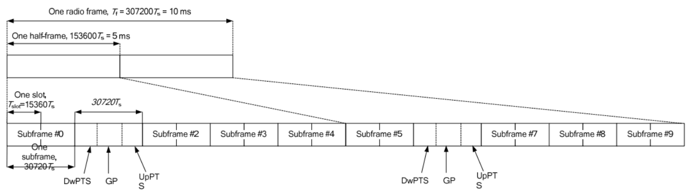


Figure 2.15: Frame structure type 2 [9] [8]

Fig 2.16 shows a resource grid which is represented by one subframe in time domain and full carrier bandwidth in the frequency domain. In the resource grid the smallest element called Physical Resource Block (PRB), can be allocated to a user by eNodeB. The number of resource blocks for both uplink and downlink are depends on the different channel bandwidth of the LTE network. Table 2.3 shows the PRB configuration for different channel bandwidths. Each PRB is a set number of Resource elements (REs) which is smallest block in the resource grid. Table 2.4 presents the list of physical channels. Each physical channel has specific tasks for the successful data transmission on uplink and downlink. The number of RB required by the user to transmit the data packet depends on the physical layer Modulation and Coding Schemes (MCS). The possible

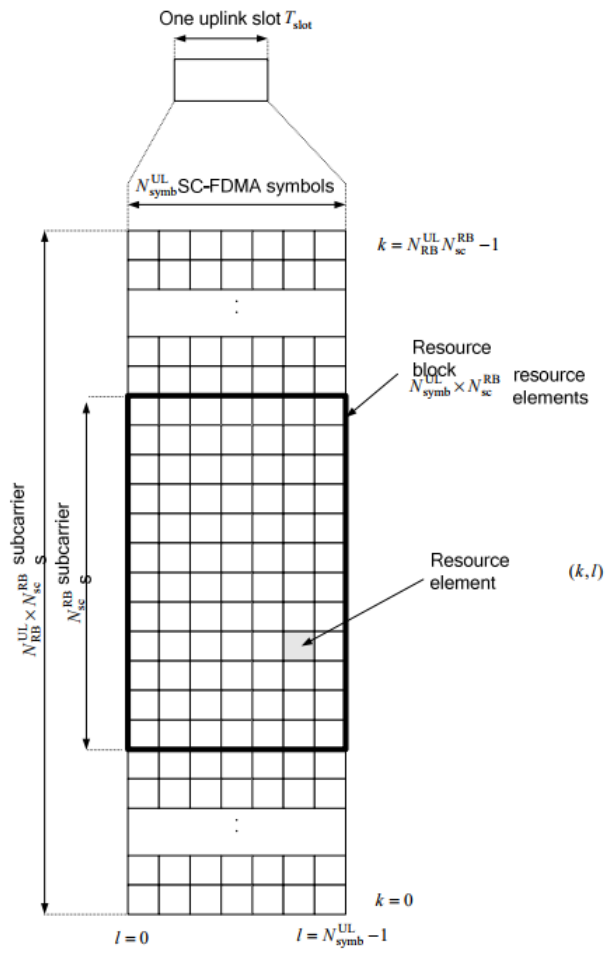


Figure 2.16: Resource grid [9] [8]

modulation schemes are 4-QAM, 16-QAM, and 64QAM. LTE can also support diffrent bit rates using proper MCS-based on the channel conditions that each user experiences.

Table 2.3: Resource Block Configuration [9]

CHANNEL	1.4	3	5	10	15	20
Number of RBs	6	15	25	50	75	100

Table 2.4: Physical Channels [8]

PBCH	Physical Broadcast Channel	Downlink
PMCH	Physical Multicast Channel	Downlink
PDCCH	Physical Downlink Control Channel	Downlink
PUCCH	Physical Uplink Control Channel	Uplink
PDSCH	Physical Downlink Share Control Channel	Downlink
PUSCH	Physical Uplink Share Control Channel	Uplink
PCFICH	Physical Control Format Indicator Channel	Downlink
PHAICH	Physical Hybrid ARQ Indicator Channel	Downlink
PRACH	Physical Random Access Channel	Uplink

2. **Medium Access Control:**

The Medium Access Control level (MAC) is the scheduler. Its goal is to distribute the available resources PRBs among the UEs. There are various resource distribution schemes, such as Round Robin (RR), First-in-Firt-Out (FIFO), Max rate, Proportional Fair (PF), Modified-Largest Weighted Delay First (M-LWDE) and Exponential/Proportional Fair (EXP/PF). The centralized LTE scheduler assignments may take into account several metrics, such as the channel condition, mobility, and user priority, to improve the reliability of data transmission. The resource allocation scheme recommence with every Transmission Time Interval (TTI).

2.2.2.2 Limitations of LTE/LTE-Advance Supporting C-ITS

- Due to the centralized nature of the cellular network, end-to-end transmission increases due to messages passing through infrastructure nodes before being redistributed back to destination vehicles [52].
- Low capacity in both uplink and downlink directions to accommodate the massive amount of small packets frequently generated by vehicles in high-density scenarios. For vehicular safety services using LTE network, it is always recommended by the network to keep the vehicles that send periodic CAMs always in connected mode, which makes the network more congested and creates transmission delay due to the lack of resources to support a number of vehicles at a time.
- Current resource allocation scheme may be insufficient for the uniqueness of road safety applications and the coexistence with human-type communication over the same spectrum.

LTE technology has been identified to support vehicular network services using V2X architecture. As mentioned in the previous section, the V2X communication services include four different modes of communication (V2V, V2I, V2P, and V2N). These links are bidirectional. 3GPP study groups in collaboration with transport industries have started standardization activities on LTE-based vehicular networks in working group 1. After several studies and developing several initial specifications on V2X services based on LTE, Release 14 was published in 2017 [8]. The standard was further developed in Release 15 in 2018 supporting enhanced V2X networking features. The 3GPP specifications did not allocate any specific frequency band to support V2X services. ETSI European Telecommunications Standard Institute (ETSI) has allocated a 70 MHz spectrum in the 5.9 GHz band in which there is

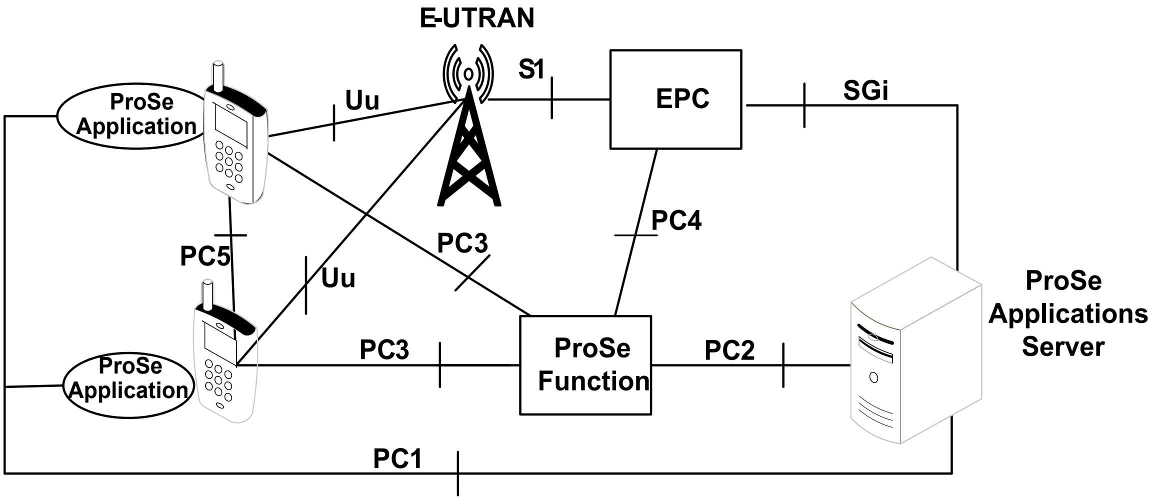


Figure 2.17: LTE release 12 D2D reference network architecture [10].

no overlap between V2X and conventional cellular network services. This separation of operating frequency will enable different operators to provide vehicular network services independent of conventional mobile operators. The 5.9 GHz LTE band will allow the system to coexist with IEEE 802.11p-based systems. However, mobile operators can also use the licensed band to support V2X services. V2X services can use the conventional air interface as well as the newly developed D2D interface using the sidelink channel. The D2D communication architecture is briefly introduced in the following section.

2.2.3 LTE-D2D standard in 3GPP Release 12

Table 2.5: PC interfaces

Interface	Main functions
PC1	The ProSe application server can communicate towards a ProSe application in the UE through the interface.
PC2	The ProSe application server can communicate with the ProSe function through this intreface.
PC3	The ProSe function can connect to the UE through the PC3 interface.
PC4	The ProSe function connects with Evolved Packet Core (EPC) in the network through PC4 interface
PC5	A PC5 interface enables direct communication between two UEs.

The LTE-V2X architecture has been developed to support diverse vehicular network services as discussed above. The architecture uses the new air interface PC5 along with the conventional Uu interface to support various services. The PC5 interface can offer enhanced network services, such as device-to-device communication, normally supported by the ad hoc network architecture. The device-to-device communication service was introduced in Release 12 which was originally developed for safety services [10]. The LTE Release 12 architecture is shown in Fig. 2.17. The figure shows a new service function, the ProSe (Proximity Service) located in the EPC (Evolved Packet Core) which allows the devices to discover peer devices for D2D communication services. The ProSe function allows users to directly communicate and exchange data with neighbouring devices by sending a registration message to the eNB with a ProSe application ID. The eNB organizes the communication between the devices using the control channels. Once the communicating devices are matched by the eNB, they can directly communicate using the PC5 interface, as shown in fig. 2.17. The PC interface functions are summarized in Table 2.5. Detail of these interfaces can be found in [53].

The channels in the Uu and PC5 interfaces are organized as logical, transport and physical channels. Fig. 2.18 shows the mapping structure of these channels used for sidelink communication in the LTE standard. There are two logical channels introduced for sidelink communication; the first is the SL Traffic Channel (STCH) and second is the SL Broadcast Control Channel (SBCCH). The STCH is an interface to the Physical SL shared Channel (PSSCH), which transports the data carrying user information over the air. The SBCCH is used to broadcast control data, for synchronization in the out-of-coverage or partial coverage or for the synchronization between UEs which are located in different cells. There is also a Transport and Physical Sidelink Control Channel carrying the SL Control Information (SCI). There is a new transport and physical channel for direct discovery: Sidelink Discovery

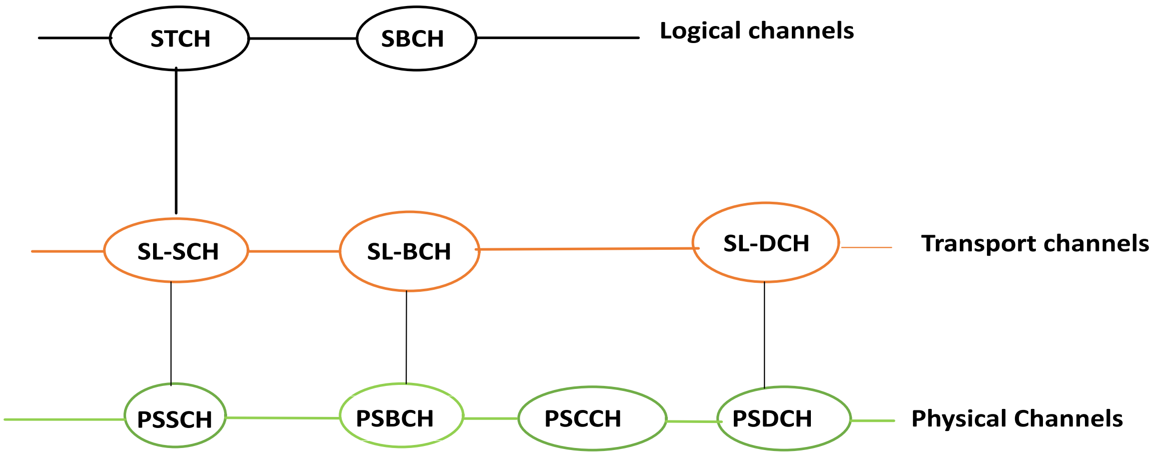


Figure 2.18: Mapping of channels for sidelink communication in 3GPP LTE.

Channel (SL-DCH) and the Physical Sidelink Discovery Channel (PSDCH).

2.2.4 Enhanced C-V2X Architecture in 3GPP Release 14 for V2X Communication

The 3GPP Release 14 focus on the support of V2V by the Evolved Packet System (EPS) with the aim to support advance automotive use case. Recently, several fundamental modifications have been carried out to enhance the PC-5 interface in Release 14 to support V2X operational scenarios and requirements. The sidelink LTE-V2X employs Single Carrier Frequency Division Multiple Access (SC-FDMA), which permits the UE to access radio resources in both time and frequency domains. In the frequency domain, the subcarrier spacing is fixed to 15 kHz and subcarriers are utilized in groups of 12 (i.e., 180 kHz). To support different V2X operational requirements, the transmission channels may use a higher carrier frequency of 6 GHz with very high relative velocity. However, due to the high relative velocity and the use of higher carrier frequency, inter-carrier interference (ICI) due to higher Doppler shift and insufficient channel estimation due to shorter coherence time could be a problem compared to the legacy 3GPP systems.

To improve the performance in the presence of high Doppler shift, the sidelink

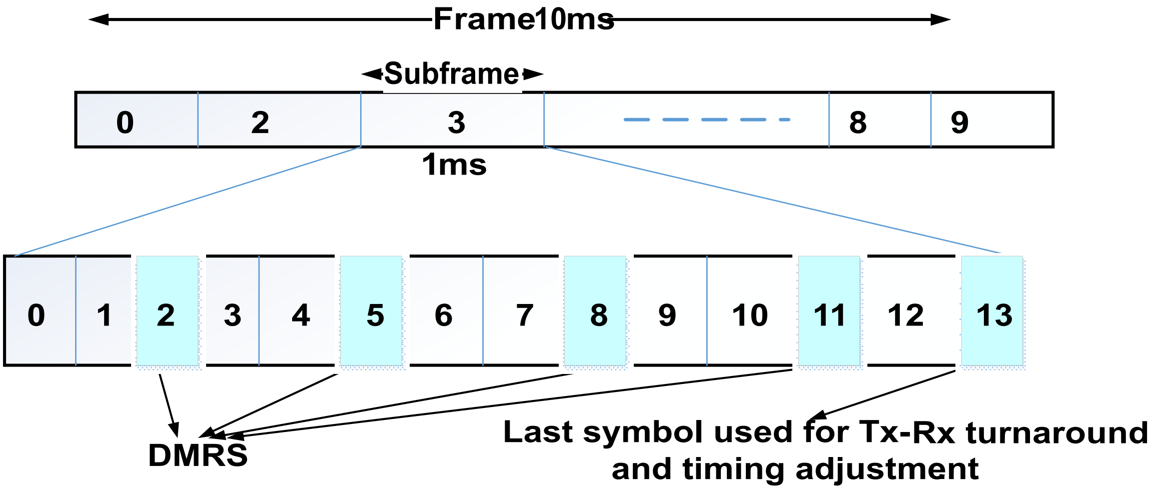


Figure 2.19: V2V sub-frame for PC-5 interface structure. [11]

interface has been tuned to counteract the severe Doppler shift experienced at high speed. In the time domain, additional Demodulation Reference Signal (DMRS) symbols have been added in one sub-frame to handle the high Doppler shift associated with relative speeds of up to 500 km/h and the use of a higher carrier frequency [54]. The new sub-frame structure is illustrated in Fig 2.19. Fourteen symbols form a sub-frame of 1 ms, also called transmission time interval (TTI), and include nine data symbols, four Demodulation Reference Signal (DMRS) symbols, and one empty symbol for Tx-Rx switch and timing adjustment. The LTE-V2X has a large number of modulation and coding schemes (MCS), with 4-QAM and 16-QAM modulations, and an almost continuous coding rate. The minimum radio resource allocated to an LTE-V2X link is the subchannel in the frequency domain, corresponding to a multiple of the 12 subcarrier groups, and the TTI in the time domain. One packet normally occupies one or more subchannels in a TTI. To improve the system-level performance under high node density while meeting the latency requirement of a V2V link, a new classification of scheduling assignment and data resources is designed where the scheduling assignment is transmitted in a sub-channel using specific Resource Blocks (RBs) across the time. More specifically, each data packet, also known as Transport

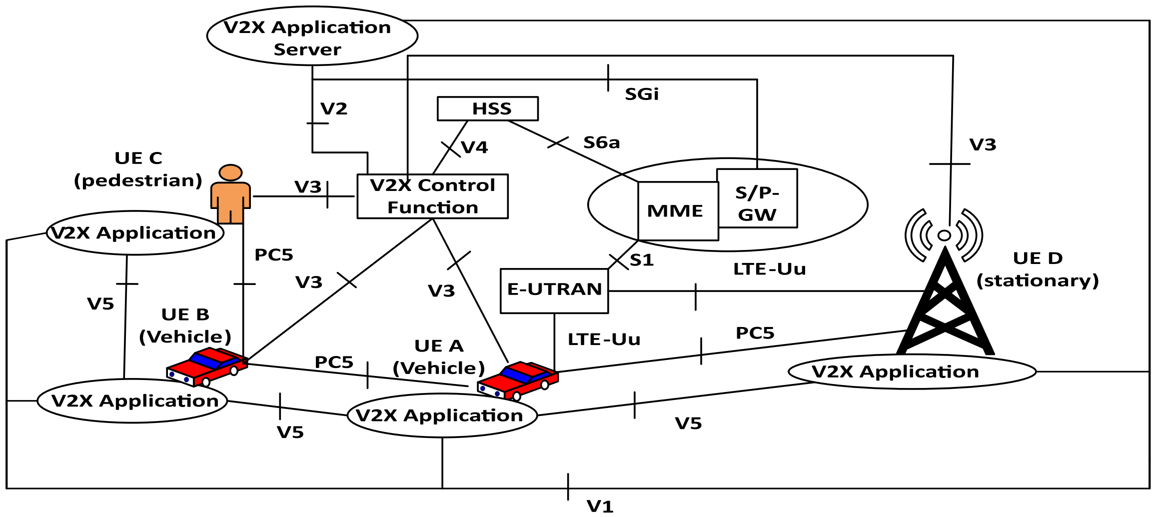


Figure 2.20: Enhanced ProSe D2D sidelink architecture for V2X communications. [12]

Block (TB) has an associated control message called Sidelink Control Information (SCI). TB and the associated SCI must be transmitted in the same subframe but can be allocated adjacent and non-adjacent resource blocks.

Fig. 2.20 depicts the overall network architecture enhancement in Release 16 for V2X services [13]. Two new entities are introduced: the V2X Application server and the V2X control function to support the V2X services. The V2X Control Function is the logical function that is used for network-related actions required for V2X. It may also obtain the parameters required for V2X communications from the V2X Application Server. It is also provisions the UEs with Public Land Mobile Network (PLMN) specific parameters that allow the UE to use V2X in this specific PLMN. The V2X Application server incorporates the V2X capability for building application functionality. It is responsible for receiving uplink data from the UE in the unicast mode, providing the parameters for V2X communications over the PC5 reference point to V2X Control Function. As per the network architecture, several new reference points (or interface) have been introduced. The roles of V2X reference points are summarized in Table 2.6.

Table 2.6: V2X interfaces

Interface	Main functions
V1	The V2X application server can communicate towards a V2X application in the UE through V1 interface.
V2	The V2X application server can communicate with the V2X control function through V2 interface. The V2X application server may connect to V2X control function belonging to multiple PLMNs.
V3	The V2X control function can connect to the UE through the V3 interface.
V4	The V2X control function connects with entity Home Subscriber Server (HSS) in Evolved Packet Core (EPC) in the 3GPP network through V4 interface.
V5	A V2X application in UE can communicate towards a V2X application in different UE through V5 interface.
SGi	An EPC can connect to the V2X application server through SGi interface.

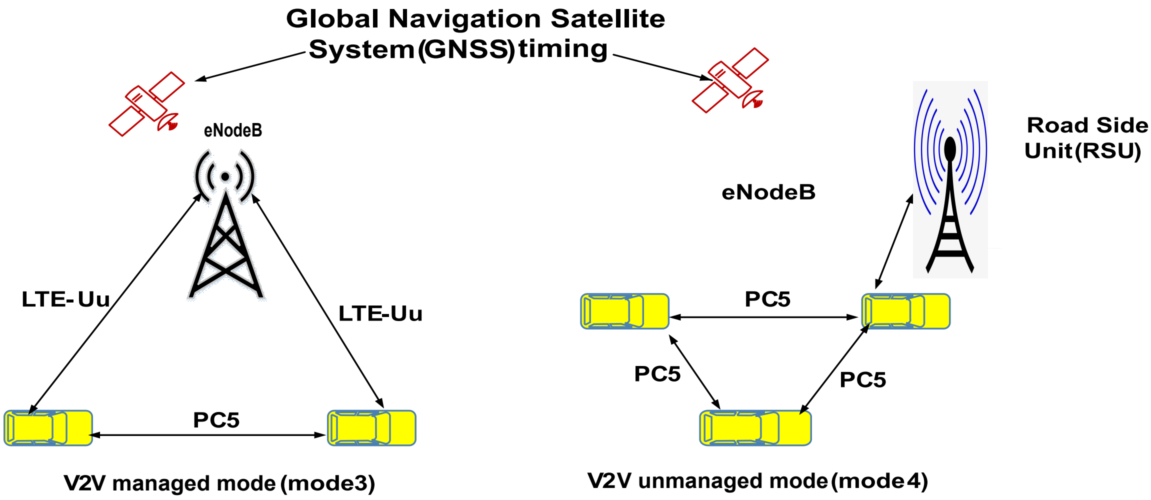


Figure 2.21: V2X communication mode defined in release 14 [13]

To support the V2X communication, Release 14 introduced the new communication modes (Mode 3 and Mode 4) as shown in Fig. 2.21. Mode 1 from Release 12 was enhanced to Mode 3 for V2X communication, similarly, Mode 2 from D2D was enhanced to mode 4 for V2X. In Mode 3, the UEs resource reservation and scheduling are performed by the eNB, while in Mode 4 the UEs choose the radio resources autonomously. Mode 3 algorithms are not defined in the specifications and their implementation is left to vendors. In contrast, Mode 4 can operate without cellular coverage and is therefore considered as the baseline V2V mode since safety applications cannot always depend on the availability of cellular coverage. In mode 4, also known as autonomous or out-of-coverage, each node selects the resources based on a sensing procedure and a Semi Persistent Scheduling (SPS) mechanism. Mode 4 includes a distributed scheduling scheme for vehicles to select their radio resources and includes the support for distributed congestion control. The detailed description by 3GPP for Mode 4 algorithm is presented in [54] [12]. The Global Navigation Satellite System (GNSS) is introduced to provide accurate timing and frequency references in the off-coverage scenario.

2.3 Next Generation Wireless Technologies Standard for V2X Communication

In this section, we present an overview of the evolution of the IEEE 802.11p and LTE-V2X communication standards for next generation V2X communication, named IEEE 802.11bd and 5G-V2X.

2.3.1 IEEE 802.11bd

In March 2018, the IEEE standards association introduced Next Generation V2X Study Group for the development of 802.11 technology to meet the requirements of advanced V2X services discussed in section 2.1.4, such as vehicle platooning, advanced driving, Cooperative adaptive cruise control(CACC), Automated parking system (APS), remote driving, Control loss warning (CLW). In January 2019, the IEEE 802.11bd Task Group was introduced with some of the primary design objectives of 802.11bd are given below [55] [56]:

- Ensure a smooth transition from the “legacy” IEEE 802.11p-based systems to the new standard. This is achieved using a congenial waveform structure and a well-known channel access mechanism, “listen-before-talk” (i.e., carrier sensing).

- Improve the MAC throughput (twice of that IEEE 802.11p) with relative velocities up to 500 km/hr.
- Achieve twice the communication range of 802.11p.
- OFDM numerology re-design: definition of new optimized tone spacing and guard interval duration to better cope with 5.9 GHz frequencies and high-speed mobility.
- MIMO diversity through STBC codes or cyclic shift diversity (CSD).

Advances in IEEE 802.11bd can support legacy IEEE 802.11p and profit from previously deployed stations. The final version of IEEE 802.11bd might be available on December 2021.

2.3.2 New Radio(NR) V2X: The evolution of C-V2X

The first steps towards 5G and new radio (NR) have been done inside Release 15, frozen in March 2019. 5G NR will provide enhancements in future releases to support next generation V2X communications. In the following sections, we will briefly present the key features of the latest 3GPP releases 15, 16 and 17 to support the advanced applications with more stringent requirements (such as platooning and advanced driving).

2.3.2.1 3GPP Release 15 FOR V2X

Release 15 [21] specified a service-based approach for the 5G Core Network (5GC), a and support for data connectivity over NR and LTE access technologies. It provides new functionalities to enhance mobility, QoS, traffic steering, and network slicing. Release 15 introduces additional, and Release 14 compatible, key enhancements in RAN for the appropriate support of Enhance V2X (eV2X) services by [57]:

- It provides support for the 64-Quadrature Amplitude Modulation (QAM) technique.

- It offers the Carrier Aggregation (CA) technique for the sidelink transmission (both in Mode 3 and Mode 4). Carrier aggregation allows multiple MAC PDUs to be transmitted in parallel on different carriers and offer a throughput increase comparable to CA for the Uu interface. Carrier aggregation also allow transmission of the same Packet Data Convergence Protocol (PDCP) packet simultaneously over multiple sidelink carriers and helps to enhance reliability. To improve reliability, sidelink packet replication is explicitly implemented by the CA algorithm..

- Communication Mode 4 supports the CA technique, with synchronisation mechanisms for multiple carriers that compose the Component Carrier (CC). It also contributes with new power-sharing rules and the introduction of resource-synchronization priorities.

- It offers radio resource pool sharing between Mode 3 and Mode 4 UEs. Sidelink Control Information (SCI) messages can be modified for optimized behaviour under resource pool sharing.

- It supports four sets of more advanced low-latency communication scenarios: vehicle platooning, advanced driving, extended sensors and remote driving.

2.3.2.2 3GPP Release 16 FOR V2X

In March 2017, 3GPP introduced the Release 16, which defines the 5G supporting role for the coexisting the New Radio (NR) and the LTE sidelink. Release 16 added several key functionalities in Radio Access Network (RAN), given below [57]:

- Introduces a sidelink congestion control similar to LTE V2X, to be used with Mode 2 in the NR V2X.
- Provides a Physical Sidelink Feedback Channel (PSFCH), a Phase-tracking reference signal (PT-RS) and a Channel state information reference signal (CSI-RS) to support sidelink transmission.
- Supports Hybrid Automatic Repeat Request (HARQ) based on transmission of positive and negative acknowledgments for sidelink unicast and groupcast services, and blind re-transmission schemes.
- Configure the UE with one active sidelink sidelink Bandwidth Part (BWP) when connected to a gNB, and the same is used for the idle mode or out-of-coverage operation.
- Provides support for performing NR sidelink transmission and reception during handover and cell reselection.
- Supports roaming, inter-PLMN opreations, broadcast mode, groupcast mode and unicast mode through the NR PC5 interface.
- Introduces Cross-Radio Access Technologies (Cross-RAT) operation for sidelink communications between a cross-RAT UE in a LTE or a NR cellular network.
- Supports the joint operation of the LTE V2X and the NR V2X, with either a Next Generation eNB (NG-eNB) or an eNB controlling and configuring the UE for V2X communications through any sidelink RAT.
- Introduces of Multi-RAT Dual Connectivity (MR-DC) for the joint operation of the LTE V2X and the NR V2X.

2.3.2.3 3GPP Release 17 and Sixth Generation (6G) for V2X

The 3GPP introduced work items in Release 17 to improve the specifications already standardized in Release 16. Release 17 will focus on the further development of sidelink-based relaying technique already standardized in Release 16 to improve the coverage and power efficiency of the devices. Improvements in Release 17 will enable the use of sidelink communications in out of network coverage scenario through the multi-hop approach [57]. Release 17 will focus on the improvement of the position resolution accuracy. The aim is to achieve position resolution accuracy with the desired latency of 10 ms.

These improvements can support essential requirements of new use cases, for example, autonomous vehicle applications, where high reliability and low communications delay are required. However, the Release 17 will incorporate Multicast Broadcast Services (MBSs) using 5G Systems (5GS) architecture to support future V2X applications. In the future, Release 17 will also focus on other new technological improvements, such as NR Multiple-Input Multiple-Output (MIMO), URLLC enhancements, power saving, NR coverage enhancements, and multi-radio dual connectivity/ cell aggregation enhancements. Sixth Generation (6G) will focus on the development of new technologies based on Deep Learning (DL), Machine Learning (ML), and Artificial Intelligence (AI) to the improve V2X communication techniques.

2.4 Simulation Packages Used in the Thesis

Network simulation has been widely used in both fields (i.e., cellular communication and vehicular ad hoc networks) to test network architectures, algorithms, communication protocols, and applications on a large scale. An OMNET++ version 5.6.1 simulation model is developed using the SimuLTE [16] that utilizes the INET framework 3.6.6. There are four frameworks that tackle vehicular networks and cellular systems, called Veins 5.0 [58], Sumo 1.6 [59], Open CV2X mode 4 v1.2.0 and SimuLTE [16]. Veins provides vehicular mobility to OMNeT++, using SUMO as the underlying vehicular traffic simulator. SimuLTE, instead, is a system-level simulator of LTE networks, based on the INET framework. Open CV2X Mode 4 [60] is an open source implementation of C-V2X Mode 4 (it implements the features of 3GPP Release 14). It is an extension of SimuLTE which integrates with Veins to provide all the C-V2X Mode 4 functionalities.

2.4.0.1 OMNET++ Framework

OMNeT++ [14] is C++ based simulation library and framework to develop network simulators. OMNeT++ allows to keep a simulation model's implementation, description and parameter values in separate files. In OMNeT++, simulation model are developed using the components or modules architecture where modules are written in C++. Further these modules are assembles larger module using Network Description (NED) language. The description of network model (i.e., gates, connections and parameter definition) is written using Network Description (NED) language. The simulation parameter values are written in initialization (INI) files. INI files contain simulation parameters that will be used to initialize the simulation model.

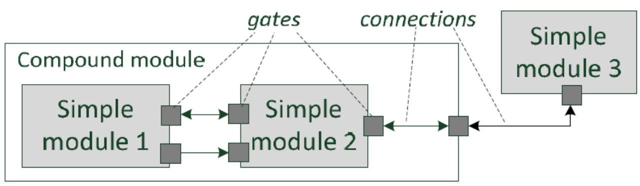


Figure 2.22: OMNet++ Module Connection [14]

Fig. 2.22 shows the module connections. The basic OMNeT++ building blocks are modules (components), which communicates by exchanging messages. These messages are usually sent and received through a connection linking the modules' gates, which act as interfaces. Modules can be simple or compound. Different modules can be grouped together to form a compound module. A network is a specific compound module, with no gates to the outside world. Simple modules implement model behaviour and use event handlers, which are called by the simulation kernel when modules receive a message. Simple modules have different function such as a initialization function and a finalization function, often used to write results to a file at the end of the simulation. The active components of the simple modules have to be written in C++ using simulations kernel and class library.

2.4.0.2 Sumo

SUMO [59] [61] is an open-source road traffic simulator developed by Germany Aerospace Centre DLR. It provides modelling of traffic systems which include vehicles, pedestrians and public transport. It can be customized as per our requirement to model the desired simulation map. The files are written in Extensible Markup Language (XML) and can be modified as per our need. There are several files for configuring the junctions, edges, connections and routes of different vehicles.

2.4.0.3 Veins

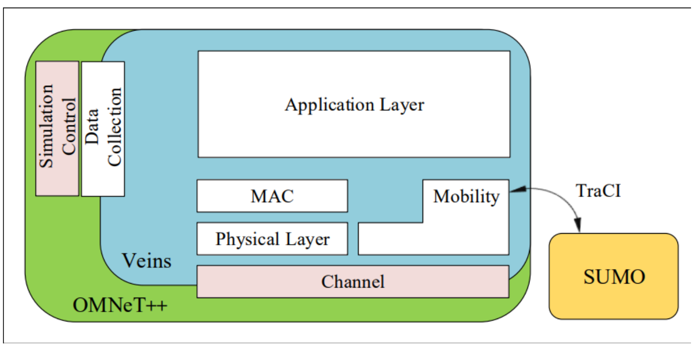


Figure 2.23: Veins Modular Structure [15]

Veins [15] [58] is an open source network simulation framework used for vehicular networks. Simulation in Veins is carried out by executing OMNeT++ and SUMO simulators which are connected by a TCP socket. Traffic Control Interface (TraCI) is a protocol used for this connection. TraCI helps in the bidirectional coupling of network and road traffic. Vehicles and pedestrians in SUMO are represented as nodes in the OMNeT++ simulation environment. DSRC Channel 178 is assigned for CCH and channel 174 is assigned for SCH in Veins. Fig. 2.23 shows the modular structure of Veins.

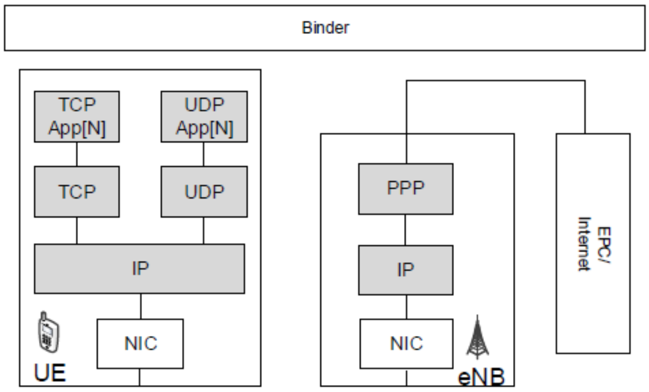


Figure 2.24: System Overview [16] [17]

2.4.0.4 SimuLTE for the implementation of C-V2X Mode 3 and Mode 4

SimuLTE allows one's to simulates the protocol stack of the LTE/LTE-A network (3GPP Release 8 and beyond). It is based on OMNeT++ and written in C++. It is fully customizable with simple pluggable interface. SimuLTE borrows the concept of modularity from OMNeT++ and exploits the INET framework to implement IP stack as well as main IP nodes such as IP routers and application servers. It can also integrated with other modules from the INET Framework. The LTE Network Interface Card (LTE NIC) is a core module of SimuLTE which provide the nodes, specifically UEs and eNBs, with LTE/LTE-A capabilities. These nodes use the upper layer modules from INET to simulate standard Internet entities. The INET library is also used to implement external entities such as third party application servers, that are used as traffic generators/receivers and communicate with the application within the UEs. A high level SimuLTE system overview is presented in Fig. 2.24. The NIC cards in the UE and eNB nodes are follows the OSI layers architecture. It is organized in layers of LTE protocol, namely PDCP, RLC, MAC and PHY.

The NIC card provides the functionality to develop IP communication nodes with different radio connectivity capabilities (e.g. LTE-Adavance, Wifi). NIC card also has a class named as ChannelModel for channel modelling, which works with the PHY layer to model the status of the air channel in order to compute CQIs and determine transmission errors.

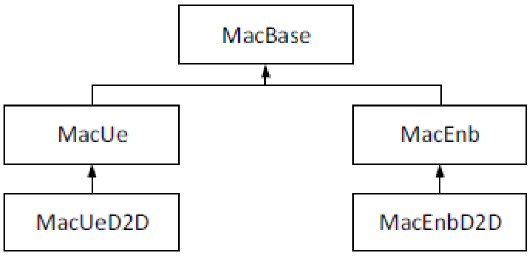


Figure 2.25: Example of Inheritence

2.4.0.5 Modelling C-V2X Mode 3 in SimuLTE

Most of the C-V2X PC-5 operations at each layer of the LTE protocol stack are introduced by extending the pre-existing SimuLTE functions, modules, leveraging inheritance and modularity. Fig. 2.26 shows the a high-level representation of a Car module implemented within SimuLTE. To add the mobility support feature in SimuLTE, a new interface known as vehicularMobility module has been added. This new mobility model can be implemented by the TraCIMobility module defined by the Veins. There is another mobility module known as INETMobility present in the INET framework. A vehicle can utilize only one mobility module during the simulation; therefore both modules (i.e., INETMobility and vehicularMobility) are defined as a conditional module within the Ned file. According to the activated mobility module, the Car subscribes itself to the signals generated by the corresponding module. OMNeT++ provides the Application Programming Interface (API) to develop a new module dynamically in Veins. A new vehicle in the simulation needs to obtain an IP address to communicate. SimuLTE uses the IPv4NetworkConfigurator module provided by INET for the assignment of IP addresses. For initial cell synchronization, the new vehicle measures the power received from every simulated eNB and select one with the largest value of received power.

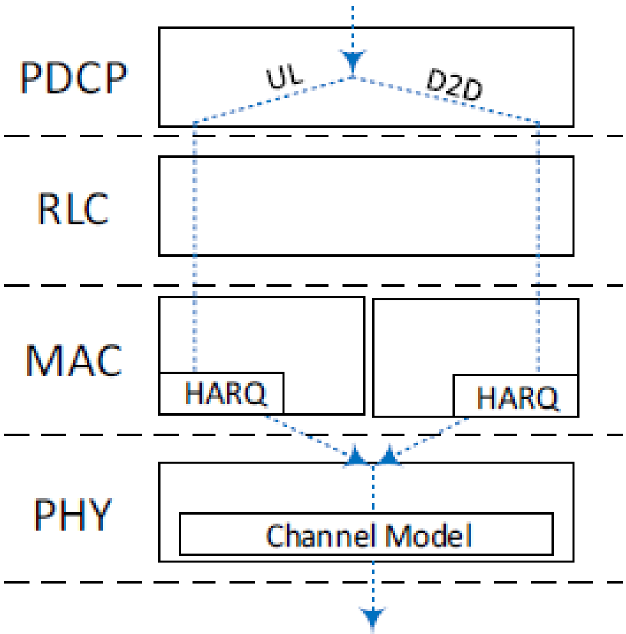


Figure 2.26: Data flow from the Sender UE Perspective [17]

The detailed description of configuring C-V2X communication in OMNET++ with SimuLTE and the main modifications to the code of SimuLTE to allow interoperability with Veins are given in [17] [62]. At the UE side, depending on whether the destination is in the peering table or not, IP datagrams arriving from the IP layer are sliced to either one of the two interfaces that is UL or PC-5 at the PDCP layer and handled accordingly at lower layers, as shown in Fig. 2.28. At the The RLC layer common operations are performed without the any requirement of additional functionalities. At the MAC layer, the UE must notify the presence of new data for a PC-5 flow by sending a Buffer Status Report (BSR) to the eNB. Based on whether the BSR refers to UL or PC-5 traffic, the eNB grants to right for UL or PC-5 transmission.

2.4.0.6 Modelling C-V2X Mode 4 using SimuLTE

An open-source OpenCV2X Mode 4 [60] framework is used for the implementation of C-V2X Mode 4 (it implements the features of 3GPP Release 14). OpenCV2X Mode 4 is an extension of SimuLTE which integrates with Sumo and Veins. The implementation details are presented in [60]. The networks models and associated C++ source files can be found at the src/ folder of the OpenCV2X Mode 4 v1.2.0 project. The implementation of sensing-based SPS algorithm and congestion control mechanisms given LteMacVUeMode4.cc/h files [63]. The initialization file, usually named as.ini, contains the main simulation parameters of physical and MAC layers, the sidelink configuration and the sensing-based SPS. The sensing-based SPS and the generation of the scheduling grant take place in the MAC layer.

2.5 Summary

In this chapter, the discussion is started by presenting the VANET applications and their data traffic requirements. This is followed by the detailed description of current standardization for vehicular communication. In the next part of this chapter, the literature related to vehicular communication is surveyed. The protocols for information dissemination in VANETs are categorized into single-hop and multi-hop transmission techniques. In the last part of this chapter, challenges faced in the performance analysis of VANETs and the simulation model used in the rest of the thesis are discussed.

C-V2X sing the proximity services (ProSe) communication models has created a host of new services. It allows direct information exchange among the network devices which are in close proximity without sending information packets via the eN-odeB, thus offering ad hoc networking services similar to the IEEE 802.11p standard. However, it introduces some interesting design challenges for 3GPP. While the basic principles of C-V2X have been established, many of the detail are still being studied and developed. Due to the design challenges and issues related to PC-5 for V2X communication, existing D2D solutions are not able to maintain the required QoS level in C-ITS.

When the C-V2X services need to share transmission resources with the LTE Human-to-human (H2H) and Human-to-machine (H2M) services, the proximity discovery delay and interference on the sidelinks may increase. Also, in such a shared networking environment, resource management becomes difficult where an LTE-based system may not be able to meet the requirement V2X services. Novel resource allocation schemes are needed for C-V2X communication in LTE-advance or 5G-V2X. The resource type and amount of resources, and the way (centralized or distributed) they are distributed among cellular and C-V2X sidelinks, users needs to be redesign in the future vehicular environment compared to conventional cellular systems.

Chapter 3

LTE Based Vehicle-to-Vehicle Communication Architecture For Safety Services

3.1 Introduction

Time-critical safety services are key features of vehicular networks. Safety critical application in vehicular networks can improve road safety as well as reduce traffic congestion. Hence the role of a communication network will be crucial in road safety and traffic management systems. Distributing periodic time-critical safety messages know as Cooperative Awareness Messages (CAMs) in vehicular networks is a challenging task for the following two reasons. It is recommended that vehicles that are transmitting safety messages always be in the connected mode in a vehicular network. However, this may create an overloading problem in cellular networks due to the large amount of signalling required in the radio and the core network to support connected vehicles. Due to increased traffic load by CAM safety messages in high vehicle density areas, network congestion may occur, thus reducing the effectiveness of safety services.

Various message transmission techniques have been developed to support safety messaging services in Vehicular Ad hoc Networks (VANETs) [4]. A large number of proposals have been developed, mostly using the IEEE 802.11p network standard [64] [65] [66]. The performance metric that is typically used to characterize the performance of the IEEE 802.11p standard is the packet delivery ratio (PDR), which is the ratio of the number of packets received at a reference receiver from a reference transmitter. The IEEE 802.11p can meet the end-to-end latency requirements (i.e., 100 ms) of safety application if the vehicle density is lower [67]. However, when the vehicular density increases and exceeds a certain limit, the performance of the IEEE 802.11p network degrades because of the higher number of packet collisions due to simultaneous transmission and hidden nodes. This results in higher end-to-end delay and lower packet delivery ratio. A Decentralized Congestion Control (DCC) mechanisms [68] introduced to overcome the above scalability issue of an IEEE 802.11p network. However, DCC which typically involve the control of transmission parameters, such as the message and transmission power and transmission rate (in the number of packets/second) partially address scalability issue of an IEEE 802.11p network.

Several proposals have been developed that utilize the LTE network standard [69] [70]. However, due to the use of a centralized architecture, a conventional cellular LTE-based system may require significant network resources to support Vehicle-to-Everything (V2X) communication needs. A V2X communication architecture would be an ideal network configuration for supporting advanced safety services. A V2X architecture allows vehicles and infrastructure nodes to exchange safety messages. In recent years, several researchers have proposed distributing safety messages using LTE/IEEE 802.11p hybrid networks in VANETs [71] [72] [23]. However, these hybrid architectures degrade a combined network's performance when the node density increases, which leads to higher message transmission delay mainly due to collisions generated in the IEEE 802.11p-based networks.

As discussed in chapter 2, networking technologies like IEEE 802.11p and LTE-Advanced have shown different limitations for successfully deploying vehicular safety applications. Recent advances in cellular communication standards such as LTE-V2X, can effectively address the needs of V2V-based safety message transmission. The new standard allows direct information exchange among the network devices which are in close proximity without sending information packets via the eNodeB, i.e using the conventional base station architecture. The new standard supports two radio interfaces. The cellular interface (Uu), supports vehicle-to-infrastructure communications in the conventional mode, while the PC5 interface could be used for V2V communication mode using the LTE sidelink channels. Release 14 of the LTE standard introduces two new communication modes (Modes 3 and 4) specifically designed for the V2V communication links. In Mode 3, a cellular network selects and manages the radio resources used by vehicles for direct V2V communications. In Mode 4, vehicles autonomously select the radio resources for their direct V2V communications, thus offering ad hoc networking services similar to the IEEE 802.11p standard. However, when it comes to resource allocation, the LTE-V2X services need to share transmission resources with the conventional LTE services. In a shared networking environment where different services utilize the same radio resources, resource management becomes difficult when an LTE-based system may not meet the requirements of delay-critical V2V safety messages.

This chapter focuses on developing a 5G-V2X-based communication architecture that uses the cluster-based cellular Vehicle-to-Vehicle communication Mode 3, where vehicles use the sidelink interface PC-5 for the V2V communication. This chapter presents a new cluster-based LTE sidelink-based vehicle-to-vehicle (V2V) multicast/broadcast architecture referred to as Cluster-Based Cellular Vehicle-to-Vehicle

(CBC-V2V) to satisfy the latency and reliability requirements of V2V safety applications. The proposed architecture takes advantage of the well-established 4G/LTE infrastructure provided by the mobile operators. Our proposed architecture combines a new ProSe discovery mechanism, referred to as Evolved Packet Core Level Sidelink Peer Discovery (ESPD) for sidelink peer discovery and a cluster-based round-robin scheduling technique to distribute the sidelink radio resources among the cluster members.

3.2 Related Work

Since introduced of LTE Release 14, several research proposals have been focused on the performance comparison of IEEE 802.11p and LTE-V2X vehicular networks. In [22], the research study is based on the comparative experiment with real devices. The research study demonstrated that C-V2X network under congested conditions could be maintained the message transmission delay under 100 ms. The use of cellular technologies for vehicular networks have been investigated to meet the safety services requirements in references [73] [74]. The work showed that traffic hazard warning messages are disseminated in less than a second. In [72] [75], authors presented the Hybrid architectures based on the LTE and the 802.11p standards to exploit the benefits of both networks. In [72] authors present a cluster-based centralized vehicular hybrid network architecture for well-known urban sensing applications and floating Car Data (FCD) applications. The authors also compared performances of the proposed centralized vehicular hybrid network architecture with other decentralized clustering protocols.

In [75], authors propose a cluster-based VANET-LTE hybrid architecture named LTE-V2X for multimedia services. The proposed cluster-based architecture exploit the benefits of both 802.11p and LTE networks. The IEEE 802.11p is used for

V2V communication and LTE network is used for V2I communication. Each vehicle transmit FCD periodically. A CH is responsible for sending application data of itself and its cluster members to the eNodeB via LTE network. Cluster members send their application data via the 802.11p link to their CH. The coverage range of cluster or the CH is at most the range of a 802.11p network so that each cluster member can reach other cluster members and CH in the cluster. The performance of the proposed architecture has been compared with Decentralized Clustering Protocol (DCP). The performance results show that the LTE-V2X protocol performs better than the DCP in terms of signalling overhead and packet delivery ratio.

In [76] authors propose a hybrid architecture known as the VMaSC-LTE that integrates the LTE network with the IEEE 802.11p-based VANET network. The authors provide the delay performance analysis of the hybrid architecture. In [77], the authors propose a Hybrid Cellular-VANET Configuration (HCVC) to distribute road hazard warning (RHW) messages to distant vehicles. In this hybrid architecture, cluster Members (CMs) communicate with the CH by using the IEEE 802.11p link, and the CHs communicate with the eNodeB by using cellular links. However, these proposed 802.11p-LTE hybrid architecture increases transmission delay while reducing reliability when the IEEE 802.11p-based network needs to support higher node densities.

In [76] authors analyse the performance of the proposed architectures known as IEEE 802.11p-Based VMaSC and LTE/IEEE 802.11p-based VMaSc-LTE in the term of the Data packet deliver ratio (DPDR). The DPDR of VMaSC and VMaSC–LTE is the figure 10 in [77]. Figure shows the DPDR is decreased up to 20% and 89% at the higher vehicle density (0.2 vehicles/meters) for VMaSC (1 hop) and VMaSC-LTE (1 hop) respectively. The DPDR of VMaSC (1 hop) is poor at low and high vehicle densities due to the disconnected network, higher medium access contention and broadcast storm problems, respectively. They observe that LTE-based hybrid architecture VMaSC-LTE (1 hop) improves the performance compare to the VMaSC. The is because, in the hybrid architecture, the IEEE 802.11p-based network decreases the number of transmissions and the LTE-based inter-cluster communication decreases the medium-access contention. However the performance of the hybrid architecture decrease is also decrease when the traffic density is increase.

In [78], author proposed a pure cellular-based vehicular architecture known as Cellular Vehicular Network (CVN) where a hybrid clustering a scheme is devised to form a dynamic and flexible cluster managed locally by the Proximity Services Cluster Head (ProSe-CHs). However, the authors do not focus on the transmission of safety messages in the network. In [24] [79] [80], the authors compare the performance of IEEE 802.11p and LTE-V2X networks in terms of reliability. They mainly use simulation techniques where the moving vehicles are considered in a highway scenario to analyse the performance of the above two technologies. Some research works studied in Manhattan architecture [79] [80]. In [81], authors compared IEEE 802.11p and LTE-V2V networks for cooperative awareness in term of maximum awareness range, and presented analytical evaluation of the proposed schemes. In [79], authors introduce a resource scheduling algorithm known as Maximum Reuse Distance (MRD) for V2V communication under network coverage. The proposed scheduling algorithm is used Cellular-V2X mode 3 to minimize the interference and increase the reliability and latency of V2V communication.

Recently, a global, cross-industry organisation named as the Fifth Generation Automotive Association (5GAA) has developed a comparative experiment model to compare the performance of IEEE 802.11p and LTE-V2X (PC-5) vehicular networks in improving vehicular safety application [82]. This research study demonstrated that the LTE-V2X (PC5) outperforms the 802.11p network in reducing fatalities and serious injuries on European roads. All of the above mentioned works agree that the LTE-V2X network can provide better performance compared to the IEEE

802.11p-based vehicular network. This is due to the superior performance of LTE-V2X (PC5) at the radio link level for ad hoc/direct communications between road users. However, the use of the LTE-V2X or C-V2X standard for vehicular applications is still under investigation.As compare to the IEEE 802.11p standard, the direct V2V communication using PC-5 interface is a newer and less-studies feature in cellular networks. The centralized control of network resource distribution using C-V2X Mode 3 offers the efficient utilization of the network bandwidth [23]. However, despite the fact that C-V2X shows the improvements compare to the 802.11p standard in high traffic density scenarios, the performance of a C-V2X degrades rapidly [24], particularly for the C-V2X Mode 4. As compare to IEEE 802.11p standard, the C-V2X Mode 4 is also prone to the hidden terminal effect because of it's Semi-Persistent Scheduling (SPS) which is sensing-based. C-V2X Mode 4 suffers packet collisions caused by the reselections that are part of the sensing-based SPS scheme and that can occur when several vehicles try to select new sub-channels at the same time when the value reselection Counter is zero. These limitations in the C-V2X-based D2D communications, are motivates to design a new C-V2X communication architecture to meet the requirements of diffrent safety applications in VANETs.

The work presented in this chapter differs from the existing works available in the literature in several ways. As discussed, in the existing hybrid architecture, vehicles use the IEEE 802.11p standard for V2V communication, and the LTE network is used for the V2I communication. However, the integration of the LTE standard with the IEEE 802.11p standard may not be successful for safety message distributions such as CAM using the V2V communication. The main reason for such a hybrid network limitation is that the contention increases significantly in high-density congested vehicular networks. In CBC-V2V architecture, resources for sidelink communication are distributed in a round-robin manner using the Time Division Duplexing (TDD) Mode. Our proposed round-robin scheduling offers an efficient collision-free resource distribution among V2V enabled vehicles when the channel load and the congestion increases. The major benefit of our proposed resource allocation scheme is that it allows to dynamically assigning the same slot to the multiple users, in turn, using node ID in ascending order. Subsequently, members of a cluster can share the same slot in turn to transmit their CAM. The other benefits come from our ESPD algorithm, which requires less control message exchange for peer discovery than existing peer discovery models described in Section 3.2.2.

3.3 CBC-V2V System Model

In this section, we present a CBC-V2V network architecture for V2X communication using the PC5 interface of the 5G-V2X standard. The model assumes that all vehicles on the road are within the coverage of a serving eNodeB. A highway road traffic scenario is considered where traffic is flowing in the same directions in a multi-lane road, as depicted in Fig. 3.1. We assume that each vehicle is equipped with a GPS device capable of providing accurate position measurements. The highway is partitioned into fixed-size regions known as a cluster, as shown in the figure. Vehicles on the road with near proximity form a cluster, where they exchange the safety messages with each other using the CBC-V2V-based packet transmission technique. We are considering two types of vehicles, the first type represents the user terminals capable of acting as a Cluster Head (CH) and supports D2D communication using the PC5 interface. The CH also manages the network resource usage among the group of devices communicating over D2D links. The second type of vehicle represents the network devices that can only act as a Cluster Member (CM). These vehicles connect to the appropriate CH to assist them in establishing the D2D links to exchange messages. In this model, a vehicle uses two communication links: the conventional Uu interface and the D2D links using the PC5 interface. Cluster members can communicate with others using the PC5 links, whereas a CH communicates with the eNB

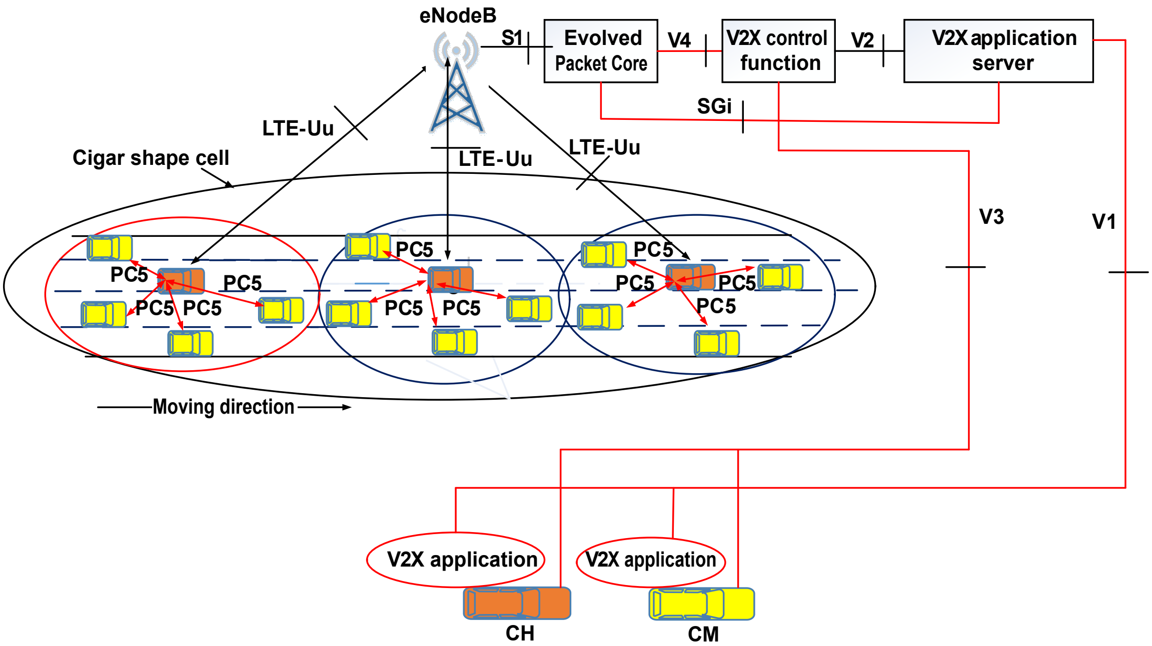


Figure 3.1: Highway scenario for proposed cluster-based V2V cellular (CBC-V2V) architecture

using the Uu interface. Although the D2D channels enable two neighbouring UEs to communicate directly, all signalling and data transmission processes should still be under the control of the eNB in order to comply with the LTE-Advance architecture requirements.

A Traffic Map Controller (TMC) proposed that is attached with the eNodeB is proposed to keep track of all vehicles in a cluster. Vehicles in the proposed architecture are equipped with ITS Proximty Services (ProSe) enabled devices which utilise the LTE and the LTE direct interfaces. The LTE Uu interface is used for Vehicle-to-Infrastructure (V2I) communications to access (Internet Protocol) IP services, while the LTE direct interface PC5 is used for inter-vehicle communication. As per the 3GPP Release 16 for V2X services, two new entities are introduced: the V2X Application server and the V2X control function to support the V2X services. The V2X control function is the logical function that is used for network-related actions required for V2X. The parameters required for V2X communications can be obtained from a V2X application server. The V2X application server incorporates the V2X capability for building the application functionality. It is responsible for receiving uplink data from the UE in the unicast mode, providing the parameters for V2X communications over the PC5 reference point to V2X control function. Each vehicle will receive its proximity information for direct communication using our proposed EPC level peer discovery model. The detailed description of the proposed EPC level peer discovery model is presented in section 3.2.2.

3.3.1 Cluster-Based cellular V2V (CBC-V2V) Communication Architecture

We propose a cluster-based cellular V2V communication architecture that combines the new sidelink peer discovery model to support safety services. We propose to use a cluster topology where communication among cluster members is coordinated by the cluster shown in Figure 3.1. Vehicular networks are generally dynamic, where vehicles may arrive new in a cluster location or may leave a cluster. For a newly arrived vehicle, it is necessary to discover the necessary system information to join an appropriate cluster. In the following section, first we present our proposed sidelink peer discovery model. Following that discussion, our cluster-based cellular V2V communication mechanism combining with a round-robin scheduling technique is proposed to distribute the radio resources among the cluster nodes.

3.3.2 EPC level Sidelink Peer Discovery (ESPD) Model

As shown in Fig 3.1, for direct communication over a sidelink channel, two ProSe-enabled devices or vehicles must be aware of each other. Therefore, peer discovery is needed before two User Equipments (UEs) can set up a sidelink connection and start direct communication. Two UEs are ProSe candidates if they find each other during the peer discovery process. To start the direct transmission ProSe peer discovery is the first step where a device searches for the potential peer in proximity and determines the discovered peer's identification. The new pair is determined to be ProSe candidates. Moreover, this phase includes several control messages that have to be exchanged between UEs and eNodeB. After completing the discovery phase, the new ProSe candidates can have actual communication. The communication phase includes resource allocation, power control, and the actual transmission of the information. The general discovery procedure for D2D communication is described as follows: first, a UE sends a discovery packet to detect potential UEs in it's proximity; then, the identities of UEs can be exchanged between the new pair, which are determined to be ProSe candidates.

In general, D2D communications used two type of peer discovery techniques. First one is direct discovery where devices communicate with each other directly using randomized procedure and frequent beacon transmission without any network assistance. A device broadcasts its identity periodically so that other devices in the proximity may be aware of its existence, and decides whether it will establish a D2D communication connection with the discovered devices [83]. The second one is network-assisted discovery where network devices detect and identify each other with the assistance of the network. A device informs the network about its intention for peer discovery using a beacon signal. After receiving the beacon signal, the network base station act as mediator in the discovery process by recognizing ProSe candidates.

Since the introduction of D2D communication architecture in Release 12, many device/peer discovery techniques have been developed using two of the above models defined in the standard. From the user's perspective, they can be classified into restricted discovery and open discovery [84]. For restricted discovery, the user entity is not allowed to be detected without its explicit permission. In this case, it prevents other users from distributing their information to protect user privacy. It suits social network applications (e.g., group gaming and context sharing with friends). For open discovery, a user entity can be detected as long as it is within another device's proximity. From the network's perspective, device discovery can be divided into direct discovery and Evolved Packet Core (EPC) discovery. In direct discovery, a device would search for a another nearby device autonomously without any network assistance. It works in both in-coverage and out-of-coverage scenarios. In EPC-level discovery, a base station notifies the terminal about other peers detected in the proximity based on the peer interest, information and the location information registered in the ProSe function [85].

Many other wireless local/personal area network technologies, such as Bluetooth [86] and Wi-Fi Direct [87], already rely on beacons for peer discovery. A reservation-based protocol called FlashLinQ provides direct discovery and operates in the licensed band [88]. Authors in [89], present a peer discovery scheme named as VANET Aided D2D Discovery (VADD) based on the IEEE 802.11p network where the vehicle first sends the discovery request along with discoveree ID to its On Board Unit (OBU). If there is no match, in the database of the OBU for the concern discoveree ID the vehicle forwards the same discovery request to the RSU within its range, which in turn looks for the requested ID in its database. If no match happens it seeks help from the neighbouring RSUs. Whenever a match occurs, either at the OBU or on the RSU side, the related node informs the eNodeB about this information using the LTE-A interface. We choose the VADD is suitable for direct comparison with our proposed ESPD schemes because VADD is hybrid protocol based on the IEEE 802.11p/LTE network. The authors claims that the proposed discovery scheme reduces the consumption of valuable resources in the LTE-A network. However, the main problem for the proposed discovery techniques is the use of the IEEE 802.11p interface when a number of vehicles enter the RSU range at the same time. In this case the IEEE 802.11p MAC layer contention process will take place, which in turn increases the discovery delay in a high density scenario. Also the node that gets

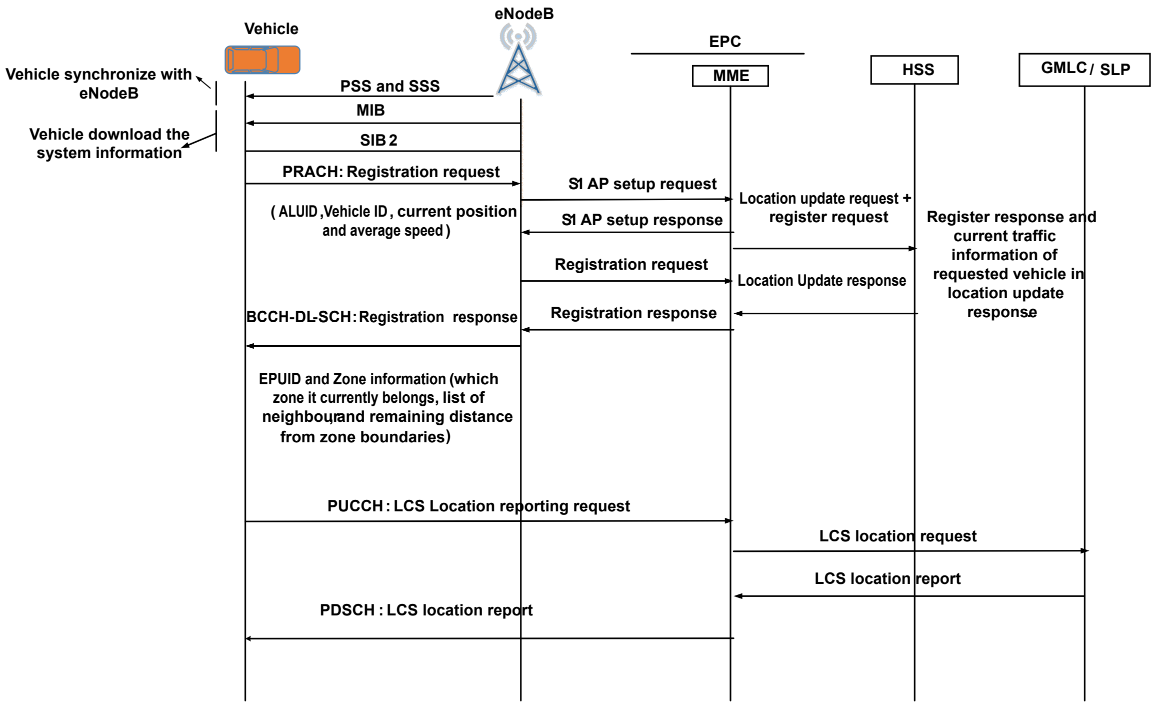


Figure 3.2: EPC level peer discovery (ESPD) model for VANET

access to the channel will wait for the RSU to send it back for the discovery answer.

All vehicles that use the D2D link must have the ProSe capability features: the ability to discover, to be discovered, and to communicate with discovered devices. Within the existing EPC level discovery model, the ProSe function authenticates the user by checking its credential with the HSS as to whether the user is permitted to utilize ProSe features. After successful authentication of the UE, the ProSe Function creates an EPC ProSe Subscriber ID (EPUID) and assigns it to the registered device. Once a vehicle is registered as a ProSe subscriber, it can run the applications that support proximity services, called ProSe enabled applications. The application server allocates the user an Application Layer User ID (ALUID) to recognize him within the context of this particular application.

However, these device discovery and EPC level discovery models require significant control signalling and resources known as peer discovery resources for beacon transmission or message exchanges, such as announce requests, monitor requests, match reports, etc. [90] [91]. Our proposed discovery mechanism diminishes network resource requirements. It assumes that every vehicle is equipped with a GPS receiver and can accurately determine its position and direction of movement. Fig. 3.2 shows the signalling diagram of the proposed EPC level discovery technique elaborated as follows:

1. When a new vehicle reaches an eNB coverage area, the downlink frame synchronization is accomplished once it has decoded the Primary Synchronization Signal (PSS) and the Secondary Synchronization Signal (SSS) messages, which are accessible on the downlink broadcast control channel. The vehicle at that point downloads the Master Information Block (MIB) from the broadcast channel. This channel incorporates the downlink and uplink carrier configuration information. Further, the vehicle utilizes the Downlink Shared Channel (DL-SCH) to download the system information block. The SIB2 block contains necessary parameters for the initial access transmission.

2. In the initial state, each vehicle on the road must register itself with the eNodeB using its current GPS position. Unlike the existing EPC level discovery, the vehicle sends its location information in the registration request to the eNodeB instead of using the ProSe function for vehicle registration. The vehicles will forward their information (such as ALU_ID, current GPS location, an average speed of the vehicle, discovery range, and vehicle ID) in the registration request message utilizing the Random Access Channel (RACH) to the eNB. The eNB acknowledges the registration request and broadcasts the registration response back to vehicles along with the current traffic profile over the broadcast channel. The vehicle's traffic profile contains an EPC ProSe Subscriber ID (EPUID), zone information (i.e., to which zone it currently belongs), neighbouring vehicle list and the vehicle's remaining distance from its location.

3. After accepting the information supplied in the registration response, the vehicle collects all the data in its Vehicle Information Register (VIR), a repository that stores vehicle and surrounding information. For D2D communication, each vehicle updates its neighbourhood table with a new list of neighbouring vehicles and builds knowledge of its local environment. The Global Mobile Location Centre (GMLC) keeps vehicle locations tracked. Once the vehicle comes to a new zone or crosses the boundary of the zone, the location alert, i.e. the Location Service Report (LCS) will be received and the vehicle will require re-registration to update its VIR.

3.3.3 Cluster Head and Semi Cluster Head Selection

Upon receiving the new proximity data in a Neighbourhood Table (NVT), an Source Vehicle (SV) searches the NVT during the time period represented as T_{search} to check the vehicles in CH, SCH, and SE state. If none of the neighbour vehicles are recorded either as CH or Semi Cluster Head (SCH) , the vehicle will check the neighboring vehicles in the Selection State (SE) . If there are vehicles in the SE state in the NVT, and the SV has the most reduced average speed and a maximum distance from its current location to the zone boundary (i.e., longest lifetime) at that point it becomes the CH. Each vehicle calculates its average speed periodically. If none of the neighbour vehicles are recorded either as CH, SCH or as a SE, a source vehicle will take the role of SCH. SCH is the state where vehicle has no potential neighbouring vehicle that can connect to it. In case the vehicle in the SCH state; gets any joining request from a neighbouring vehicle during the time period represented as T_{SCH} then it will take the role of the CH. Otherwise, it will reach in the Selection State (SE) and require re-registration to receive new proximity data.

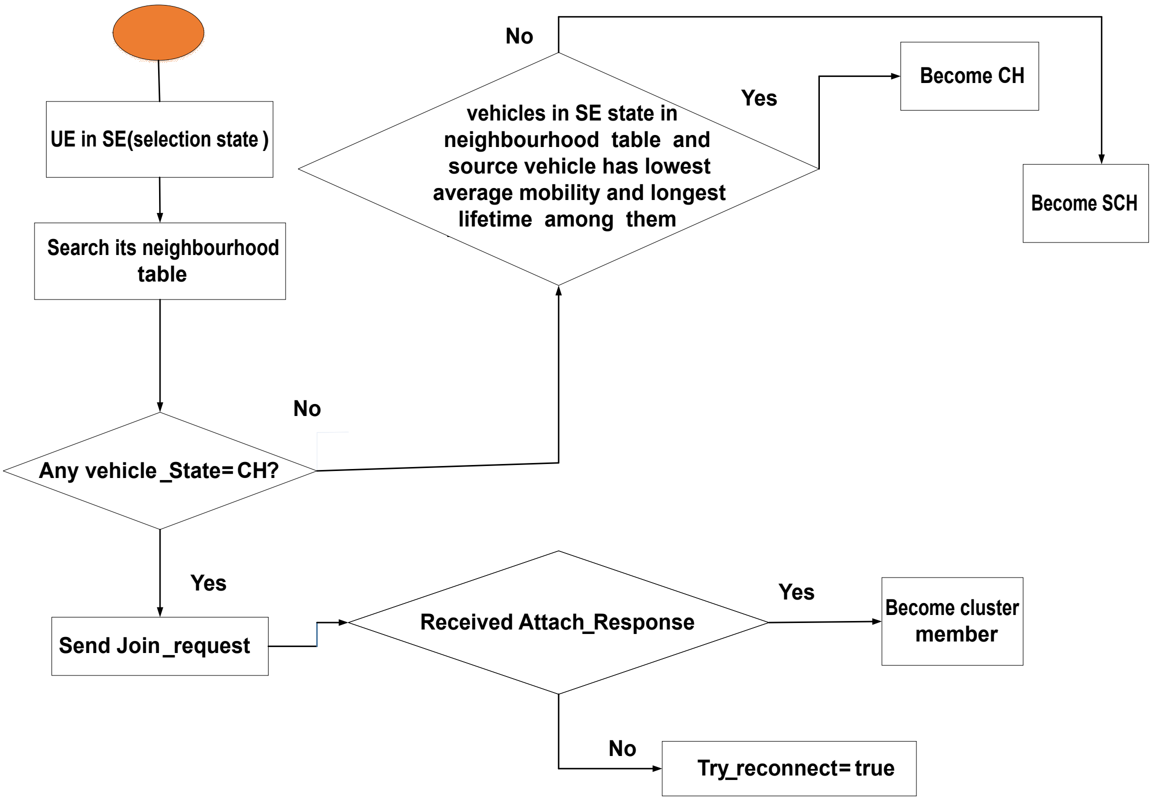


Figure 3.3: CBC-V2V clustering approach

3.3.4 Cluster formation

After peer discovery, each vehicle needs to select an appropriate CH to associate with it. Using the peer discovery model, after successful registration, each vehicle updates its NVT in its VIR with the new proximity data (i.e., a list of neighbouring vehicles) along with the vehicle ID, a total number of vehicles and current state of the vehicle. Once the new proximity data is received, the vehicle will reach in the SE. As shown in fig 3.3, a vehicle in the selection state first tries to connect to the existing cluster to minimize the number of clusters. Hence, the SV first checks the total number of vehicles, their position and the state of each vehicle in its NVT.

If the vehicle finds a CH in its NVT, and the number of members in the cluster is lower than the maximum number of members allowed, the SV will attempt to connect to the existing CH. In the NVT, if none of the neighbouring vehicles are listed as

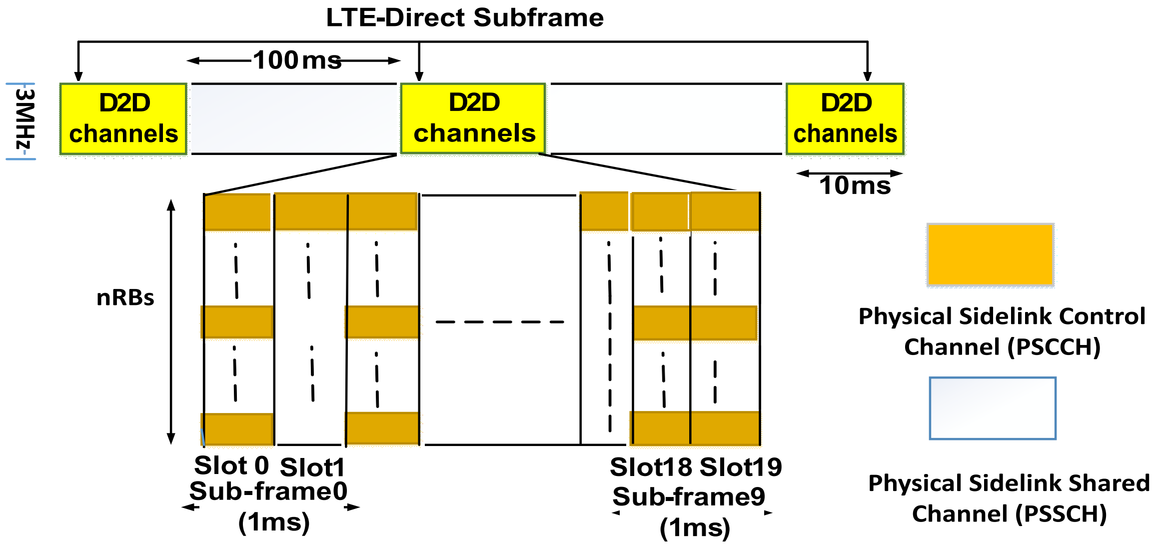


Figure 3.4: V2V sidelink subframe structure

CH or the vehicle is unable to connect to any of the neighbouring CHs, the vehicle inspects the neighbouring vehicles in the SCH state. If there are vehicles in the SCH state in its NVL, the SV tries to connect to the existing SCH. If none of the neighbour vehicles are listed as CH or SCH, the SV checks the neighbouring vehicle in the SE. If the SV discovers the vehicles in SE in NVT and it has the lowest average speed and the maximum distance from its current location to the zone boundary (i.e., longest lifetime) among them then it will take the role of CH. Otherwise, the SV becomes a SCH.

3.3.5 V2X sidelink channel structure

Using communication mode 3, we suggest the 3GPP standard-based V2V sidelink channel structure as shown in Figur 3.4. The figure shows that an eNB reserves ten D2D subframes on uplink cellular traffic channels in the TDM (Time Division Multiplex) manner. The D2D subframe repetition rate is 100 ms. Each subframe contains two slots, hence a single carrier offers twenty slots for sidelink communications. The RBs are used to transmit data and control information. The data is transmitted using transport blocks (TBs) over the Physical Sidelink Shared Chan-

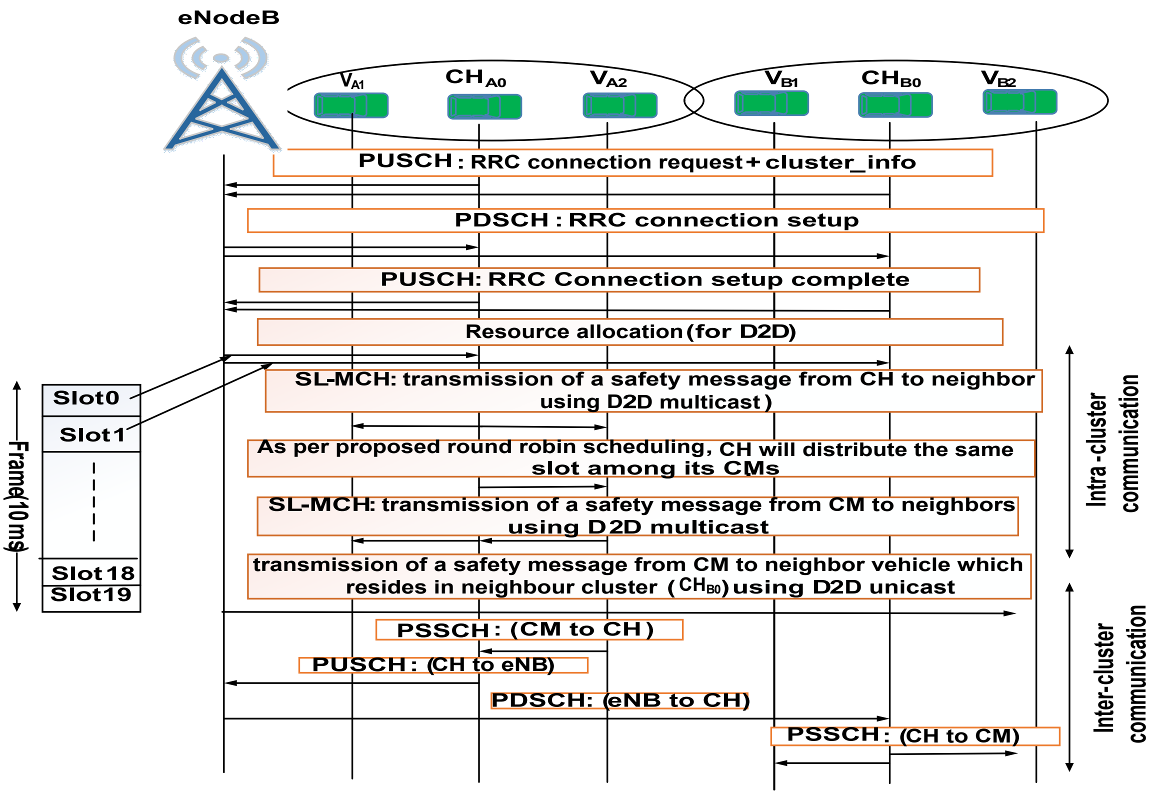


Figure 3.5: CBC-V2V communication over sidelink channels

nels (PSSCH). Sidelink Control Information (SCI) messages are transmitted over the Physical Sidelink Control Channels (PSCCH) [16]. The number of RBs in a slot depends on the bandwidth of an LTE-V network cell. Using a 3MHz transmission bandwidth, there will be 15 RBs in one slot available for the D2D communication.

3.3.6 CBC-V2V communication

Our proposed CBC-V2V communication for safety message transmission is shown in fig. 3.5. As seen, the intra-cluster communication procedure between cluster members (V_{A1} and V_{A2}) belongs to a neighbouring cluster (CH_{A0}) and inter-cluster communication from V_{A1} to the vehicle (V_{B1}) which belongs to a neighbour cluster (CH_{B0}). For the rest of the vehicles in the network the same procedure will follow. A CH acts as a ProSe gateway node for Vehicle-to-Infrastructure (V2I) and Infrastructure-to-Vehicle (I2V) communication. The CH utilizes the Physical Uplink

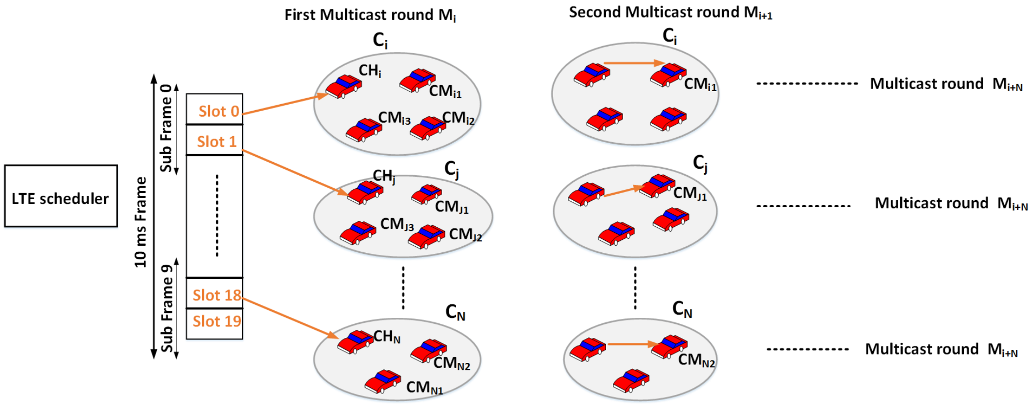


Figure 3.6: Example of our proposed round robin scheduling

Shared Channel (PUSCH) uplink grant allocated during the random access procedure to send the RRC connection request along with the data structure, represented as $cluster_{info}$. In the $cluster_{info}$, each CH keeps the information, such as the CH_{ID} and the number of CMs attached to it. Based on the $cluster_{info}$ in the RRC connection request, an eNB dynamically allocates resources to a CH for D2D communication. At the cluster level, each cluster head further schedules the resources among its CMs using the new cluster-based round-robin scheduling as described below.

Radio resources are initially allocated to the CH for each cluster of nodes. The CH then conducts round-robin resource scheduling among its CMs (i.e., vehicles) based on the vehicle ID. The round-robin scheduling approach is based on the idea of being fair to all active users in the long term by granting an equal number of Physical Resource Blocks (PRBs). fig 3.6 shows our proposed round robin scheduling. Our proposed resource allocation scheme is operated by dynamically assigning the same slot to the multiple users, in turn, using node ID's in ascending order. Subsequently, members of a cluster can share the same slot in turn to transmit their own CAM.

As shown in Figure. 3.4, ten subframes for D2D communication show up in every 100 ms which are shared between different clusters. Since each cluster is designated one slot, the same subframe will support two clusters. In the example, slot 1 is assigned CH_{A0} and slot 2 is assigned CH_{B0}. When the resource is allocated, the CH chooses PRBs within the available slot to transmit its CAM to its CMs in the multicast mode. A ProSe-enabled node cannot receive and decode the D2D message while it is transmitting, due to the half-duplex nature of most transceiver designs. Therefore, in the cluster, when one vehicle is transmitting, the rest of the vehicles will receive the CAM from the transmitting vehicle. Each safety message can be accommodated utilizing four PRBs based on the selected Modulation and Coding scheme (MCS)and the packet size. On completion of the transmission from the CH it will assign the same slot to its CMs. The next vehicle (VA_1) is thereby allocated the same slot in its turn based on its vehicle ID. Then VA_1 multicast its own safety message to its neighbouring vehicles. The same procedure will follow by the remaining vehicles in the cluster. To maximise reuse of the spectrum, the same D2D resource can be assigned to different non-overlapping clusters.

In this architecture, the inter-cluster communication is required to share safety messages by vehicles which are found at the edge of the two neighbouring clusters. In the example, vehicle VB_1 is in the neighbour list of VA_1 but out of range of its CH_{A0}. Therefore, direct communication is not conceivable between VA_1 and VB_1. In this case, CH_{A0} collects the safety message from its cluster member VA_1 over the D2D Physical Sidelink Shared Channel (PSSCH) and transmits to the eNodeB over the LTE interface in the unicast mode. At that point , the eNodeB conveys the safety traffic message to a concerned neighbour CH_{B0} over the LTE interface. The CH_{B0} multicasts the safety message to its cluster member VB_1 and VB_2 via the LTE-D2D PC5 interface.

3.3.7 Delay Models

Fig 3.7 shows the delay models for the proposed CBC-V2V architecture combining with peer discover model ESPD, round robin resource distribution for periodic CAM

Table 3.1: Delay model timing parameters

Notation	Description
$T_{eNodeB,rsp}$	eNodeB process delay to broadcast registration response.
$T_{V,RACH}$	Delay required to access the RACH channel.
$T_{VIR,update}$	Vehicle information registration update delay.
$T_{clustering}$	Cluster formation delay.
$T_{slot,req}$	Delay required to send the slot request.
T_{PDD}	Peer discovery delay.
T_{RR}	Resource distribution delay.
$T_{CAM,M}$	CAM multicast transmission delay.

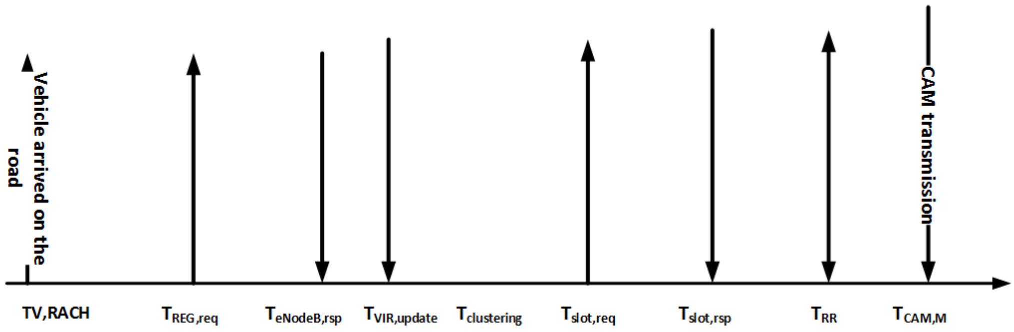


Figure 3.7: Major delay components for CBC-V2v

message transmission. Delay parameters are explained in table 3.1. As per our peer proposed ESPD, each vehicle must register itself with the eNodeB. To send the registration request a vehicle has to wait for a certain period represented by $T_{V,RACH}$ for sending registration request T_{Reg} to eNodeB. The eNodeB broadcasts the registration response after $T_{eNodeB,rsp}$ delay. Once the vehicle receives the registration response it will update its VIR after $T_{VIR,update}$ delay. After the peer discovery, they will grouped to-gather to form the cluster using our proposed cluster scheme. The $T_{clustering}$ represent the delay for the clustering process. Once the clustering has completed the cluster head send a scheduling request to the eNodeB after $T_{slot,request}$. The eNodeB allocates a reserved slot after the $T_{slot,response}$ delay. The CH distributes the allocated slots among its cluster members (CMs) after T_{RR}. Further, the CM which receive the mulicast slot, multicasts its CAM message after $T_{CAM,M}$. The total delay T_{PDD} for peer discovery and delay for CAM message transmission T_{CAM} is represented by (3.1) and (3.2) respectively.

$$T_{PDD} = T_{V,RACH} + T_{Reg} + T_{eNodeB,rsp} + T_{VIR,update} + T_{clustering} \tag{3.1}$$

$$T_{CAM} = T_{slot,request} + T_{slot,response} + T_{RR} + T_{CAM,M} \tag{3.2}$$

3.4 Simulation Model

An OMNET++ version 5.1.1 based simulation model is developed utilizing the SimuLTE library [17] that utilizes the INET framework 3.4.0. For enhanced traffic simulation, GPS data incorporation and mobility support, we utilized the Veins package with a realistic mobility model generated by the microscopic road traffic simulation package: Simulation of Urban Mobility (SUMO) [59]. To add the mobility support feature in SimuLTE, a new interface known as vehicularMobility module has been added. This new mobility model can be implemented by the TraCIMobility module defined by the Veins. There is another mobility module known as INETMobility present in the INET framework. A vehicle can utilize only one mobility module during the simulation, therefore both modules (i.e., INETMobility and vehicularMobility) are defined as a conditional module within the Ned file. Veins uses the OMNeT++ API to create and initialize the new module dynamically. When a new vehicle is created, it needs to obtain an IP address to communicate. SimuLTE demands the assignment of IP addresses to the IPv4NetworkConfigurator module provided by INET.

A new parameter, i.e., d2dcapable is utilized in the initialization (.ini) file to

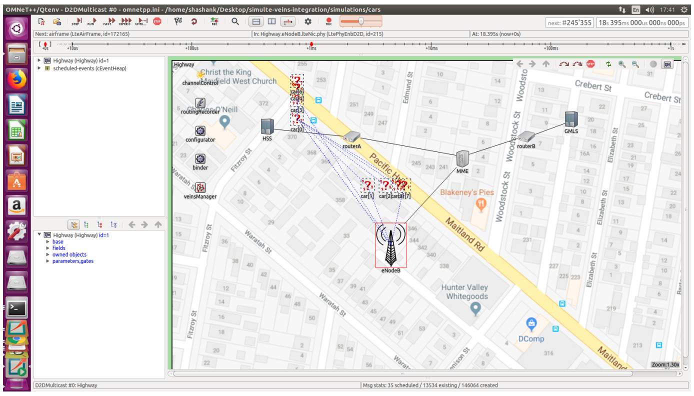


Figure 3.8: CBC-V2V simulation model

enable direct communication between two UEs. Most of the PC-5 operations at each layer of the LTE stack are created by extending pre-existing SimuLTE capacities. For each D2D competent user, an LTE binder keeps up a data structure that contains the set of directly reachable destinations. In an expansion of the existing downlink and uplinks flow paths in SimuLTE, a new flow path, PC-5, has been distinguished. From the UE point of view, IP datagrams reach the PDCP layer and either the PC-5 or the UL directions can be associated with the corresponding flow, depending on whether the destination is in the LTE Binder peering table or not. The detailed description of configuring D2D communication in OMNET++ with SimuLTE is given in [16] [17]. Results from the simulation were acquired by taking the average of the 20 simulation runs with different seeds value. The key simulation parameters are summarized in Table 3.2.

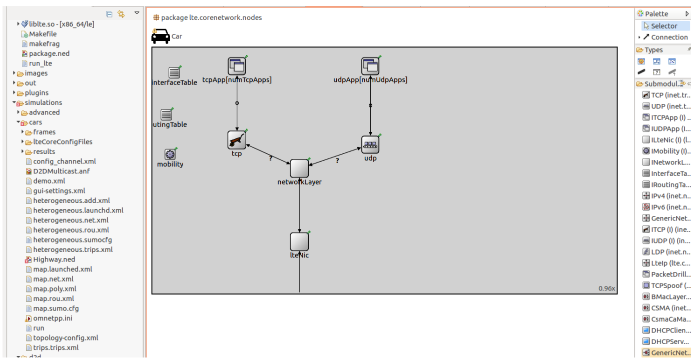


Figure 3.9: vehicle structure in simulation

Table 3.2: Main simulation parameters

Parameter	Value
Maximum velocity	40-70 km/h
Number of vehicles	96 vehicles/km
Road length & number of lanes	5km & 4 (i.e., 2 in each direction)
Carrier frequency	2.6 GHz
Duplexing mode	TDD
CAM generation rate	10 packets/sec
Transmission bandwidth	3MHz (i.e., 15 RBs)
Path loss model	Free space
Fading model	Shadowing
eNodeB Tx power	46 dBm
UE Tx Power	26 dBm (Uplink), 5 dBm (Sidelink)
Coverage range	1000 m
Noise figure	5 dB
Cable loss	2 dB
Simulation time	800s
Packet size	340 bytes
T_{safety}	100 ms
Number of vehicle/cluster	12
$CH_{\text{maxmember}}$	11

We modified the existing D2D communication model in the SimuLTE to support our proposed cluster-based cellular V2V architecture. Fig. 3.8 shows the CBC-V2V communication model consists of an access network entity (single eNodeB) and core network entities (MME, HSS, and GMLS) that are utilized to support our proposed EPC level peer discovery model (ESPD). Fig. 3.9 to 3.11 show the access network and core network modules structure used in the SimuLLTE. The ESPD simulation model is developed by using the information structure shown in Fig. 3.2. In the simulation, we design a multilane highway scenario where the vehicles are distributed according to the Poisson process. The vehicles form the clusters using our proposed clustering scheme for D2D communication. To implement our proposed clustering scheme, we utilize the sample source code accessible online [92]. Each cluster node keeps up neighborhood table that contains its neighbor's ID and their state. In the simulation,

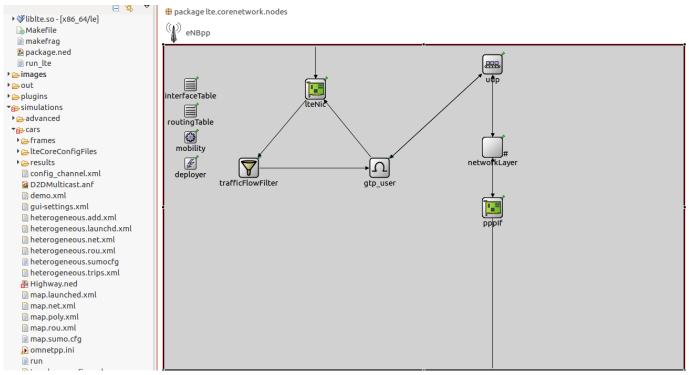


Figure 3.10: Base station (eNodeB) structure in simulation

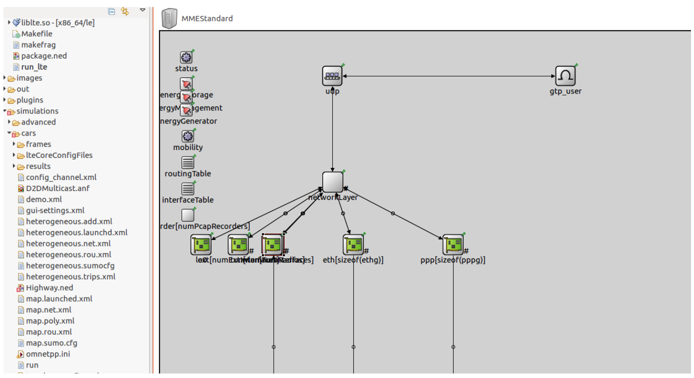


Figure 3.11: Mobility Management Entity structure in simulation

we include scenarios of both multicast and unicast shown in Fig. 3.5. The model is simulated for both scenarios utilizing the parameters presented in Table 3.1 for 800 seconds. At the MAC layer in the SimuLTE, we modified the scheduling model (i.e., LTEDrr) to implement our proposed round-robin scheduling scheme. Utilizing the proposed round-robin scheduling technique, each cluster node receives an equal share of the radio resource for D2D communication.

3.4.1 Performance analysis of proposed EPC Level Peer discovery Model (ESPD)

Using the traffic load (i.e., number of vehicles/total road length) parameters, we examine the peer discovery delay (PDD), Peer Discovery Resource (PDR) utilization and control signalling overhead performance of our ESPD. The performance of the ESPD is compared with the existing solutions, namely, the VANET Aided D2D Discovery (VADD) [89] and 3GPP EPC level peer discovery scheme [85]. The following performance metrics are used to evaluate the proposed algorithm:

3.4.1.1 Control Signalling Overhead

The control signalling overhead is measured for the proposed EPC level peer discovery techniques. The average control signalling required for ESPS is represented as $\overline{x}_{pd}$ that is calculated as the number of slots used for peer discovery out of the total number of n subframe available in the cell i as

$$\overline{x}_{pd} = \frac{x_{ir1} + x_{ir2} + x_{ir3}, ..., x_{irn}}{n} \times 100 \tag{3.3}$$

Figure 3.12 shows the average signaling overhead for the ESPD, VADD, and 3GPP EPC level peer discovery scheme. Fig. 3.12 shows that the ESPD introduces a much lower control signalling overhead than other solutions. The main reason for the

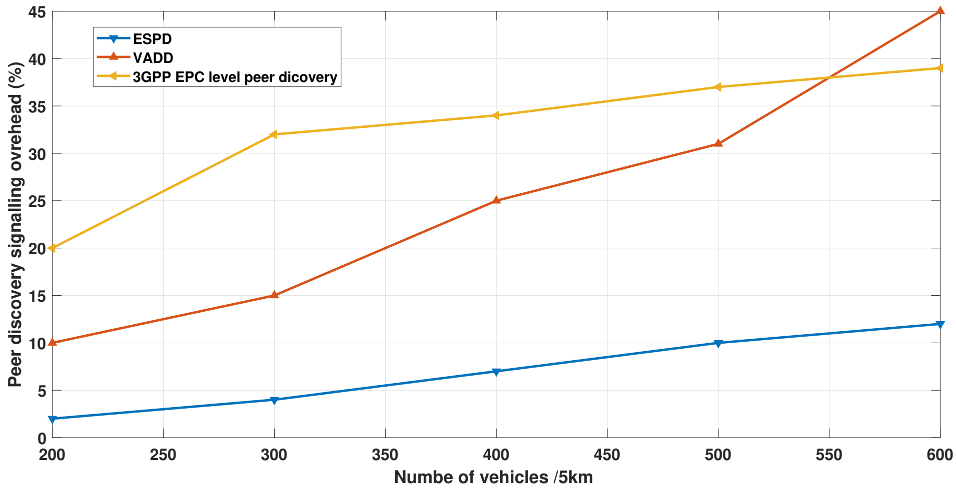


Figure 3.12: Performance comparison of in terms of signalling overhead for peer discovery

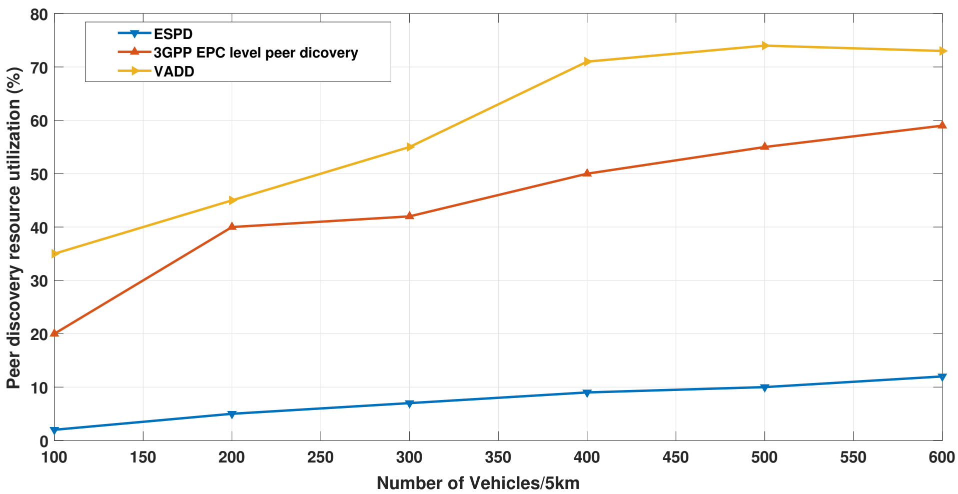


Figure 3.13: Performance comparison in terms of occupied RBs for peer discovery

performance improvement is the requirement of control signalling for peer discovery. Our proposed ESPD scheme requires less control message exchange for peer discovery compared to existing peer discovery models. Unlike the existing solutions, in the ESPD algorithm, a vehicle receives the proximity information after the successful registration, which requires much less control message exchange.

3.4.1.2 Peer Discovery Resource (PDR) utilization

Peer Discovery Resource (PDR) utilization is represented as a $ESPD_{RU}$ is average number of resource blocks used for peer discovery. The $ESPD_{RU}$ is calculated as a ratio of the number of RBs used to the total number RBs available:

$$ESPD_{RU} = \frac{RBs_{UL} + RBs_{DL}}{RBs_{avilable}} \times 100 \tag{3.4}$$

Where RBs_{UL} and RBs_{DL} represent the number of resource blocks used on uplinks and downlinks respectively. $RBs_{avilable}$ represents the total number of resource blocks available on each LTE uplink and downlink channel.

Fig 3.13 shows the resource utilization of ESPD, VADD and ProSe 3GPP direct and network assisted schemes. Fig. 3.13 shows that our proposed ESPD introduces lower resource consumption compared to other existing schemes. Resource utilization for peer discovery is depends on the number of RBs used for control message transmission to the total number RBs available. The main reason for the performance improvement of ESPD is the requirement for few control messages for peer discovery. Thereby, fewer RBs are consumed on the uplink and downlink channels.

3.4.1.3 Peer Discovery Delay (PDD)

Peer discovery, represent as δ_{PD} is the average delay required by the vehicle to discover all ProSe enabled peers in its proximity range, which is assumed 500 meter in the simulation. Here, it is worth noting that the peer discovery delay required by our proposed ESPS is equal to the time difference between sending a request for registration and receiving an eNodeB response.

Fig 3.14 evaluates and compares the peer discovery delay of the ESPD with the 3GPP ProSe peer discovery model described in Section 4. In the proposed ESPD, the peer discovery delay is the time taken by each vehicle for successful registration.

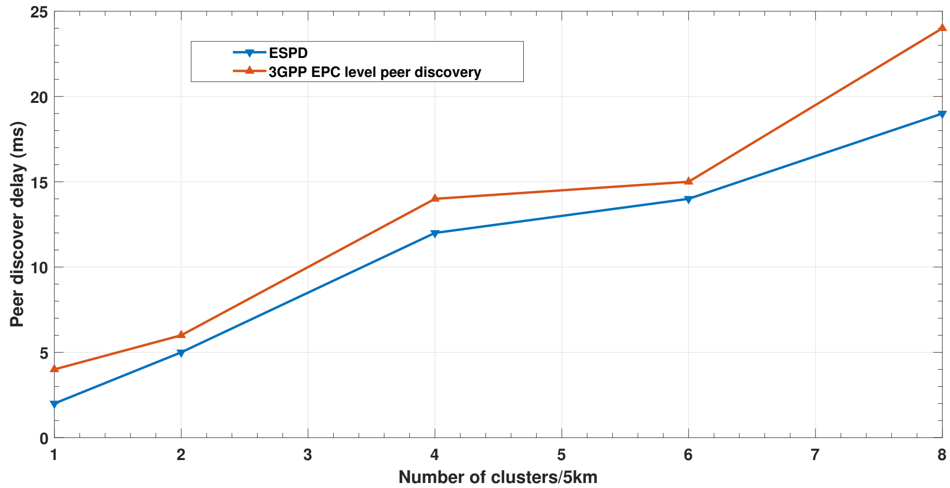


Figure 3.14: Performance comparison in terms of peer discovery delay

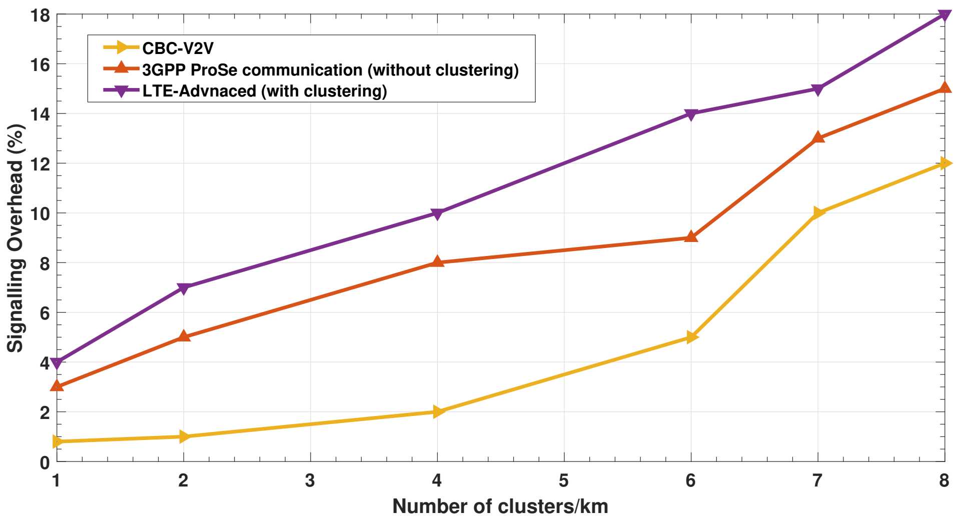


Figure 3.15: Performance comparison in terms of total signalling overhead

In the registration response, each vehicle receives its current traffic profile which contains the list of directly reachable vehicles in its vicinity. Due to less resource utilization and a minimal control signalling overhead requirement, ESPD shows lower delay values for the peer discovery task compared to the existing 3GPP ProSe peer discovery model.

3.4.2 Performance analysis of proposed CBC-V2V architecture

Using the traffic load (i.e., number of vehicles/total road length) parameters, we examine the Data Packet Delivery Ratio (DPDR), Overall Resource utilization and control signalling overhead, and End-to-End delay performance of our CBC-V2V architecture. We also implemented a default 3GPP ProSe algorithm and IEEE 802.11p and hybrid LTE/802.11p simulation models to simulate the VMaSC and VMaSC-LTE [76] basic algorithms to obtain several performance parameters for comparisons. In the following paragraphs, we present the performance analysis of CBC-2V2 and comparisons with exiting works.

Fig. 3.15 shows the signalling overhead required by the CBC-V2V algorithm, the default 3GPP ProSe algorithm, and the LTE-Advanced algorithm using a conventional cellular network architecture. The results clearly show that the CBC-V2V algorithm introduces lower signaling overhead than the other two standards, which can be used in a VANET. The main reason for the performance improvement is the lower control signaling requirement for the CBC-V2V algorithm. This is because the CH does not require to send multiple resource scheduling requests to the base station on the uplink control channel. Once an eNB allocates resources to a CH for the sidelink communication, each cluster head further schedules the resources among its CMs in a round-robin manner. The major benefit comes from our ESPD algorithm, which requires less control message exchange for peer discovery compared to the existing peer discovery models described in Section 3.2.2. Unlike the existing 3GPP peer discovery model, in the ESPD algorithm, a vehicle receives the proximity information after successful registration, which requires fewer control message exchanges, as shown in Fig 3.2. The smaller control signalling overhead requirement will improve the performance of safety services and guarantee the timely delivery of active safety messages.

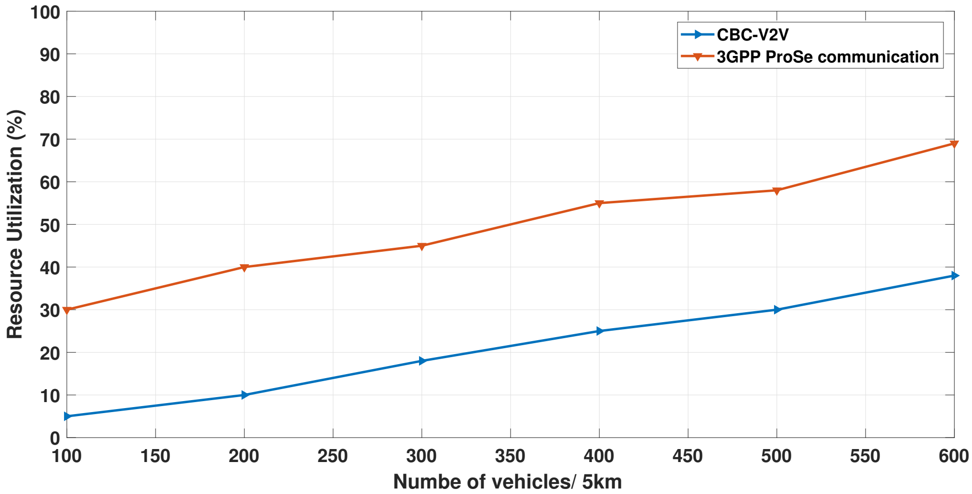


Figure 3.16: Performance comparison in terms of total occupied RBs

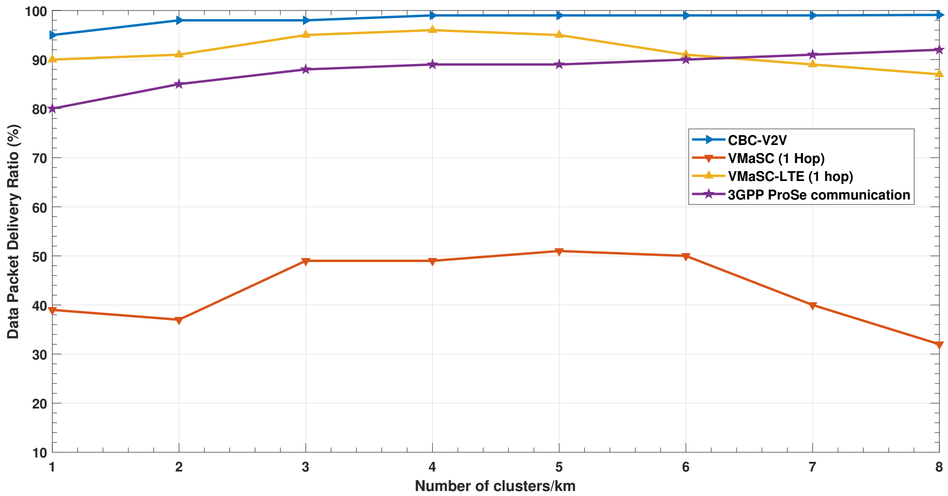


Figure 3.17: Performance comparison in terms of data packet delivery ratio

Fig. 3.16 shows the overall resource utilization of the CBC-V2V algorithm for the safety services. We compare the results with the standard ProSe solutions in terms of the number of occupied RBs. The efficient scheduler minimizes resource utilization and distribution levels. In the CBC-V2V, each of the CH acts as a scheduler and distributes the resources among its CMs using the proposed round-robin scheduling technique. Radio resources are initially allocated to the CH for each cluster of nodes. The CH then use the round-robin resource scheduling among its CMs (i.e., vehicles) using vehicle ID. The round-robin scheduling approach tries to distribute network resources fairly to all active users in the long term by granting an equal number of Physical Resource Blocks (PRBs). Two clusters can be served in a single subframe, and non-overlapping clusters can share the same resource. This reduces the utilization of the control channel for resource allocation thus reducing the control signalling overhead. Due to the lower control signalling requirements as shown in Fig 3.15 and 3.12, the resource utilisation can be reduced compared to the 3GPP ProSe technique by introducing efficient resource allocation and clustering techniques.

Fig. 3.17 shows the Data Packet Delivery Ratio (DPDR) of the CBC-V2V technique and compares it with two existing standard procedures. The DPDR algorithm is characterized by the proportion of the total number of received safety packets to the total number of scheduled safety packets. Due to the closer vicinity of vehicles, the DPDR value increases with the number of clusters. As shown in the figure, 3GPP ProSe communications and the system based on IEEE 802.11p and IEEE 802.11p/LTE standard, such as the VMaSC (1 hop) and the VMaSC-LTE (1 hop), offers the lowest DPDR value, because, at higher vehicle density, data packets are lost due to increased collisions increases at the MAC layer. The proposed CBC-V2V is contention-free because the sidelink/PC5 resource scheduling is implemented centrally at eNodeB. Since all the vehicles in the simulation are associated with the same eNodeB, the collisions are avoided even for the highest considered vehicle density.

3.4.2.1 Total end-to-end delay

The total end-to-end delay ($\delta E2E$) for the transmission of a safety message consists of two major delay components as

$$\delta_{E2E} = \delta_{PD} + \delta_{D2D} \tag{3.5}$$

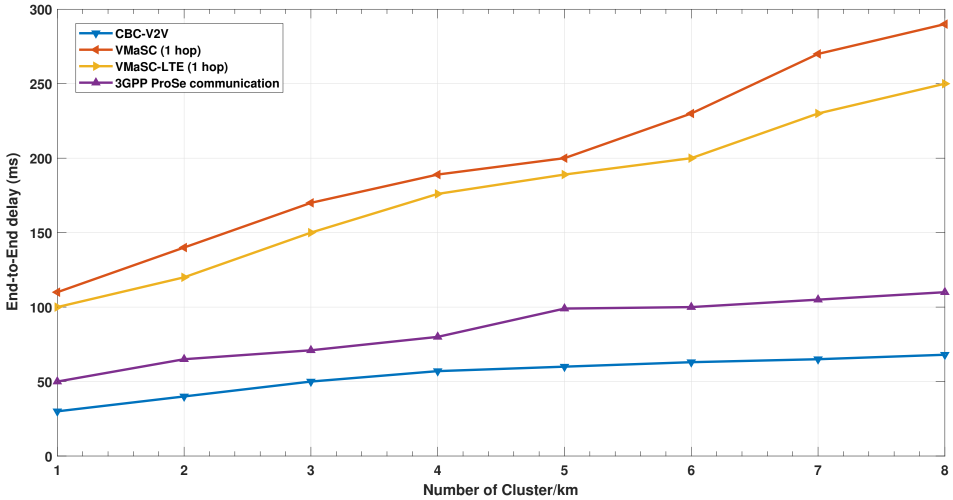


Figure 3.18: Performance comparison in terms of total E2E packet delay

Where δ_{PD} represents the total delay in peer discovery, which is the time difference between sending a request for registration and receiving an eNodeB response, and $\delta D2D$ represents the total delay in D2D packet communication, which is the sum of the intra-and inter-cluster delays in communication. To ensure timely delivery of active safety messages, the maximum delay (i.e., $\delta E2E$) of the safety message should be less than the required delivery delay (i.e., $Tsafety$). Fig 3.18 presents the delay analysis of the CBC-V2V algorithm as a function of the total number of clusters formed based on the number of vehicles/km. The results show that the CBC-V2V outperforms the traditional approaches such as the 3GPP ProSe communication, VMaSC (1 hop), and the VMaSC-LTE (1 hop) for the CAM safety message transmission in a VANET. As shown in equations (3.1 and 3.2), all the delay components CBC-V2V are deterministic with a small range of variabilities due to the message arrival process and the time frame structure of the channel. The result shows that CBC-V2V offered a much lower end-to-end delay compared to the existing protocols. lower end-to-end delay is achieved due to the absence of any contention process in the LTE network. The contention process introduces a longer delay, particularly with higher node densities in a cluster, mainly due to the retransmission requirements.

The CBC-V2V algorithm is less sensitive to the cluster size variation due to use of multicast technique. However, as shown in the figure 3.18, when the vehicle density increase, the end-to-end delay for CBC-V2V, slightly increase due to the use of the round-robin packet transmission techniques.

3.5 Summary

This chapter has introduced an advanced new cluster-based V2V packet communication architecture combined with an EPC level peer discovery model suitable for vehicular safety applications. The ESPD model reduces the control signalling overhead and end-to-end delay with the awareness of proximity utilizing the GPS information compare to the existing protocols VADD and 3GPP EPC level peer discovery. The CBC-V2V also combines a cluster-based round-robin scheduling technique to distribute the radio resource among the cluster nodes. The CBC-V2V can improve resource utilization and reduce the end-to-end delay to meet the QoS requirements of the safety services in VANETs. Simulation results show that the CBC-V2V offers higher QoS than do the IEEE 802.11p and other LTE networking architectures.

Chapter 4

LTE-Direct Inter-Cluster Communication and Multicast Transmitting Power Control Protocols for periodic safety Message Transmission

4.1 Introduction

Clustering techniques have been applied in the VANET to support various networking tasks such as load balancing, improving QoS and information dissemination in high density networks [93]. In a cluster-based communication system, the first layer of the network is called intra-cluster communication, where a cluster member can directly communicate with its cluster head or a nearby cluster member within the same cluster. The second level of the network supports inter-cluster communication, where a cluster head communicates with nearby cluster heads via road side infrastructures.

However, inter-cluster communication using road side infrastructure may result in higher end-to-end delay and significantly degrade the performance of safety services in VANETs [93].

In Chapter 3, a Cluster-Based-Cellular Vehicle-to-Vehicle (CBC-V2V) communication architecture [94] [95] is presented. The CBC-V2V architecture combines a peer discovery, resource allocation and intra-cluster communication schemes to satisfy the latency and reliability requirements of the Cooperative Awareness Message (CAM) transmission. The proposed intra-cluster schemes utilize the sidelink communication channels where the our peer discovery model and the D2D multicast data packet transmission technique show significant performance improvement in terms of resource utilization, data packet delivery ratio and end-to-end delay to meet the QoS requirements of safety services in VANET.

Fig 4.1 shows a typical highway scenario where a LTE-based clustered vehicular network architecture is presented. In this vehicular network, multiple clusters are used to support CAM message transmissions using the D2D multicast mode. Cluster areas are shown using circular boundaries, where each cluster contains a number of member vehicles controlled by the respective cluster heads. Each cluster has edge nodes that which have neighbours in the adjacent cluster. To maintain safety requirements, all neighbouring nodes in the adjacent cluster in the same lane must exchange their CAM messages for cooperative collision avoidance, as well as neighbouring nodes in the adjacent cluster in adjacent lanes for lane change warning and blind spot detection. Therefore, a low delay inter-cluster communication algorithm needs to be developed to enable the neighbouring node in adjacent clusters to exchange CAM messages.

As mention previously, for intra-cluster communication we utilized multicast transmission as an efficient way to exchange safety message between multiple recipients based on our round robin scheduling technique. However, in a high mobility

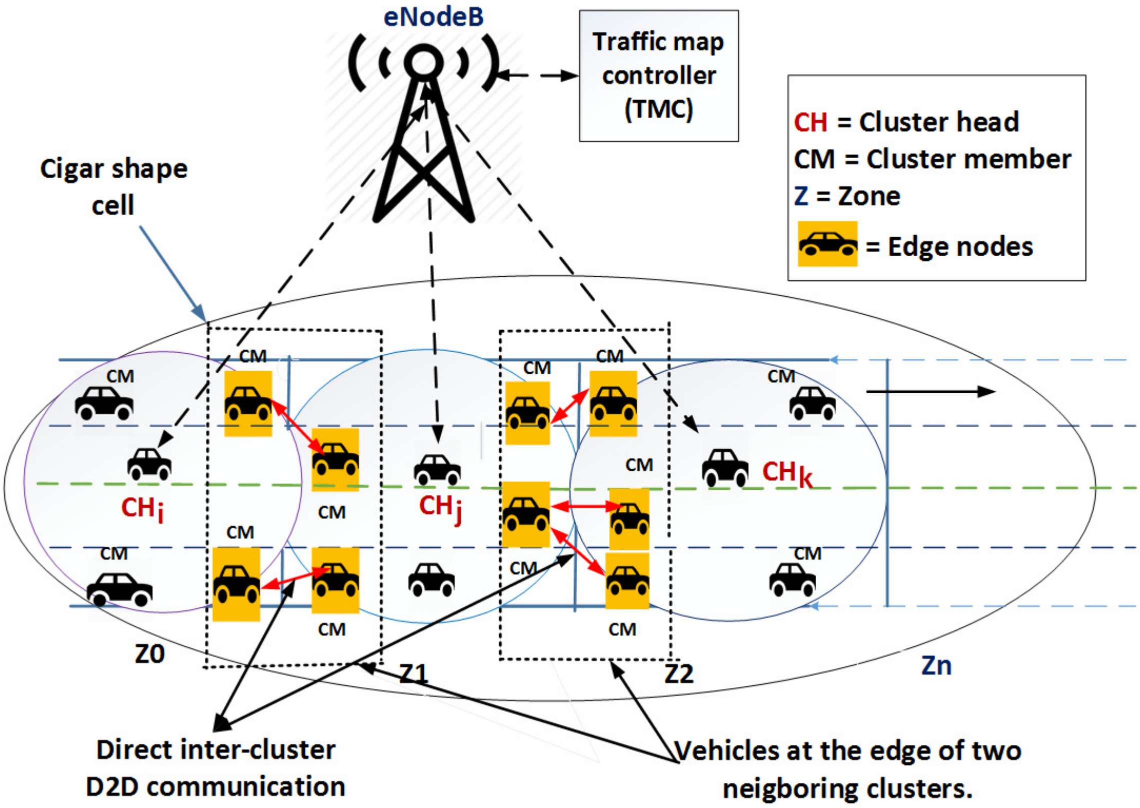


Figure 4.1: A highway scenario for the proposed inter-cluster communication in VANET

scenario, the distance between multicast transmitter and receivers could vary. As a result, the recipients of the wireless multicast may experience different channel conditions (i.e., path loss and fading effect caused by building or vehicles intervening between vehicles). Propagation characteristics in a vehicular network can change rapidly due to the variable transmission conditions generated by the movement of vehicles. Thus, if a fixed transmission power is applied to each vehicle, it will make it difficult for a multicast sender to transmit safety packet successfully to all recipients. In our proposed D2D multicast packet communication technique, a packet from a cluster node must reach to all the member nodes. In this case, there is one transmitter and N receivers, where each reception is represented by different channel coefficients. The transmitter must optimize its transmission power based on N channel characteristics, otherwise retransmission needs to be initiated on some of the links. Therefore, an efficient Transmit Power Control (TPC) mechanism needs to be developed to improve the reliability of safety message transmissions.

As discussed in Chapter 3, to accommodate a seamless and reliable exchange of information between vehicles, roadside units, and vulnerable pedestrians in the current LTE and in the future 5G networks, 3GPP has introduced C-V2X communication features in Release 14 [54]. Two additional modes of operation, termed Mode 3 and Mode 4 were introduced based on scheduling preferences. Mode 3 employs a centralized scheduling approach under the coverage of the LTE eNodeB, where two vehicles can communicate directly, but the selection of the sub-channels or radio resources for C-V2V transmission is managed by the control signalling from the cellular infrastructure. Mode 4 adopts the new PC5 interface using sidelink channels for direct communication between vehicles without the need for coverage from the LTE eNodeB.

Compare to the conventional LTE uplinks, where transmission power level can be adjusted based on the TPC command from the eNodeB [54], the communication Mode 3 and 4 in C-V2X uses a fixed transmit power level without any TPC mechanism from the eNodeB. According to the ETSI ITS recommendations, 10 dbm of transmission power level is suitable for communication Mode 4 to minimize interference among the vehicles [96]. In the literature, most of the research papers focus on transmission power control schemes for C-V2X communication Mode 4 [54] [10] [97]. However, to the best of our knowledge, the TPC techniques for C-V2X Mode 3 has not been studied much until now. An adaptive power transmission for communication Mode 3 may support higher QoS links for V2V communication.

In this chapter, two new algorithms for cluster-based multicast vehicular networks are introduced. An advanced LTE Device-to-Device (D2D) cluster communication technique, referred to as LTE-DICV2V, and a cluster-based multicast power transmission control technique, referred to as CMTPC, for the C-V2X Mode 3 communications are proposed. These algorithms support inter-and intra-cluster packet communications, offering a high packet delivery ratio for CAM messages. The LTE-DICV2V algorithm supports both inter-and intra-cluster safety packet distribution mechanisms, whereas the CMTPC algorithm is a multicast packet transmission power control technique that is used by the LTE-DICV2V algorithm. Both algorithms are combined to improve the CAM packet success rate in clustered vehicular networks. These algorithms have been proposed for an LTE-based vehicular network to achieve high QoS for a highway safety message distribution system. A new CAM message structure is also introduced to support the proposed power control algorithm.

4.2 Related work

In this section existing works related to intra- and inter-cluster communication and transit power control (TPC) techniques to improve the performance of periodic safety messages transmission in VANETs are presented. A number of transmitting power control and clustering schemes have been proposed in the literature to control network congestion, minimize the interference between conventional cellular and sidelink users and improve the safety awareness of vehicles.

Concerning the intra- and inter-cluster communication, reference [98] proposed a cluster-based D2D routing method in which vehicular nodes are clustered according to their communication range, speed and direction of movement. Data is transferred to all vehicles in the same and neighbouring clusters using the D2D communication mode. However, for the inter-cluster communication (when the source and destination are in different clusters), one or more base stations may be involved in the communication from the source to the destination. Reference [99] proposed a cluster-based broadcast mode where the cluster head forwards the multimedia data to its members by using a broadcasting technique. The proposed scheme enables users to form a cluster by using a broadcast-based information exchange mechanism and to coordinate the channel access in a cluster or between clusters to communicate with each other. Users can broadcast multimedia information using inter- and intra-cluster communication links without the help of a cellular network. However, the authors did not publish any results. In [100], Nokia proposed a voice group call service based on D2D communication. The proposed scheme can support cluster-based communication in a Public Safety (PS) situation. After forming a cluster, the cluster head transmits voice packets to cluster members using D2D links, and to the eNodeB using the uplink channel. Further, the eNodeB transmits information to cluster heads, which propagate the information to cluster members using D2D links. However, as discussed, the inter-cluster communication via road side infrastructures may result in higher end-to-end delay and significantly degrade the performance of safety services in VANETs.

Concerning the transmission power control algorithm, most of the research papers consider the vehicle's speed, inter-vehicle distance, propagation and transmission channel conditions and vehicle density information to select the optimal transmission power for periodic or event-based safety message transmission. Research work in [101] proposed a transmission power control scheme, taking into account the transmission distance between vehicles and the corresponding cluster head to adjust the transmission power of transmitters. However, in cluster-based routing, by increasing the transmission range of a cluster, transmitters may generate high levels of disruptive interference in dense traffic conditions. The work in [102] proposed an adaptive power control method based on propagation and traffic measurements in real vehicular networks. Reference [103] proposed an adaptive power control solution for a multicast service in a green cellular railway communication network. Study in [104] presented an adaptive multicast transmit power control scheme where base stations with clients share their downlink channels over an allocated frequency band on a spatial-TDMA basis. The algorithm works in two modes, such as centralized mode and distributed mode, where base stations are time-slot synchronized and to determine their transmission schedules and transmit power levels.

To address dynamic power allocation issues of vehicles switching between different base stations, authors in [105], proposed a NOMA-Based power allocation algorithm which is depends on the distance between the BS and vehicles to allocate transmission power. In [106], authors proposed a NOMA-enabled hierarchical power control scheme for dynamic power allocation from BSs to vehicles. This proposed scheme improved the performance in terms of switching rate and spectrum efficiency. However, the performance of proposed scheme can be degrade because of the feedback delay.

Concerning the Mode 3, the authors in [107] presented a joint power control and resource allocation scheme for safety-related V2X communications in the mixed environment where the Vehicular users (VUEs) and Conventional Cellular Users (CCU) co-exists. The proposed model allow Vehicular Users (VUEs) to work either in the Mode 3 (centralized system) or in the Mode 4 (distributed system). The Mode was further divided into two different communication modes: dedicated mode and reuse mode. Along with the stringent restrictions for latency and reliability, the authors also consider the ProSe Per-Packet Priority (PPPP) data transmission scheme proposed by the 3GPP standard [21] for safety-related V2X information. For data transmission, the application layer assigns an independent ProSe Per-Packet Priority to each V2X message to be transmitted at a lower layer. Furthermore, the PPPP is used by the ProSe access stratum to prioritise both, intra and inter UE data transmissions. Further, the authors propose different power control approaches, reffered to as Vacant Resource Blocks and Power Allocation (VRBPA) and Occupied Resource Blocks and Power Allocation Algorithm (ORBPA) for each of the proposed resource allocation modes, such that, in each case, the information value of a single VUE is maximized and the co-channel interference between the VUEs and its reuse CCUs is drastically reduced.

Several research studies on the performance enhancement of C-V2X Mode 3 and 4 are limited to specific performance metrics. The above proposals related to communication Mode 3 and Mode 4 only focus on the development of TPC schemes to improve system performance in the terms sidelink resource allocation. The algorithms do not consider the scenario where the path loss is due to variable inter-vehicle distance and speed of vehicles. These issues can considerably impact a V2X system performance. Resource allocation in C-V2X can either be carried out using Mode 3 or without any network support using Mode 4.

This motivation has led us to propose two new algorithms for cluster-based multicast vehicular networks. An advanced LTE Device-to-Device (D2D) cluster communication technique, referred to as LTE-DICV2V and a multicast power transmission control technique, referred to as CMTPC are proposed. These algorithms support inter- and intra-cluster packet communications, offering a high packet delivery ratio for the CAM messages. The proposed algorithms have several key advantages compared to the currently published works. Our proposed algorithm LTE-DICV2V differs from the above works because the proposed algorithm supports both inter- and intra-cluster communication using LTE D2D links in a multicast mode that is less network resource intensive. We also propose a multicast power control algorithm, CMTPC, which adapts the multicast transmission power of transmitters based on N-channel feedback where the multicast channel condition could change with the vehicle mobility. The key advantage of the CMTPC algorithm is that it requires no additional channel estimation processes and it uses received CAM messages to estimate the channel conditions.

4.3 LTE-DICV2V System model

As depicted in Fig. 4.1, we consider a cigar-shaped cell for a highway scenario where traffic is flowing in both directions in a multi-lane road. We assume that each vehicle is equipped with a GPS device capable of providing accurate position information. The highway is divided into fixed size areas, referred to as zones. Vehicles within each zone form a cluster where they exchange, safety messages among all cluster members. A Traffic Map Controller (TMC) keeps track of each cluster on the road in its database. The TMC is located within the eNodeB. Fig 4.1 shows the edge nodes in each cluster, which need to exchange CAM messages with their cluster members as well as with edge nodes of their neighbouring cluster. In Chapter 3, we utilized a unicast LTE communication technique for inter-cluster communication where each edge node shared its safety messages with its neighbours through the eNodeB. However, inter-cluster communication using roadside infrastructure may result in higher end-to-end delay and increased LTE resource utilization. Due to longer link distances for inter-cluster communication, it may also affect the age of the safety packets. The safety data may become outdated and will not be useful once it reaches to the destination. In this paper, we propose a new direct communication technique for edge nodes to share the CAM messages.

4.4 Proposed Inter-Cluster Vehicle-to-Vehicle Communication

Inter-cluster communication will allow each cluster to distribute their safety information to a neighbouring cluster. The range of communication can be decided based on the safety application needs. Our proposed algorithm use edge nodes to forward packets to the neighbouring nodes. Below we first discuss the edge node selection techniques, then we introduce the LTE-DICV2V algorithm.

4.4.1 Edge nodes selection

We utilize the proposed clustering algorithm presented in Chapter 3 to support direct inter-cluster communication among edge nodes located at the boundary of neighbouring clusters. In the proposed mechanism, the vehicle with the lowest average relative speed and the maximum distance from its current location to the zone boundary is chosen as the cluster head (CH). The CH stays within a cluster for a longer period to maintain the cluster stability. In the LTE-DICV2V algorithm, as soon as a CH is selected and the cluster is formed, the CH selects its farthest members as the edge nodes. As shown in the Fig 4.2, it is possible that two or more members have the same distance from their CH. Therefore, a cluster may contain multiple edge nodes and the edge nodes will be present at both ends of a cluster. Once the CH identifies the edge nodes, it will share their identities with neighbouring CHs via the eNodeB.

4.4.2 LTE-Direct Inter-Cluster for Vehicle-to-Vehicle Communication (LTE-DICV2V)

In this proposed architecture, inter-cluster communication is required to share safety messages among the edge nodes of two neighbouring clusters. As shown in a Fig. 4.2, vehicle EN_{J1} is in the neighbour list of EN_{i2} but it belongs to the neighbouring cluster CH_j. Both the EN_{j1} and the EN_{i2} are located at the edge of the two neighbouring clusters (i.e., CH_i and CH_j). After the Edge Nodes (EN) selection, each CH sends their EN list via the eNodeB to the Traffic Map Controller (TMC) which stores the EN list in its database. Further, the TMC, which keeps the up-to-date information about each cluster in its database, will broadcast the stored EN list to all CHs on the road. In this way, each CH will receive the information about the edge nodes of their neighbouring cluster. In this example, CH_i and CH_j are two neighbouring clusters that send their EN list to the TMC. Once the TMC broadcasts the EN

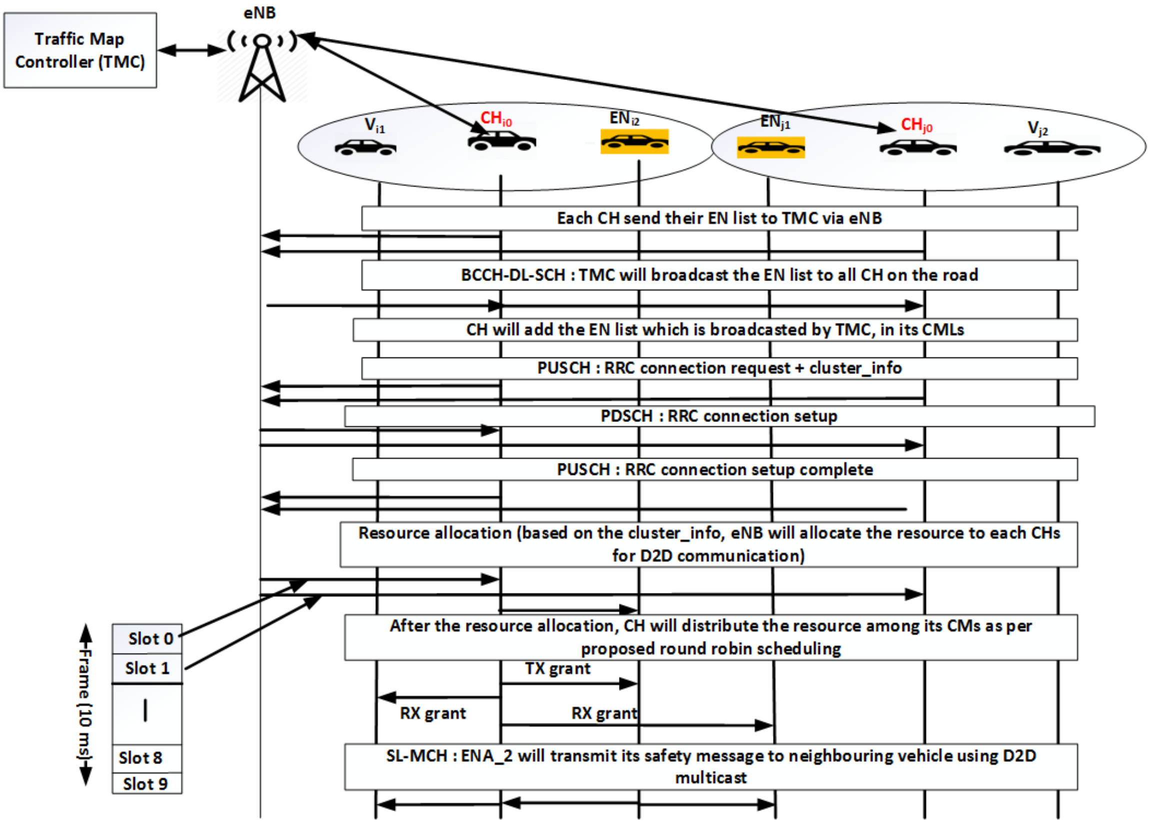


Figure 4.2: The proposed LTE-DICV2V algorithm

list to all the CHs on the road, CH_i can identify the edge nodes (i.e., EN_{j1}) of its neighbouring cluster (i.e., CH_j). Similarly, CH_j can identify the edge nodes (i.e., EN_{i2}) of its neighbouring cluster (i.e., CH_i). As a result, CH_i adds the edge node of a neighbouring cluster to its Cluster Member list (CML). In such cases, EN_{j1} on the edge of cluster CH_j will also become the CM of CH_i and hold the memberships of two clusters.

For each cluster node, radio resources are first allocated to the CH by the eNodeB. Each CH further schedules the resources among its CMs using a round robin scheduling technique, as described in Chapter 3. In this case, the resource scheduling is carried out dynamically by assigning multiple users to the same slot in a round robin fashion using their IDs in ascending order. Therefore, members of a cluster can share the same slot in turn to transmit their own CAM in the multcast mode.

According to our proposed sidelink channel structure for CBC-V2V communication architecture presented in Chapter 3, ten subframes appear every 100 ms and are shared among different clusters for the D2D multicast communication. Since each cluster is allocated a single slot, two clusters can be served by a single subframe. The LTE slots can be reused at a certain distance interval.

As shown Fig. 4.2, the EN_{j1} is now a member of the CH_{i0} and gets its grant from CH_{i0} to receive the safety packets from EN_i2. The same procedure will be followed by other clusters. Thus, vehicles located at the edge of two clusters tunes to different slots in each CAM message cycle. Vehicle EN_{j1} tunes to two different slots (i.e., slot 0 and slot 1) at the same time. Once the EN_i2 receives slot 0 in its turn, based on its vehicle ID, it will multicast its own safety to its neighbouring vehicles V_{i1} and EN_{j1} located at the edge of the neighbour cluster (CH_{j0}). Due to the half-duplex transmission nature of TDD transceivers, a D2D-enabled TDD node cannot receive and decode messages while it is transmitting. Therefore, in a cluster, when one vehicle is transmitting, the remaining vehicles will receive the CAM from the transmitting vehicle. Using the algorithm, the same D2D resources can be assigned to different non-overlapping clusters to maximize the spectrum reuse.

4.5 Clustered Multicast Transmitting Power Control (CMTPC)

In a vehicular network, the distance between a multicast transmitter and its receivers varies over time. However, the major challenge is how the transmitter determines and adapts (if the channel condition changes) its transmit power to optimally transmit data packets to receivers? To solve the above problem, we propose the CMTPC algorithm, where each multicast transmitter selects the transmitter power based on the channel conditions, namely the received signal strength, transmit power and

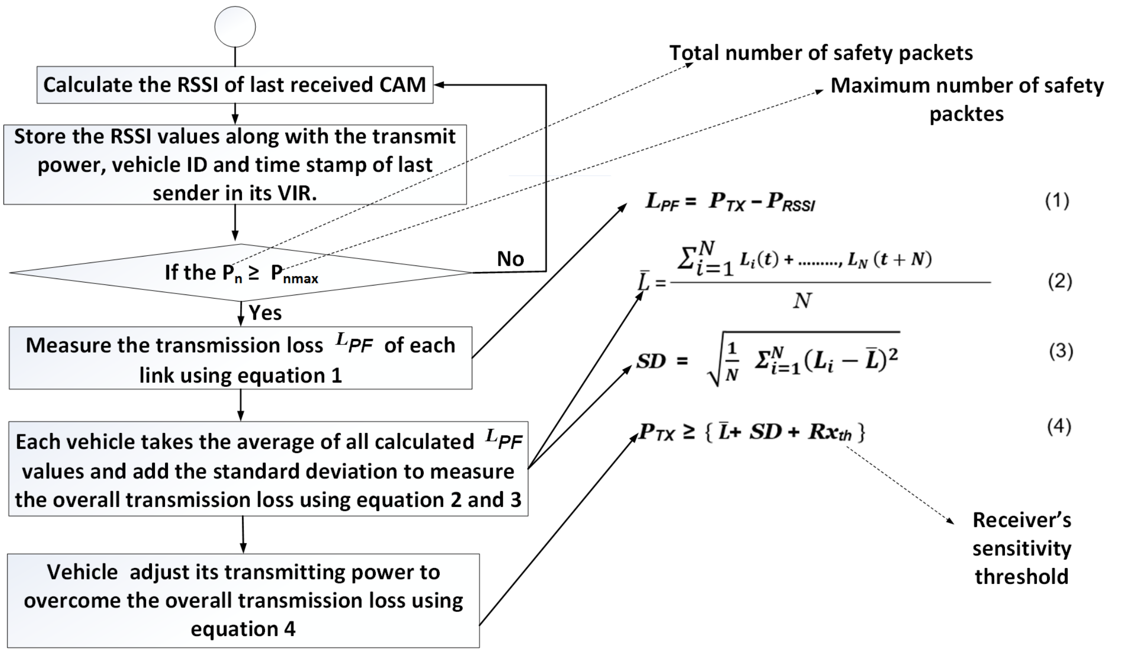


Figure 4.3: Operation of the CMTPC algorithm

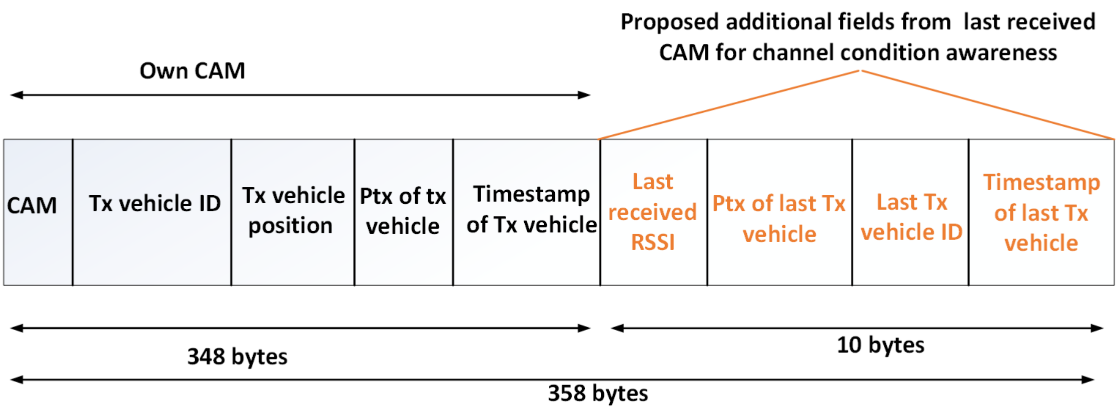


Figure 4.4: The proposed CAM message structure

timestamp of the last received packet.

The CMTPC procedure is summarized in Fig. 4.3. Assume a set of vehicles inside a cluster $C = \{V_1 ..., V_n\}$ are moving on highway road in the same direction. Each vehicle V_i multicasts its safety packet, using a certain transmit power $P_{TX} \epsilon \{0, P_{max}\}$. Once the vehicle receives the safety packet from its neighbouring vehicle, it will calculate the Received Signal Strength Indicator (RSSI) of the last received packet and record it, along with other information (i.e., Transmit power, vehicle ID, and

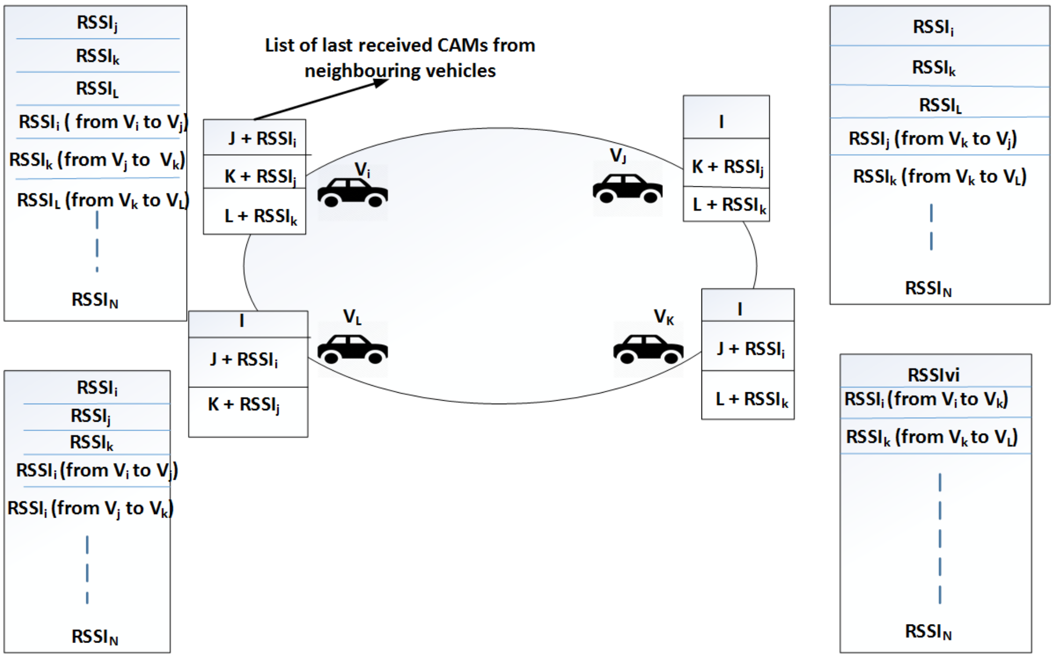


Figure 4.5: Operation of the CMTPC algorithm

timestamp) from the last sender, in its Vehicle Information Register (VIR).

Similarly, each receiving vehicles records the received RSSI along with the information from the last sender in its VIR. Further, for channel condition awareness, each vehicle will share the stored information of the last received packet with its neighbouring vehicle. For this purpose, each vehicle adds the stored information toits own safety packet, and multicast it to its neighbouring vehicles. It is important to note that each vehicle only shares the information from the last received packet from its VIR. To facilitate the algorithm implementation in a practical network, we propose to include four new fields (RSSI value of the last received packet, vehicle ID, transmitting power and the timestamp). In total, an additional 10 bytes are included in the CAM message, as illustrated in Fig. 4.4.

Fig 4.5 shows an example in which each vehicle inside a cluster transmits its safety packet using the proposed multicast approach in the round robin manner. In the first cycle of multicast transmission, vehicle V_i multicasts its safety packet to its neighbouring vehicles (V_j,V_K and V_L). Once the neighbouring vehicles receive the safety packet from vehicle V_i, they will calculate the RSSI of the received packet and record it along with other information (transmit power, vehicle ID, and timestamp) in its Vehicle Information Register (VIR). Further, based on the round robin scheme, the next vehicle V_j will multicast its safety packet along with its stored information to its neighbouring vehicles (i.e., V_i,V_K and V_L). This information will propagate to all members in the same manner.

The same process will be followed by all cluster members to propagate every member's information within this and neighbouring clusters. In this way, each vehicle will store multiple RSSI values depending on the number of safety packets received from neighbouring vehicles in each transmission cycle. Using the collected information from the last received packets, each vehicle creates an array of RSSI values in its VIR and builds knowledge about the channel conditions in its local surroundings for the next transmission.

Assume in each round, vehicles create an array $A_N\big(t\big) = \big\{RSSI_i, RSSI_j....., RSSI_N\big\}$ of the last received RSSI values based on the total number of received safety packets, which are represented by P_n. We consider that after receiving the maximum number of safety packets represented by P_{nmax} from neighbouring vehicles, each vehicle will measure the transmission loss represented by L_{PF} of each link, which includes both path and fading losses. The link transmission loss for each path can be calculated using equation (4.1). Note that transmitter power values can be extracted from the CAM packets as shown Fig 3.

$$L_{PF} = P_{TX} - P_{RSSI}. \tag{4.1}$$

where L_{PF} represents total loss which includes a path and fading losses measured by the each vehicle, using stored information, where P_{TX} represents the transmitting power and P_{RSSI} indicates the received signal strength of the last received packets in its VIR.

Further, each vehicle takes the average of all calculated L_{PF} values and adds the standard deviation to calculate the overall multicast transmission loss. $\overline{L}$ and SD represent as the average and standard deviation of all the multicast transmission losses.

$$\overline{L} = \frac{\sum_{i=1}^{N} L_i(t) + \ldots.., L_N(t+n)}{N} \tag{4.2}$$

$$SD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(L_i - \overline{L}\right)^2}. \tag{4.3}$$

Based on the multicast loss estimation of each previous multicast transmission cycle, each vehicle adjusts its transmit power to increase the packet reception success probability. The transmission power of a multicast transmitter is calculated using (4.4).

$$P_{TX} \geq \left\{\overline{L} + SD + Rx_{th}\right\}. \tag{4.4}$$

where Rx_{th} is the receiver's sensitivity threshold.

4.6 Simulation Model and Performance Analysis

A simulation model was developed (presented in section 4.6.1) to assess the effectiveness of the proposed algorithms. The propagation model used in the simulations is the Nakagami-m fading, with $m = 1, 2, 3$ to represent a wide range of fading intensities. We used the Nakagami fading channel because it is a generalised distribution that can model Line-of-sight (LOS) and non LOS fading environments. The model is used for its flexibility and many empirical studies [108] support the applicability of Nakagami fading for highway communications. The received power follows the Gamma distribution with the shape parameter m as shown in (4.5).

$$P_r(d;m) \approx \Gamma\Big(m, \frac{P_{rdet}(d)}{m}\Big). \tag{4.5}$$

An OMNET++ version 5.1.1 simulation model is developed using the SimuLTE [17] [16] that utilizes the INET framework 3.4.0. For enhanced traffic simulation, GPS data incorporation and mobility support, we use the Veins with a realistic mobility model generated by the microscopic road traffic simulation package Simulation of Urban Mobility (SUMO) [59]. Results from the simulation were acquired by taking the average of the 20 simulation runs with different seeds value. The key simulation parameters are listed in Table 4.1. The SimuLTE model implements direct inter- and intra-cluster communications for V2V communication utilizing the CMTPC power control algorithm for communication Mode 3. Some of the major steps of CMTPC in the simulation are presented in algorithm 1.

For comparison purpose, we also implemented communication C-V2X Mode 4 introduced in Release 14 [109] and an existing Adaptive Transmit Power Control Algorithm (A-TPC) presented in [110]. The key simulation parameters for A-TPC and 3GPP Mode 4 are listed in Table 4.2. To implement the C-V2X mode 4 and A-TPC, we used an open source OpenC-V2X Mode 4 frame work. The detail description of OpenCV2X is given in section 2.5.0.6 of chapter 2. In C-V2X Mode 4, each vehicle selects transmission resources based on channel sensing referred to as sensing-based semi-persistent scheduling. Fig 4.6 presents the flow diagram for C-V2X mode 4. Specifically, each vehicle executes the following steps for resource selection and reservation for V2X message transmissions [111] [112] [113].

- Channel sensing: For channel sensing, vehicles keep measuring the sidelink received signal strength indication (SRSSI) on each sub-channel as a measure of

Algorithm 1 CMTPC

1: Initialization
2: Input = information of last received CAM (i.e., RSSI, P_{TX}, vehicle ID and timestamp)
3: output= (a power setting for vehicle V_i)
4: **while** First transmission cycle t **do**
5: V_i calculate the P_{RSSI} values of last received safety packets;
6: Create an array $A[RSSI_i.....,RSSI_N]$ of collected RSSI values in its VIR;
7: **for** $i = 0, i < P_{nmax}, i++$ **do**
8: **if** $i < P_{nmax}$ **then**
9: Repeat the steps 5 and 6;
10: **else**
11: Calculate the L_{PF} for previous cycle based on the RSSI values from an array using equation (4.1);
12: **end if**
13: **end for**
14: **end while**
15: Calculate the $\overline{L}$ and SD of all path loss values using equation (4.2) and (4.3)
16: Adjust the transmitting power of V_i to overcome the P_{Lmax} using equation (4.4); =0

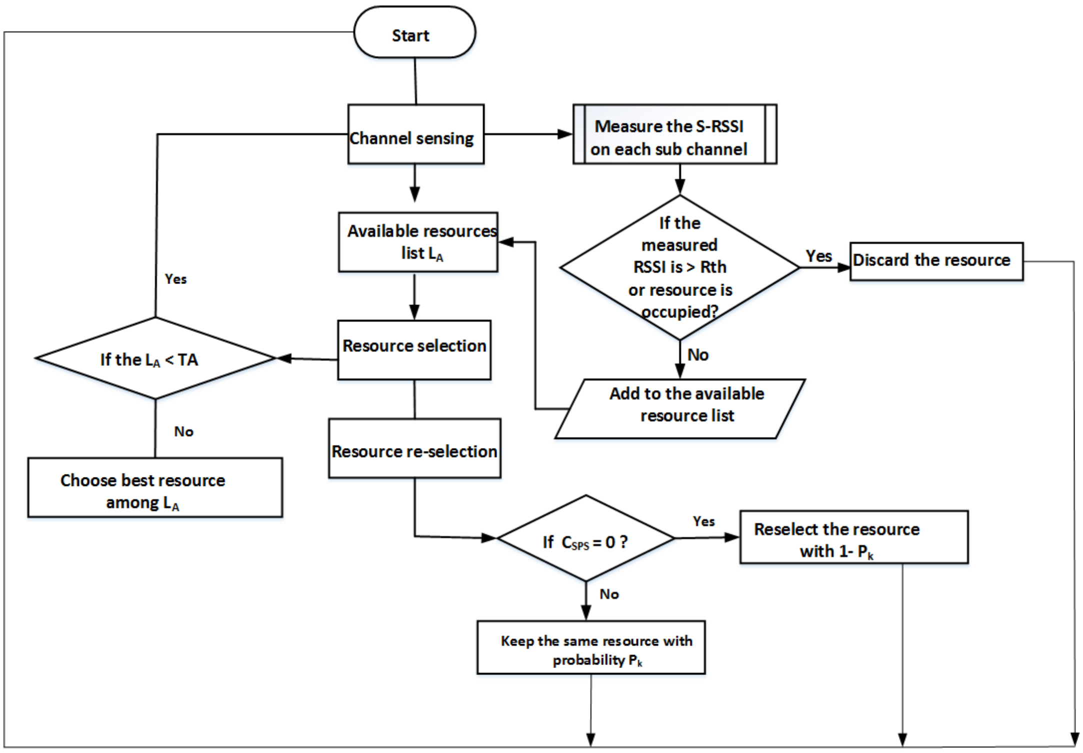


Figure 4.6: Flow diagram of C-v2x mode 4

interference every subframe and collect the sensing measurements for a predefined sensing period, typically set to be 1s.

- Available resource list: Based on the sensing measurement results, the vehicle creates its own available resource list, L_A.
- Resource selection: The vehicle identifies the best 20 percentage resources (i.e., the resources having the lowest 20 percentage RSSI values) among L_A. Finally, the vehicle randomly selects transmission resources among the best 20 percentage resources. Once selecting its transmission resource, the vehicle reserves the same frequency resources for the random number of subsequent transmissions with the same transmission interval. For example, the reserved number of subsequent transmission for CAM messages can be between 5 and 15.
- Resource reselection: After each packet transmission, the number of remaining consecutive packets, denoted as SPS counter, decreases. If a vehicle encounters zero SPS counter, it decides to maintain its resources with a probability P_k or reselect resources with a probability 1 - P_k.

To implement autonomous resource scheduling in communication Mode 4, we listed all the required parameters for autonomous resource scheduling in the configuration files based on the simulation study presented in [110]. All the parameters have pre-defined values for the highway traffic scenario in the configuration files will be executed during the initialization procedure. All CAM messages generated at the same transmission frequency (i.e., 10 Hz) and use the same Modulation and Coding Scheme (MCS) settings for each traffic scenario. Following the ETSI recommendation, C-V2X is configured with 5 sub-channels per sub-frame and each sub-channels has 10 RBs [54].

The model considers a multi lane highway scenario where the vehicles are distributed according to the Poisson distribution process. We consider a 5-km highway

Table 4.1: Main simulation parameter for LTE-DIV2V and CMTPC

Parameter	**Value**
Vehicle speed	40-70 km/h
Number of vehicles	96 vehicles/km
Inter-vehicle distance	10 to 120m
Road length & number of lanes	5km & 4
Carrier frequency	2.6 GHz
Transmission time interval (TTI)	10 ms
CAM generation rate	10 packets/sec
Transmission bandwidth	3MHz (i.e., 15 RBs)
Path loss model	Free space
P_{nmax}	30 packets
Fading model	Nakagami-m (m = 1, 2, 3)
eNodeB Tx power	46 dBm
UE Tx Power	26 dBm (Initial)
Noise figure	5 dB
Receiver sensitivity threshold Rx_{th}	-105 dBm
Cable loss	2 dB
Simulation time	800s
Packet size	358 bytes
T_{safety}	100 ms
Cluster size	6 to 12 vehicles/cluster

Table 4.2: Main simulation parameter for C-V2X Mode 4 and A-TPC

Parameter	**Value**
Sensing Period	1 sec
Receiver sensitivity threshold Rx_{th}	-105 dBm
Probability of maintaining the same resource p_k	0
Path loss model	Free space
Fading model	Nakagami-m (m = 1, 2, 3)
eNodeB Tx power	46 dBm
UE Tx Power	23 dBm (for higher vehicle density)
UE Tx Power	10 dBm (for lower vehicle density)
UE Tx Power	23 dBm (in case of 3GPP mode 4)
Antenna gain	3 dB
Minimum SINR	2.76 dB
Simulation time	800s
CAM Packet size	358 bytes

with four lanes in the same direction. The clustering process starts in the simulation at the 160th second when all the vehicles have entered the road. We analyse the

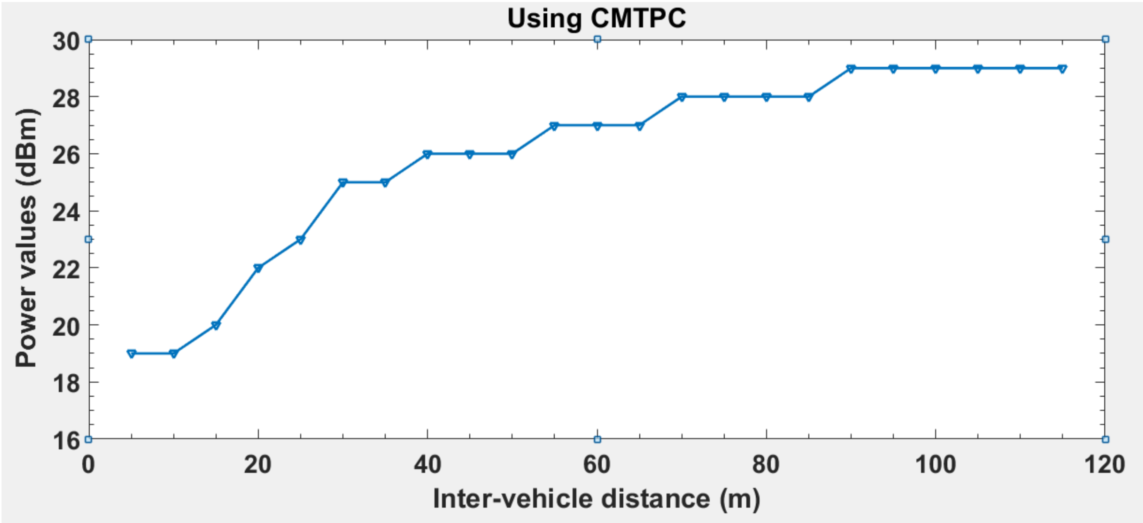


Figure 4.7: Transmit power values using CMTPC

performance of the proposed algorithm in two scenarios. In the first scenario, each vehicle uses a fixed transmission power to transmit its safety packets using communication Mode 3 and Mode 4. In the second scenario, each vehicle adjusts its power dynamically using the CMTPC algorithm for communication Mode 3 and compares this with Mode 3 and Mode 4 using fixed transmission power. The model is simulated for different inter-vehicle distances, different cluster sizes and different fading intensities. According to the proposed round robin scheduling, each cluster node receives an equal share of radio resources for the D2D communication.

Fig 4.7 shows the adapted transmission power values using the CMTPC algorithm for different inter-vehicle distances. The algorithm enables each vehicle to adjust its transmit power based on the channel conditions and the locations of the member vehicles. Each vehicle estimates the average multicast link loss based on the signal strength of the N received packets from its neighbouring vehicles. The figure shows that for longer inter-vehicle distances (i.e., from 55 to 115m), the transmission power values vary from 27 to 29 dBm. At a lower distance range (between 10 to 50m), the transmission power values vary from 19 to 25 dBm.

Fig 4.8 shows the cumulative distribution function (CDF) of the inter-vehicle dis-

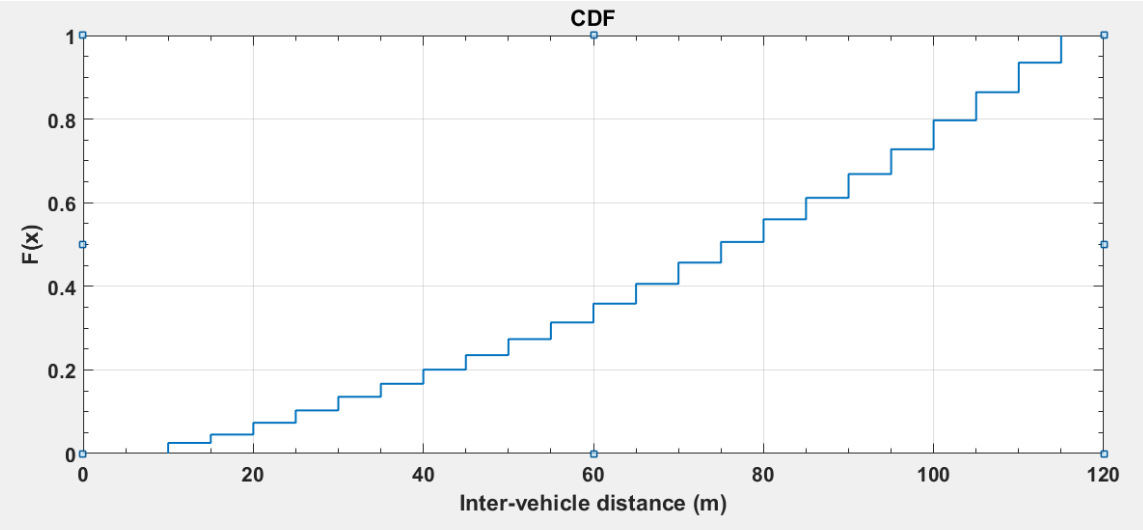


Figure 4.8: Cumulative Distribution Function of inter-vehicle distance

tances, where the inter-vehicle distances are modelled by an exponential distribution function using a mean value of 70 meters. Using the exponential distribution in the simulation settings, 40% of the vehicles have an the inter-vehicle distance from 10 to 60 m and remaining vehicles are having the inter-vehicle distance from 60 to 115 m.

Fig 4.9 shows the received signal strength values of the cluster communication techniques with and without using the CMTPC algorithm. The RSSI values are measured for different fading intensities. The figure shows that for fixed power transmission, the RSSI values drop below the receiver sensitivity level of -95 dBm. For the fixed power transmission, we use the value of 26 dBm. For longer inter-vehicle distances (from 65 to 115m) and for a higher fading intensity (m = 1), the received signal strength drops to -120 dBm. As compared to the fixed transmitting power operation, the CMTPC algorithm improves the received signal strength, maintaining received signal power levels above the receiver sensitivity level of -95dbm.

Figure 4.10 shows the packet success rate of the LTE-DICV2V algorithm with and without the CMTPC algorithm. The packet success rate is calculated for different fading intensities with respect to the inter-vehicle distance. The figure shows that almost 96% of the transmitted packets are successfully received for different inter-

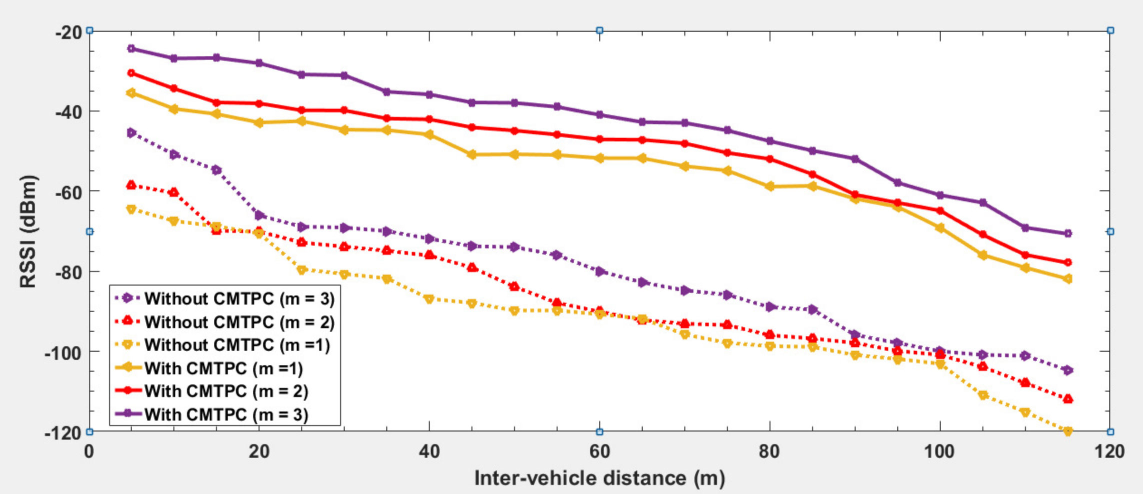


Figure 4.9: RSSI values with and without using our proposed CMTPC

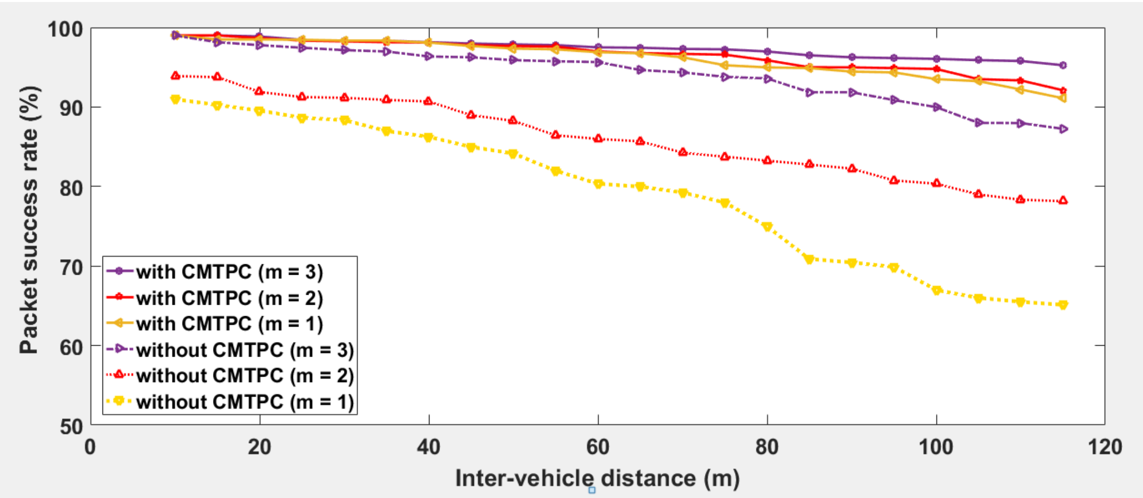


Figure 4.10: Packet success rate with respect to different inter-vehicle distance with and without using proposed CMTPC

vehicle distances for good Channel condition with m = 3. The packet success rate decreases as the inter-vehicle distance increases. For $m = 1$, the packet success rate drops by to 65% at the inter-vehicle distance of 115m. The figure shows that when the CMTPC algorithm is used, almost 90% of the transmitted packets are successfully received at larger distances (up to 115m) with higher fading intensity (i.e., m = 1). At 115m distance, the proposed algorithms provide an improvement of almost 26% over the fixed transmission power operation.

Fig. 4.11 presents the end-to-end delay analysis of our cluster-based architecture

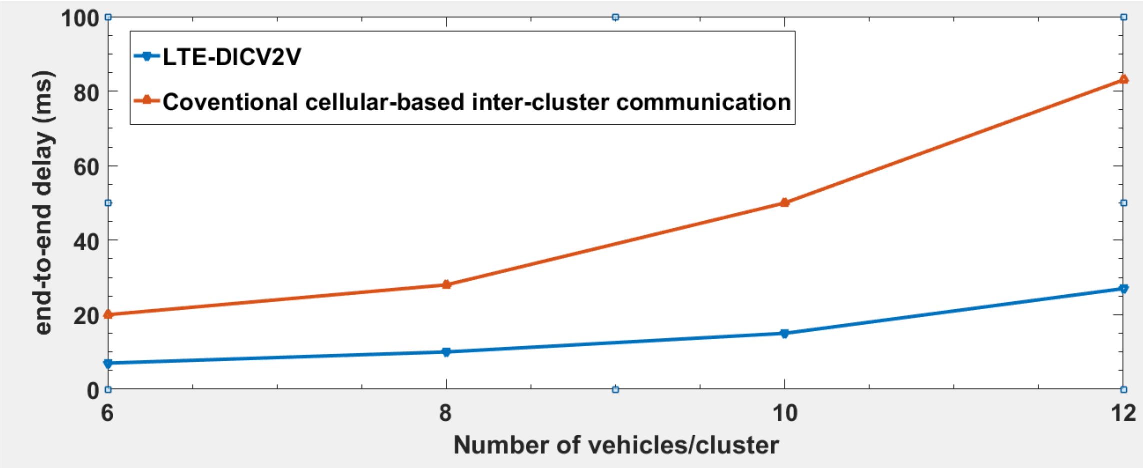


Figure 4.11: Performance comparison in term of end-to-end delay

as a function of the total number of vehicles/cluster. The figure evaluates and compares the overall end-to-end packet delay of the proposed LTE-DICV2V algorithms with a conventional cellular-based inter-cluster communication technique operating in the unicast mode [114]. Due to the use of a direct link between the edge nodes of two neighbouring clusters, the LTE-DICV2V algorithm offers much lower end-to-end delay for the CAM packet distribution compared to the unicast cellular communication technique. The cellular-based inter-cluster communication technique needs at least two unicast links and a multicast link to share the CAM messages among the edge nodes in neighbouring clusters.

Fig 4.12 shows the received signal strength values for our proposed scheme CMTPC, A-TPC, and 3GPP Mode 4 communications. The RSSI values are measured for different fading intensities. The A-TPC algorithm proposed in [110] considers the power adaptation for the vehicles in a highway scenario only with a fixed traffic density. However, power allocation based on fixed vehicle density is not practical. The power variation from 10 dBm to 23 dBm with a step of 13 dBm can increase the interference among vehicles and could result in overall performance degradation. The figure shows that for A-TPC and conventional 3GPP Mode 4 using fixed power transmission, the RSSI values drop below the receiver sensitivity level of -105 dBm. For the fixed power

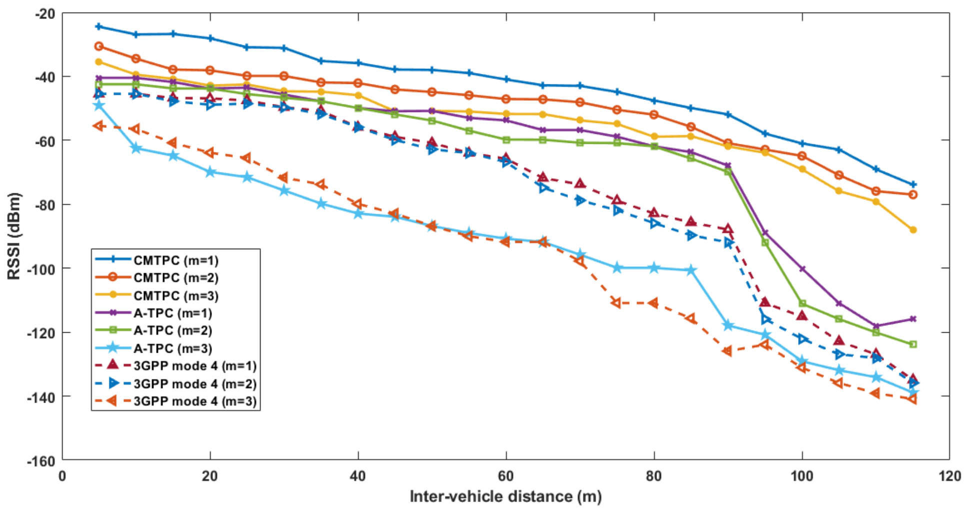


Figure 4.12: RSSI values with and without using our proposed CMTPC

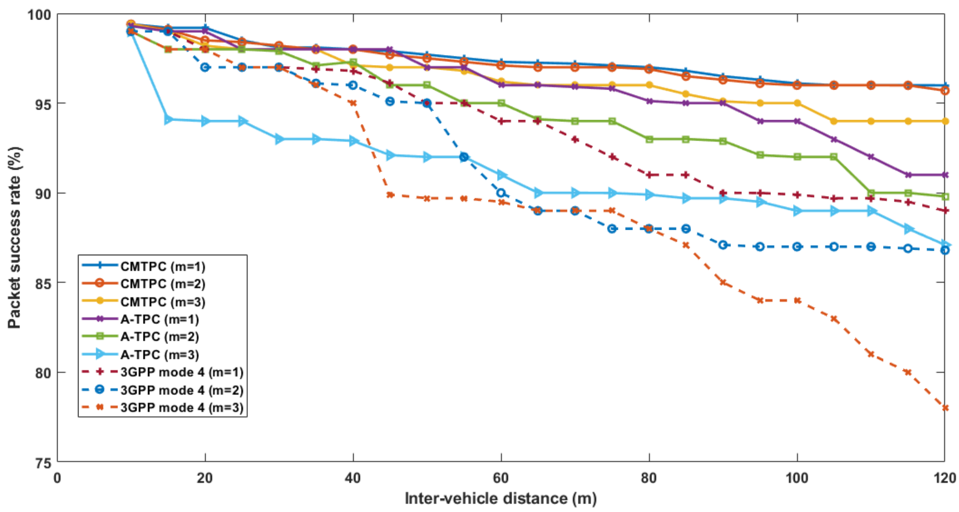


Figure 4.13: Packet success rate with respect to different inter-vehicle distance using proposed CMTPC, 3GPP mode 4 and A-TPC for traffic density (300 vehicles/road length)

transmission, we use the value of 26 dBm. For longer inter-vehicle distances (from 65 to 115m) and a higher fading intensity (m = 1), the received signal strength drops to -120 dBm. Compared to the fixed transmitting power operation 3GPP Mode 4 and A-TPC, the CMTPC algorithm improves the received signal strength, maintaining received signal power levels above the receiver sensitivity level of -105dbm.

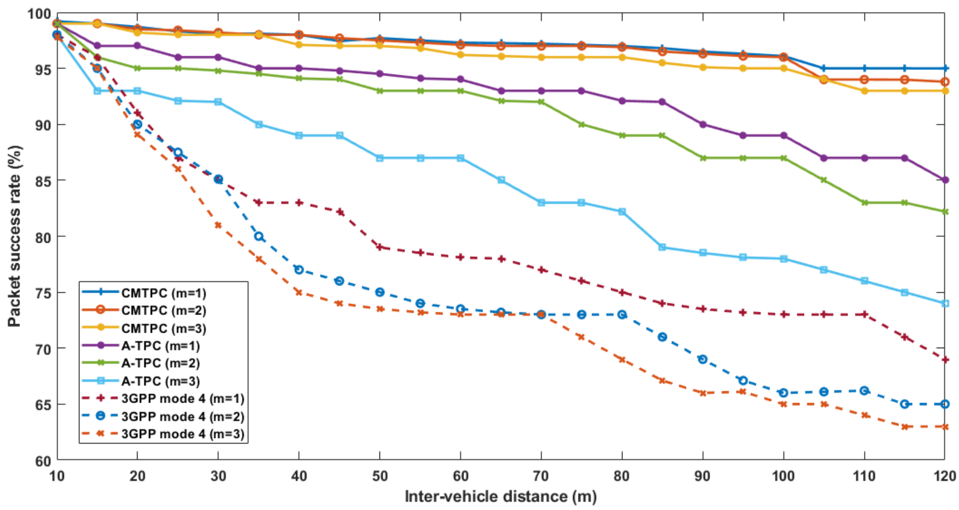


Figure 4.14: Packet success rate with respect to different inter-vehicle distances using the proposed CMTPC, 3GPP Mode 4 and A-TPC for traffic density (600 vehicles/road length)

Fig 4.13 and 4.14 show the packet success rate for the our proposed scheme CMTPC, A-TPC and 3GPP Mode 4 communications in different vehicle density scenarios. The figures show the packet success rate is calculated for different fading intensities at vehicle density 300 and 600 per road length, respectively. As seen for different inter-vehicle distance and traffic density, the proposed CMTPC scheme has higher success rates compared to the existing techniques A-TPC and 3GPP mode 4. It should be noted that for the different inter-vehicle distance beyond 50 m, the fixed transmit power cannot meet the minimum SINR requirements at the receiver side, resulting in degradation of the packet delivery ratio.

4.7 Summary

This chapter introduced a new direct inter- and intra-cluster communication technique for vehicular networks using the LTE-D2D communication technique. We have also proposed a novel cluster-based multicast transmission power adaptation scheme to improve the CAM message delivery rate in different propagation environments.

Simulation results show that the proposed LTE-DICV2V and CMTPC algorithms offer lower end-to-end delay for inter-cluster communication compared to a cellular unicast transmission mode. The proposed algorithms offer a higher packet success rate and reduce the end-to-end delay compared to a fixed transmission power operations. The proposed architecture can be incorporated within the 3GPP structure to support various applications using LTE-D2D communication services.

Chapter 5

Clustered Multicast Protocols for Warning Message Transmission in a VANETs

5.1 Introduction

In Chapters 3 and 4, techniques for efficient dissemination of basic safety messages such as CAM in VANETs were presented. The proposed techniques named as CBC-V2V, ESPD , LTE-DICV2V and CMTPC [94] [95] [115] significantly improve the performance of safety message transmission. Future intelligent transportation systems will rely on efficient communication networks to improve safety of passengers, road users and vehicles. Various safety messages and information need to be exchanged among vehicles and infrastructure to support vehicular network services [4]. Safety messages represent both the periodic CAM and the event-triggered Decentralized Environment Notification Message (DENM) which are exchanged among neighbouring vehicles. A DENM is generally event driven where a particular vehicle or vehicles or an infrastructure object could detect an event and generate a Warning

Message (WM) such as road accident warning, emergency vehicle warning, etc.

The warning message is delivered to vehicles approaching towards the area of an event occurrence. The warning message has many roles, one of the key roles is that it can act as an awareness message; informing drivers or vehicles about road or surrounding situations in a specific area. Such messages could improve the road and pedestrian safety as well as they improve driving experience. A vehicle or an infrastructure node which detects an event is referred here as the Originating Node (ON). An ON immediately broadcasts or multicasts a safety message to other vehicles in an area exposed to the potential danger. The warning message should forward to all vehicles in an Area of Relevance (AOR). An AOR is a geographical area where an event could impact traffic movements in the area. For example, a stalled vehicle on a lane could impact multiple lanes and vehicles on and around the road. In this case, all vehicles in the affected area should receive the warning message. All the vehicles in the area of relevance should be notified before they reach the potential danger. One of the main performance goals of the warning message transmission technique is high reliability, which is measured as the percentage of vehicles that receive the WM within a specified delay. Major challenges to satisfy the above requirements of a warning message are the availability of necessary transmission resources and limited transmission range of side link channels of the Long Term Evolution (LTE) network. In this work, we are proposing the use the PC5 interface of the LTE standard to distribute the warning messages along with the CAM by sharing the sidelink transmission resources.

A multi-hop transmissions is required to transmit the warning messages to the distant vehicles which are not in the transmission range of source vehicle or the Originating Node (ON). For this purpose, several multi-hop transmission protocols have been developed for many emergency applications such as post-crash warning, road condition warning and alert of approaching emergency vehicles [116] [117] [118]

[119] [120]. Various message transmission techniques have been developed to support safety messaging services in Vehicular Ad hoc Networks (VANETs) [121], [122]. In [116], the authors proposed contention based mechanism to disseminate warning messages based on the distance between a receiver and a source node. In [120], the authors proposed a Distributed Vehicular Broadcast (DV-CAST) scheme to suppress broadcast storm and also adopts the store-carry forward mechanism for disconnected networks. Large number of proposals have mostly been developed using the IEEE 802.11p network standard.

However, the IEEE 802.11p standard uses the Carrier-Sense Multiple Access with Collision Avoidance (CSMA/CA) medium-access scheme. The CSMA/CA based protocols can experience some challenges when guaranteeing strict reliability levels and ensuring the scalability feature particularly with the increasing traffic load. Researchers are exploring other networking standard to support efficient delivery of time critical messages such as the CAM and the WM. Several proposals have been developed that utilise the LTE network standard. However, due to the use of centralized architecture, a conventional cellular LTE-based system may requires significant network resources to support Vehicle-to-Vehicle (V2V) or Vehicle-to-Everything (V2X) communication needs. In recent years, several research have proposed to distribute safety messages using LTE/IEEE 802.11p hybrid networks in VANETs [72] [23] [77] [76]. However, these hybrid architectures degrade the performance of a combined network when the node density increases which leads to higher message transmission delay mainly due to collisions generated in the IEEE 802.11p-based networks.

In 2014 and 2015, the Third Generation Partnership Project (3GPP) has published the first version of Release 12 and 13 respectively, which include a new LTE standard to support public safety services using the LTE sidelink (or device-to-device communication) and Proximity Services (ProSe) communication models. In the releases 12 and 13 of the standard [123], the D2D communication model allows direct information exchange among the network devices which are in close proximity without sending information packets via the eNB thus offering ad hoc networking services similar to the IEEE 802.11p standard. The standard includes two radio interfaces. The cellular interface (named Uu) supports vehicle-to-infrastructure communications, while the PC5 interface supports V2V communications based on direct LTE sidelink. The LTE sidelink includes two modes of operation: mode 1 and mode 2. Both modes were designed with the objective of lengthen the battery lifetime of mobile devices at the cost of increasing the latency. Connected vehicles require highly reliable and low-latent V2X communications; therefore, modes 1 and 2 are not suitable for vehicular applications.

This chapter proposes an LTE-based multi-hop multicast communication network architecture to support Warning Message (WM) transmissions in a vehicular network by sharing the network resources with other types of messages such as the Cooperative Awareness Message (CAM). We propose two warning message information distribution protocols utilizing the LTE PC5 interface. The Clustered Multi-hop Multicast Protocol (CMMP) uses a staggered multicast multi-hop transmission technique to deliver warning messages within an AOR. The Clustered Multi-hop Broadcast and Multicast Protocol (CMBMP) uses a staggered broadcast/multicast transmission technique to distributes the warning messages within an AOR. We also propose a time slot reservation technique where a separate side link channel time slot will be reserved for the warning message transmission. For both CMMP and CMBMP protocols, the eNodeB's scheduler allocates the reserved time slot to each ON using a time staggered resource allocation technique for the Warning Message (WM) transmission. Our aim is to keep the resource utilization at a minimum level and successfully disseminate warning messages to the distant vehicles within an AOR by maintaining the lowest packet transfer delay. Extensive performance analysis of the proposed protocols is presented in this chapter. The proposed protocol's performances are also compared with the existing IEEE 802.11p/LTE hybrid networks. The proposed protocols distribute warning messages over a geographical area (i.e., AOR) quicker than the IEEE 802.11p based VANET and the IEEE 802.11p/LTE hybrid vehicular networks.

5.2 Related work

To address the reliability and scalability issues of the IEEE 802.11p-based VANET, the usage of cellular technologies have been investigated to meet the requirements of safety services [124] [125] [126]. Several hybrid architectures based on the both the LTE and the 802.11p standards have been proposed to enhance the safety services in term of reliability and scalability [127] [128]. The authors in [127] present a cluster-based centralized vehicular network architecture which uses both the 802.11p and the LTE standards for well known urban sensing application, Floating Car Data (FCD) application and studied those system performances with other decentralized clustering protocols. The authors in [128] proposed a cluster-based VANET-LTE hybrid architecture for multimedia-communication services. However, these proposed hybrid architectures do not focus on the safety message dissemination in vehicular networks.

In [76] and [77], the authors provide the delay performance analysis of hybrid architectures. The authors in [76] propose a hybrid architecture known as the VMaSC-LTE that integrates the LTE network with the IEEE 802.11p-based VANET network. In [77], the authors proposed a Hybrid Cellular-VANET Configuration (HCVC) to distribute Road Hazard Warning (RHW) messages to distant vehicles. In this hybrid architecture, Cluster Members (CMs) communicate with the Cluster Head (CH) by using the IEEE 802.11p link, and the CHs communicate with the eNodeB by using cellular links. However, this proposed 802.11p-LTE hybrid architecture increase the transmission delay at same time reduces the reliability when the IEEE 802.11p-based network need to support high node density, leading to higher medium access delay. In [129], the authors propose a Cellular Vehicular Network (CVN) solution as a reliable and scalable operator-assisted opportunistic architecture that supports hyper-local ITS services as the 3GPP Proximity Services (ProSe). A hybrid clustering approach is suggested to form a dynamic and flexible cluster managed locally by the ProSe-CHs. However, the authors do not focus on the transmission of safety messages transmission.

Work presented in this chapter differs from the existing works available in the literature. As discussed, in the existing hybrid architecture, vehicles use the IEEE 802.11p standard for the single-hop safety message transmission and the LTE-network is used for multi-hop warning message transmission. However, the integration of the LTE standard with the IEEE 802.11p standard may not be very efficient for warning message transmission. The main reason for the limitation of such a hybrid network is that the contention increases significantly in a high density congested vehicular networks.

We propose a sidelink V2V multicast/broadcast architecture based on a clustering approach to organize vehicles into dynamic clusters. Compared to other 802.11p-LTE hybrid systems, in our proposed LTE sidelink based architecture, Cluster Members (CMs) communicate with the Cluster Head (CH) using an LTE sidelink communication link, and the CHs communicate with the eNodeB by using the LTE Uu air interface. In the proposed model, only the CH can communicate with the eNodeB. Thereby, the traffic load on the uplink and downlink LTE channels will be minimised by reducing the data exchange requirements with the eNodeB. The proposed architecture is unique which shares common network resources for CAM and WM transmissions to minimize the radio resource requirements. The algorithm use the emerging LTE-based Device-to-Device (D2D) communication techniques to overcome the drawbacks of the 802.11p-LTE based hybrid architectures to support vehicular ITS services.

Compared to the existing Hybrid Cellular-VANET architectures for safety message transmission, namely, VMaSC-LTE [76] and HCVC-PROB [77], the proposed CMMP and CMBMP algorithms to use minimum LTE channel resources while forwarding a message in a contention-free mode; ensuring timely and successful delivery of warning messages. We employ a time-slot reservation technique where all cluster members use a reserved slidelink time slot to exchange warning messages. The other benefits such as an efficient and collision free resource distribution come from the staggered multicast multi-hop transmission, which allows CMMP and CMBMP to distribute the sidelink reserved slot for multi-hop warning message transmission in a time staggered manner that offer a chain transmission pattern of WM messages to all clusters in an AOR.

The chained transmission and time staggered resource distribution techniques offer an efficient and collision-free resource distribution for CAM and DENM transmissions among V2V enabled vehicles. Time staggered resource allocation technique also minimizes control signalling requirements when a eNodeB receives the allocation request from a source cluster in an AOR, it will allocate transmission resources to the source cluster. At the same time, it also sends the resource allocation information to all other distant clusters in the AOR. In this way, each cluster in the chain process receives a reserved slot in advance to forward the warning message to neighbouring vehicle. Thereby, the CMMP and the CMBMP offer a lower distribution delay of WM in an AOR compared to the existing hybrid architecture available in the current literature.

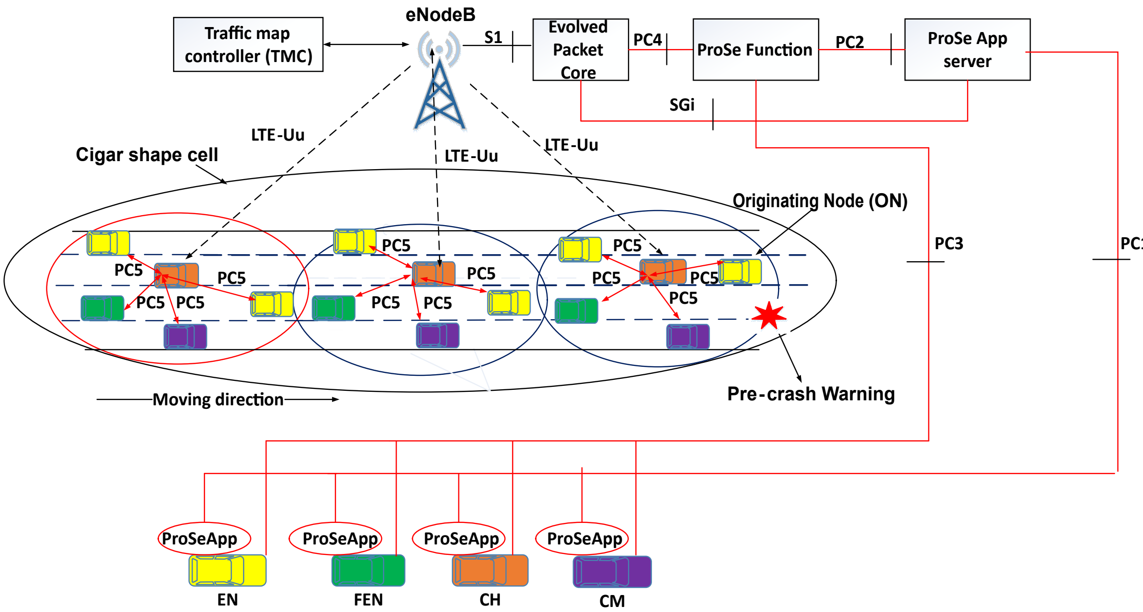


Figure 5.1: A highway scenario for the proposed protocols in the VANET

5.3 Proposed System Model

Figure 5.1 shows a typical highway scenario where vehicles are connected via the eNodeB of a LTE network. Vehicles on a multilane highway will form clusters where the cluster heads will coordinate its operation. In [94], we have introduced cluster formation technique where the vehicle with the lowest average relative speed and the maximum distance from its current location to the zone boundary is chosen as the cluster head. We have introduced a LTE-D2D (Device-to-Device) multicast communications technique that utilises the side link channels for D2D communications to multicast CAM messages within clusters. For each cluster node, radio resources are first allocated to the CH by the eNodeB. Each CH further schedules the resources among its CMs using a round robin scheduling technique as described in section 3.2.6 of chapter 3. In this case, the resource scheduling is carried out dynamically by assigning multiple users to the same slot in a round robin fashion using their IDs in the ascending order. Therefore, members of a cluster can share the same slot in turn to transmit their own CAM in the multicast mode.

A Traffic Map Controller (TMC) attched with the eNodeB keeps the track of each vehicles in cluster. Vehicles in the proposed architecture are equipped with ITS Proximty Services (ProSe) enabled devices which utilise the LTE and the LTE direct interfaces. The LTE Uu interface is used for V2I communications to access (Internet Protocol) IP services, while the LTE direct interface PC5 is used for inter-vehicle communication. The ProSe App server is an application server which incorporates the ProSe capability for building the application functionality. The application server can communicate with an application in the vehicles. The ProSe function is part of the 3GPP standard that connects with other Evolve Packet CORE (EPC) through PC4 interface. Each vehicle will receive its proximity information for direct communication using our previously proposed EPC level peer discovery model presented in [94].

Each cluster consists of number of members including the Edge Nodes (ENs) which are used to pass the CAM messages to the neighbouring clusters. Figure 5.1 shows the location of ENs at both ends of clusters. As soon as a CH is selected and the cluster is formed, the CH selects its farthest members as the edge nodes. It is possible that two or more members have the same distance from their CH. Therefore, a cluster may contain multiple edge nodes and the edge nodes will be present at the both ends of a cluster. Edge nodes are member of two clusters which allow them to pass CAM messages to neighbouring clusters. Details of the ENs selection and operation is presented in section 4.4.1 of chapter 4 [115]. We utilise this cluster-based architecture to transmit both CAM and warning messages. To support the CMMP protocol, these edge nodes act as a forwarder node to distribute the warning message to other nodes located in immediate neighbouring clusters. A cluster may contains multiple edge nodes, in such a case, to avoid the duplication of the warning messages, each CH randomly chooses one edge node as a Forwarder Edge Node (FEN) and updates other edge nodes about the selection of the forwarder node. Hence, once the edge nodes will receive the WM, only the designated FEN will forward the warning

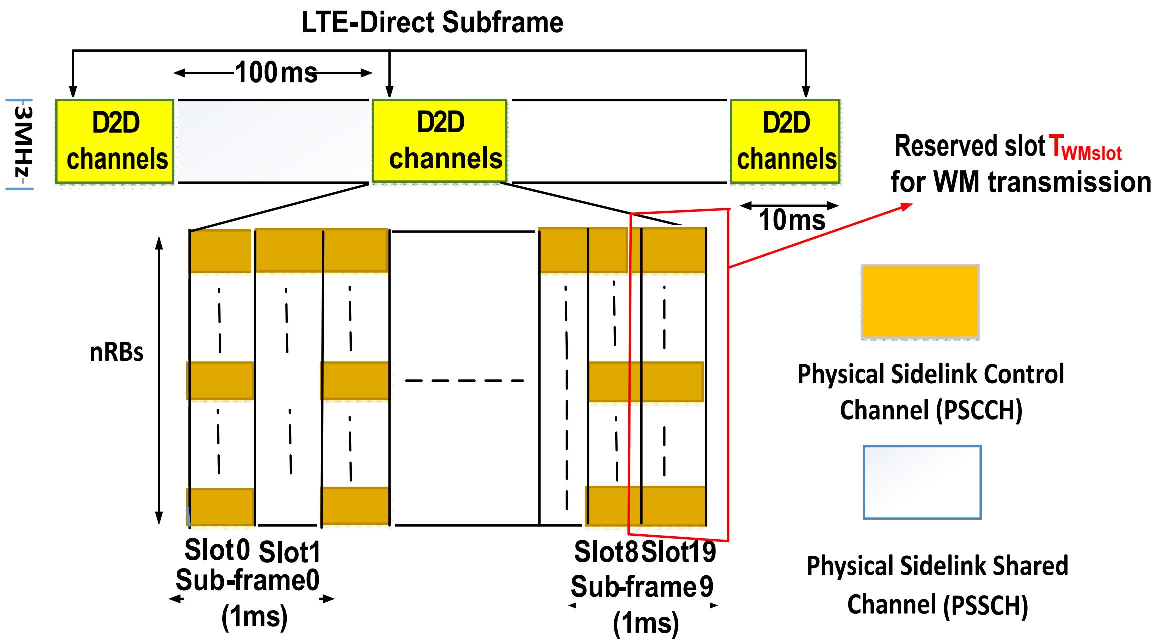


Figure 5.2: D2D sidelink channel structure

message to its neighbouring clusters.

5.4 Sidelink Channel Structure for the CMMP and the CMBMP

The LTE release 14 introduced two new communication modes (modes 3 and 4) specifically designed for V2X communications. In mode 3, selection of subchannels is managed by the eNodeB. The eNodeB provides dedicated radio resources for User Equipments (UEs) to transmit data. On the uplink, UEs need to deliver buffer status reports and scheduling requests for the eNodeB to decide the amount of resources to grant for mode 3 communication. Further, the eNodeB delivers a scheduling assignment (SA) that contains decoding information for the UE. This scheduling information is used to decode subsequent data. Mode 3 is only available when vehicles are under a eNodeB coverage. Unlike mode 4, the standard does not specify a resource management algorithm for the mode 3. Therefore, each operator can implement its own algorithm [130].

To support the CMMP and CMBMP algorithms for the warning message transmission, we employ a time-slot reservation technique . In line with the communication mode 3, we suggest the 3GPP standard based D2D sidelink channel structure as shown in figure 5.2. Figure shows that the eNodeB reserves ten D2D subframes on uplink cellular traffic channel in the TDM (Time Division Multiplex) manner. The D2D subframes repetition rate is 100 ms. Each subframe contains two slots, hence a single carrier offer twenty slots for sidelink communications. Out of the twenty slots, one slot (warning message slot is represented as a T_{WMslot}) will be reserved for the warning message transmission. The number of RBs in a slot depends on the bandwidth of a LTE channel.

The RBs are used to transmit data and control information. The data is transmitted using transport blocks (TBs) over the Physical Sidelink Shared Channels (PSSCH), and the Sidelink Control Information (SCI) messages are transmitted over Physical Sidelink Control Channels (PSCCH) [131]. Both CMMP and CMBMP algorithms share the side link channel time slots to support CAM and WM message transmissions. Each cluster uses the reserved time slot for WM transmission using a time staggered resource allocation techniques which is described in section IV. For CAM messages transmission, each cluster uses a time slot using the proposed round robin scheduling given section 3.2.6 of chapter 3 [94]. As presented in chapter 3, the proposed round robin resource allocation scheme is operated by dynamically assigning multiple users to the same slot in turn, i.e., one after another based on their specific ID in the ascending order.

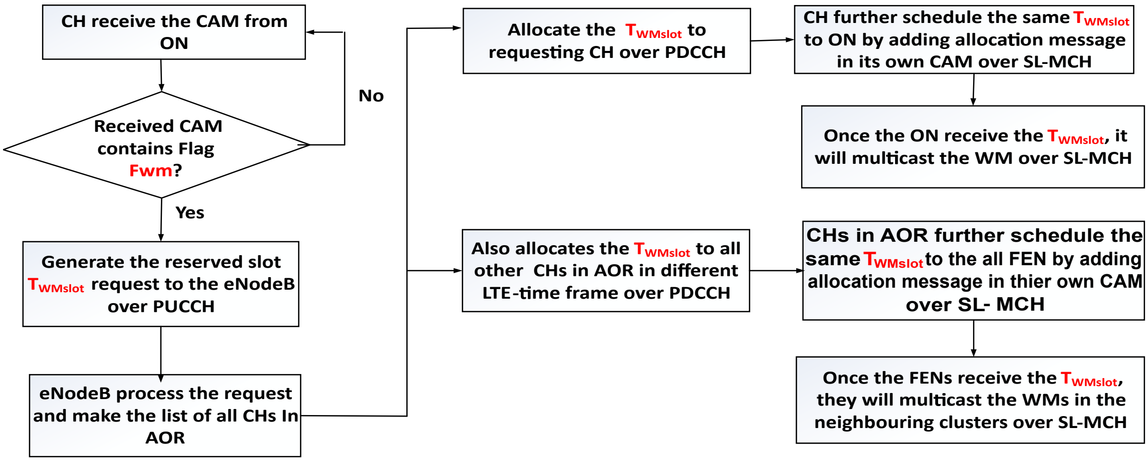


Figure 5.3: Warning message transmission using the CMMP

5.5 Warning Message Transmission Protocols for Highway Sceanrio

In the following sections we will present the two warning message transmission protocols named as CMMP and CMBMP for multi-hop safety messages transmission in highway sceanrio.

5.5.1 Clustered Multi-hop Multicast Protocol

The CMMP algorithm transmits warning messages using a multicast multihop communication technique. The flow chart of the CMMP message propagation is depicted in figure 5.3. Figure 5.5 depicts the structure of the warning message, which is compliant with the ETSI (European Telecommunications Standards Institute) specification [132]. The warning message header format is composed of a common Intelligent Transport System Protocol Data Unit (ITS PDU) header and management containers, which constitutes the warning message payload. The ETSI specifies that the warning message payload is divided into four containers: 1) management container, 2) situation, 3)location, and 4) à la carte containers. For all types of warning message, the ITS PDU header and the management container are mandatory. The situation container, the location container and the à la carte container are optional containers. As shown in the figure 5.5, The ITS PDU container includes the type of the message type (CAM or DENM) and vehicle type and ID that generates the message. A management container includes the warning message detection time, relevant distance within which an event is considered relevant to the receiving vehicles, relevance traffic direction along which the warning message should be disseminated, location of the originating vehicle and time stamp of the generated warning message.

When a vehicle or an infrastructure node detects an event, it generates a WM. The message is queued in the ON for distribution. To transmit the message from the ON, the node generates a flag within its own CAM message as shown in figure 5.6. A F_{wm} represents the warning message flag. The F_{wm} flag indicates to the CH that a WM message is waiting for transmission. On receiving the F_{wm} flag, the CH will send a request to the eNodeB via the Physical Uplink Control Channel (PUCCH) to allocates the reserved slot T_{WMslot} in the D2D channel to the ON for the WM transmission. The eNodeB will send the allocation information via the Physical Downlink Control Channel (PDCCH) to the requesting CH which will subsequently forwards the reserved slot T_{WMslot} information by piggybacking the message with its own CAM as shown in figure 5.6. On receiving the reserved slot, the ON will multicast its WM message via the Side Link Multicast Channel(SL-MCH) to all nodes in the source cluster. The eNodeB also allocates reserved slot via the PDCCH in a time staggered manner in order to support a chain transmission of WM messages to all clusters in an AOR.

The figure 5.4 shows the example of time staggered resource allocation technique used by the CMMP. The eNodeB will allocate a slot in LTE frame n for the cluster CH_i, then it will allocate the same slot to cluster CH_{i+1} and CH_{i+2} (in the direction of message travel) in the $n+1$ and $n+2$ LTE frames respectively. Such deterministic allocation of resource will support the delivery of the message to the final destination

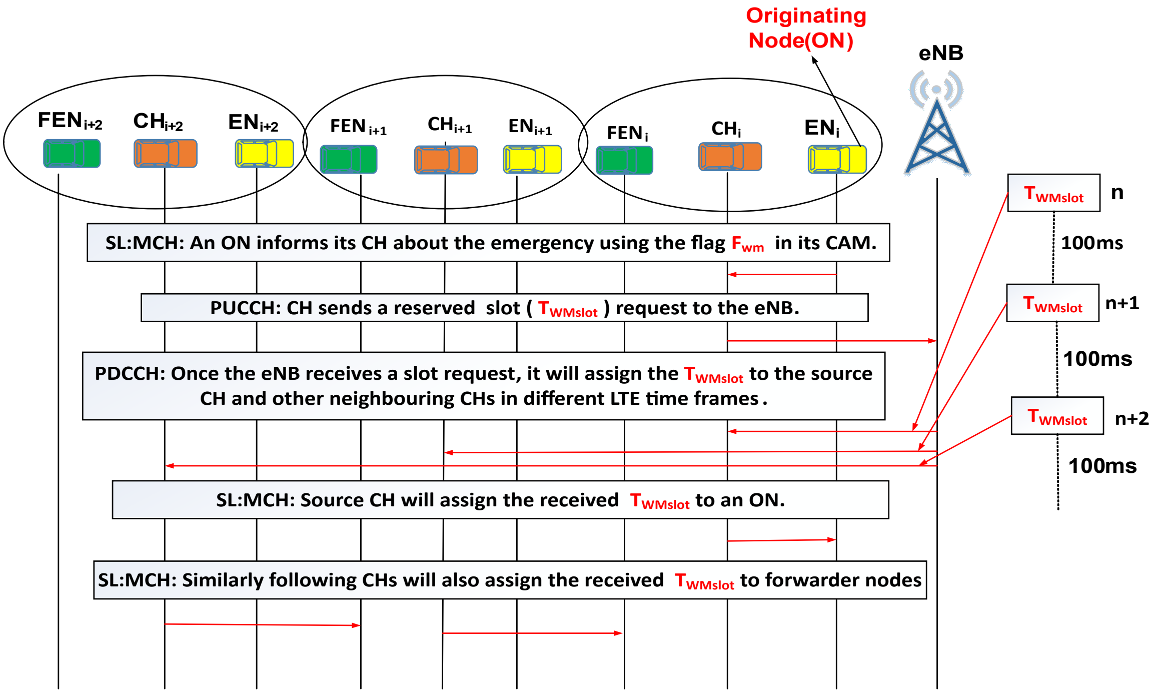


Figure 5.4: Reserved slot allocation in the CMMP

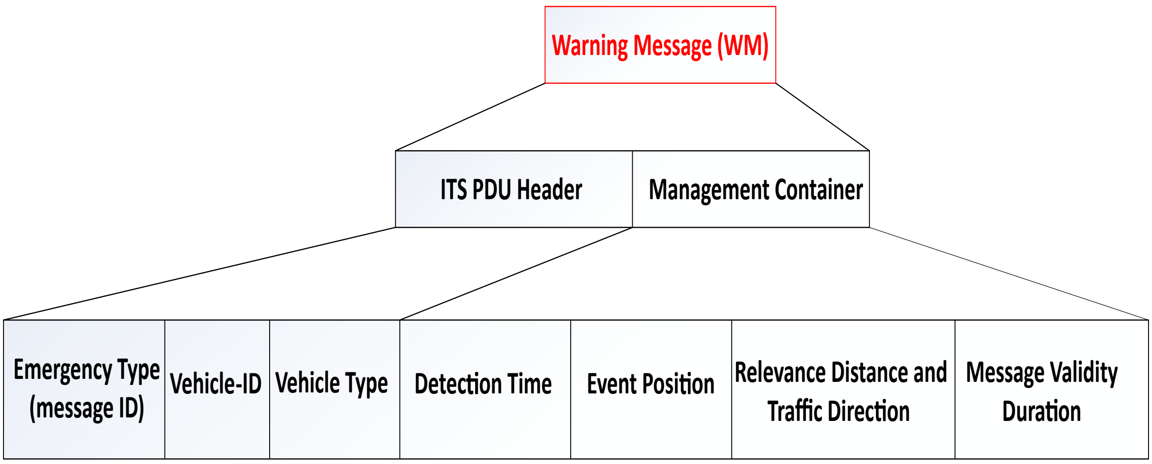


Figure 5.5: Warning message structure

with in a fixed time.

In our approach, each designated FEN will hold membership of two clusters at a same time. Figure 5.4 shows the FEN_i is located at the boundary of the two clusters CH_i and CH_{i+1}. The FEN_i is the member of CH_i but it is also in the transmission range of neighbouring cluster CH_{i+1}. Based on our previous approach in [115] , FEN_i will also become a member of CH_{i+1} and hold the membership of both clusters CH_i

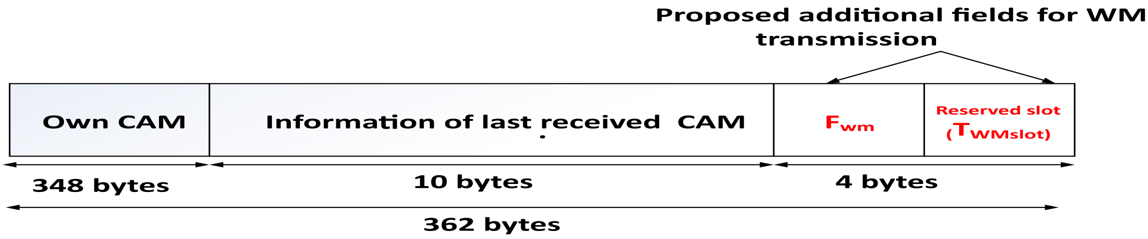


Figure 5.6: CAM structure with additional fields to support the CMMP and the CMBMP

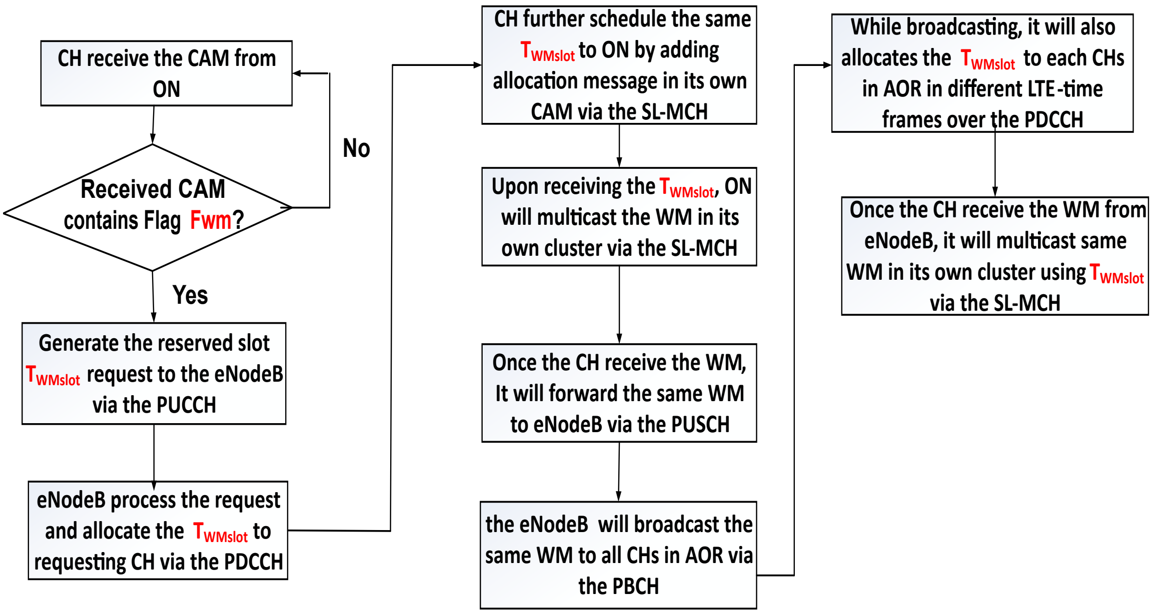


Figure 5.7: Warning message transmission using the CMBMP

and CH_{i+1} at the same time. Each forwarder node will then receive a reserved slot from its neighbouring CH to forward a warning message to neighbouring clusters. Once the cluster CH_{i+1} will receive the slot information, it will allocate the same slot to the FEN_i of neighbouring cluster CH_i. The same procedure will apply to each forwarder node in following clusters.

When the WM arrives in the FEN of the originating cluster, it will multicast the WM to the neighbouring cluster using the reserved slot. The WM message will thus propagates through the clusters of AOR reaching the farthest node. The same procedure will follow by the each cluster in the AOR.

5.5.2 Clustered Multi-hop Broadcast and Multicast Protocol

The second algorithm that is referred to as the CMBMP which uses both broadcast and multicast techniques to distribute WM messages within an AOR presented in this section. The flow chart of the CMBMP message propagation is depicted in figure 5.7. In this algorithm, the WM message is distributed within the source cluster using the reserved slot as described in the CMMP. When the WM message arrives at the CH of the source cluster, the CH transmit the WM to the eNodeB via the uplink using the LTE Physical Uplink Shared Channel (PUSCH). Once the eNodeB receives the warning message, it will calculate an AOR using the Traffic Map Controller (TMC) and broadcast the warning message to all the CHs located within an AOR. The eNodeB will broadcast the WM to all the CHs at the same time using LTE broadcast channel. The figure 5.8 shows an example of time staggered resource allocation technique used by the CMBMP. Once the eNodeB received the WM from the source cluster head CH_i, it will broadcast the same WM to all the subsequent clusters CH_{i+1} and CH_{i+2} in an AOR via downlink using the LTE broadcast channel. While broadcasting the warning message, the eNodeB will also allocate the reserved slots T_{WMslot} via downlink using the PDCCH in different LTE time frames $n+1$ and $n+2$ and so on to all clusters CH_{i+1} and $CH_{i+2}...CH_{n+N}$ in an AOR. Further, the CHs within the AOR will multicast the same WM in its own cluster by using the reserved slot T_{WMslot}. The difference between the CMMP and CMBMP is that the CMMP distributes the WM using a chain process whereas the the CMBMP distributes message in a staggered transmission mode.

5.5.3 Delay Models

Figure 5.9 shows the delay models for the proposed the CMMP and the CMBMP protocols. Delay parameters are explained in table 5.1. Delay models show that

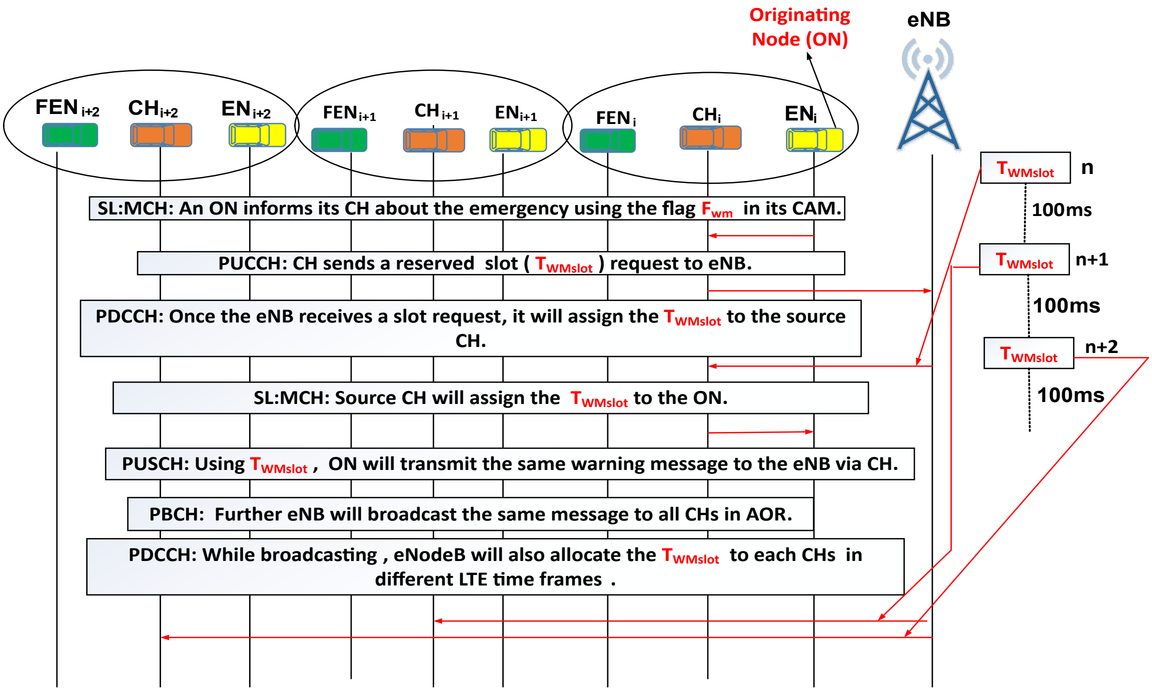


Figure 5.8: Reserved slot allocation in CMBMP

both algorithms introduce same delay for the distribution of WM in source cluster, but the neighbouring clusters in an AOR experience different delays. In the CMMP protocol, the ON has to wait for a certain period for its CAM multicast slot which is represented by $T_{C,ON}$. As mentioned before that the waiting WM message is indicated by the flag contained within the CAM message of the ON. Following the reception of a WM from an ON within CAM, the CH sends a reserved slot request to the eNodeB and a delay for sending slot request from CH to the eNodeB represented by $T_{CH,UP}$. The eNodeB allocates a reserved slot after the T_{AL} delay. The CH forwards the slot allocation information to the ON by using its own CAM message. Following to the reception of the reserved slot allocation information at the ON it waits for the $T_{W,RS}$ period to multicast the WM message. When a WM message is multicasted, the message is received by all cluster members including the FEN. As mentioned earlier that eNodeB uses a staggered slot allocation technique to allocate reserved slots to all CHs in the AOR. All CH receives its reserved slot allocation when the source

CH receives its allocation. To support the chain transmission process of the WM, clusters receive staggered slot allocation. In the staggered allocation, clusters in the direction of WM propagation receive their reserved slot in subsequent LTE frames to support the message multicast delay requirements in each cluster. Using the CMMP protocol a WM reach the final cluster after propagating through N clusters. Source cluster WM message distribution delay T_{SC} is shown in (5.1). The WM distribution end-to-end delay T_{EM} is represented by (5.2).

$$T_{SC} = T_{C,ON} + 3T_M + T_{CH,UP} + T_{AL} + T_{C,CH} + T_{W,RS} \tag{5.1}$$

$$T_{EM} = T_{SC} + \big[(N-1)\big(T_{W,RSN} + T_M\big)\big] \tag{5.2}$$

The CMBMP delay components are shown in figure 5.9. The source cluster message distribution delay is same as the CMMP which is represented by (5.1). However, the WM distribution delay for neighbouring clusters is different since the source CH forwards the message to the eNB which is then broadcast the message to all CHs in the AOR. The source CH again has to wait for a certain period for forwarding the warning message to the eNodeB which is represented by $T_{ch,eNB}$. Each CH gets its transmission opportunity to transmit its CAMs in a time division manner. The end-to-end WM message distribution delay of the CMBMP protocol is represented by (5.3).

$$T_{EM} = T_{SC} + T_{ch,eNB} + T_B + \big[(N-1)\big(T_{W,CH} + T_M\big)\big] \tag{5.3}$$

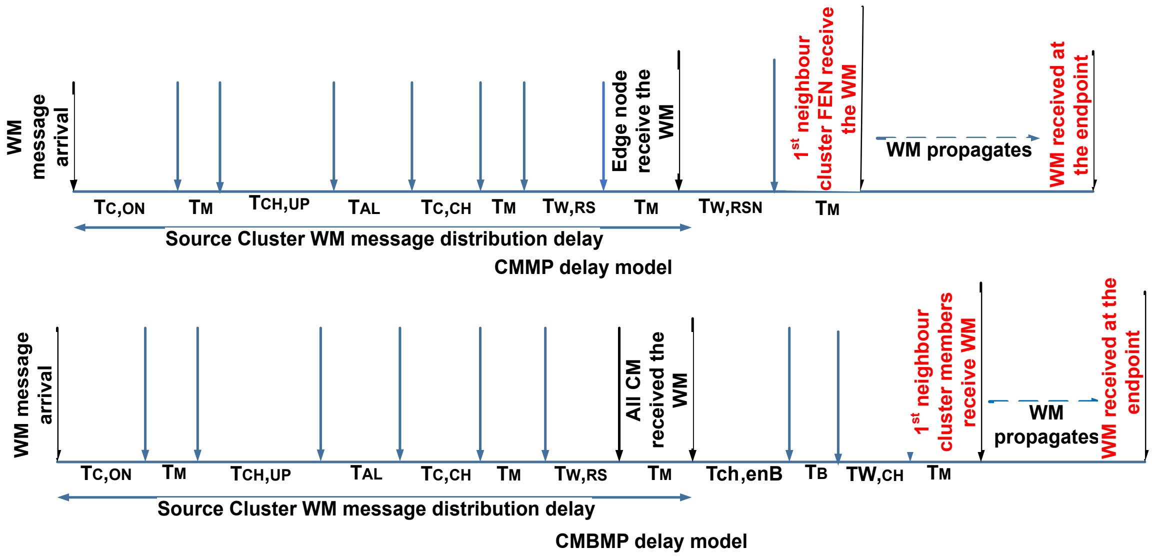


Figure 5.9: Major delay components of the CMMP and the CMBMP

Table 5.1: Delay model timing parameters

Notation	Description
$T_{C,ON}$	Source node CAM slot wait delay.
T_M	Multicast slot duration which is 0.5 ms.
$T_{CH,UP}$	CH wait delay to transmit slot allocation request to the eNodeB.
T_{AL}	eNodeB slot allocation delay.
$T_{C,CH}$	CH wait delay for the CAM slot
$T_{W,RS}$	ON wait time for reserved slot to transmit the WM message.
$T_{W,RSN}$	FEN wait time for reserved slot to transmit the WM message in neighbouring node.
$T_{W,CH}$	CH wait for reserved slot to transmit the WM message.
$T_{ch,eNB}$	Cluster head wait delay to transmit WM to eNodeB.
T_B	eNodeB WM broadcast delay.
T_{SC}	Source cluster WM message distribution delay.
T_{EM}	WM distribution end-to-end delay.

5.6 Simulation Model and Performance analysis

A simulation model is developed to analyze the performance of CMMP and CMBMP protocols. An OMNET++ 5.1.1 simulation model is developed utilising the Si-

Table 5.2: Main simulation parameter

Parameter	Value
Vehicle speed	40-70 km/h
Number of vehicles	180 vehicles/km
Inter-vehicle distance	10 to 120m
Road length & number of lanes	2 km & 4
Carrier frequency	2.6 GHz
CAM generation frequency	10 Hz
DENM generation frequency	2 to 4 Hz
Number of warning message senders	2
Warning message size	350 to 520 bytes
Warning message notification region	2 km
Transmission bandwidth	3MHz (i.e., 15 RBs)
Fading model	Nakagami-m (m = 1, 2, 3)
eNodeB Tx power	46 dBm
UE Tx Power	26 dBm (Initial)
Noise figure	5 dB
Receiver sensitivity threshold Rx_{th}	-95 dBm
Cable loss	2 dB
Simulation time	700s
Safety message size	362 bytes
T_{safety}	100 ms
Number of clusters	16 to 26/ 2km
Number of vehicle/cluster	6 to 10/cluster

muLTE [133] [134] model and the INET3.4.0 framework. The SimuLTE, instead, is a system-level simulator of LTE networks, based on the INET framework. It is based on OMNeT++ and exploits the INET framework to implement all the higher layers of the IP stack as well as the main IP nodes of the communication network, such as IP routers and application servers. Moreover, INET provides the concept of Network Interface Card (NIC) modules, which can be included within other modules to implement models of various communication protocols between network devices. The Veins package is used for enhanced traffic simulation where GPS data was incorporated for the mobility support. A realistic mobility model is generated by the microscopic road traffic simulation package Simulation of Urban Mobility (SUMO) [59]. The Veins provides vehicular mobility to OMNeT++, using SUMO as the underlying vehicular traffic simulator. For the integration of simuLTE and veins, a vehicular Mobility module has been added. This is define as an interface that can be implemented by the TraCIMobility module define by Veins. The detail description on veins and simuLTE intigration is presented in [16] [17] [135].

The simulation model used the Nakagami m fading model with m values varies from 1 to 3 to represent a wide range of fading conditions. Results from the simulation were acquired by taking the average of the 20 simulation runs with different seeds value. Key simulation parameters are listed in table 5.2. A two km four lanes highway is used to simulate the network where vehicles in four lanes are flowing in the same direction. Vehicle density on the road is simulated by the Poisson distribution process. The inter-vehicle distance is modelled by an exponential distribution function with a mean value μ (in meters) where a safety headway distance of three second is maintained. The model placed two emergency vehicles on the road to generate event based warning messages. The entire 2 km highway is considered as an AOR. The CMMP and the CMBMP algorithms are implemented in the SimuLTE model. We also implemented two LTE/802.11p simulation models to simulate the VMaSC-LTE [76] and the HCVC-PROB [77] basic algorithms to obtain several performance parameters for comparisons.

Figure 5.10 shows the average single cluster warning message distribution delays for CMMP, CMBMP, VMaSC-LTE and HCVC-PROB protocols. The proposed protocols were simulated for different WM generation frequencies. Figure shows that both proposed protocols offered much lower end-to-end delay compared to the existing protocols. Also the CMMP and CMBMP protocols performances are less sensitive to the cluster size variation due to use of the multicast technique where delay increases slightly due to the use of round robin packet transmission techniques. Low message distribution delays are achieved due to the absence of any contention process in the LTE network. The contention process introduce a longer delay particularly

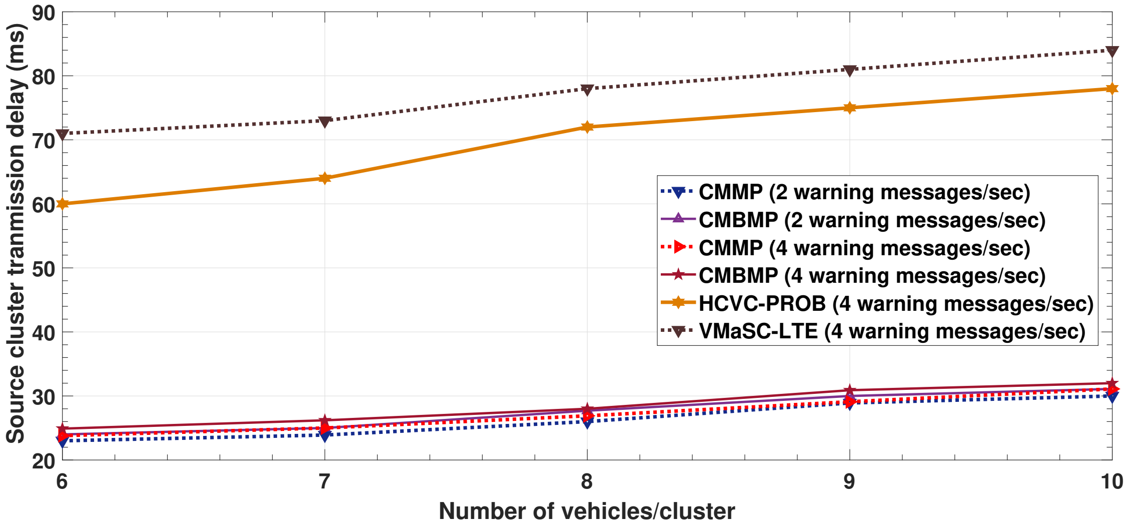


Figure 5.10: Single cluster transmission delay for the CMMP and the CMBMP with respect to different cluster size and warning message generation rates

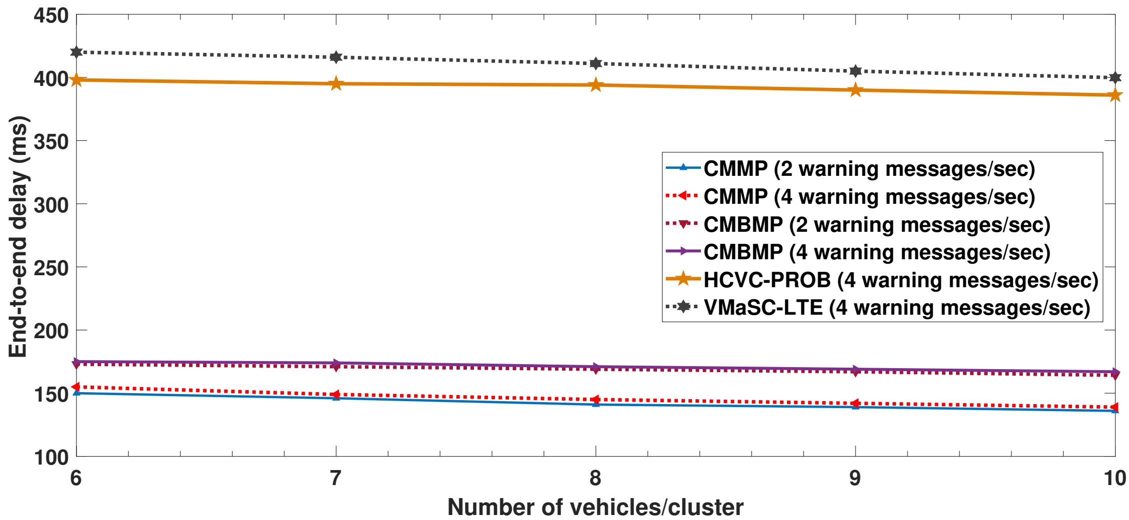


Figure 5.11: All cluster transmission delay for the CMMP and the CMBMP with respect to different cluster size and warning message generation rates

with higher node densities in a cluster mainly due to retransmission requirements. As shown in (5.1) that all the delay components of the CMMP and the CMBMP protocols are deterministic with small range of variabilities due to the message arrival process and the time frame structure of the channel.

Figure 5.11 shows the end-to-end warning message distribution delay with the

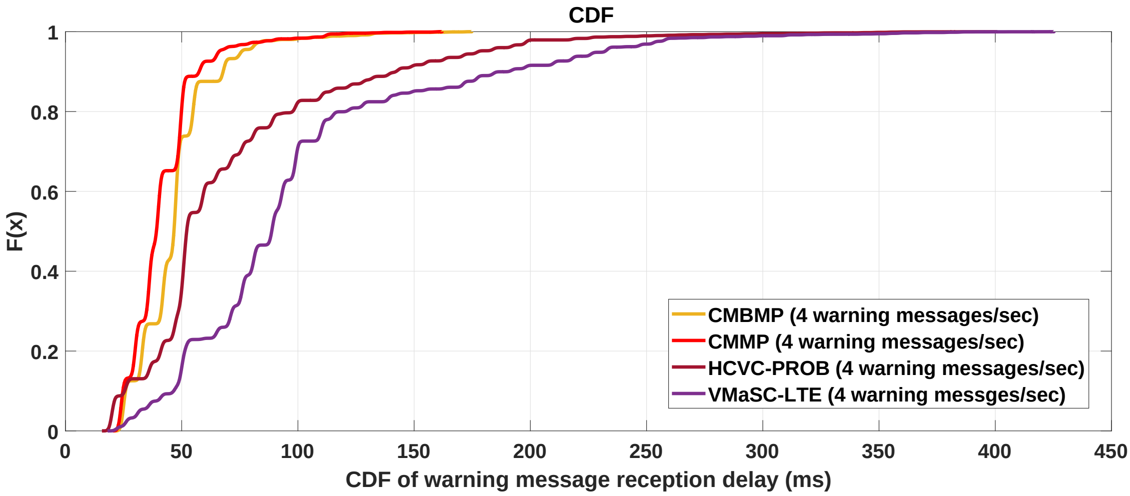


Figure 5.12: CDF of warning message reception delay

increasing cluster size. In this case the delay slightly fall with the increasing cluster size because fewer clusters in an AOR. In this case both proposed protocols introduced very similar delay values. Delays introduced by the existing hybrid VMaSC-LTE and HCVC-PROB protocols are significantly higher due to the presence of multiple collision domains in each cluster.

Figure 5.12 shows the Cumulative Distribution Function (CDF) plot of the end-to-end message distribution delays. This plot shows that around 97% message delays are below 100 ms for the proposed protocol whereas about 80% message delays of the HCVC-PROB protocol are below 100 ms and about 70% of messages are transmitted with the same delay by the VMaSC-LTE protocol. From the delay profiles it can be seen that the cellular only based VANET performs significantly better than the existing hybrid networks.

Figures 5.13 and 5.14 show the message reception ratio at the far end of the AOR. Both plots show that the CMMP and the CMBMP protocols offer almost 100% message delivery ratio due to deterministic nature of the channel structure used in the VANET. The simulated channel Signal to Noise Ratio (SNR) was relatively high in this model hence, almost none of packets were corrupted due to low SNR

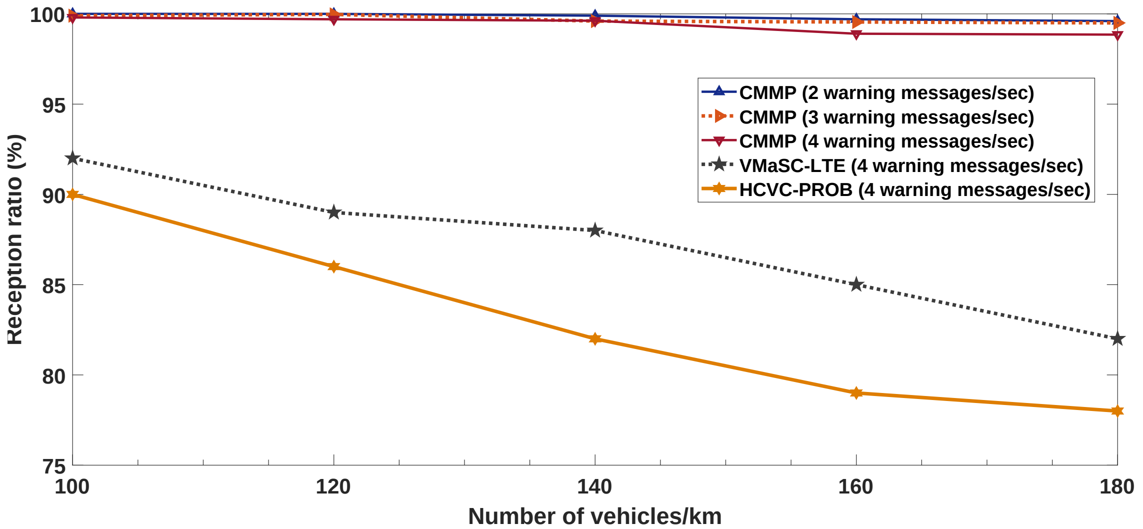


Figure 5.13: Reception ratio of warning message for the CMMP with respect to different vehicle density and warning message generation rates

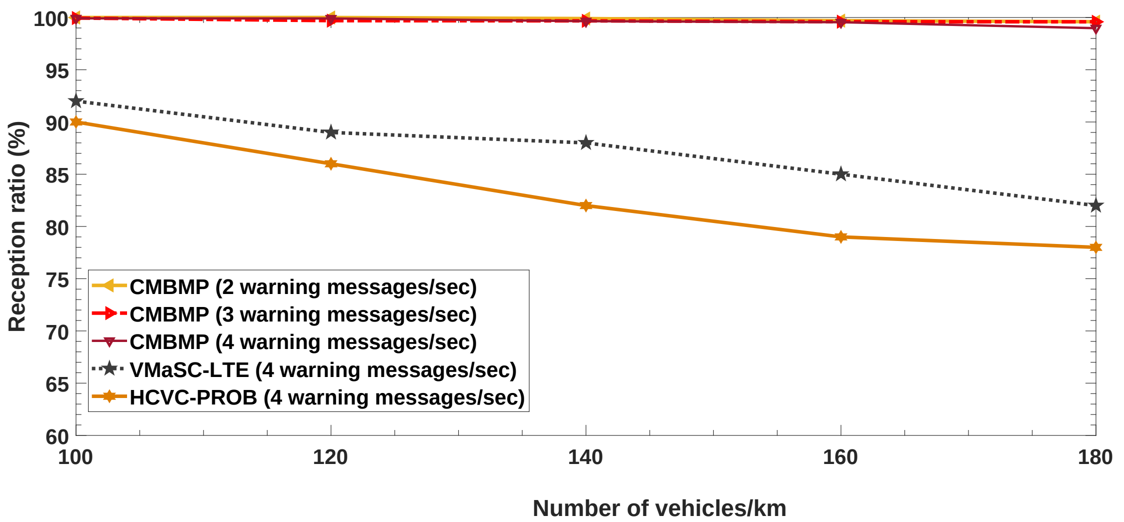


Figure 5.14: Reception ratio of warning message for the CMBMP with respect to different vehicle density and warning message generation rates

values. The hybrid protocols showed lower message reception ratios again mainly due to lower efficiency of the CSMA/CA protocol. Within the increasing number of vehicles, the performance of the 802.11p networks decline resulting fewer messages are forwarded to the end cluster of an AOR.

Figure 5.15 and 5.16 shows the message reception ratio of both the CMMP and

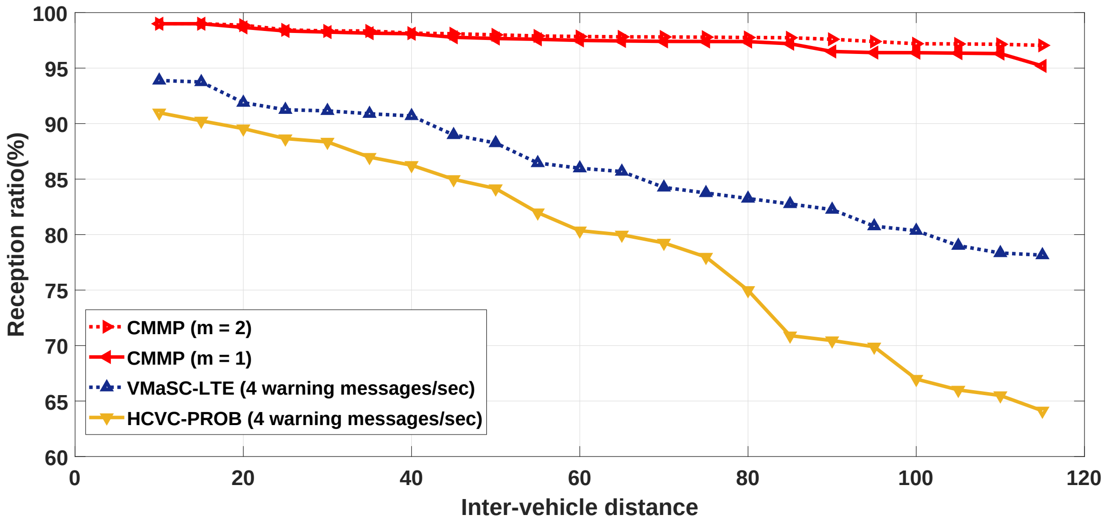


Figure 5.15: Reception ratio of warning message for the CMMP with respect to inter-vehicle distance and different channel conditions

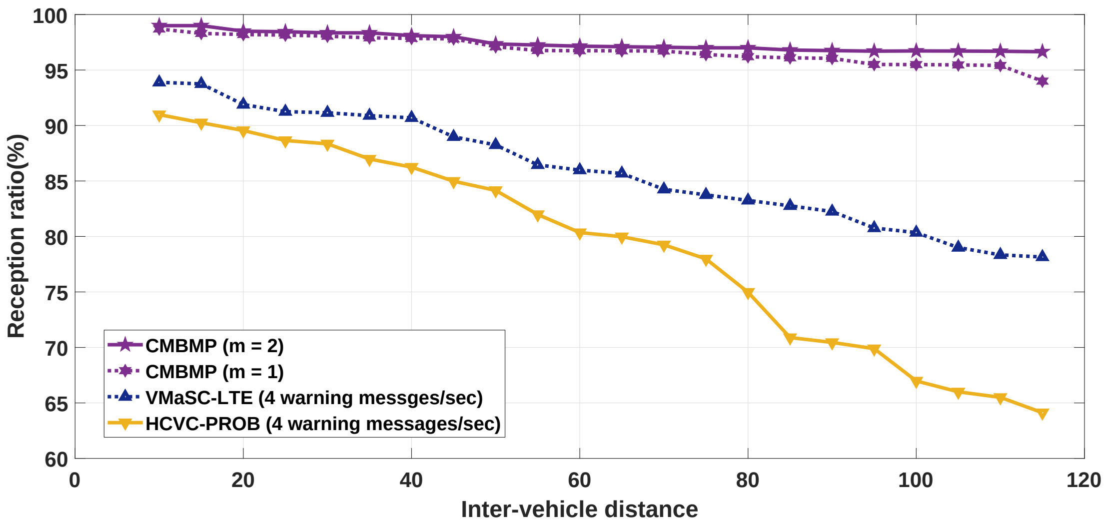


Figure 5.16: Reception ratio of warning message for the CMBMP with respect to inter-vehicle distance and different channel conditions

the CMBMP algorithms. The message reception ratio is calculated for different fading intensities with respect to the different inter-vehicle distances. Compared to the existing hybrid protocols the VMaSC-LTE and HCVC-PROB, the proposed protocols, offer almost 97% message delivery ratio for a channel condition with $m = 2$. The packet success ratio decreases as the inter-vehicle distance increases.

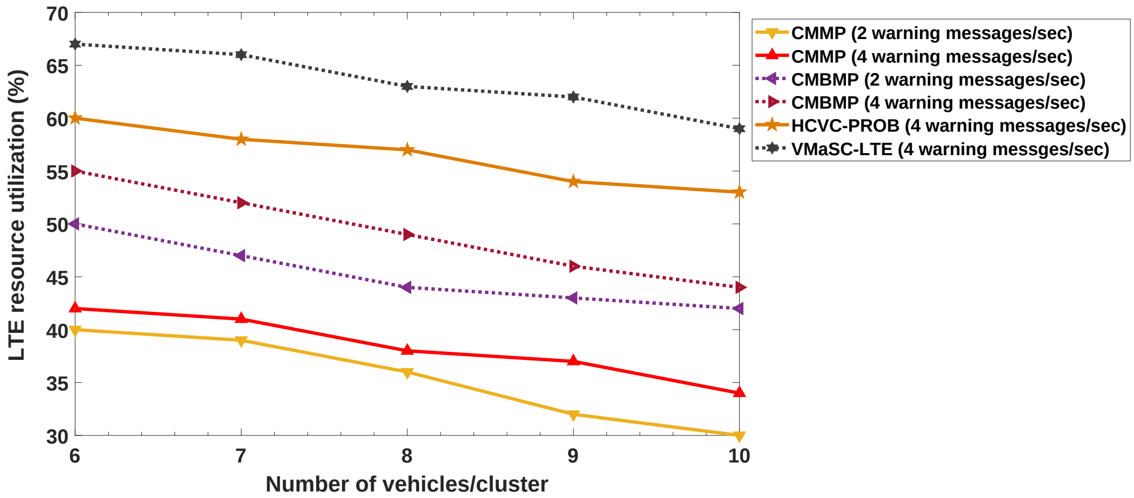


Figure 5.17: LTE resource utilization for the CMMP and the CMBMP with respect to different cluster size and warning message generation rates

Finally, we compare the transmission resource requirements of all protocols studied in this work. We consider the resource utilization for the LTE air interfaces only. Fig. 5.17 shows the LTE resource utilisation for all protocols. Resource utilisation values are calculated using (4), where the ratio of number of RBs used to the total number RBs available represent the efficiency figure.

$$LTE_{RU} = \frac{RBs_{UL} + RBs_{DL}}{RBs_{avilable}} \times 100 \qquad (5.4)$$

Where RBs_{UL} and RBs_{DL} represent number of resource blocks used on uplink and downlinks respectively. $RBs_{avilable}$ represents the total number of resource blocks available on each LTE uplink and downlink channels. The plot shows the resource utilisation reduces with the increasing cluster size mainly due to lower signalling and forwarding channel requirements. The efficiency of the CMMP and the CMBMP is higher due to sharing of transmission resources with CAM transmission resources.

5.7 Warning Message (DENM) Transmission Protocols for City Scenarios

In this section, our focus is to further develop the Clustered Multi-hop Multicast Protocol (CMMP) [136] presented in section 5.5.1 of this chapter to improve the reliability of the warning message transmission named Decentralized Environment Notification Message (DENM) in city road scenarios. The proposed schemes exploit the mobility metrics that include moving direction, relative velocity, and relative distance. It is important to note that, to further develop the CMMP protocol for city scenario, we used a our prediction-based protocol, referred to as Prediction-Based Updating, Monitoring, and Joining (PUMJ) presented for different road structure in the chapter 6. Fig. 5.18 shows a city scenario where vehicles are connected via the eNodeB of a 5G-V2x network. A city road is divided into the four road segments R1, R2, R3, and R4, and each road segment has four lanes. Vehicles in multilane road segments will form clusters where the cluster heads will coordinate their operation. When a vehicle or an infrastructure node detects an event, it generates a WM. The message is queued in the source vehicle. A vehicle that generates the Warning Message (WM) is named as Originating Node (ON). On the straight highway, the vehicle ON will use the CMMP and CMBMP protocols to transmit a warning message in the Area of Relevance (AOR). For the city scenario, the area of relevance is measure according to the future moving direction of the ON.

As shown in the fig. 5.18, a vehicle ON on the road segment R2 is moving towards the road segment R1. When ON generates a warning message, all the vehicles in the area of relevance should be notified before they reach the possible collision area. For example, the vehicles on the road segments R3 and R1 fall under the AOR of the ON. However, circulating a WM message to neighbouring and distant vehicles on road segment R3 and R1 in the AOR in the city road can be a bit challenging compared

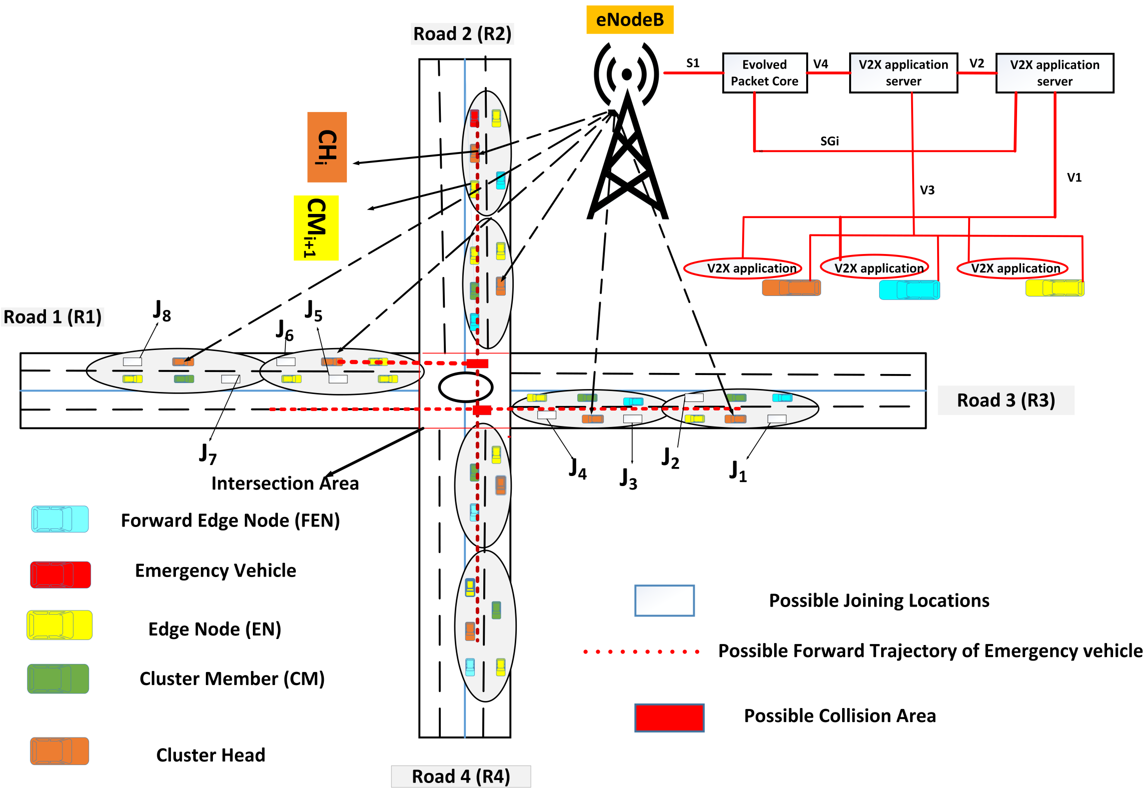


Figure 5.18: A city intersection scenario for the proposed 5G-Based Vehicular Network Architecture

to the straight highway road. One of the major limiting factors in transmitting a WM is the Line of Sight (LOS) requirement. As shown in the figure, the vehicles moving on the road segments R3 and R1 are not in the direct line of sight (LOS), and they are not aware of each other's locations. There is always a high probability of the collision between vehicles moving towards the same intersection from different road segments. In order to overcome the above problem, we modified our proposed protocol, CMMP using PMUJ, refereed to as Prediction-Based CMMP (PB-CMMP), to transmit warning messages in a city road scenario. In the following section, we will discuss our proposed protocols PB-CMMP using PMUJ.

5.8 PB-CMMP for Warning Message Transmission in City Scenario

Maintaining cluster stability near an intersection such as a city road intersection is challenging compared to cluster maintenance on a multilane straight highway. Joining and leaving a cluster near a city intersection requires a reliable cluster management technique that can offer quick organization and re-organization of the cluster. To support the above requirements, we have designed and developed a prediction-based algorithm to support the following criteria:

- To improve the cluster stability.
- To support our previously developed multi-hop communication protocol CMMP to disseminate emergency warning safety messages (i.e., DENM) in a geographic region ahead of the vehicle in a city roundabout.
- TO reduce the emergency safety message transmission delay to neighbouring and distant vehicles in the areas of relevance. In this way, other road users can be warned earlier and are provided with detailed information about the route of the approaching emergency vehicle. This enables them to react in a timely and appropriately way so that they do not block the emergency vehicle.

Fig. 5.18 shows the trajectory of Source and Host clusters moving towards the same roundabout. We assume that the clusters moving on the road segments R1 and R3 are the Host Clusters (HCs), and clusters moving on the road segment R2 are the Source Clusters (SCs). The cluster CH_{i+1}, along with its cluster members, are moving towards the roundabout and looking for the host cluster to merge with at the roundabout. However, due to variable speed and the changing position of vehicles, it can be very challenging for the source cluster to join or merge with other clusters

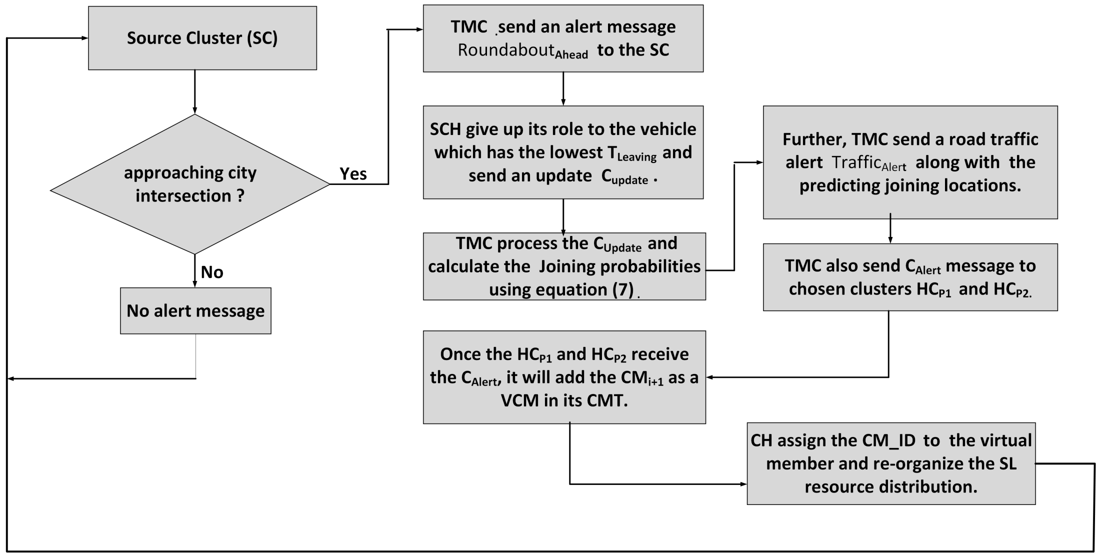


Figure 5.19: Flow diagram of the PB-CMMP using PMUJ

at a roundabout. In our proposed clustering approach, the Traffic Map Controller (TMC) maintains a database that keeps the up-to-date information about all the clusters moving on the road. All CHs send an update to TMC about any change in their cluster. In our study, we consider that TMC will generate a $Roundabout_{Ahead}$ when the source cluster (SC) is at a distance represented as $Roundabout_{D_{Th}}$ away from the roundabout. In this case, if the cluster is approaching a highway intersection, the TMC will send a $Rounabout_{Alert}$ alert message to the cluster. Figure 5.19 shows the flow diagram of the PUMJ algorithm. To enable the inter-cluster soft handover at the roundabout, we propose to choose a vehicle which will leave the cluster last as the new Cluster Head (CH). Once the SCH will receives the $Rounabout_{Alert}$, it will give up its CH role and assign the CH head role to the vehicle which has the longest lifetime or the highest remaining distance from the roundabout among all the cluster members. Thereby, CMs can be connected to their old CH before the leaving the source cluster and joining the HCs at the roundabout.

TMC makes a list of all the existing clusters approaching the roundabout on different road segments and calculates the possible joining locations for each destination cluster, into which the source cluster members can insert themselves at the roundabout. In each host cluster, the TMC calculates the possible joining locations based on the two vehicles' headway distance. The possible joining location is defined as the inter-vehicle spacing, which is higher then or equal to the headway distance required to accommodate a new vehicle. Let's assume that the headway distance required to accommodate a new vehicle is represented by $X_{joining}$, and the minimum safe headway distance is represented as X_{safe}. We assume that to accommodate a new vehicle, the inter-vehicle distance should be two times higher than the minimum safe headway distance. Thus, the headway distance required to accommodate a new vehicle can be given as:

$$X_{joining} = 2 * X_{safe} \tag{5.5}$$

5.8.0.1 Joining Probability Between Source and Host Clusters

Further, TMC will calculate the joining probabilities between the member of a source cluster and possible joining locations in host clusters. In our case the required information for approaching source cluster member CM_{i+1} and possible joining location J_1 consists of the distance from the roundabout of their trajectories $d_{CM_{i+1}}$ and d_{J_1} and the speed $V_{CM_{i+1}}$ and V_{J_1}, maximum acceleration, deceleration, yaw angle and yaw rate. As shown in Fig. 5.18, CM_{i+1} is moving towards the intersection area. Based on the headway distance between the the two vehicles, there are eight possible joining points J_1, J_2, J_3, J_4 and J_5,J_6, J_7, J_8 in host clusters on the road segments R3 and R1, respectively. The probability that a member of the source cluster will insert itself in any of the possible joining points will depend on the probability of collision between the member of the source cluster and any possible joining location at the roundabout. For simplicity, we will consider only CM_{i+1} and possible joining

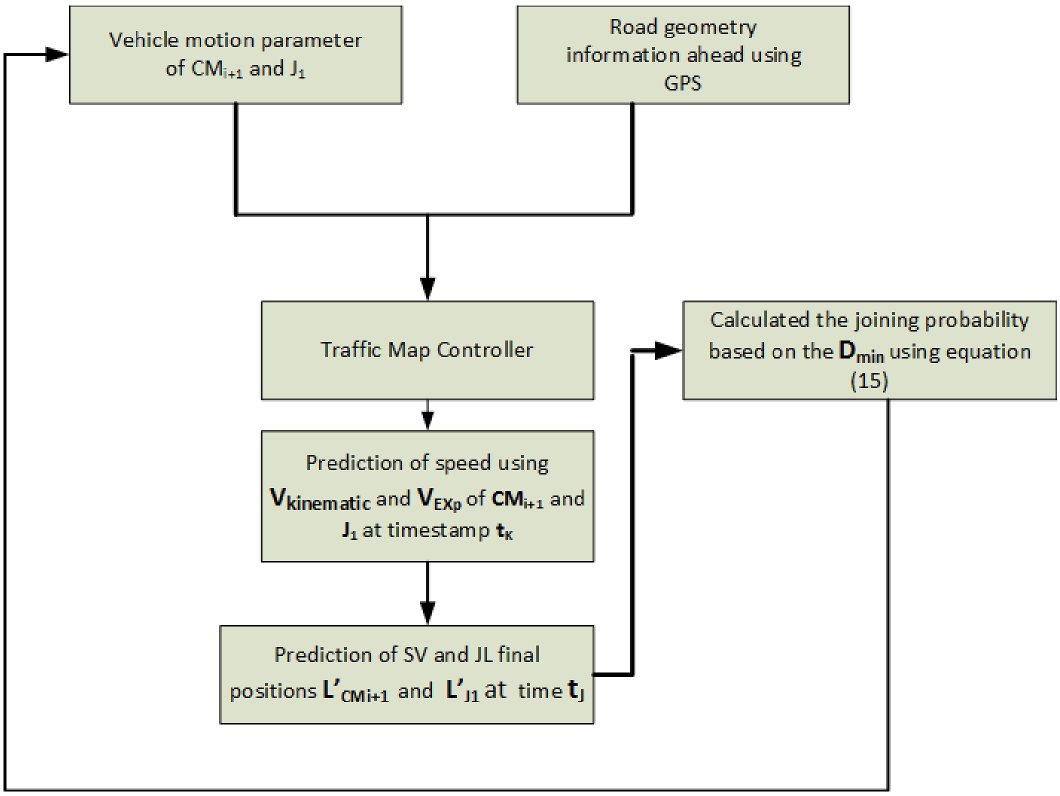


Figure 5.20: Calculation of the joining probability using PMUJ

location J_1 for the probability calculation. Fig. 5.20 shows the algorithm used by TMC to predict the joining probability between $d_{CM_{i+1}}$ and d_{J_1}. Let's assume that speeds of the CM_{i+1} and J_1 are approximate to linear near the intersection point where the collision is possible. Therefore, the current position of each vehicle can be written as:

$$L(t) = x + tv \tag{5.6}$$

where x is an current position vector along the line at time $t = t_0$ and v is the velocity. The positional relationship between vehicles using the point of intersection can be written as:

$$x_{CM_{i+1}} + t_0 v_{CM_{i+1}} = x_{J_1} + t_0 v_{J_1} \tag{5.7}$$

In the configuration, CM_{i+1} and J_1 pass the roundabout at some time $t_{CM_{i+1}}$ and t_{J_1} respectively. Therefore, the encounter velocity is:

$$U = v_{CM_{i+1}} - v_{J_1} \tag{5.8}$$

To accurately predict the joining probability, the current motion parameters, such as speed, distance to the roundabout and acceleration of source vehicle and host joining location, should be considered in the proposed prediction algorithm. In our study, the proposed prediction algorithm is developed using the existing vehicle trajectory and collision prediction techniques presented in [137] [138] [139]. Our proposed prediction algorithm uses the vehicle future moving direction and road trajectory with which the future distance between both CM_{i+1} and J_1 will be calculated. Following the existing vehicle trajectory and collision prediction techniques presented in [137] [138] [139], our proposed prediction algorithm consists of two main models. First one is the kinematic model to predict vehicle future state parameters, such as vehicle speed, position, and acceleration. Second model is used to predict the future trajectory of road geometry ahead. The predictions of the vehicle speed by the kinematic models at the timestamp t_K is calculated using the basic equations of motion:

$$V_{Kinematic,k} = V_k + a_x t_k, \tag{5.9}$$

Where $a_x t_k$ is the vehicle longitudinal acceleration at the current timestamps t_k. According to the road structure ahead, we consider vehicle moving at certain speeds on the expected trajectory. The expected trajectory of a source vehicle near the entry point is described by a hyperbolic curve parameterized by the road width W and the crossing angle θ. The authors in [137] presented the evaluation of these parameters in the real-time field. The future trajectory curve based on the moving direction can be obtained using (5.10)

$$y' = f(x', \theta, W_1, W_2) = tan\frac{\theta}{2}\sqrt{x'^2 + \frac{b^2(W_1 + W_2)^2}{tan(\frac{\theta}{2}}} \tag{5.10}$$

Where (x′, y′) is the expected vehicle position in the standard coordinate for the hyperbola (x′-axis and y′-axis). W1 and W2 are road widths of road segment R3 and R2 respectively shown in Fig. 5.18, θ is the roundabout crossing angle and b is relevant to the driving behaviour. The expected speed v_{Exp} in the standard hyperbola coordinates, varies while the vehicle is passing through the roundabout. v_{Exp} is assumed to follow a piecewise Gaussian function and an arctangent function of expected vehicle positions, $[x_{Exp}, y_{Exp,k}]$, as expressed in (5.11) and (5.12).

$$V_{EM,k}(i) = \begin{cases} V_{L_{Vmax1}} + (V_{L_{Vmax1}} - V_{L_{Vmax1}}) \exp\Big(- \frac{x_{Exp}(t_k^2}{s_1^2}\Big), & \text{if} x_{Exp,k}(i) \neq 0, \\ V_{L_{Vmax1}} + (V_{L_{Vmax1}} - V_{L_{Vmax1}}) \exp\Big(- \frac{x_{Exp} t_k^2}{s_2^2}\Big), & \text{otherwise}, \end{cases} \tag{5.11}$$

$$\begin{aligned} S_{t_k} &= (V_{L_{Vmax1}} - V_{L_{Vmax2)t_{de}}}, \\ S_{t_k} &= (V_{L_{Vmax3}} - v_{L_{Vmax2}})t_{ac}, \\ a_{Exp}(t_k) &= \arctan\Big(- \frac{a^2 x_{Exp}(t_k)}{b^2 y_{EXP}(t_k)}\Big), \end{aligned} \tag{5.12}$$

where $V_{L_{Vmax1}}$ and $V_{L_{Vmax3}}$ are speed limits on two intersected roads at an intersection, $V_{L_{Vmax2}}$ is the lower speed that a vehicle decelerates to when it passes the intersection and t_{de} and t_{ac} are the deceleration time and acceleration time respectively, these values are calculated when vehicles approach a roundabout. From (2)–(7), we can obtain predictions of $v_{Kinematic}(t_k)$, ad $v_{Exp}(t_k)$ parameter for source cluster member and possible joining location according to (5.13) and (5.14)

$$V_{CM_{i+1}}(t_k) = \beta(i)V_{Kinematic}(t_k) + [1 - \beta(i)]v_{Exp}(t_k), \tag{5.13}$$

$$V_{J_1}(t_k) = \beta(i)V_{Kinematic}(t_k) + [1 - \beta(i)]v_{Exp}(t_k), \tag{5.14}$$

Where $\beta(i)$ is the weighted coefficient at timestamp t_k. The $v_{Kinematic,k}$ and $v_{Exp}(t_k)$ are predicted speed from kinematic models and expected trajectory model, respectively. The TMC will calculate the time it will take a vehicle to reach the roundabout. Let's assume that the CM_{i+1} will take the t seconds to reach the boundary of the intersection area. The TMC will predict the time for CM_{i+1} to reach the roundabout, and on the other hand, it will also calculate the final position of the both CM_{i+1} and J_1 after t seconds. The final positions of the joining location and source cluster member after t can be calculated as:

$$L'_{CM_{i+1}}(t) = \frac{1}{2}a_{CM_{i+1}}t_k t^2 + V_{CM_{i+1(t_k)}} + x_{CM_{i+1}}(t_k) \tag{5.15}$$

$$L'_{J_1}(t) = \frac{1}{2}a_{J_1}(t_k)t^2 + V_{J_{1(t_k)}} + x_{J_1}(t_k) \tag{5.16}$$

where $L'_{CM_{i+1}}$ and $L'_{J_1}(t)$ represent the final positions of a source cluster member and possible joining location, respectively, after t time, $a_{CM_{i+1}}$ and a_{J_1} represent the acceleration source cluster member and joining location, respectively, $V_{CM_{i+1}}$ and V_{J_1} are the staring velocity and $x_{CM_{i+1}}$ and x_{J_1} are the starting position of source cluster member and possible joining location, respectively. Based on the final position of the joining location, the TMC will measure the future distance between the CM_{i+1} vehicle and the joining location J_1. There is a possibility that moving vehicles with variable velocities will have unique time at which the distance between CM_{i+1} and J_1 becomes minimum near the intersection point. By calling this specific time $t+1$, we get the following minimum distance

$$D_{min} = |L'_{CM_{i+1}}(t) - L'_{J_1}(t)|. \tag{5.17}$$

At the time $t+1$, the joining point J_1 located at the intersection point and minimum distance D_{min} is smaller than then distance threshold D_{th}. D_{th} represents the specified collision radius. Collision is possible if D_{min} is smaller than a specified collision radius τ, i.e., $\Delta t < \Delta t_{col}$, where Δt_{col} is given by:

$$\Delta t_{col} = \frac{U * D_{min}}{|V_{CM_{i+1}} * V_{J_1}|} \tag{5.18}$$

The collision radius τ would be the sum of the physical radii of the two vehicles. Thus, the probability that the CM_{i+1} will placed itself in a cluster depends on the D_{min} between CM_{i+1} and J_1. Therefore, the CM_{i+1} will insert itself at J_2 in the cluster when the collision will occur at time $t+2$. Considering that CM_{i+1} passes the intersection point, the probability P_{join} that CM_{i+1} collides with joining points J_1 is

$$P_{join} = \frac{\Delta t_{col}}{t+1} = \frac{2\tau U}{|V_{CM_{i+1}} j_1| t+1} \tag{5.19}$$

Similarly, the TMC will calculate the joining probability between all the members of the source clusters and other possible joining locations. Among all possible joining locations, the TMC will choose the joining location with the first and the second highest probability.

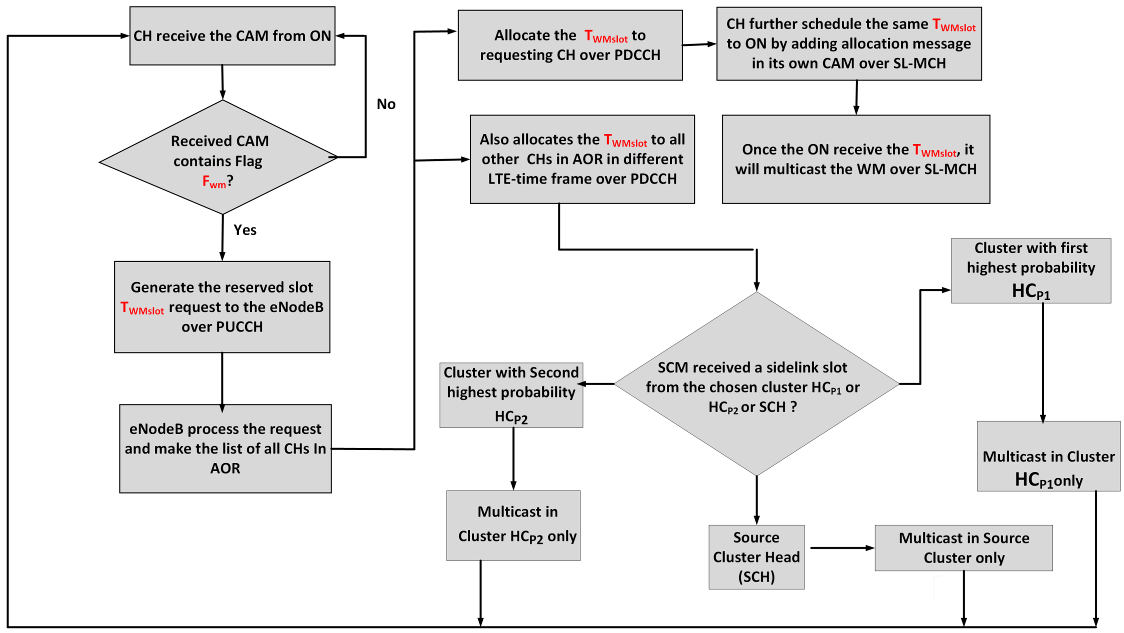


Figure 5.21: Warning message transmission using PMUJ combined with CMMP

5.8.0.2 Monitoring and Updating the Source Cluster and Host Cluster

Once the TMC calculates the joining probabilities, it will generate the $Traffic_{Alert}$ and send it to the source cluster. At the same time, the TMC also sends a C_{Alert} message to the chosen host cluster with first and second highest probability. Upon reception of $Traffic_{Alert}$, the SCH extracts all the information from the alert message and updates its VIR with the new proximity data. On the other hand, once the chosen cluster head receives the alert message, it will create a new virtual entry in its Cluster Member Table (CMT) and add the members of a source cluster to its CMT as a Virtual Cluster Member (VCM). Further, the CH assigns a new vehicle ID to the VCM and reorganizes the resource distribution based on the vehicle ID. As per our proposed round-robin scheduling, each member of the cluster will receive the sidelink (SL) resources based on their ID in ascending order.

As mentioned in the above section, in our prediction-based protocol, once the TMC calculates the joining location with higher probability, it will send an alert message to both the chosen cluster and host cluster moving towards the same intersection. Further, the member of the source cluster joins the predicted host clusters at the intersection. However, due to high dynamic topology, such as different speed profiles, there is the possibility that the vehicle will fail to join the predicted cluster with the highest joining probability. In this case it may join other neighbouring clusters with the second or third highest probability at the intersection. To overcome the above situation, we devise a procedure where the TMC will multicast an alert message to both the chosen clusters with first and second highest probabilities at the same time. In this way, immediate neighbours with the second-highest probability will also become aware of the vehicle approaching towards the intersection area.

Once the chosen clusters receive the update message, they will extract the Source Cluster Member (SCM) information and add the source cluster member virtually in their cluster member list. Thereby, the source vehicle becomes a virtual cluster member of the chosen clusters (i.e., both with first and second highest probability). The term Virtual Cluster Member (VCM) defines a vehicle which does not join the host or chosen cluster physically, but it can connect to the host cluster virtually for safety message transmission. When the source vehicle becomes the virtual member (VM), the host or chosen clusters will reorganize its resource distribution. Our proposed resource distribution scheme is operated by dynamically assigning multiple users to the same slot in turn, where they share the slot using their ID in the ascending order. Once the vehicle joins virtually, HCs assign a new ID to the SCM according to the predicted joining location, where it will insert itself into the cluster. Further, each member will receive the sidelink slot as per its respective vehicle ID. Unlike the chosen cluster, the neighbouring cluster will create a temporary entry and add the SCM as a the Virtual Temporary Cluster Member in its cluster member list. That means, the SCM will not assign a new vehicle ID or receive transmission resources from the CH.

In this case, the SV will hold membership of the two clusters at the same time. However, if the SV holds membership of two clusters, then which cluster will assign the sidelink slot to the SV for its safety message transmission? To resolve the situation, we devise a procedure where the SV will form a new multicast group in its Vehicle Information Register (VIR). Fig. 5.21 shows the resource allocation procedure for both virtual members and the warning massage transmission technique. The SCM will create two different multicast groups in its VIR. In the first multicast group, it will add all the members of the chosen cluster with the first highest joining probability HC_{P_1}, and in the second multicast group, it will add the member of the cluster with the second-highest probability HC_{P_2}. As SCM holds the dual membership, so it will receive the SL slot from both chosen clusters using the proposed round-robin scheduling. Once the source vehicle receives the slot, it will check whether it is for the chosen cluster with the first highest probability or second-highest probability. If the SCM receives the slot from the cluster, it will only multicast the safety message in the first multicast group, whereas if it receives this from the SC, it will multicast the safety packet in its second multicast group cluster. The TMC keeps up-to-date information about all the clusters on the road. Once the SCM becomes the virtual member of both chosen clusters, the TMC keeps monitoring both chosen clusters' velocity profiles and source vehicles. As mentioned above, due to different speed profiles, the vehicle may join a different cluster instead of the predicted one at the intersection. To overcome the prediction error, we suggest a procedure where, after a particular period, i.e., represented as one-half time of the total monitoring time, and the TMC recalculates t he SCM's joining probabilities and chosen clusters, and compares them with previously calculated probabilities. If the joining probabilities are the same as the previous ones, the TMC will instruct the cluster with the second-highest probability to remove the SCM from the cluster member table. If the probability is different from the previous one, then it will instruct the chosen cluster with the highest probability to release the VCM from its CMT and reorganize the cluster accordingly.

5.8.1 Warning Message (DENM) Transmission Using PB-CMMP

As mentioned previously in Section 5.4, to transmit the message from the ON, the node generates a flag within its own CAM message2. A F_{wm} represents the warning message flag. The F_{wm} flag indicates to the CH that a WM message is waiting for transmission. On receiving the F_{wm} flag, the CH will send a request to the eNodeB via the Physical Uplink Control Channel (PUCCH) to allocate a reserved slot T_{WMslot} in the sidelink channel to the ON for the WM transmission. The eNodeB will send the allocation information via the Physical Downlink Control Channel (PDCCH) to the requesting CH, which will subsequently forward the reserved slot T_{WMslot} information by piggybacking the message with its own CAM. On receiving the reserved slot, the ON will multicast its WM message via the SideLink Multicast Channel(SL-MCH) to all nodes in the source cluster. The eNodeB also allocates reserved slots via the PDCCH in a time staggered manner in order to support a chain transmission of WM messages to all clusters in an Area of Relevance (AOR).

Fig. 5.22 shows an example of the time-staggered resource allocation technique used by the CMMP. The eNodeB will allocate a slot in LTE frame n for the cluster CH_i, then it will allocate the same slot to cluster CH_{i+1} and CH_{i+2} (in the direction of message travel) in the n+1 and n+2 LTE frames, respectively. Such a deterministic allocation of resources will support delivering the message to the final destination within a fixed time. In our approach, each designated FEN will hold membership of two clusters at the same time. The FEN_i is located at the boundary of two clusters CH_i and CH_{i+1}. The FEN_i is a member of CH_i but it is also in the transmission range of a neighbouring cluster CH_{i+1}. Based on our previous approach in [115], the

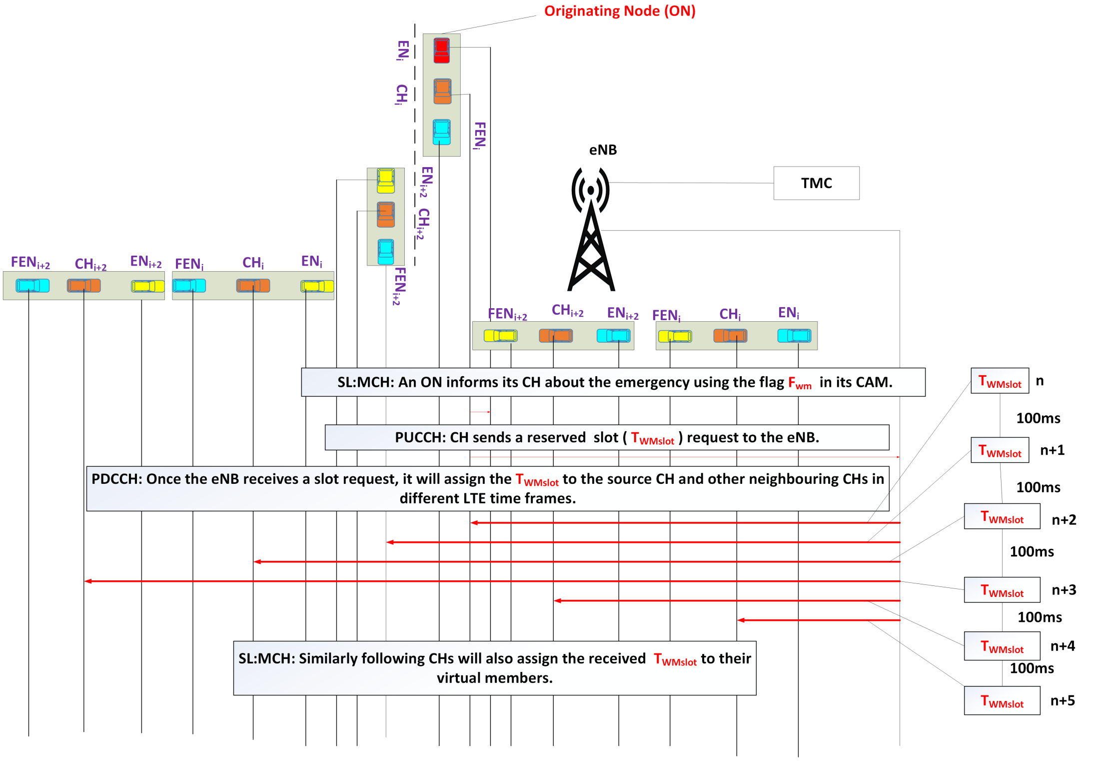


Figure 5.22: Reserved slot allocation for WM message transmission using CMMP

FEN_i will also become a member of CH_{i+1} and hold membership of both clusters CH_i and CH_{i+1} at the same time. Each forwarder node will then receive a reserved slot from its neighbouring CH to forward a warning message to neighbouring clusters. Once the cluster CH_{i+1} will receives the slot information, it will allocate the same slot to the FEN_i of neighboring cluster CH_i. The same procedure will apply to each forwarder node in the following clusters. When a WM arrives in the FEN of the originating cluster, it will multicast the WM to the neighbouring cluster using the reserved slot. The WM message will thus propagate through the AOR, reaching the farthest node. The same procedure will be followed by each cluster in the AOR.

5.9 Simulation Model and Performance analysis

We performed vehicular network simulation for a realistic urban environment by considering a city road intersection of the city of Sydney. We simulated our proposed

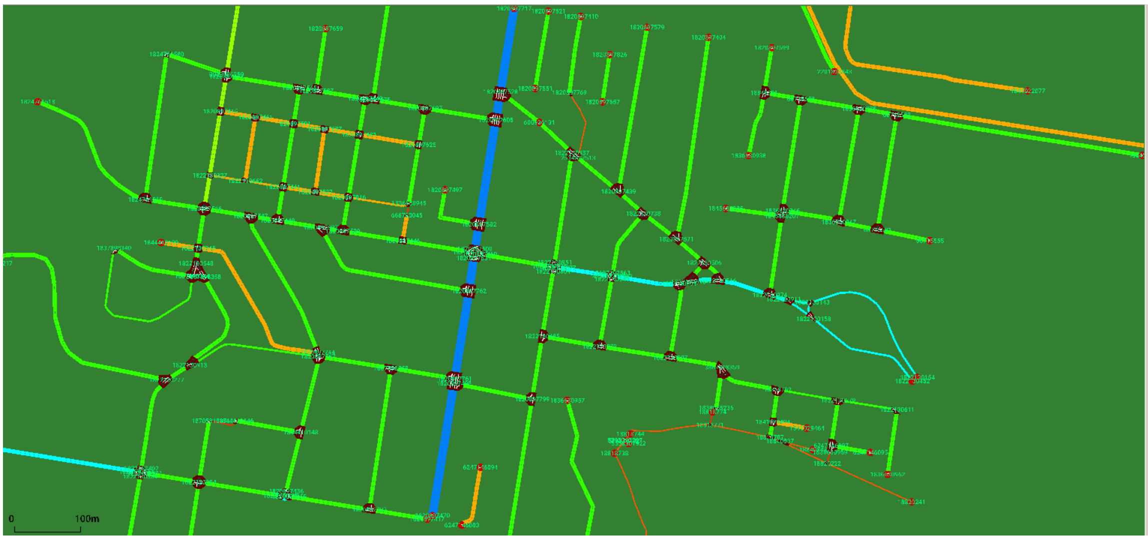


Figure 5.23: Real traffic (city roundabout road) scenario imported to SUMO using OpenStreetMap and modified using NETEDIT

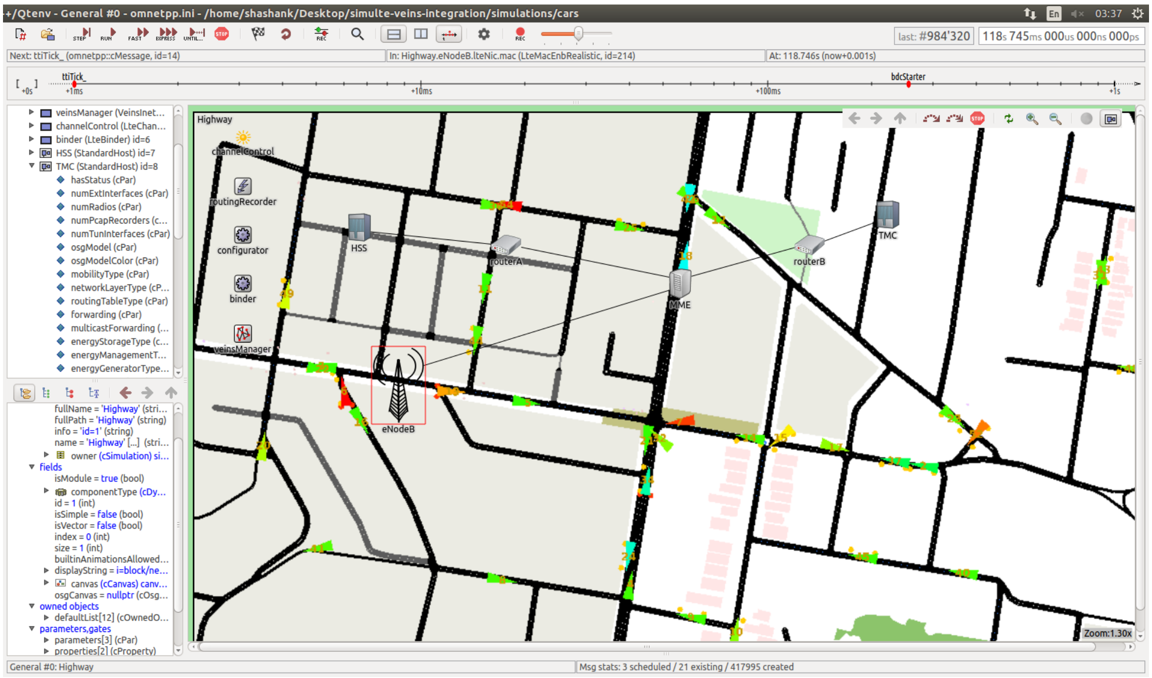


Figure 5.24: Developed simulation model (Integration of SimuLTE, SUMO, and Veins)

protocols using OMNET++, SUMO, and Veins simulators. An OMNET++ version 5.1.1 simulation model is developed using the SimuLTE [17] [16] that utilizes the INET framework 3.4.0. For enhanced traffic simulation, GPS data incorporation

Table 5.3: Main Simulation Parameters

Parameter	**Value**
Vehicle Average speed	intuniform [20-x, 40-x] km/h, X= rand(1.10)
Average Number of vehicles	350 to 400
Length of the vehicle	6 meter
Traffic flow rate	16 vehicle/min on R1, R3
Traffic flow rate	12 vehicle/min on R2, R4
Averge Inter-vehicle distance	30m
Road length & number of lanes	1.5 km & 4
$Roundabout_{D_{Th}}$	1.5
Carrier frequency	2.6 GHz
CAM generation frequency	10 Hz
DENM generation frequency	2 to 4 Hz
Number of warning message senders	1
Warning message size	350 to 520 bytes
Warning message notification region	2 km
Transmission bandwidth	3MHz (i.e., 15 RBs)
Fading model	Nakagami-m (m = 1, 2, 3)
eNodeB Tx power	46 dBm
UE Tx Power	26 dBm (Initial)
Noise figure	5 dB
Receiver sensitivity threshold Rx_{th}	-95 dBm
Simulation time	700s
Safety message size	362 bytes
T_{safety}	100 ms

and mobility support, we use Veins with a realistic mobility model generated by the microscopic road traffic simulation package Simulation of Urban Mobility (SUMO) [59]. Results from the simulation were acquired by taking the average of the 20 simulation runs with different seeds value. The key simulation parameters are listed in Table 5.3.

The model considers a multi-lane city scenario where the vehicles are distributed according to the Poisson distribution process. We consider a city intersection scenario with four road segments R1, R2, R3, R4 shown in figure 5.18. We selected a real city intersection from the Open Street Map (OSM) [140] which considers road directions, number of lanes, and maximum allowed speed for the real street. Fig. 5.23 and

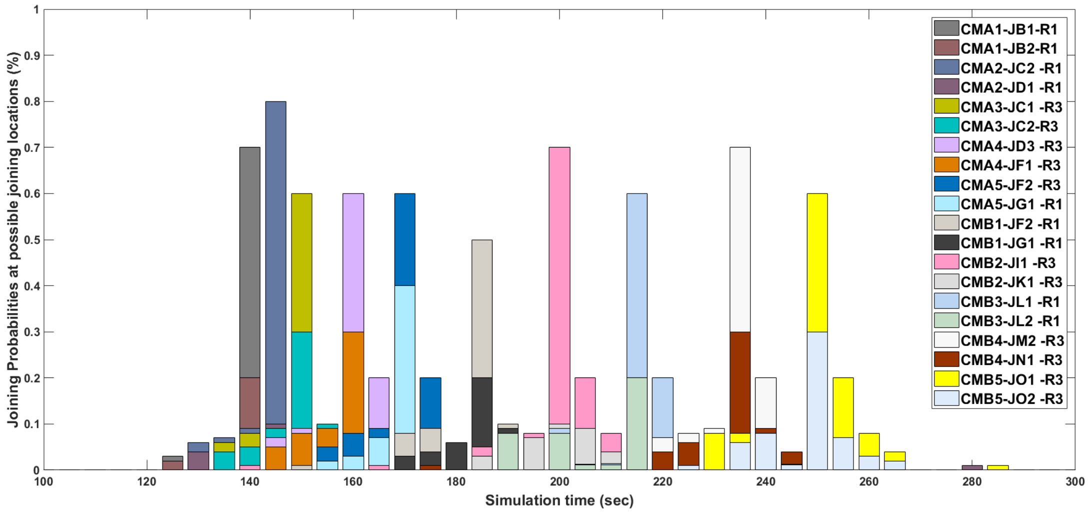


Figure 5.25: Joining probability between source vehicles and possible joining locations

5.24 show the selected city intersection, which is represented by four different road segments. Each road segment is 1.5 km long with two lanes per direction. Vehicular traffic is generated using SUMO. SUMO'S is a graphical network editor, NETEDIT, was used to design the synthetic city road.

Vehicle density on the road is simulated by the Poisson distribution process. The simulation model was run with different traffic flow rates on different road segments from different directions. The inter-vehicle distance is modelled by an exponential distribution function with a mean value μ (in metres) where a safety headway distance of three seconds is maintained. The model placed one emergency vehicle on the road segment R2 to generate event-based warning messages. All the road segments are considered as an AOR. The PB-CMMP protocol is implemented in the SimuLTE model. We also implemented a LTE/802.11p-based simulation model to simulate the HCVC-PROB [77] algorithm to obtain several performance parameters for comparisons.

Fig. 5.25 to 5.26 show the measured joining probabilities of the source cluster

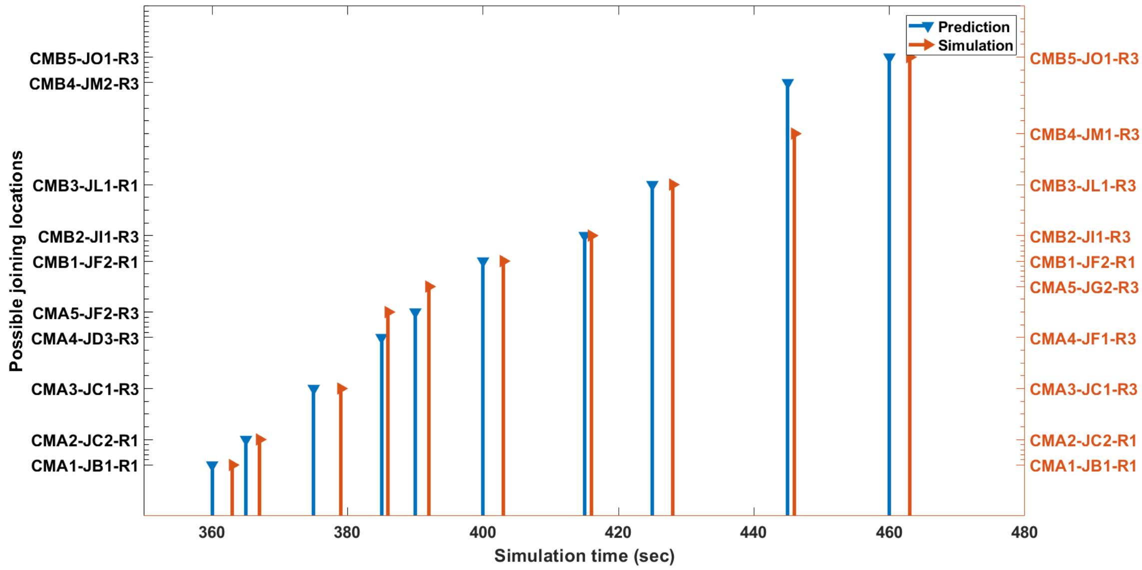


Figure 5.26: Comparison between predicted and simulated data

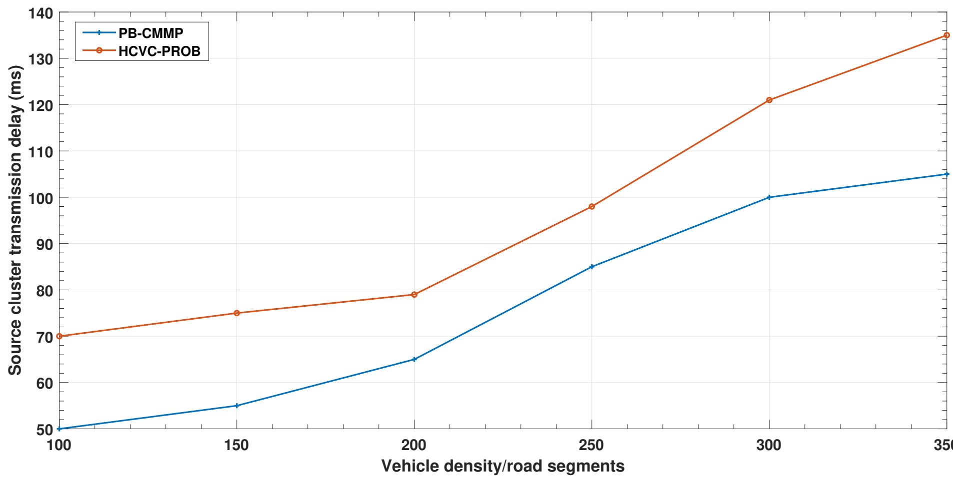


Figure 5.27: Single cluster transmission delay for PB-CMMP

head and its members and joining locations at the city intersection using our proposed prediction-based protocol. In the first simulation experiment, based on the current position, speed, and moving direction, the TMC will calculate the joining probability between source vehicles and possible joining locations approaching the same intersection. In the second simulation experiment, TMC will measure each vehicle's actual

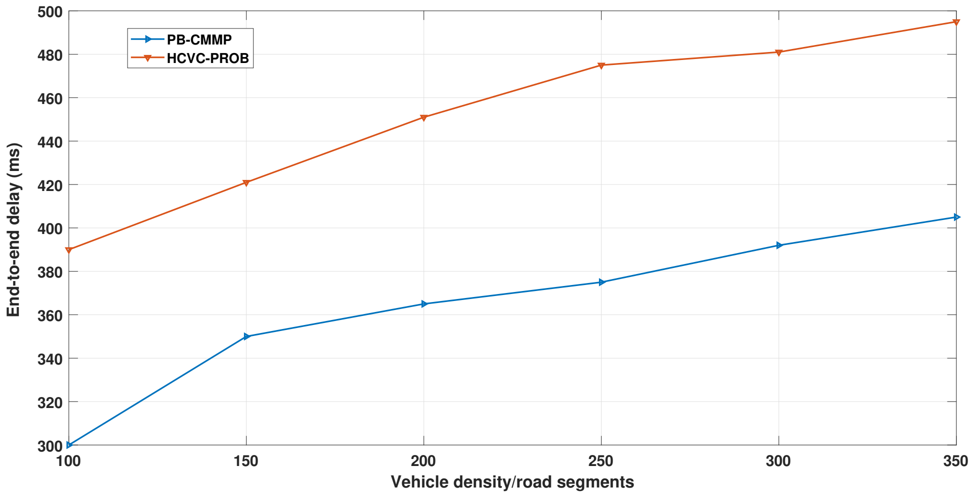


Figure 5.28: All cluster transmission delay for PB-CMMP

joining location at the intersection in the simulation and compare it with predicted joining locations during the first experiment. The purpose of comparing the first and second experiments is to check the accuracy of the proposed prediction-based protocol for predicting the future joining location of the source vehicle. The figures show the 80 % of vehicles are joining at the first-highest predicted location, and the remaining 20 % of vehicles are joining at the second-highest predicted location.

Fig. 5.27 shows the average single cluster warning message distribution delays for PB-CMMP, and HCVC-PROB protocols. The Figure shows that the proposed protocol offered much lower delay compared to the existing protocols. Also the PB-CMMP protocol performances are less sensitive to the vehicle density variation due to use of the multicast technique where the delay increases slightly due to the use of round-robin packet transmission techniques. Low message distribution delays are achieved due to the absence of any contention process in the LTE network. The contention process introduces a longer delay, particularly with higher node densities in a cluster, mainly due to retransmission requirements.

Fig. 5.28 shows the end-to-end warning message distribution delay which is required to distribute the warning message from source cluster to all destination

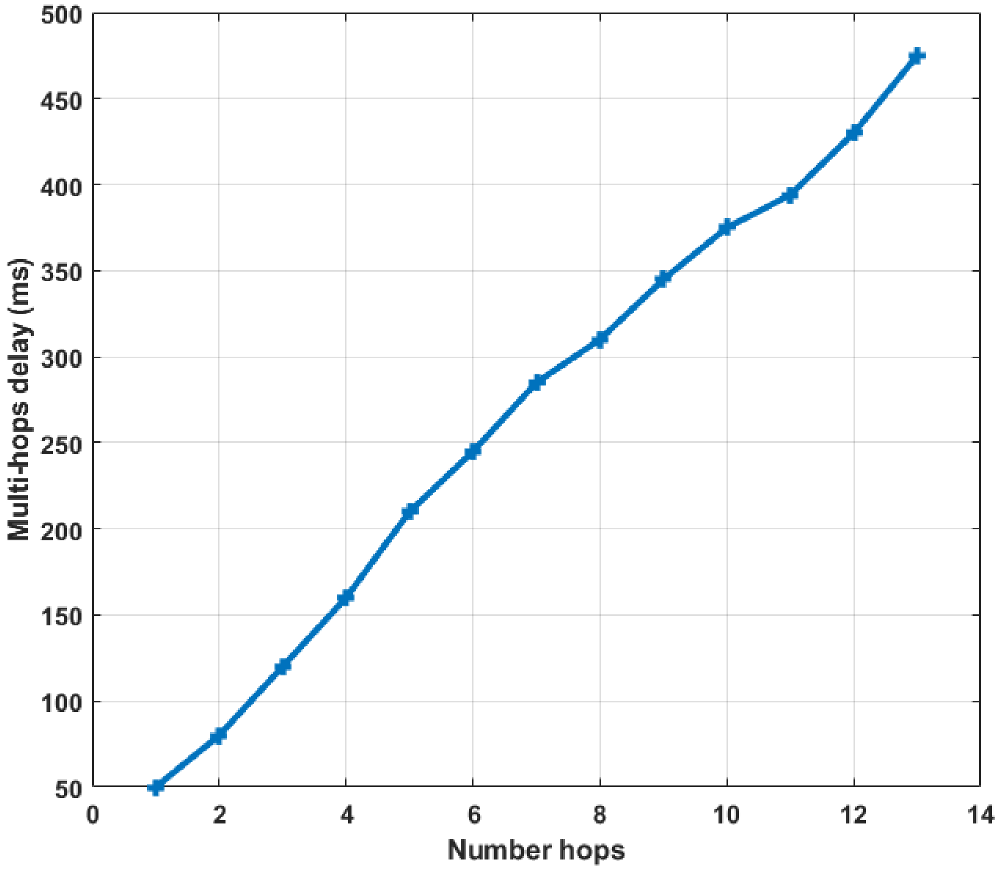


Figure 5.29: Multi-hope warning message reception delay for The PB-CMMP

clusters in an AOR. As shown in the figure, due to the efficient mechanism of the time-staggered resource allocation technique, chain transmission of warning messages and advance joining of the host cluster using prediction-based protocols, PB-CMMP offers lower delay compare to the existing hybrid protocol HCVC-PROB. Delays introduced by the existing hybrid protocol HCVC-PROB are significantly higher due to the presence of multiple collision domains in each cluster.

Figs. 5.29 and 5.30 show the multi-hop and the Cumulative Distribution Function (CDF) plot for the end-to-end warning message reception delays, respectively. Fig. 5.29 shows the hop-to-hop delay of warning message transmission from source cluster to all destination clusters in an AOR. Fig. 5.30 shows that around 97% of message

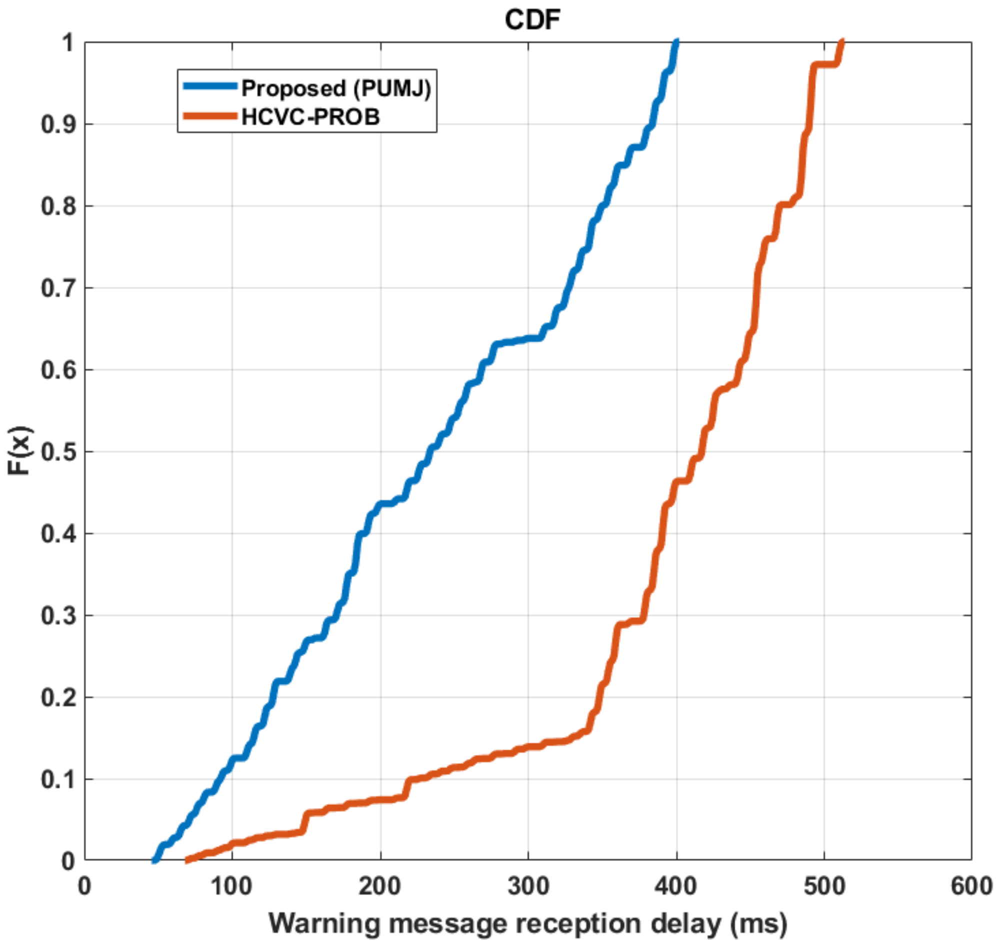


Figure 5.30: CDF of warning message message reception delay for PB-CMMP

delays are below 350 ms for the proposed protocol whereas about 80% of messages delays for the HCVC-PROB protocol are below 500ms. From the delay profiles it can be seen that the cellular only based VANET performs significantly better than the existing hybrid network.

5.10 Summary

This chapter introduced two 5G-based protocols for transmitting warning messages for a highway scenario in VANET. We proposed an efficient channel structure which shares the resources for the CAM and the WM messages. We further developed the proposed protocol, CMMP, using a prediction based protocol, PMUJ, to transmit the warning message in the city scenario. The proposed techniques offer low delay and very high, near 100%, message delivery ratio. The CMMP further extended to using PMUJ to analyse its performance in city scenario. The proposed protocols offers low delay and performs significantly better than the hybrid LTE/IEEE802.11p protocols. Simulation results show that the PMUJ offers higher QoS than do the IEEE 802.11p and other LTE networking architectures.

Chapter 6

PMUJ: A Prediction-Based C-V2X Protocol to Enhance Safety Message Transmissions in VANETs

6.1 Introduction

Worldwide efforts are underway by government organizations, automobile and ICT industries, and researchers to make roads safer, reduce environmental impact, and better manage road traffic by developing new V2X communication architecture. An efficient V2X communication infrastructure is an important element of a multi-service vehicular network which can support safety, traffic control and other relevant applications. Typical applications in a V2X network include cooperative manuver, cooperative broadcasts, road transportation emergency services and intelligent traffic signalling. A V2X network connects vehicles and the road side infrastructure needed to adopt a dynamic network topology where vehicles are rapidly changing their relative positions. For such scenario, traditional single-hop and multi-hop message transmission schemes use a linear network topology may not perform very well. A linear network topology is generally not scalable where packet losses could result in lower packet delivery ratio for many safety application [106]. In the literature, cluster-based communication infrastructure in a VANET forms a reliable backbone network for sharing information and is considered to be an efficient solution to support the dynamic network topology. A clustered network architecture allows communication between neighbouring vehicles and infrastructure units using a control entity known as the cluster head. A clustered network architecture can also support long distance communication using an efficient routing architecture. Over the last two decades, a large number of cluster-based routing approaches have been proposed for vehicular networks to implement different tasks, which includes cluster maintenance issues such as forming a stable cluster of high speed vehicles, scalability issues such as network load balancing and minimizing control signalling overhead and reliability issue such as improving information dissemination efficiency in high-density vehicular networks [141].

In Chapter 3, a cluster-based communication architecture named CBC-V2V is presented. The CBC-V2V architecture combines peer discovery, resource allocation and intra-cluster communication schemes to satisfy the latency requirements of Cooperative Awareness Message (CAM) transmissions. The proposed intra-cluster schemes utilize sidelink communication channels. In Chapter 4, a low delay direct inter-cluster communication algorithm named LTE-DICV2V is presented to to enable the neighbouring node in adjacent clusters to exchange CAM messages. However, the proposed inter- and intra-cluster communication schemes in Chapter 3 and 4 are only adaptable for simple road topologies such as a straight highway. Their results cannot be applied for all roads scenarios, such as roads with intersections and entry/exit roads. A good clustering scheme requires efficient cluster re-formation, joining, maintenance, and merging mechanisms which can efficiently deal with different road structures. Fig. 6.1 shows the three different scenarios for cluster joining

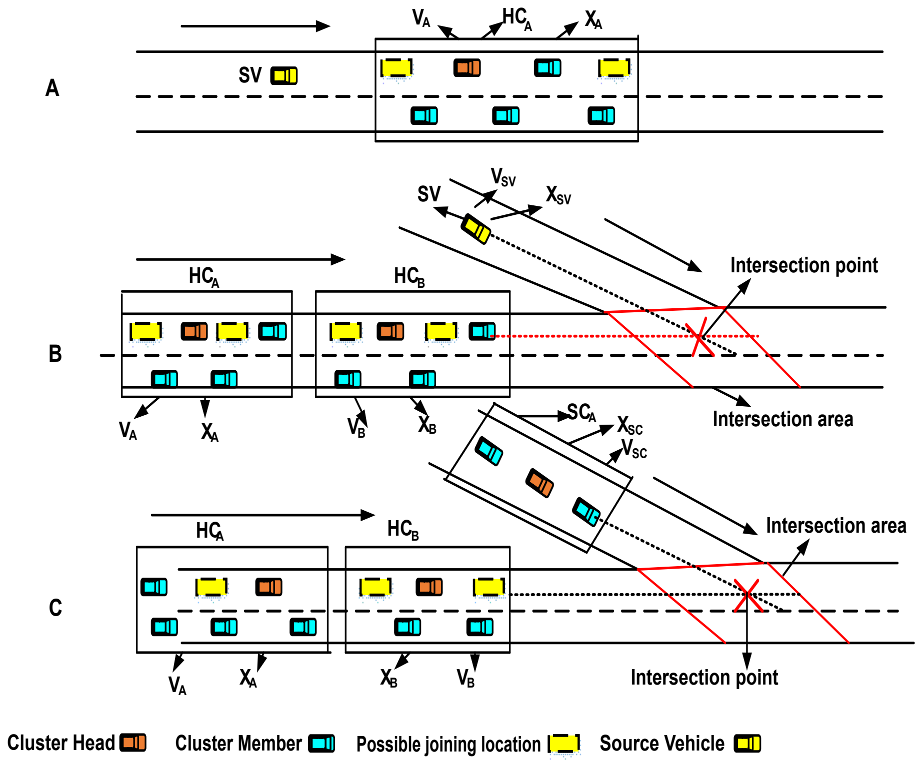


Figure 6.1: Statement of Problem

and merging on a straight highway and a highway with entry roads. cluster maintenance on the highway intersection is more challenging than on a straight highway for following reasons.

- Weak Line of Sight (WLOS): The main advantage of clustering on a straight highway is Line-of-Sight (LOS) between source vehicle and neighbouring clusters in its vicinity. As we can see in Fig. 6.1(A), a Source Vehicle (SV) is moving towards the host cluster HC_A. Both SV and HC_A are in LOS. AS shown in Fig 6.1(B), unlike the straight highway, both SV and HC_A are in the Weak line of Sight (WLOS). Joining the cluster near the highway entry point in the WLOS situation is challenging and requires a clustering scheme that can quickly reorganize the cluster. As shown in the figure, SV or SC_A and the host clusters are moving towards the same entry point at different speeds. It is possible that they may collide with each other at the entry point. For collision avoidance, preliminary information such as the accurate location of the existing cluster moving towards the same entry point is very important.

- High mobility: Usually on the highway vehicles moving at high speeds result in a fast-moving cluster near the highway entry point. It makes it very challenging for source vehicle and source cluster to join and merge with the fast-moving cluster at the highway entry point. There can be a few challenges, such as how the SV will find the joining location and insert itself at the entry point? Once a SV inserts itself at the chosen joining location, how does the host cluster quickly re-organize itself without interrupting ongoing safety message transmission? In the case the source cluster, which requires a soft merging approach with other clusters at the entry point, there is a requirement of the clustering scheme that can offer the soft handover between source cluster and host clusters at the entry point.

Recently, the majority of the research works have focused on clustering techniques using a hybrid architecture that consists of a cellular network and the 802.11p WLAN standard to exploit useful features of these standards [72] [23]. However, the key drawback of the hybrid architecture is the use of the IEEE 802.11p standard for the intra-cluster communication link between the CH and the cluster members. The problem generally occurs at high vehicle traffic density. At a high traffic load, the packet delay and the number of packet collisions significantly increases with number of vehicles transmitting packets. To overcome this, the 5G-based-V2X, also known as Cellular V2X (C-V2X) technology, is gaining a lot of industry attention. 5G-based V2X technologies for connected and fully autonomous vehicles are rapidly evolving.

In September 2016, the Third Generation Partnership Project (3GPP) published the LTE (Long Term Evolution) Release 14, which includes support for V2X communications. The standard is commonly referred to as the LTE-V/LTE-V2X, or C-

V2X [21] [13]. A global, cross-industry organisation named as the Fifth Generation Automotive Association (5GAA) has developed a comparative experiment model to compare the performance of IEEE 802.11p and LTE-V2X (PC-5) vehicular networks in improving vehicular safety application [82]. This research study demonstrated that the LTE-V2X (PC5) outperforms the 802.11p network in reducing fatalities and serious injuries on European roads.

This chapter proposes a new 5G-V2X based dynamic clustering scheme for efficient single and multi-hop safety message transmissions in a vehicular ad hoc network. A novel 5G-V2X-based clustering scheme referred to as Prediction-Based Updating, Monitoring, and Joining (PMUJ) algorithm is presented in this chapter. The proposed scheme improves the reliability of single-hop and multi-hop safety messages transmissions in highway roads with entry and exit roads . This approach offers a new procedure for trajectory prediction at a highway intersection and assists the cluster formation and reformation procedures. The proposed algorithm is a substantial extension of previous works presented in Chapter 3.

6.2 Related Work

Despite the uniqueness of each clustering algorithm in the literature, they almost share the same procedural steps. Their fundamental clustering process is to select a cluster leadership and develop a technique to maintain stable cluster operation. Some of the proposed systems use the IEEE 802.11p-Based clustering schemes to support V2V communication features such as opportunistic routing [142]. In [142] the authors proposed a direction-based clustering algorithm known as MC-DRIVE for an intersection area. In the proposed algorithm, the first vehicle moving from a certain direction act as a CH and clusters are formed using a single-hop based transmission range. In [143], the authors proposed a first technique known as Mobility Metric-

Based Clustering algorithm (MOBIC) proposing aggregate mobility where each node calculates its relative mobility to all of its neighbours based on the Received Signal Strength (RSS). However, these simple CH selection mechanism is only suitable for simple road topology, like a straight highway with no entry and exit roads. In [144], the authors proposed a Adaptable Mobility-Aware Clustering Algorithm based on Destination positions (AMACAD) where vehicle's final destination is used as a criteria to form a cluster. The vehicles with similar destinations have higher probability of staying in the same cluster. In [145], the author proposed a lane-based clustering algorithm to improve the stability in urban scenario. In the proposed algorithm, the cluster head selection and formation is based on the traffic flow i.e., vehicles' relative speed, relative position and moving direction.

Until now most research has focused on the development of hybrid architectures based on the cellular and 802.11p standards to exploit useful features of both cellular and IEEE 802.11p standards [72] [23]. In [77], the authors propose a Hybrid Cellular-VANET Configuration (HCVC-PROB) to distribute Road Hazard Warning (RHW) messages to distant vehicles. In this hybrid architecture, Cluster Members (CMs) communicate with the Cluster Head (CH) using the IEEE 802.11p link, and the CHs communicate with the eNB by using cellular links. The authors in [76] proposed a hybrid architecture known as a the VMaSC-LTE that intregates the LTE network with IEEE 802.11p-based VANET network. In [146], the authors proposed a cluster-based Heterogeneous (HetNet) IEEE 802.11p–LTE network architecture combining the IEEE 802.11p-based multihop clusters with the Long-Term Evolution (LTE) network, with the aim of achieving better result in term a higher data packet delivery and lower message transmission delay for urban environments.

The main problem of the above existing hybrid clustering solutions is the cluster scalability. These algorithms ignore the impact of IEEE 802.11p MAC layer's effect on cluster scalability and stability issues. The key drawback of these above proposed hybrid architecture is the usage of the IEEE 802.11p link for intra-cluster communication between the CH and cluster members. The major problem occurs in high vehicle traffic density scenario, where the message transmission delay and the number of packet collisions rapidly increases with the number of vehicles try to transmit their message at the same time.

The proposed 802.11p-LTE hybrid architecture increases the transmission delay which reduces the reliability when the IEEE 802.11p-based network needs to support high vehicle density, leading to higher packet delay. On the other hand, none of the above proposed hybrid architectures consider the impact of the random access protocol of the 802.11p standard on the cluster formation. A higher number of collisions or packet loss at the MAC layer could also impact the clustering algorithm.

In [147], the authors propose a pure cellular-based two-level clustering scheme for 5G V2X network, where the Fuzzy logic and Q-Learning techniques are used the first and second layer clustering respectively. A stable CH is selected based on the relative velocity, connectivity and the link reliability. The layer one cluster-head offers V2V communication among other cluster members over a sidelink channel. On the other hand layer two cluster-head offers the V2I communication. However, the main problem with this approach is the requirement for control signalling in terms of request messages to reach out to the layer one cluster head and in the discovery of a route to the layer two cluster head. The authors also did not focus on the required discovery time for the layer one and two cluster head and impact discovery time on the data dissemination delay.

Unlike the hybrid clustering scheme such as the VMaSC-LTE where the IEEE 802.11p network is used for the V2V communication, our proposed 5G-V2X architecture uses Sidelink Vehicle-to-Vehicle (SL-V2V) channels for the V2V communication to implement the ad hoc network feature as implemented by the IEEE 802.11p standard. Our PC5-based ad hoc network architecture removes packet collisions, thus

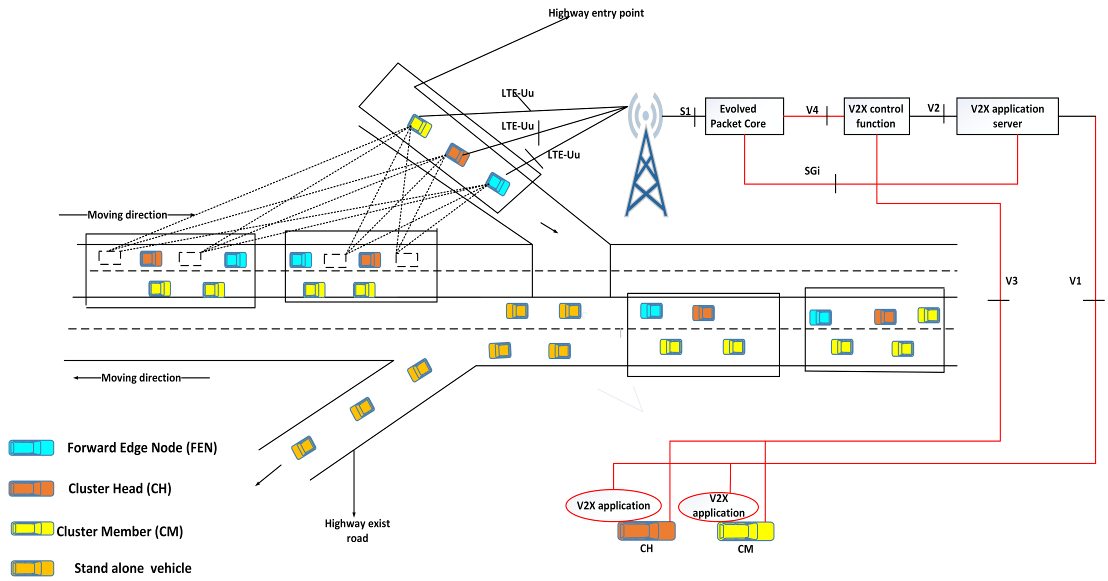


Figure 6.2: A highway scenario with entry and exit point in the VANET

enhancing the V2X network performance. The proposed schemes exploit mobility-related metrics such as the direction of movement, relative velocity, relative distance, and other metrics related to communication link quality. We perform an analysis of such metrics under different radio channel conditions.

6.3 PMUJ System Model

Fig 6.2 shows a highway scenario with an entry and exit point where vehicles are connected via the eNodeB of a LTE network. Vehicles in a multilane road will form clusters where the cluster heads will coordinate thier operation. A vehicle with the lowest average relative speed and the maximum distance from its current location to the zone boundary is chosen as the cluster head. We have introduced an LTE-D2D (Device-to-Device) multicast communications technique that utilizes the side link channels for D2D communications to multicast CAM messages within clusters. For each cluster node, radio resources are first allocated to the CH by the eNodeB. Each CH further schedules transmission resources among its CMs using a round-robin scheduling technique, as described in [94]. The detailed description of the proposed clustering scheme, called CBC-V2V is combining with a peer discovery model named ESPD and direct inter- and intra-cluster communication, presented in Chapter 3 and 4 respectively. Each vehicle will receive proximity information for direct communication using ESPD as presented in [94]. The operational diagram of our 5G-based CBC-V2V architecture is shown in Fig. 6.3.

In this model a Traffic Map Controller (TMC) attached to the eNodeB keeps track of each vehicle in the clusters. Vehicles in the proposed architecture are equipped with ITS Proximity Services (ProSe) enabled devices that utilize the LTE-Uu and the PC5 interfaces. The LTE-Uu interface is used for V2I communications to access (Internet Protocol) IP services, while the LTE direct interface PC5 is used for inter-vehicle communication. Cluster members can communicate with other members via the PC5 interface, whereas a CH communicates with its cluster members using the PC5 links and with the eNodeB using the LTE-Uu interface. The V2X application server incorporates the ProSe capability for building the application functionalities. The application server can communicate with applications located in vehicles. The V2X control function is a part of the 3GPP standard connecting with Evolve Packet Core (EPC) using the V4 interface. Each vehicle will receive proximity information for direct communication using our previously proposed EPC-level peer discovery model presented in [94]. Each cluster consists of several members, including the Edge Nodes (ENs), which are used to pass the CAM messages to the neighbouring clusters.

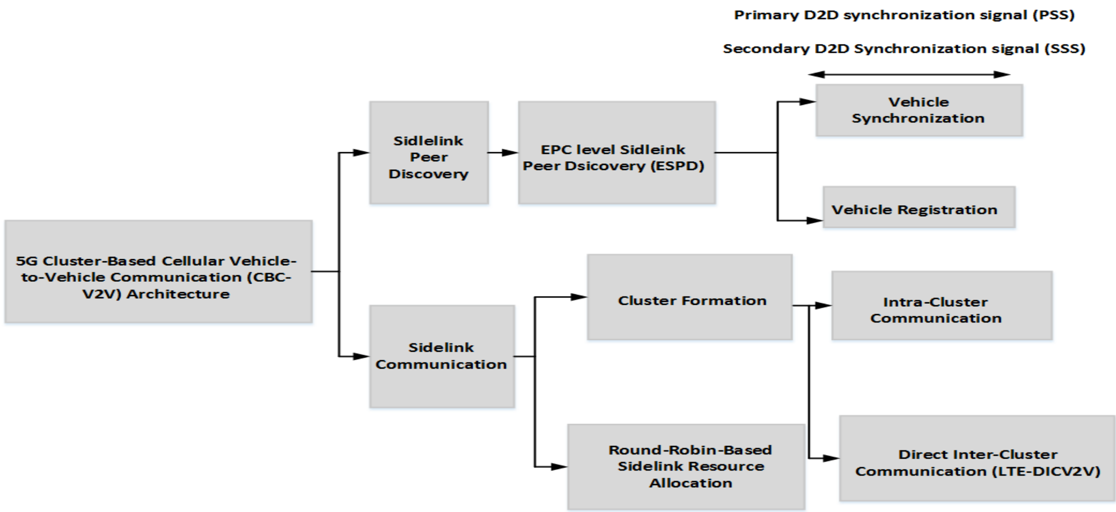


Figure 6.3: Operation of 5G CBC-V2V combining with ESPD and LTE-DICV2V

6.4 Prediction-Based Protocol PMUJ for Safety Message Transmission

In a cluster-based architecture, a cluster's stability plays a major role in maintaining the reliability of periodic and aperiodic safety message delivery systems. Due to the dynamic nature of vehicular communication and different road conditions, vehicles keep joining and leaving clusters frequently, introducing additional maintenance which makes clusters less stable. Our previous work was developed for a simple road topology like a straight highway with no entry and exit roads. Maintaining the cluster stability near intersections such as the highway side roads is challenging compared to cluster maintenance on a multi-lane straight highway. Joining and leaving a cluster near a highway intersection requires a reliable cluster management technique that can offer quick organization and re-organization of the cluster. To support the above requirements, we have designed and developed a prediction-based algorithm to support the following criteria:

- To improve the cluster stability.

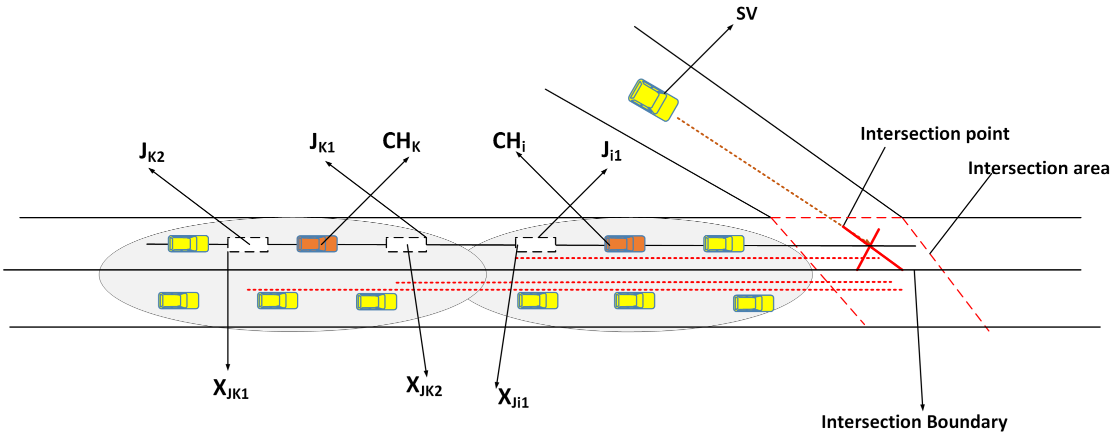


Figure 6.4: Linear Trajectory of SV and joining locations intersecting each other

- To improve the reliability of periodic and aperiodic safety message (i.e., CAM) distribution.
- To avoid collision between vehicles moving towards each other at the intersection point.
- To offer soft cluster merging between a source cluster and host cluster moving towards each other at an intersection point on highways.

In the following sections, We present the PMUJ protocol, where a single standalone vehicle, called a Source Vehicle (SV) on the roadside and the clusters called Host Clusters (HCs), are on the highway moving towards a highway entry road, as shown in Fig. 6.4.

6.4.0.1 Vehicle joining techniques at a highway entry point

In our proposed clustering approach, the Traffic Map Controller (TMC) maintains a database where it keeps the up-to-date information for all the clusters moving along a road. All CHs send an update to TMC about any change in their cluster. Fig. 6.4 shows the highway intersection scenario with an entry point on the left side. Clusters CH_i and CH_K, along with their cluster members, are moving towards an entry point.

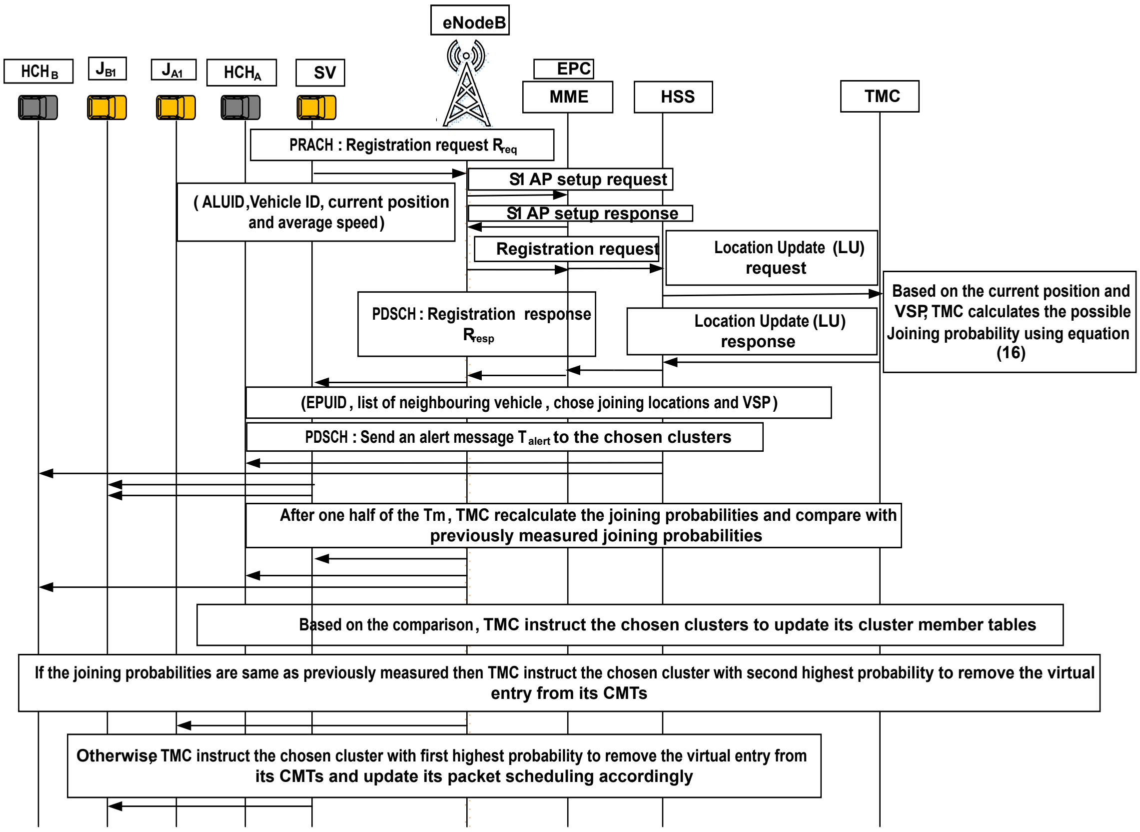


Figure 6.5: Signalling diagram for joining a cluster at a highway intersection

On another side, a Source Vehicle (SV) is also approaching the same highway entry point. We assume that SV is in Selection State (SE) and looking for an appropriate CH to associate with it. As per our CBC-V2V architecture, a vehicle in the SE state requires the network registration and sends the registration request R_{req} to the eNB. Fig. 6.5 shows the example where a vehicle in SE state sends a registration request message R_{req} along with its information (such as ALU_id, current position, and speed) over the Random Access Channel (RACH) to the eNB. Once the eNB receives the R_{req}, it will forward the R_{req} to other entities (such as HSS and TMC) in the EPC for user registration and location update. If the SV is in the SE state and moving towards a highway entry point, the TMC will make the list of all the existing clusters CH_i and CH_K, which are moving towards the same entry point.

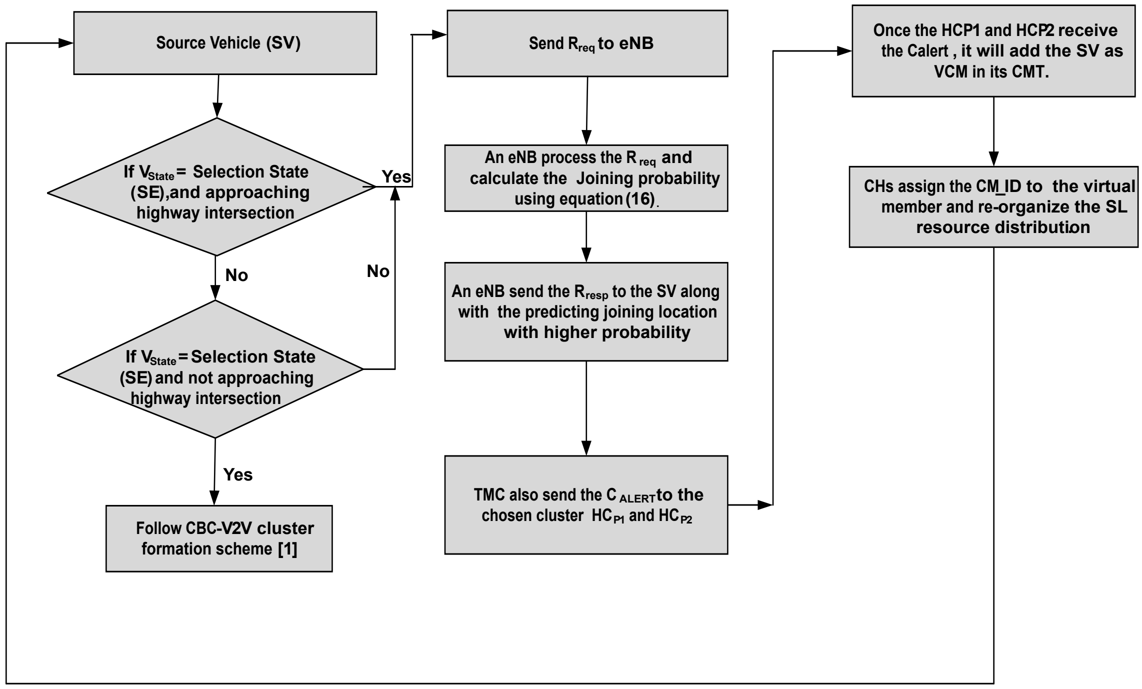


Figure 6.6: Flow diagram for SV joining a Host cluster at highway intersection)

6.4.0.2 Possible joining locations

Fig. 6.4 shows the SV's linear trajectory and existing clusters intersecting each other at the highway entry point. TMC makes the list of all the host clusters on the highway and calculates the possible joining locations in each host cluster where the SV can insert itself at the highway entry point. In each host cluster, the TMC calculates the possible joining locations based on the two vehicles' headway distance. The possible joining location is defined as the inter-vehicle spacing, which is higher or equal to the headway distance required to accommodate a new vehicle. Let's assume that the headway distance needed to accommodate the new vehicle is represented as $D_{joining}$, and minimum safe headway distance is represented as D_{safe}. We assume that to accommodate a new vehicle, the inter-vehicle distance should be two times higher than the minimum safe headway distance. Thus, the headway distance required to accommodate a new vehicle can be given as:

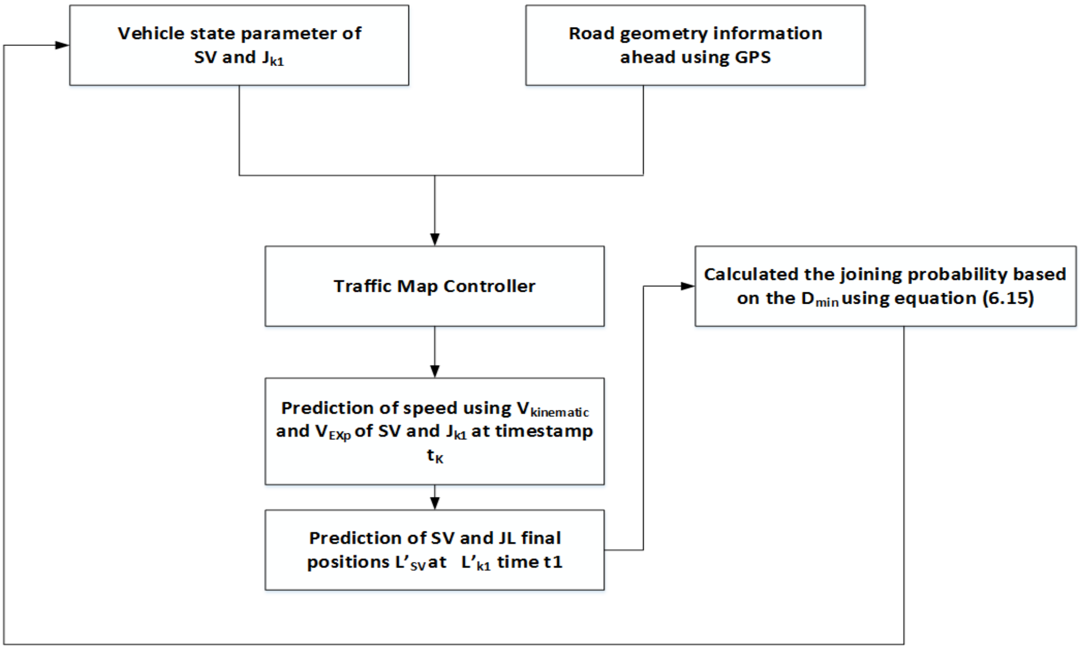


Figure 6.7: Operation of the TMC to calculate the joining probability using PMUJ

$$D_{joining} = 2 * D_{safe} \tag{6.1}$$

6.4.0.3 Joining probability

As shown in Fig 6.4, CH_i and CH_i are moving towards the entry point. Based on the headway distance between two vehicles, there are three possible joining points J_i, J_{k1}, and J_{k2} where SV can insert itself in the host cluster. The probability that the vehicle will insert itself in any of the joining points will depend on the probability of collision between SV and any of the possible joining locations near an entry point. For simplicity, we will consider only the SV and possible joining location J_{K1} for the probability calculation. Fig. 6.7 shows the algorithm used by TMC to predict the joining probability between d_{SV} and J_{K1}. Let's assume that speeds of the SV and J_{K1} are approximate to linear near the intersection point where the collision is possible. Therefore, the current position of each vehicle can be written as:

$$L(t) = x + tv \tag{6.2}$$

Where the x is a current position vector along the line at time $t = t_0$ and v is the velocity. The position relation between vehicles using the point of intersection can be written as:

$$x_{SV} + t_0 v_{SV} = x_{J_{K1}} + t_0 v_{J_{K1}} \tag{6.3}$$

In the configuration, SV and J_{K1} pass the intersection at the time t_{SV} and $t_{J_{K1}}$ respectively. Therefore, the encounter velocity is:

$$U = v_{SV} - v_{J_{K1}} \tag{6.4}$$

To accurately predict the joining probability, the vehicle's current motion parameters, such as speed, distance to the entry point, and acceleration of source vehicle and host joining location, should be considered in the proposed prediction algorithm. In our study, the proposed prediction algorithm is developed using the existing vehicle trajectory and collision prediction techniques presented in [137] [138] [139]. Our proposed prediction algorithm uses the vehicle future moving direction and road trajectory with which the future distance between both SV and J_{K1} will be calculated. Following the existing vehicle trajectory and collision prediction techniques presented in [137] [138] [139], our proposed prediction algorithm consists of two main models. First one is the kinematic model to predict vehicle future state parameters, such as vehicle speed, position, and acceleration. Second model is used to predict the future trajectory of road geometry ahead. Predictions of the vehicle speed by the kinematic models at the timestamp t_K is calculated using the basic equations of motion:

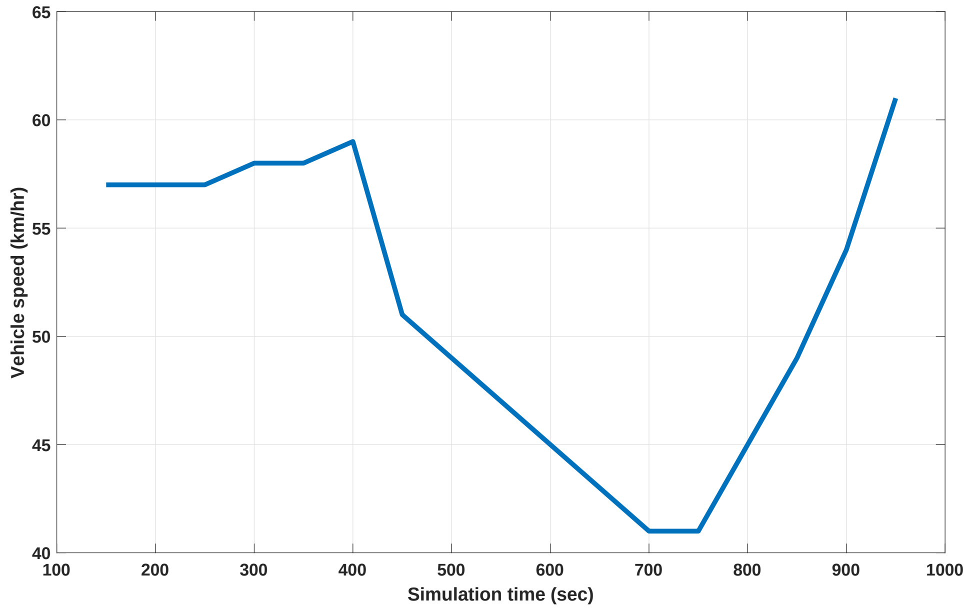


Figure 6.8: Simulated average speed profile of road side vehicles

$$V_{Kinematic,k} = V_k + a_x t_k, \tag{6.5}$$

Where $a_x t_k$ is the vehicle longitudinal acceleration at the current timestamps t_k. According to the road structure ahead, we consider vehicle moving at certain speeds on the expected trajectory. The expected trajectory of a source vehicle near the entry point is described by a hyperbolic curve parameterized by the road width W and the crossing angle θ. The authors in [137] presented the evaluation of these parameters in the real-time field. The future trajectory curve based on the moving direction can be obtained using (6.6)

$$y' = f(x', \theta, W_1, W_2) = tan\frac{\theta}{2}\sqrt{x'^2 + \frac{b^2(W_1 + W_2)^2}{tan(\frac{\theta}{2}}} \tag{6.6}$$

Where (x', y') is the expected vehicle position in the standard coordinate for the hyperbola (x′-axis and y′-axis). W_1 and W_2 are road widths of the side road and highway road, respectively, θ is the entry point crossing angle, and b is relevant to the uncertain driving behavior. The expected speed v_{Exp} in the standard hyperbola coordinates varies while the vehicle is passing through the entry point. v_{Exp} is assumed to follow a piecewise Gaussian function and an arctangent function of expected vehicle positions, $[x_{Exp}, y_{Exp,k}]$, as expressed in (6.7) and (6.8). The variation of the expected speed of the source vehicle is shown in Fig. 6.8.

$$V_{EM,k}(i) = \begin{cases} V_{L_{Vmax1}} + (V_{L_{Vmax1}} - V_{L_{Vmax1}}) \exp\Big(-\frac{x_{Exp}(t_k^2}{s_1^2}\Big), & \text{if} x_{Exp,k}(i) \neq 0, \\ V_{L_{Vmax1}} + (V_{L_{Vmax1}} - V_{L_{Vmax1}}) \exp\Big(-\frac{x_{Exp}t_k^2}{s_2^2}\Big), & \text{otherwise}, \end{cases} \tag{6.7}$$

$$\begin{aligned} S_{t_k} &= (V_{L_{Vmax1}} - V_{L_{Vmax2}})t_{de}, \\ S_{t_k} &= (V_{L_{Vmax3}} - v_{L_{Vmax2}})t_{ac}, \\ a_{Exp}(t_k) &= \arctan\Big(-\frac{a^2 x_{Exp}(t_k)}{b^2 y_{EXP}(t_k)}\Big), \end{aligned} \tag{6.8}$$

Where $V_{L_{Vmax1}}$ and $V_{L_{Vmax3}}$ are lane speed limits on two intersected roads i.e main highway and side road, $V_{L_{Vmax2}}$ is the lower speed that a vehicle decelerates when it moving towards and passes the entry point, and t_{de} and t_{ac} are the deceleration time and acceleration time, respectively; these values are calculated when vehicles approach a roundabout. From (6.2)–(6.7), we can obtain predictions of $v_{Kinematic}(t_k)$, and $v_{Exp}(t_k)$ parameter of SV and possible joining location J_{K1} according to (6.9) and (6.10)

$$V_{SV}(t_k) = \beta(i)V_{Kinematic}(t_k) + [1 - \beta(i)]v_{Exp}(t_k), \tag{6.9}$$

$$V_{J_{K1}}(t_k) = \beta(i)V_{Kinematic}(t_k) + [1 - \beta(i)]v_{Exp}(t_k), \tag{6.10}$$

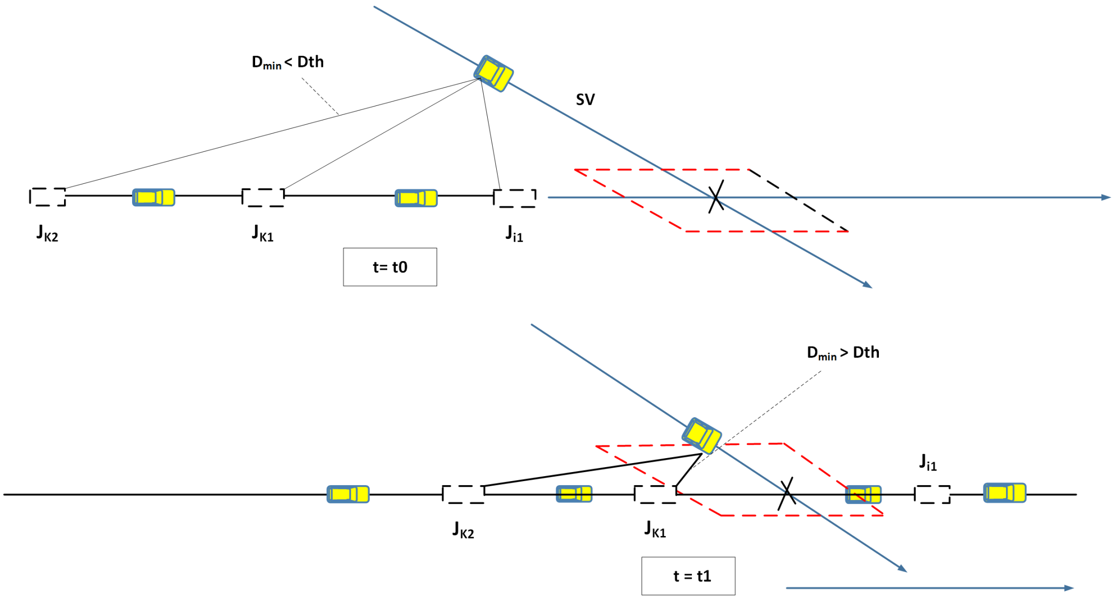


Figure 6.9: Time slice of intersecting vehicles at intersection

Where $\beta(i)$ is the weighted coefficient at timestamp t_k. The $v_{Kinematic,k}$ and $v_{Exp}(t_k)$ are predicted speed from kinematic models and expected trajectory model, respectively. The TMC will calculate the time for SV to reach the entry point. Let's assume that the SV will take the t_{k+1} seconds to reach the intersection area boundary. On the other hand, TMC also calculates the final position of both SV and J_1 after t_{k+1} second. The final positions of the joining location and source cluster member after t_{k+1} can be calculated as:

$$L'_{SV}(t_{k+1}) = \frac{1}{2}a_{SV}t_{k+1}t^2 + V_{SV(t_{k+1})} + x_{SV}(t_{k+1}) \tag{6.11}$$

$$L'_{J_{K1}}(t_{k+1}) = \frac{1}{2}a_{J_{K1}}(t_{k+1})t^2 + V_{J_{K1}(t_{k+1})} + x_{J_{K1}}(t_{k+1}) \tag{6.12}$$

where $L'_{SV}(t_{k+1})$ and $L'_{J_{K1}}(t_{k+1})$ represent the final positions of a source cluster member and possible joining location respectively after t_{k+1} time, a_{SV} and $a_{J_{K1}}$ represent the acceleration source cluster and joining location respectively, V_{SV} and

$V_{J_{K1}}$ is the staring velocity and x_{SV} and $x_{J_{K1}}$ is the starting position of the source cluster member and possible joining location respectively. Based on the final position of joining location, the TMC will measure the future distance between the SV vehicle and the joining location J_{k1}. As shown in Fig. 6.9, there is a possibility that moving vehicles with variable velocities have a unique time when the distance between the SV and J_{k1} becomes minimum near the intersection point. By calling this specific time t_{k+1}, we get the following minimum distance.

$$D_{min} = |L'_{SV}(t_{k+1}) - L'_{J_{K1}}(t_{k+1})|. \tag{6.13}$$

At the time t_{k+1}, the joining point J_{K1} located at the intersection point and minimum distance D_{min} is smaller than distance threshold D_{th}. The D_{th} represents the specified collision radius. Collision is possible if D_{min} is smaller than a specified collision radius τ, i.e., $\Delta t < \Delta t_{col}$, where Δt_{col} is given by:

$$\Delta t_{col} = \frac{U * D_{min}}{|V_{SV} * V_{J_{K1}}|} \tag{6.14}$$

The collision radius τ would be the sum of the physical radius of the two vehicles. Thus, the probability that the CH_{i+1} will place itself in a cluster depend on the D_{min} between SV and J_{K1}. Therefore, the SV will insert itself at the J_{K1} in the cluster when the collision will occur at time t_{k+1}. Considering that SV passes the intersection point, the probability P_{join} that SV collides with joining points J_{K1} is

$$P_{join} = \frac{\Delta t_{col}}{t_{k+1}} = \frac{2\tau U}{|V_{SV} j_{k1}| t_{k+1}} \tag{6.15}$$

Similarly, the TMC will calculate the joining probability of SV and other possible joining locations. Among all possible joining locations, the TMC will choose the joining location with the first and the second highest probability.

Once the TMC calculates the joining probabilities, the TMC sends the chosen joining locations with first and second highest probabilities to the source vehicle. At the same time, the TMC also sends a C_{Alert} message to the chosen host clusters with first and second highest probabilities named HC_{P1} and HC_{P2}. Upon reception of the registration response, the SV updates its VIR with the new proximity data. On the other hand, once the host clusters HC_{P1} and HC_{P2} receive the alert message, it will create a new virtual entry in their Cluster Member Table (CMT) and add the members of the source cluster in their CMT as a Virtual cluster Member (VCM). Further, the CH assigns a new vehicle ID to the VCM and reorganizes the resource distribution based on the vehicle ID. According to the proposed round-robin scheduling, each member of the cluster will receive the sidellink (SL) resources based on their ID in ascending order.

As mentioned in the above section, in our prediction-based protocol, once the TMC calculates the joining location with higher probability, it will send an update to both the SV and host clusters moving towards the same entry point. Further, the source vehicle joins the predicted host clusters at the entry point. However, due to high dynamic topology, such as the different speed profiles shown in Fig 6.8, there is a possibility that the vehicle will fail to join the predicted cluster with the highest joining probability. In this case, it may join other neighbouring clusters with the second-highest probability at the intersection. To overcome this situation, we devise a procedure where the TMC will multicast an alert message to both the chosen cluster with the first and second highest probabilities at the same time.

Once the chosen clusters receive the update message, they will extract the SV information and add the SV virtually to their cluster member table. In this way, the source vehicle becomes a virtual cluster member of the chosen clusters (i.e., both with first and second highest probability). The term Virtual Cluster Member (VCM) defines it as a vehicle that does not join the host or chosen cluster physically, but

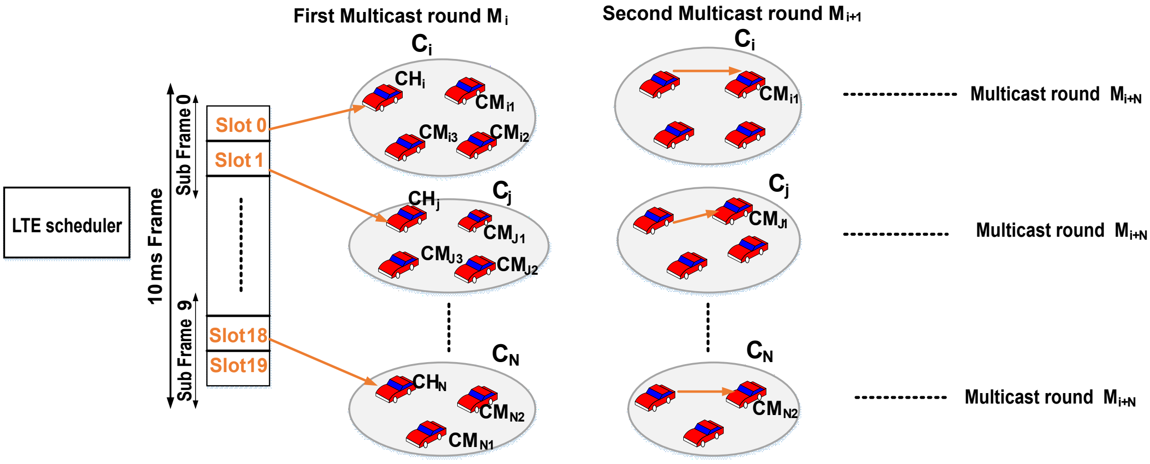


Figure 6.10: Sidelink slot allocation using our proposed Round Robin scheduling

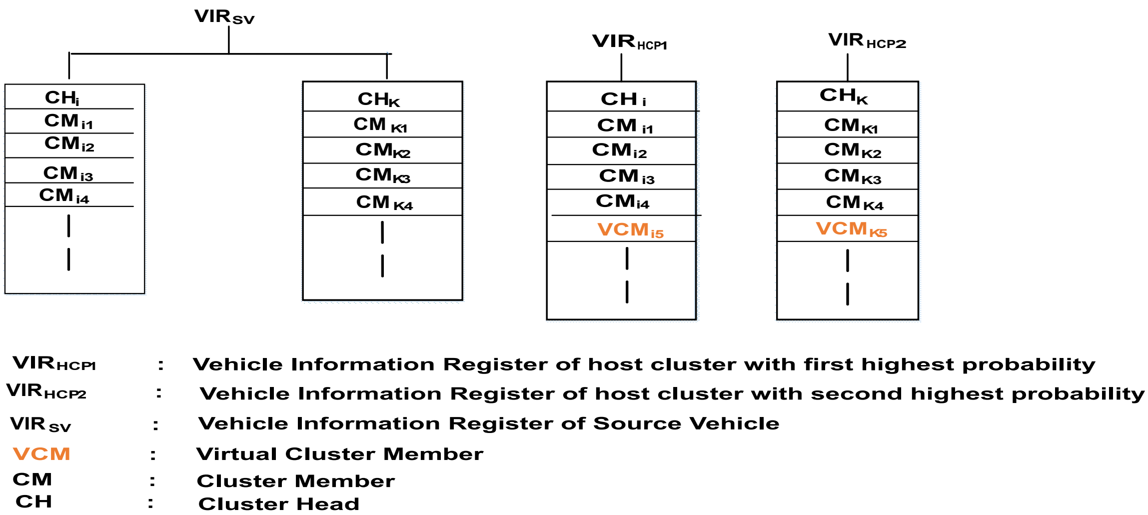


Figure 6.11: VIR of SV, HC_{P1} and HC_{P2}

it can connect to the host cluster virtually for safety message transmission. When the source vehicle becomes the Virtual Cluster Member (VCM), the host or chosen clusters will reorganize its resource distribution. As shown in the Fig 6.10, our proposed resource distribution scheme is operated by dynamically assigning multiple users to the same slot in turn, where they share the slot using their ID in ascending order. Once the vehicle joins virtually, HCs assign a new ID to the SV according to the predicted joining location where it will insert itself in the cluster. Further, each member will receive the sidelink slot as per its respective vehicle ID. Unlike

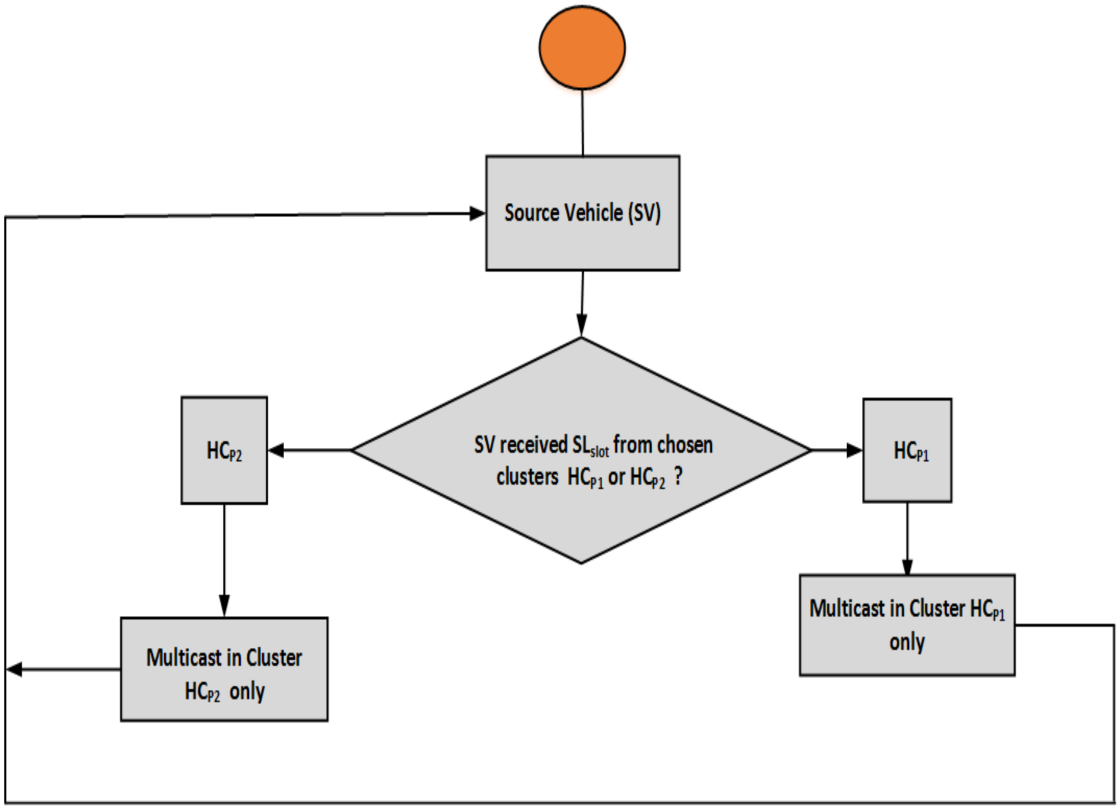


Figure 6.12: Multi-casting as per the Sidelink slot allocation

the chosen cluster, the host cluster HC_{P2} will create a temporary entry and add the SV as a temporary Virtual Cluster Member (VCM) in its cluster member table. That means the SV will not be assigned a new vehicle ID and receive transmission resources from the CH.

In this case, the source vehicle will hold the membership of the two clusters simultaneously. However, if the SV holds membership of two clusters, then which cluster will assign the sidelink slot to the SV for its safety message transmission? To resolve the situation, we devise a procedure where the SV will form a new multicast group in its Vehicle Information Register (VIR). Fig. 6.12 shows the resource allocation procedure for virtual members. Fig. 6.11 shows that the SV will create two different multicast groups in its VIR. In the first multicast group, it will add all the members of the chosen cluster with the first highest joining probability HC_{P_1}. In the second multicast group, it will add the member of the cluster with the second-highest probability HC_{P_2}. As SV holds the dual membership, it will receive a SL slot from both chosen clusters using the proposed round-robin scheduling. Once the source vehicle receives the slot, it will check whether it is for the chosen cluster with the first highest probability or second-highest probability. Suppose the SV receives the slot from the cluster. In that case, it will only multicast the safety message in the first multicast group, whereas if it receives it from the SC, it will multicast the safety packet in its second multicast group cluster.

6.4.0.4 Monitoring and update of Source and host clusters

The TMC keeps up-to-date information about all the clusters on the road. Once the SV becomes a the virtual member of both chosen clusters, the TMC keeps monitoring both chosen clusters' velocity profiles and source vehicles. As motioned above, due to different speed profiles, the vehicle may join a different cluster instead of the predicted one at the intersection. To overcome the prediction error, we suggest a procedure where, after a particular period, i.e., representing half of the total time that it will take the SV to reach the entry point, the TMC recalculates the SV's joining probabilities and chosen clusters and compares it with previously calculated probabilities. If the joining probabilities are the same as the previous one, the TMC will instruct the cluster with the second-highest probability to remove the VCM from its cluster Member Table (CMT). In case the probability is different to the previous one, then it will instruct the chosen cluster with the highest probability to release VCM from its CMT and re-organize the cluster accordingly.

6.4.0.5 Cluster merging at the highway intersection

In this section, we will present the second scenario where, instead of the standalone vehicle, a Source cluster (SC) is approaching a highway entry point and joining other

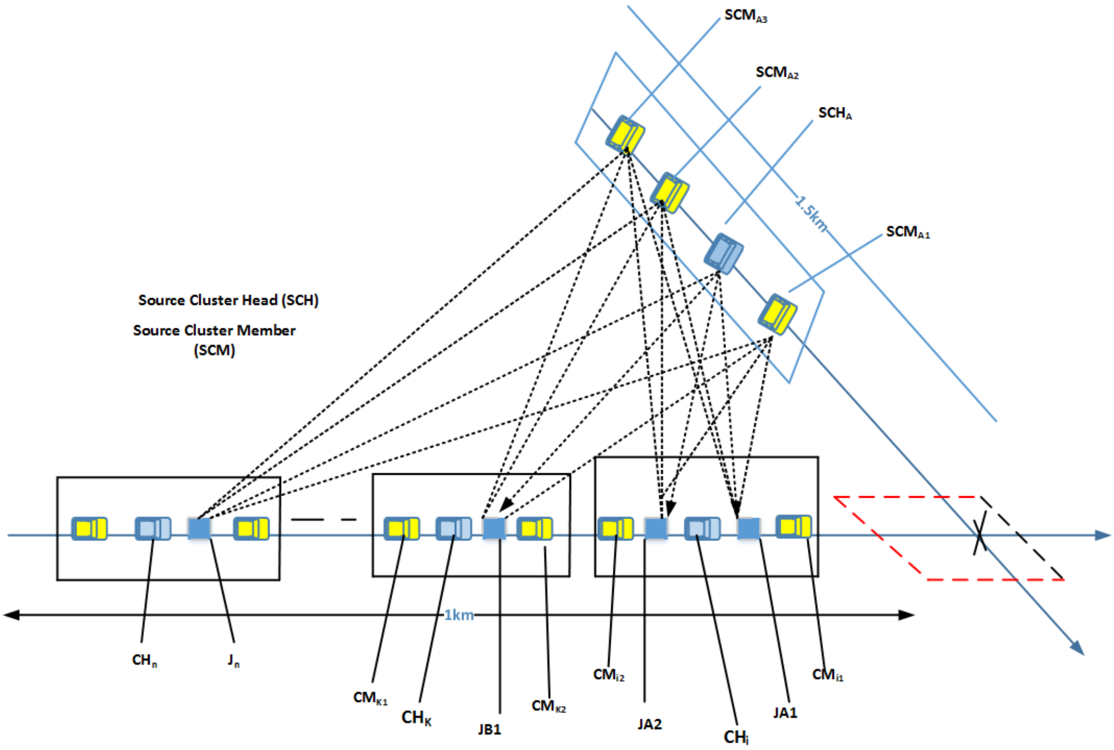


Figure 6.13: cluster Merging at highway intersection

clusters (host clusters) which are also moving towards the same intersection area. Due to the high dynamics of the vehicles, such as variable speed and variable position, it is very challenging to the source cluster to join or merge with another cluster at the highway intersection.

Fig. 6.13 shows the trajectory of Source and Host clusters moving towards the same highway entry point. The source cluster represented as SCH_A, along with its cluster members, are moving towards the entry point and looking for the host cluster to merge with at the entry point. However, due to variable speed and changing positions of vehicles, it can be very challenging for the source cluster to join or to merge with other clusters at a roundabout. In our proposed clustering approach, the TMC maintains a database where it keeps the up-to-date information of all the clusters moving on the road. All CHs send an update to TMC about any change in their cluster. In our study, we consider that TMC will generate a warning message, repre-

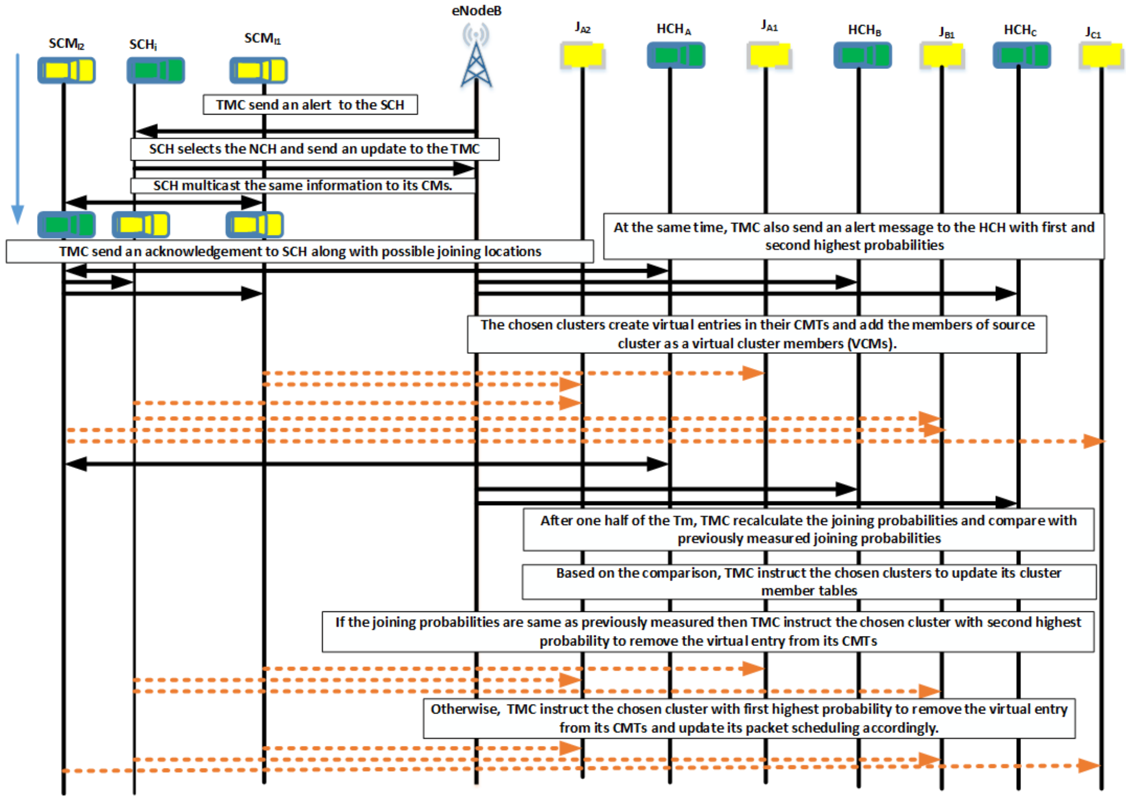


Figure 6.14: Signalling diagram for cluster merging at highway intersection

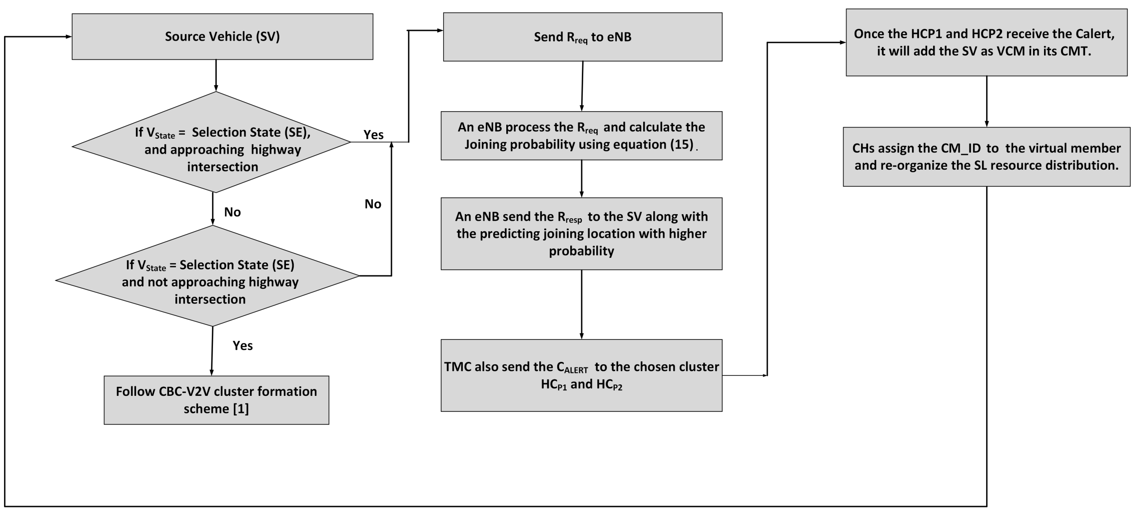


Figure 6.15: Flow diagram for source cluster merging with host cluster at intersection

sented as $entrypoint_{Ahead}$, when the Source Cluster (SC) is at a distance represented as $Intersection_{D_{Th}}$ away from the highway entry point. In this case, if the cluster is

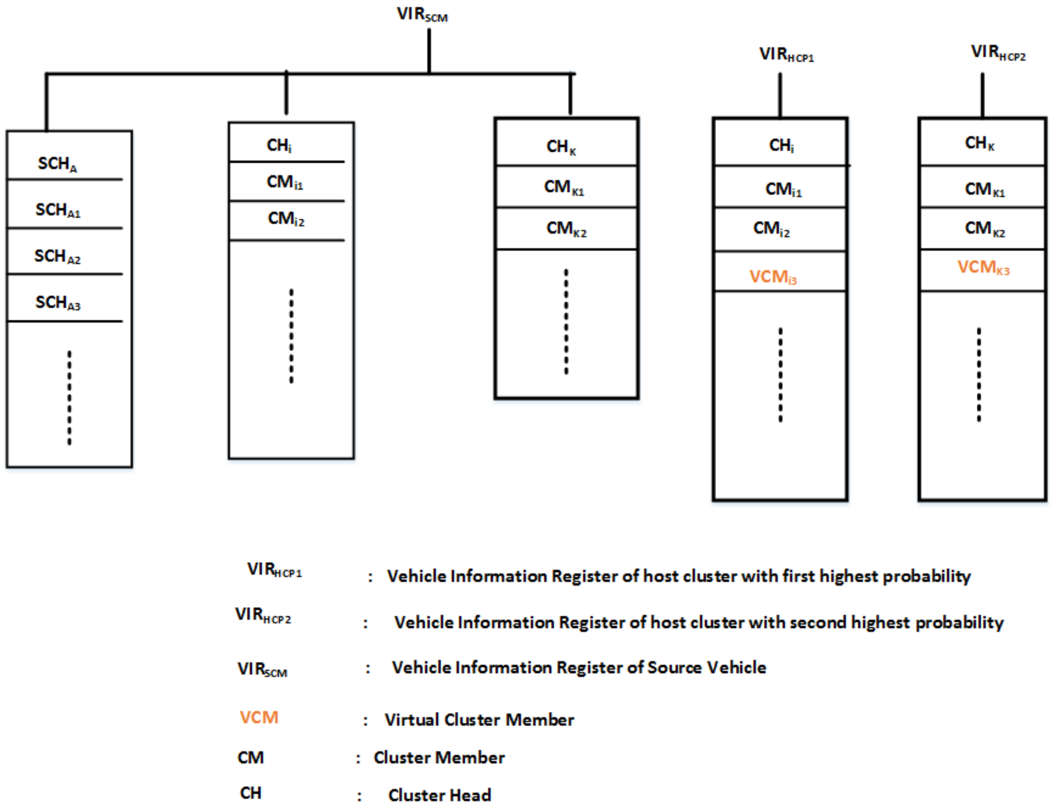


Figure 6.16: VIR of SCM, HC_{P1} and HC_{P2}

approaching a highway intersection, the TMC will send a $entrypoint_{Ahead}$ alert message to the source cluster. Figs. 6.14 and 6.15 show the signaling and flow diagram of the cluster merging at the highway entry point. To enable the inter-cluster soft handover at the roundabout, we propose to choose a vehicle that will leave the cluster last as the new Cluster Head (CH). Once the SCH receives the $entrypoint_{Ahead}$, it will give up its CH role and assign the CH head role to the vehicle which has the longest life time or the highest remaining distance from the highway entry point among all the cluster members. Thereby, CMs can have continuous connection with the old CH before leaving the source cluster's and joining the host clusters head at the roundabout.

Further, the TMC will follow the same procedure as discussed in the last section for cluster reformation and will calculate the joining probabilities between the mem-

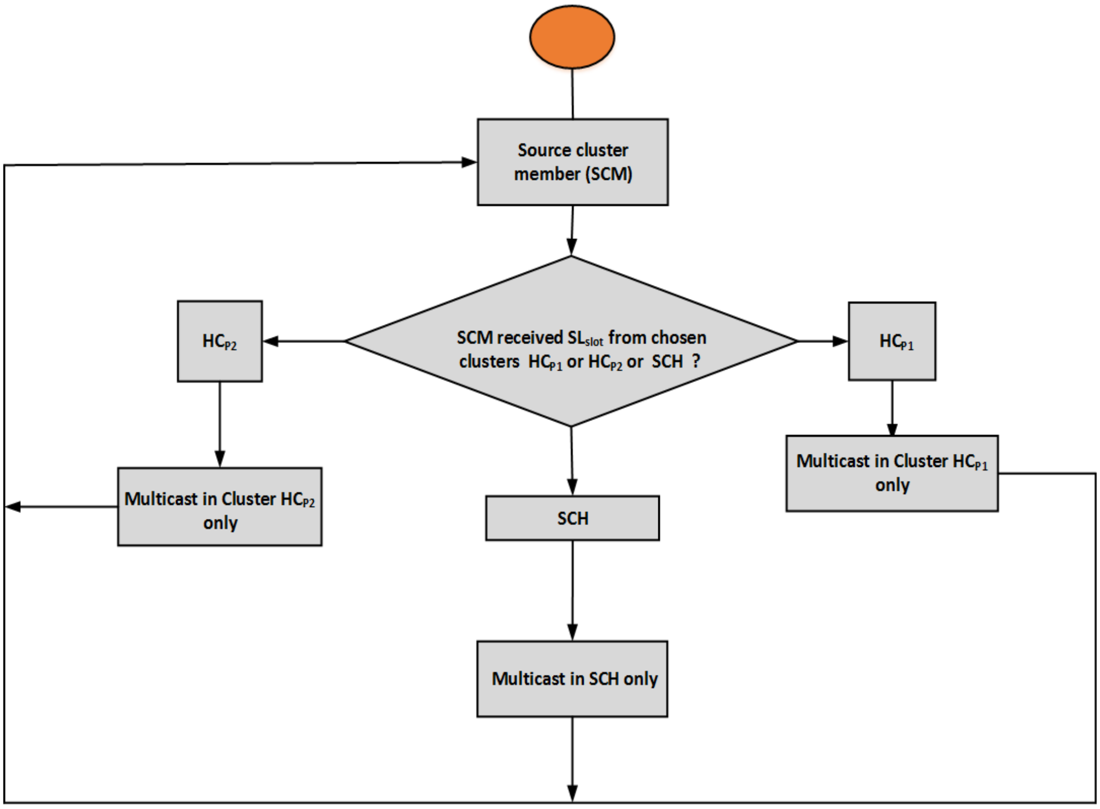


Figure 6.17: Multi-casting as per the Sidelink slot allocation

ber of Source Cluster Members (SCMs) and possible joining locations in host clusters using equation (6.15) presented in 6.4.0.3. Unlike the SV, the SCM holds membership of the three clusters simultaneously. However, if the SCM holds membership of three clusters, then which cluster will assign the sidelink slot to the SV for its safety message transmission? Similar to the SV, to resolve the situation, we devise a procedure where the SV will form a new multicast group in its Vehicle Information Register(VIR). Fig. 6.16 shows an example where, the SCM will create a three different multicast groups in its Vehicle Information Register (VIR). In the third multicast group, it has members of the current cluster that is Source cluster Head (SCH). In the second multicast group, it will add all the members of the chosen cluster, with the first highest joining probability HC_{P_1}. In the third multicast group, it will add the members of the cluster with the second-highest probability HC_{P_2}. As SV holds dual

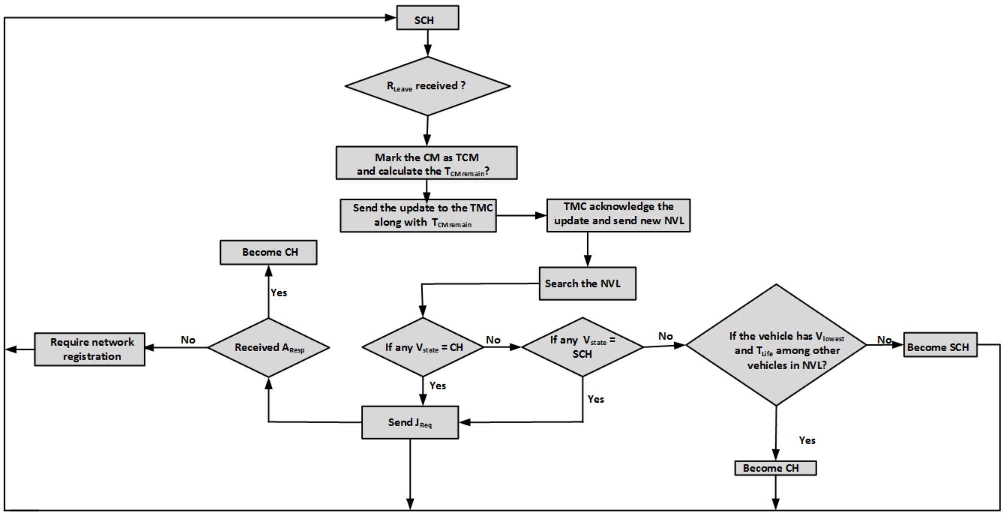


Figure 6.18: Algorithm for leaving the cluster

membership, it will receive the SL slots from both chosen clusters and source cluster head using the proposed round-robin scheduling. Fig. 6.17 shows a flow diagram of slot distribution. Once the source vehicle receives the slot, it will check whether it is for the chosen cluster with the first-highest probability or the second-highest probability. Suppose the SV receives the slot from the SC. In that case, it will only multicast the safety message in the first multicast group. If it receives it from the HC_{P_1}, it will multicast the safety packet in its second multicast group cluster. If it receives from the HC_{P_2}, it will multicast the safety packet in its third multicast group cluster. Further, TMC will follow the same procedure to monitor and update the source cluster and the host cluster as discussed in the previous section.

6.4.1 Leaving The Cluster

A cluster needs maintenance when either the new member joins or an existing member leaves the cluster. The algorithms for a CM leaving a cluster and a CH leaving a cluster are presented in Figs. 6.18 and 6.19, respectively. Each CH keeps the information about its cluster, CH_ID (Cluster ID), and the number of CMs attached in the data structure denoted by cluster_Info. Each CH creates and updates a cluster_Info dynamically. Once the cluster head receives the leaving request from its CM, it will mark the CM as a Temporary Cluster Member (TCM) and calculate the remaining time $T_{CMremaining}$ of TCM in the cluster. At the same time, CH updates the TMC and sends the CM_ID and $T_{CMremaining}$ in the update message. Once the TMC receives the update message, it will record the information and send the new proximity data (i.e., Neighbouring Vehicle List (NVL)) to the TCM. If the TCM finds any potential neighbour in the NVL before leaving the cluster, it may again become the CM of any neighboring cluster or may take the role of a CH to depending on the state of the vehicles in the NVL, otherwise it will transfer to the Semi Cluster Head (SCH). Further, if the vehicle in the SCH state receives any joining request from the neighbouring vehicle during the time period T_{SCH}, it will take the role of CH; otherwise, it will reach in the Selection State (SE) and require re-registration to receive new proximity data. Once the TCM leaves the cluster, CH updates its Cluster Member Table (CMT) accordingly. In such a way, every CH can monitor its CM dynamically. Once the cluster_Info is updated, the edge node selection started, and the new edge nodes list will be updated.

6.4.2 Cluster Reformation: CH Departure

In our proposed scheme, like the CH, each non-cluster head node keeps the information about itself and its neighbouring vehicles in the Vehicle information register (VIR), a repository storing data about the vehicle and its surroundings. Once a vehicle has connected to the appropriate cluster head successfully, it becomes a CM and updates its VIR with a cluster identifier (i.e., CH_ID). Once the CM and the TMC receive leaving request from its CH, the TMC will mark the CH as a Temporary Cluster Head (TCH), calculate the remaining time of the CH in the cluster and select a new cluster head among the CMs connected to the TCH. The TMC will

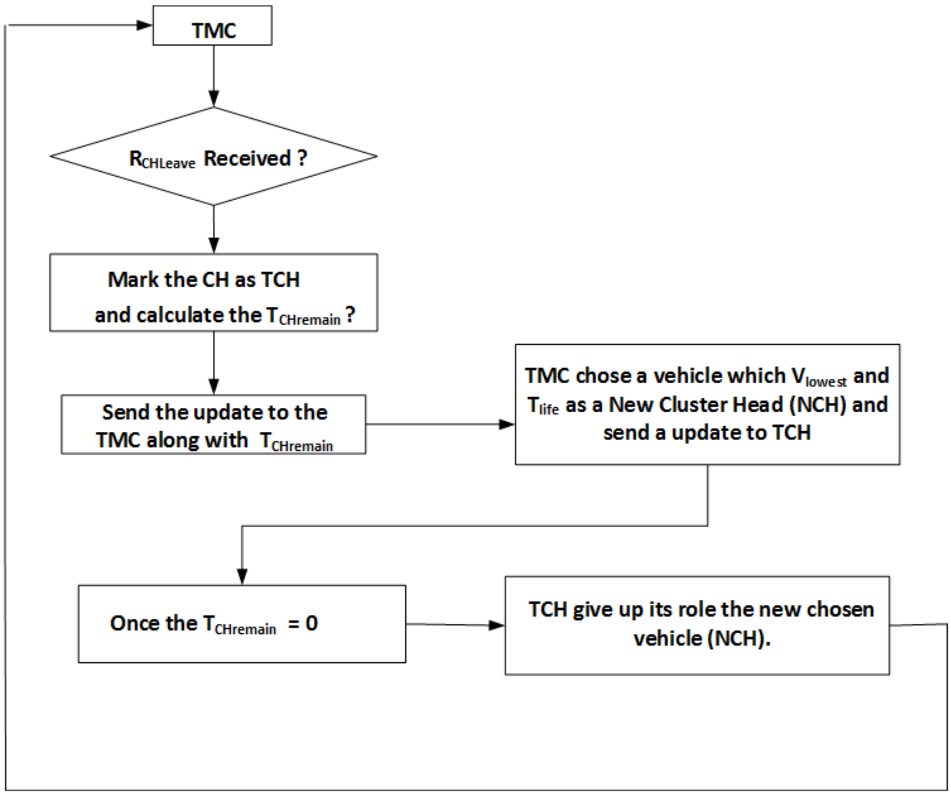


Figure 6.19: Algorithm for the cluster head (CH) leaving the cluster

select the vehicle which has the lowest average speed and longest lifetime among all CMs, a New Cluster Head (NCH), and update the CMs with NCH_ID. Once TCH leaves the cluster $T_{CMRemain} = 0$, it will give up its role to the NCH. Further, CMs update their VIR with the NCH_ID and join the NCH.

6.5 Simulation Model and Performance analysis

We performed vehicular network simulation over a realistic urban environment by considering the road network infrastructure of the highway scenario of Newcastle, NSW, Australia. We simulated our proposed protocols using OMNET++, SUMO, and Veins. An OMNET++ version 5.1.1 simulation model is developed using the SimuLTE [16] [17] that utilizes the INET framework 3.4.0. For enhanced traffic

Table 6.1: Simulation parameter for roadside vehicles and main highway vehicles

Parameter	**Value**
Roadside average speed	50 km/h
Roadside traffic flow rate (in case of SV)	8 vehicles/min
Roadside traffic Flow rate (in case of SC)	10 vehicles/min
Roadside average inter-vehicle distance (in case of SV)	100m
Roadside average inter-vehicle distance (in case of SC)	55m
Roadside length & number of lanes (in case of SV)	1.5 km & 1
Roadside length & number of lanes (in case SC)	3 km & 1
Simulation time	1000 second
Main highway Average speed	70 km/h
Main highway traffic flow rate	20 vehicles/min
Main highway Average inter-vehicle distance	50m
Main highway Road length & number of lanes	5 km & 2
Simulation time	1000 second
Carrier frequency	2.6 GHz
Duplexing mode	TDD
Transmission time interval (TTI)	10ms
CAM generation rate	10 packets/sec
Transmission bandwidth	3MHz (i.e., 15 RBs)
Path loss model	Highway scenario
Fading model	Nakagami-m (m =1, 2, 3)
eNodeB Tx power	46 dBm
UE Tx Power	26 dBm (Uplink), 5 dBm (Sidelink)
Coverage range	1000 m
Packet size	340 bytes

simulation, GPS data incorporation and mobility support, we use the Veins with a realistic mobility model generated by the microscopic road traffic simulation package Simulation of Urban Mobility (SUMO) [59]. Results from the simulation were acquired by taking the average of the 15 simulation runs with different seeds value. The key simulation parameters are listed in Table 6.1.

Fig. 6.20 shows the selected M1 pacific highway which is about 5 km in the Newcastle, NSW with two lanes per direction. The simulation model considers a multi-lane highway scenario where the vehicles are distributed according to the Poisson distribution process. We consider a 5 km highway scenario with entry and exit points. We selected a real highway from the Open Street Map (OSM) [140] which

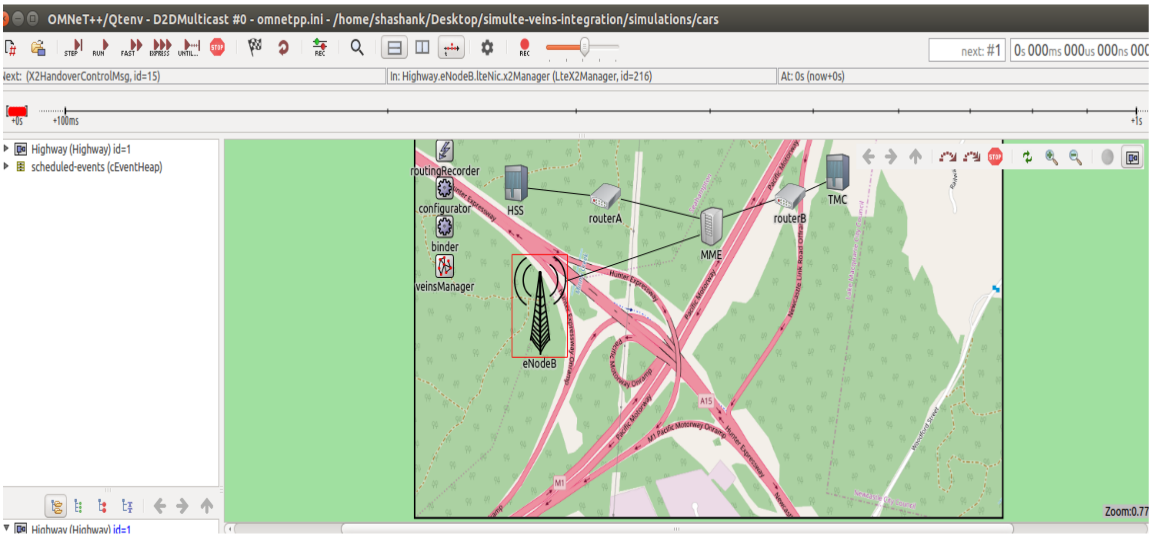


Figure 6.20: Simulation Model

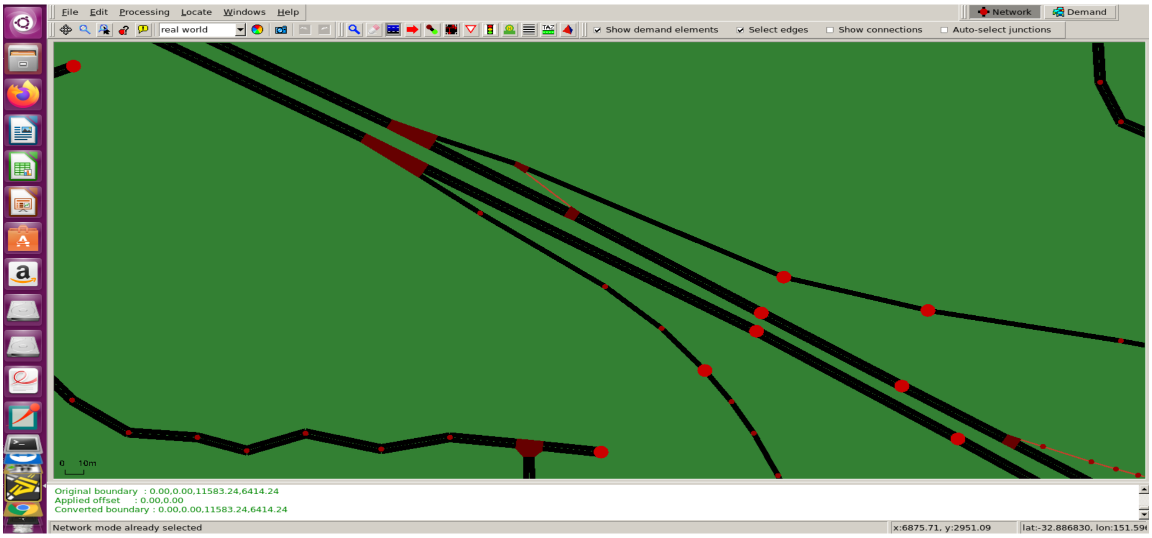


Figure 6.21: Simulation Model

took into consideration road directions, number of lanes, and maximum allowed speed of the real street. We selected the M1 pacific highway pacific highway from the Open Street Map (OSM) Vehicular traffic is generated using SUMO. The SUMO graphical network editor, NETEDIT, was used to design the synthetic highway with entry and exit roads shown in Fig. 6.21 and to edit the realistic one. In the simulation, Three types of experiments are performed.

- Experiment A: Traffic Map Controller (TMC) will use the prediction-based

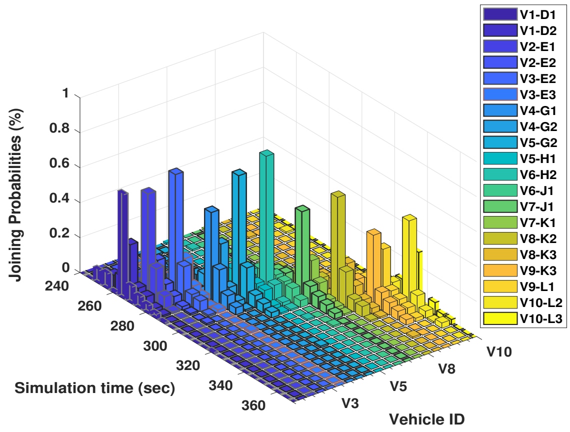


Figure 6.22: Calculation of the joining probability using PMUJ

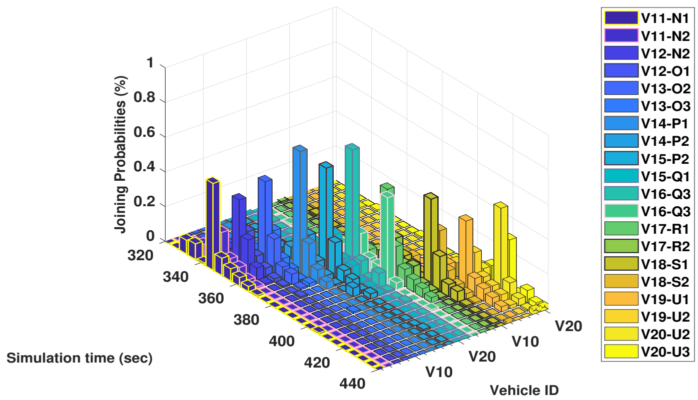


Figure 6.23: Calculation of the joining probability using PMUJ

protocol to calculate the joining probabilities of the source vehicles or source cluster at the possible joining location in the host clusters approaching the same highway intersection.

- Experiment B: TMC will calculate the actual joining location where the SV has inserted itself in the cluster at the intersection point and compare with the predicted joining location in the first experiment.

- Experiment C: The proposed protocol performance will be evaluated using a various number of vehicles with different speed profiles.

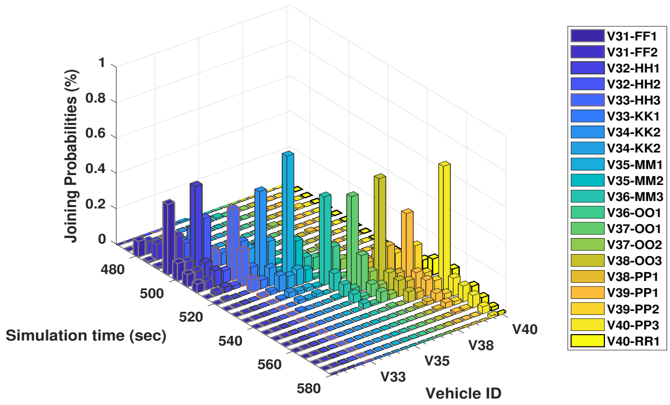


Figure 6.24: Calculation of the joining probability using PMUJ

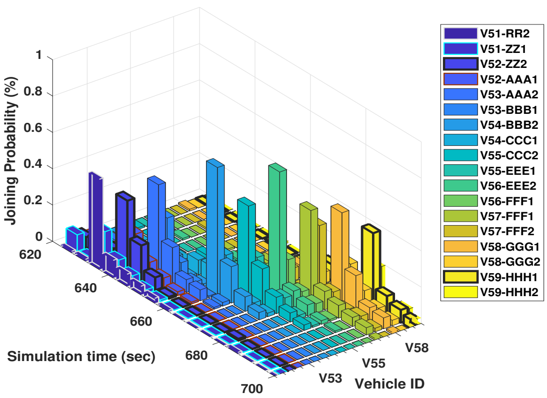
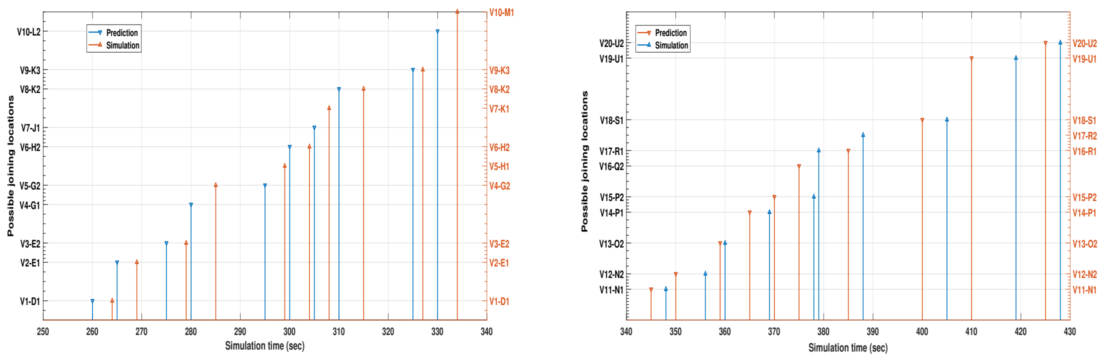


Figure 6.25: Calculation of the joining probability using PMUJ

The clustering process starts in the simulation at the 150th second when all the vehicles have entered the road. The model is simulated for different inter-vehicle distances, different cluster sizes and different fading intensities. The inter-vehicle distance was modelled by an exponential distribution function with a mean value µ (in metres) where a safety headway distance of three second was maintained.

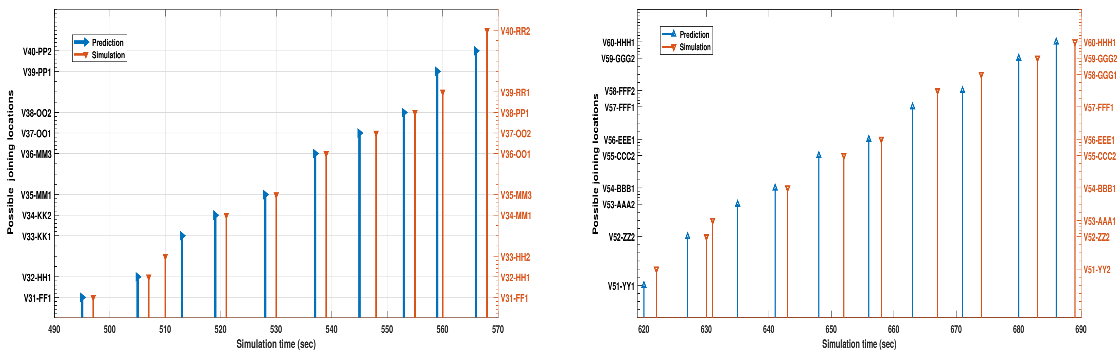
6.5.1 Performance Evaluation Metric

Various evaluation metrics are used to evaluate the performance of the proposed algorithm. We will classify the evaluation metrics into three categories: predictability,



(a) (b)

Figure 6.26: Comparison between predicted and simulated data



(a) (b)

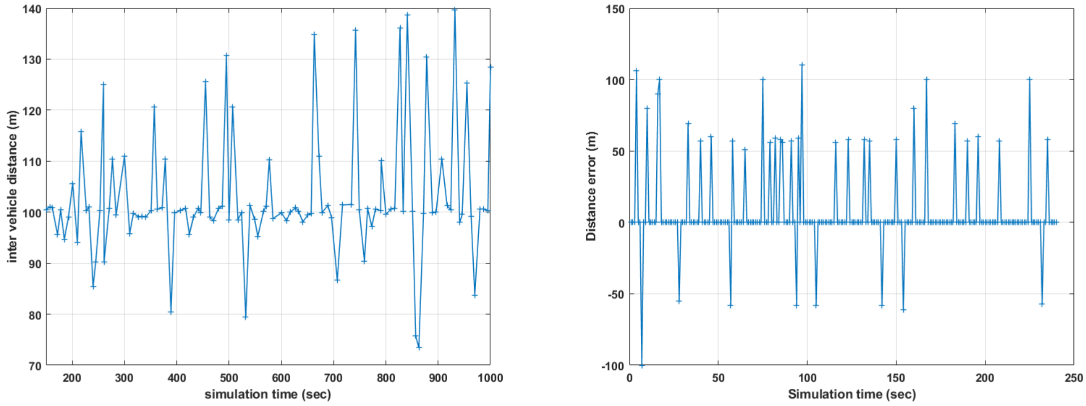
Figure 6.27: Comparison between predicted and simulated data

stability and efficiency metrics.

6.5.2 Predictability

Predictability metrics are used to measure the accuracy of the proposed prediction-based algorithm. Predictability metrics are as follows-

- Prediction error rate: is the average number of vehicles joining at the first predicted location compared to vehicles joining at the second predicted location. We also measure the prediction error based on the predicted joining location compared to the joining location generated in the simulation.



(a) Inter-vehicle distance distribution (b) Distance error

Figure 6.28: Inter-vehicle distance distribution and distance error between predicted and actual joining locations

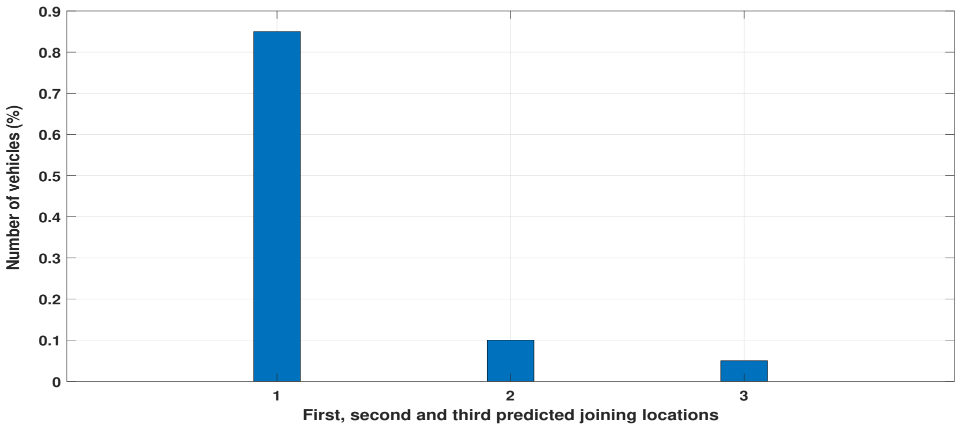


Figure 6.29: Prediction error

Figs 6.22 to 6.25 show the measured joining probabilities between source vehicles and possible joining locations in host clusters at the highway intersection using the proposed prediction based protocol PMUJ. In the first simulation experiment, based on the current position, speed, and moving direction, the TMC will calculate the joining probability of source vehicles and possible joining locations approaching the same intersection. In the second simulation experiment, the TMC will measure each vehicle's actual joining location at the intersection in the simulation and compare it with the predicted joining locations during the first experiment. The purpose of

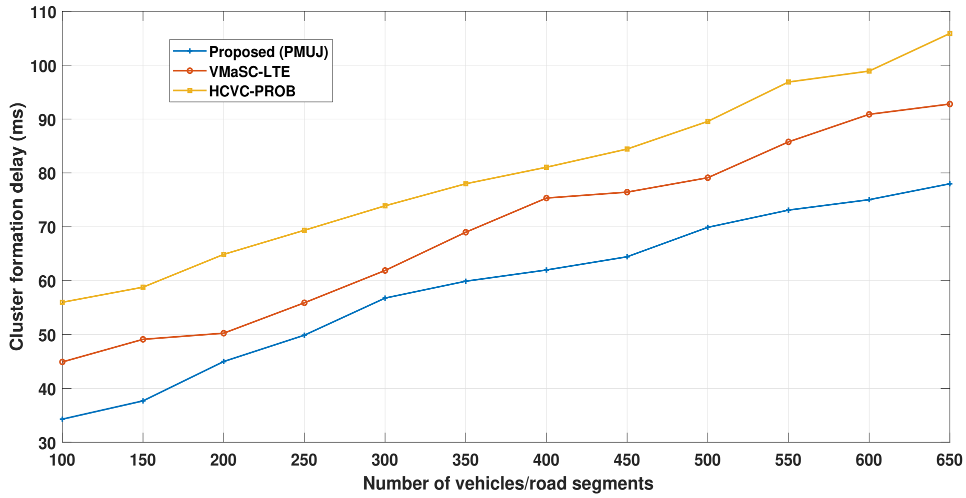


Figure 6.30: Cluster formation time compared to the existing works VMaSC-LTE (802.11p/LTE) and HCVC-PORB and in case of SV handover near intersection.

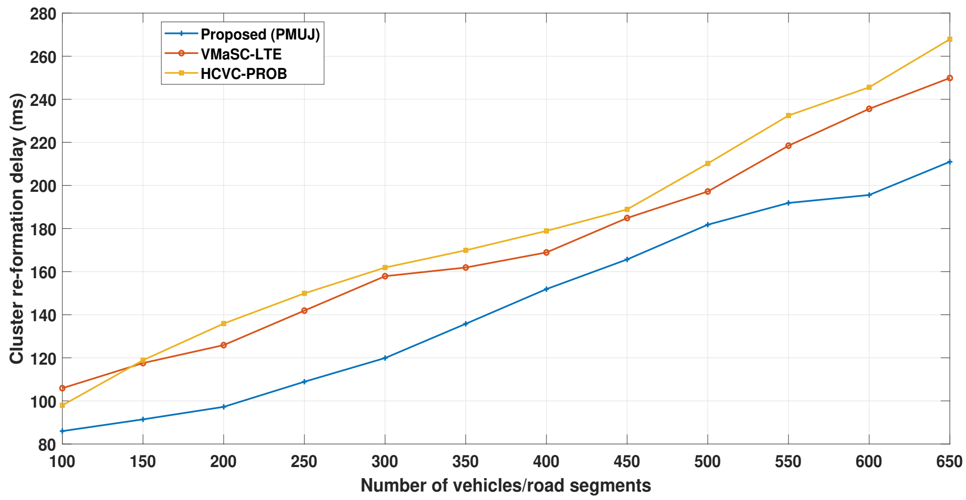
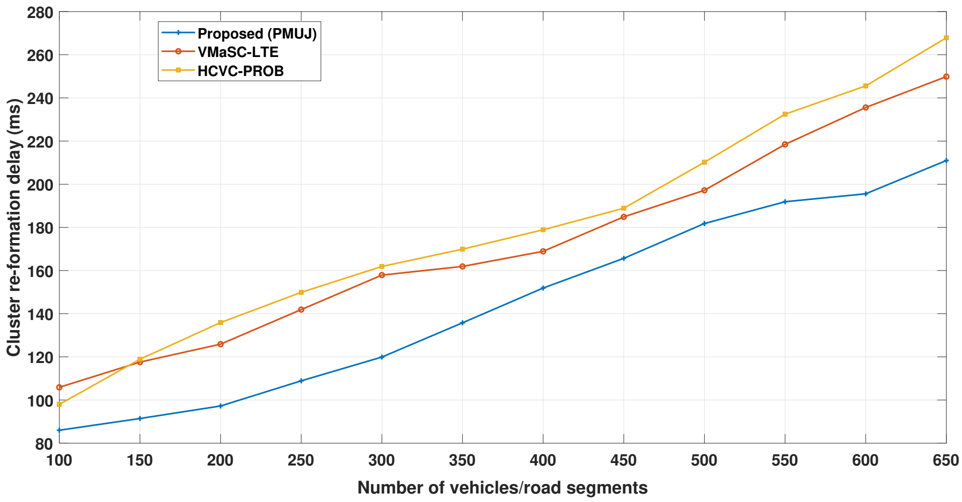


Figure 6.31: Cluster re-formation time compared to the existing works VMaSC-LTE and HCVC-PORB in case of SV handover near intersection.

comparing the first and second experiments is to check the accuracy of the proposed prediction-based protocol for predicting the future joining location of the source vehicle. The figures 6.26 to 6.27 comparison between predicted and simulated joining locations. The figures show that average 85 % of vehicles are joining at the first highest predicted location, and the other 15 % of vehicles are joining at the second-highest predicted location.



(a)

Figure 6.32: Cluster re-formation time compare to the existing works VMaSC-LTE and HCVC-PORB in case SC handover near intersection.

In Fig. 6.28a the inter-vehicle distances are modelled by an exponential distribution function using a mean value of 100 metres and 55 metres in the case of the SV and the SC respectively. Fig. 6.28b and Fig. 6.29 show prediction error in terms of distance error between predicted joining locations and actual joining locations in the simulation, and prediction error based on the comparison between predicted data, and simulated data respectively. Fig. 6.28b and Fig. 6.29 shows that 85% vehicles join at the first predicted joining location, and 15% of vehicles are joining at the second and third predicted locations in the simulation compared to the predicted joining locations.

6.5.3 Stability Metrics

The stability metrics are used to estimate the ability of an algorithm to form and maintain a stable cluster. Stability metrics are as follows:

- Cluster reformation time: is the average time that a CH spends reorganizing the packet multicast sequence when a new vehicle joins or leaves a cluster.

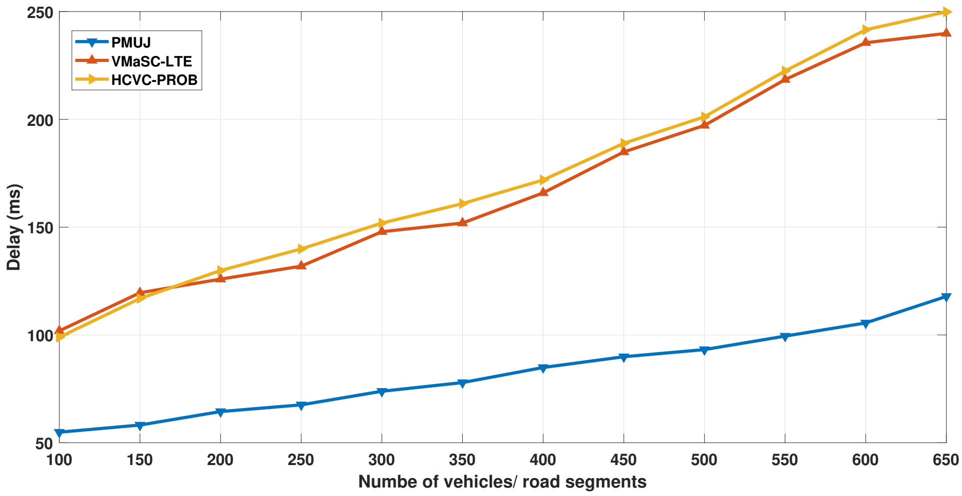


Figure 6.33: Single-hop CAM safety message transmission delay using PMUJ

Fig. 6.30 shows the average cluster formation delays for the PMUJ, VMaSC-LTE, and HCVC-PORB protocols. We implemented two LTE/802.11p simulation models to simulate the VMaSC-LTE [76] and the HCVC-PROB [77] basic algorithms to obtain several performance parameters for comparisons. The proposed protocols were simulated for different vehicle densities. The figure shows that our proposed offers a much lower cluster formation delay compared to existing protocols. The reason for the superior performance of PUMJ over existing protocols is the efficiency of our proposed clustering technique, known as CBC-V2V, which has lower control signalling overhead and requires few resources to locate available cluster heads in proximity. Other hybrid architectures such as VMaSC-LTE and HCVC-PROB require separate control signalling channels and resources for periodic message exchange, also known as "Hello Packets", to initiate clustering procedures. In the CBC-V2V, the eNodeB provides each vehicle with the list of cluster heads during the registration process.

Figs. 6.31 and 6.32 show the cluster reformation delay of the PUMJ, VMaSC-LTE, and HCVC-PORB protocols for two scenarios respectively. In the first scenario a SV will join the hot cluster near a highway entry point and in the second scenario, a Source cluster (SC) will join the hot cluster near the highway entry point. Both scenarios are presented in sections 6.4.0.1 and 6.4.0.5 respectively. The cluster reformation delay is defined as an average time required to reorganize a cluster when either a new vehicle joins or leaves a cluster. As shown in the figures the PMUJ technique offers lower delay compared to existing VMaSC-LTE and HCVC-PROB protocols. As discussed in the previous sections, our prediction-based protocol PMUJ offers the advance joining option where a vehicle can predict the future joining location and join the host cluster as a virtual cluster Member (VCM) while approaching an intersection. In such a way, a source vehicle does not require any further control signalling and additional resources to join its predicted host cluster at an entry point. However, the performance of the exiting hybrid architectures VMaSC-LTE and HCVC-PROB are affected by the network node densities, which could vary on a road. In a highly density scenario, the channel contention increases among vehicles, which causes high packet collision rate and higher channel access delay. The high collision rate and higher channel access delay considerable degrade the performance of IEEE 802.11p. This will affect the cluster reformation where a vehicle experiences longer channel access delay to send joining and leaving requests to its CH. Our proposed protocol, PMUJ, offers lower cluster reformation delay in a high-density scenario due to the advanced joining procedure and round-robin-based resource scheduling.

6.5.4 Efficiency Metrics

The metrics that indicate algorithm efficiency are as follows:

- CAM messages end-to-end delay
- CAM messages reception ratio

Fig. 6.33 shows the single-hop (CAM) safety message transmission delay for PMUJ, VMaSC-LTE, and HCVC-PROB protocols with different vehicle densities.

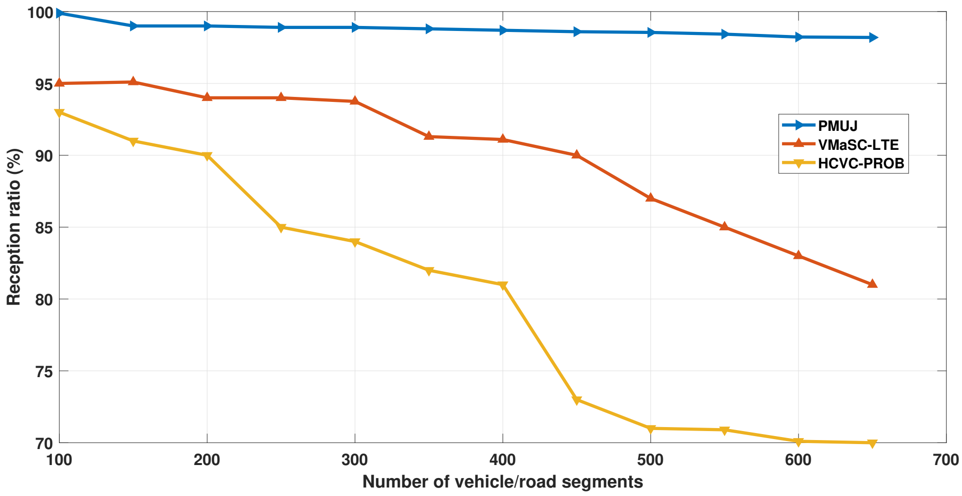


Figure 6.34: Reception ratio of CAM safety messages using PMUJ

The figure shows that the PMUJ requires less delay compared to the existing protocols. This is due to the use of the sidelink interface for direct inter- and intra-cluster communications, lower resource requirements, and minimal signalling overhead resulting in a lower delay for the peer CAM messages transmission compared with the VMaSC-LTE and HCVC-PROB protocols. Low message distribution delays are achieved due to the absence of any contention process in the LTE network compared to the existing protocols, where the 802.11p network introduces the contention process. The contention process introduces a longer delay, particularly with higher node densities in a cluster, mainly due to retransmission requirements.

Fig. 6.34 shows the safety messages reception ratio for CAM transmission. The reception ratio is defined as the ratio of the total number of received safety packets at a destination vehicle to the total number of scheduled safety packets. The reception ratio increases with the number of clusters due to the closer proximity of vehicles. Both plots show that the PMUJ offers an almost 100% message delivery ratio due to the deterministic nature of the channel structure used in the VANET. The IEEE 802.11p-based system shows the lowest reception ratio value because packets are lost due to collisions. The proposed D2D packet communication technique is contention-free; hence, the packet loss probability is small, only due to the transmission channel conditions. The existing hybrid protocols showed lower message reception ratios, mainly due to the lower efficiency of the CSMA/CA protocol. Within the increasing number of vehicles, the 802.11p networks' performance declines, resulting in lower packet reception ratio.

6.6 Performance comparison of CBC-V2V Modes 3, C-V2X Mode 4 and the IEEE 802.11p standard

In Chapters 3, 4 and 5 we presented our proposed cluster-based cellular architecture named as CBC-V2V combining with a proposed peer discovery model, proposed round-robin-based sidelink resource distribution, direct-inter cluster communication and transmission power control schemes, respectively. However, the studies in the previous chapter do not consider the variability present in the size of the V2X safety messages such as the CAM. In [148], study shows that the variability can significantly impact the operation and performance of the Medium Access Control (MAC) protocol. Based on the study presented in [148], in this section, we considers possible configurations of the CBC-V2V Modes 3, C-V2X Mode 4 and the IEEE 802.11p standard. We demonstrate that our proposed cluster-based architecture, named as CBC-V2V operating in communication Mode 3, can better cope with variations of the safety message lengths. We demonstrate that the 802.11p and the C-V2X Mode 4 standards using sensing-based semi-persistent scheduling faces certain inefficiencies when transmitting periodic safety messages of variable size.

In the literature, several proposals have compared the IEEE 802.11p and C-V2X standards for V2X communications. For example, in [149] authors presented a scheduling scheme referred to as the DIRAC (aDaptive spatIal Reuse of rAdio resourCes), that use the communication Mode 4. They compare the performance of proposed protocol DIRAC with the 3GPPP Mode 3 and Mode 4 communication and claim that proposed DIRAC ensures a more scalable and stable network operation as the channel load and congestion increase. The C-V2X Mode 4 is also vulnerable to the hidden node effect because it is based on Semi-Persistent Scheduling (SPS) scheme. It suffers some packet collisions caused by the re-selections of sidelink resources that are part of the sensing-based SPS scheme and that can occur when several vehicles try to select new sub-channels at the same time. In [150], authors proposed a cluster-based resource selections scheme using the communication Mode 4 to reduce the packet collision caused by the re-selections of sidelink resources. The resources are divided into orthogonal resource sets to mitigate interference between clusters in proximity. The cluster head is responsible for the resource distribution among its cluster members. Based on the channel sensing, it selects resource set that suffers less interference based on sensing and schedule resources for members to reduce resource collision. Simulation results show that, the propose scheme has better performance for both periodic and aperiodic traffic compared with 3GPP C-V2X Mode 4. The studies shows that the MAC of both IEEE 802.11p [107] and LTE-V2X Mode 4 [110] can significantly impact the system performance when the channel load increases.

Many research studies [22] [151] [24] has been done to compare the performance of IEEE 802.11p and C-V2X. However, most of the existing studies generally consider a simplified traffic model for generating periodic and aperiodic safety messages. ETSI and SAE define in [3], respectively, the safety messages generation rate and size. Some studies [25] shows that CAMs are not generated periodically and their size constantly varies. The variable messages generation rate and their size can significantly impact systme performance in term of message transmission delay and delivery ratio. This could also impact operation of the MAC where vehicles autonomously select their radio resources such as C-V2X Mode 4.

In the light of above facts, this section present a comparison study of CBC-

V2V Modes 3, C-V2X Mode 4 and the IEEE 802.11p standard, when considering only periodic safety messages know as CAMs of constant and variable size that are generated following the ETSI standard. The study analyses how CAM of constant or variable size can affect the performance of CBC-V2V Modes 3, C-V2X Mode 4 and the IEEE 802.11p standard. This includes different possible configurations of IEEE 802.11p and C-V2X under various traffic densities. The detail description of the IEEE 802.11p and C-V2X Mode 4 presented in the chapter 2 and chapter 4.

6.6.1 Configuration of the IEEE 802.11p and C-V2X

In the following sections, we will discuss the configuration of IEEE 802.11p and 3GPP C-V2X Mode 4 simulation model for the comparison with the proposed cluster-based cellular architecture named CBC-V2V. The configurations of our proposed CBC-V2V using Mode 3 simulation models are presented in chapters 3, 4, 5 and 6 respectively.

6.6.1.1 IEEE 802.11p standard

The performance evaluation of IEEE 802.11p has been carried out using the Veins which is composed of the SUMO microscopic road traffic simulator and the OMNET++ network simulation core. For the purpose of comparison, we implement a basic scheme of IEEE 802.11p. The basic principle of the resource selection technique of the IEEE 802.11p standard is presented in Fig. 6.35. The IEEE 802.11p standard uses the CSMA/CA mechanism for direct communications and connecting vehicles to vehicles (V2V) and to roadside infrastructure (V2I). Once a CAM is generated, the IEEE 802.11p transmit the CAM based on idle-channel sensing which confirms that there are no other ongoing transmissions. IEEE 802.11p is configured to operate over a 10 MHz channel in the 5.9 GHz frequency band. The main simulation parameters for the IEEE 802.11p is given in Table 6.2. In the implementation, we model the path loss using the Nakagami-model with an antenna height of 1.5 m for transmitter and

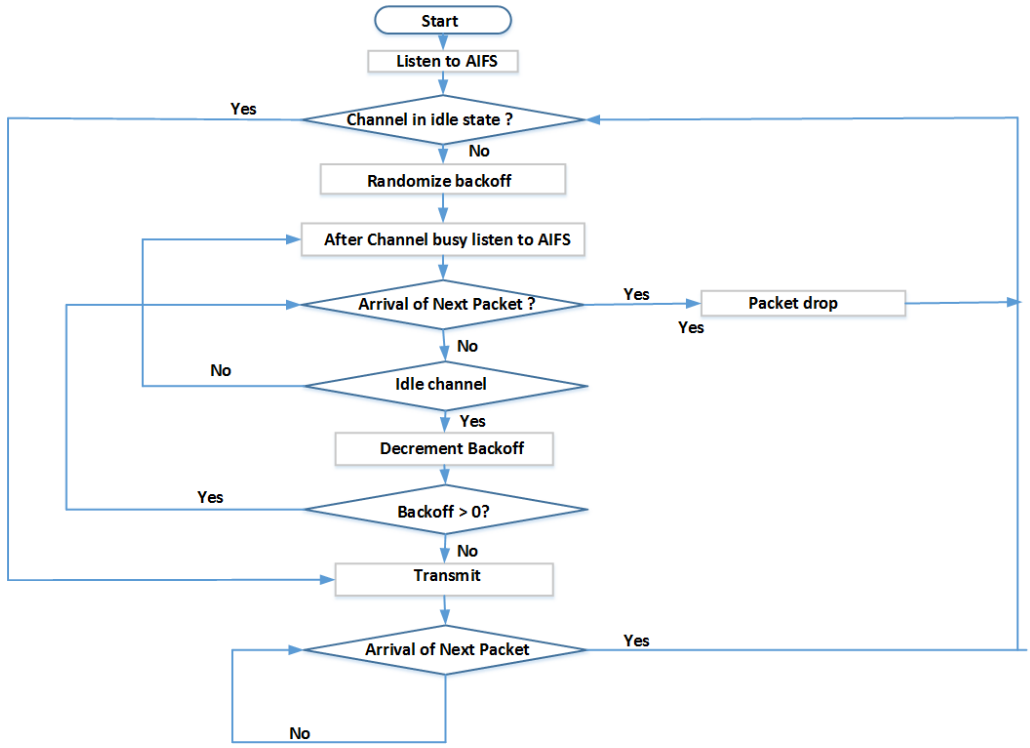


Figure 6.35: Operation of IEEE 802.11p

Table 6.2: Main simulation parameters for IEEE 802.11p

Parameter	Value
Sensing Period	1 sec
Receiver sensitivity threshold Rx_{th}	-95 dBm
Number of subcarrier	52
Subcarrier spacing	156.25
Fading model	Nakagami-m (m = 1, 2, 3)
Tx power	26 dBm
Antenna gain	3 dB
Minimum SINR	2.76 dB
Simulation time	800s
CAM Packet size	300 to 520 bytes

receiver because it is a generalised distribution that can model Line-of-sight (LOS) and non LOS fading environments, unlike Rayleigh's which is not favoured for LOS distribution. The shadowing effects are modelled using a log-normal distribution with zero mean and a standard deviation of 3 dB.

Table 6.3: Main simulation parameters for 3GPP C-V2X Mode 4

Parameter	Value
Sensing Period	1 sec
Receiver sensitivity threshold Rx_{th}	-105 dBm
Probability of maintaining the same resource p_k	0
Path loss model	Free space
Fading model	Nakagami-m (m = 1, 2, 3)
UE Tx Power	26 dBm
Antenna gain	3 dB
Minimum SINR	2.76 dB
Simulation time	800s
CAM Packet size	300-520 bytes bytes

6.6.1.2 C-V2X Mode 4

The performance evaluation of CBC-V2V using Mode 3 has been carried out using SimuLTE which is composed of Veins and the SUMO microscopic road traffic simulator and the OMNET++ network simulation core presented in Chapter 3. For the implementation of the C-V2X Mode 4, we use the OpenCV2X Mode 4 which is an open source implementation of SimuLTE that integrates with Veins to provide all the C-V2X Mode 4 functionalities. In C-V2X Mode 4, each vehicle selects transmission resources based on channel sensing referred to as sensing-based semi-persistent scheduling.

Following the ETSI recommendation, C-V2X is configured with 5 sub-channels per sub-frame and each sub-channels has 10 RBs [54]. The simulation parameter for C-V2X Mode 4 and Mode 3 is given in Table 6.3 and 6.4 respectively. The simulations steps for C-V2X Mode 4 is presented in sections 4.6 of chapter 4.

Fig. 6.36 and 6.37 shows the performance analysis of the CBC-V2V Mode 3, the IEEE 802.11p standard and the C-V2X Mode 4 in terms of CAM reception rate for constant and variable CAM packet size respectively. The figures shows in higher vehicle density, that PDR of IEEE 802.11p and C-V2X Mode 4 degrade due to the increase of the Channel Busy ratio (CBR) that causes packet collisions and

Table 6.4: simulation parameter C-V2X Mode 3

Parameter	**Value**
Average speed	70 km/h
Traffic Flow rate	20 vehicles/min
Average inter-vehicle distance	50m
Highway Road length & number of lanes	5 km & 2
Simulation time	800 second
Carrier frequency	2.6 GHz
Duplexing Mode	TDD
Transmission time interval (TTI)	10ms
CAM generation rate	10 packets/sec
Transmission bandwidth	3MHz (i.e., 15 RBs)
Path loss model	Highway scenario
Fading model	Nakagami-m (m =1, 2, 3)
eNodeB Tx power	46 dBm
UE Tx Power	26 dBm (Uplink), 5 dBm (Sidelink)
Coverage range	500 m
Receiver sensitivity threshold Rx_{th}	-105 dBm
Packet size	300-520 bytes

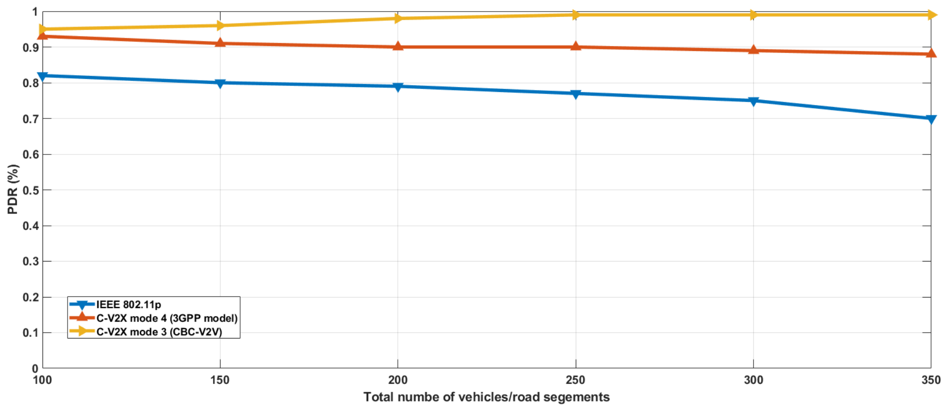


Figure 6.36: PDR experienced with periodic messages CAM (constant size) for vehicle density/road segment and fading intensity (m=1)

propagation effects. With C-V2X Mode 3, sidelink/PC5 resource scheduling is done in centralized manner using eNodeB. Since resource scheduling is centralized and collision-free, our proposed C-V2X Mode 3 offer the higher packet delivery ratio compare to C-V2X Mode 4 and IEEE 802.11p. The Fig. 6.37 shows the PDR for variable packet size. As shown for CBC-V2V Mode 3, the PDR is similiar for both constant and variable CAM packet size due to collision-free scheduling in round-robin

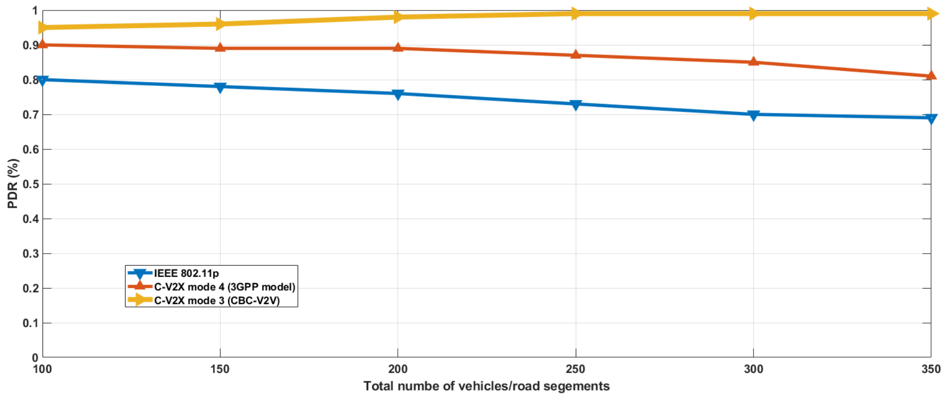


Figure 6.37: PDR experienced with periodic messages CAM (variable size) for vehicle density/road segment and fading intensity (m=1)

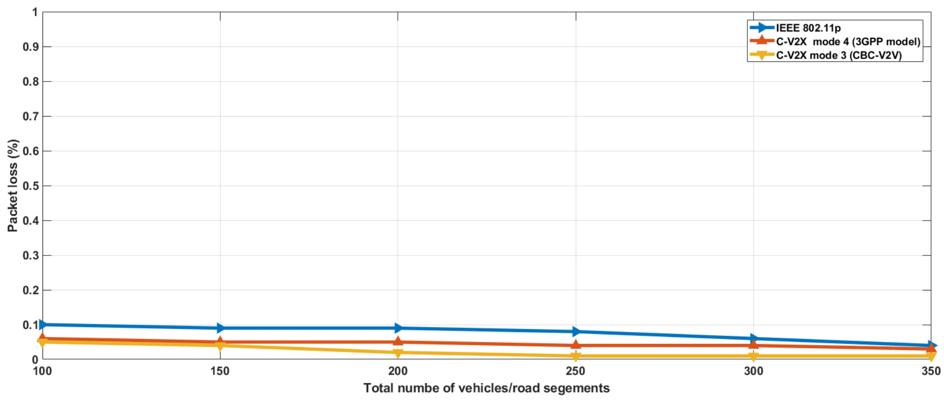


Figure 6.38: packet lost rate due to fading experienced with periodic messages CAM (constant size) for vehicle density/road segment and fading intensity (m=1)

manner, however for IEEE 802.11p and C-V2X Mode 4 the PDR varies as collison increase at the MAC layer.

In Figs. 6.38 and 6.39, the packet loss rate due to fading is displayed for constant and variable CAM packet sizes at different vehicle densities respectively. For the communication CBC-V2V, the packet loss due to channel conditions is the total loss, which includes both path and fading losses. As shown in the figure, the loss rate due to fading is nearly similar for all communications technologies because all the three protocol use the same and higher transmission power, resulting in a loss rate due to the fading that is less than 0.1%.

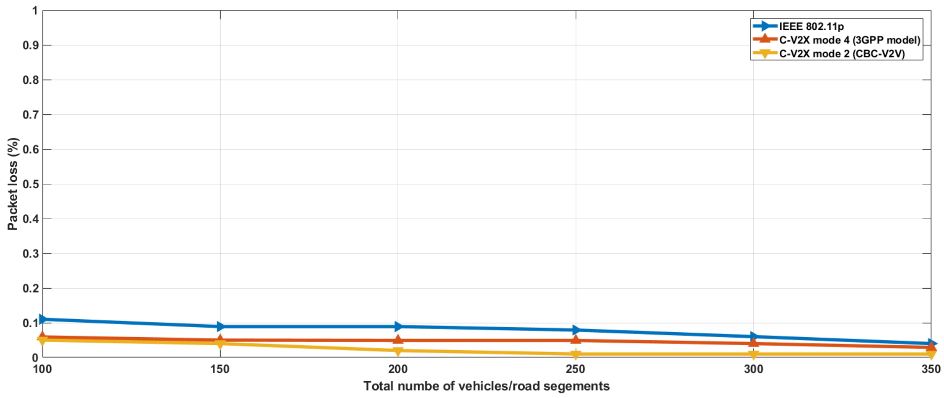


Figure 6.39: packet lost rate due to fading experienced with periodic messages CAM (variable size) for vehicle density/road segment and fading intensity (m=1)

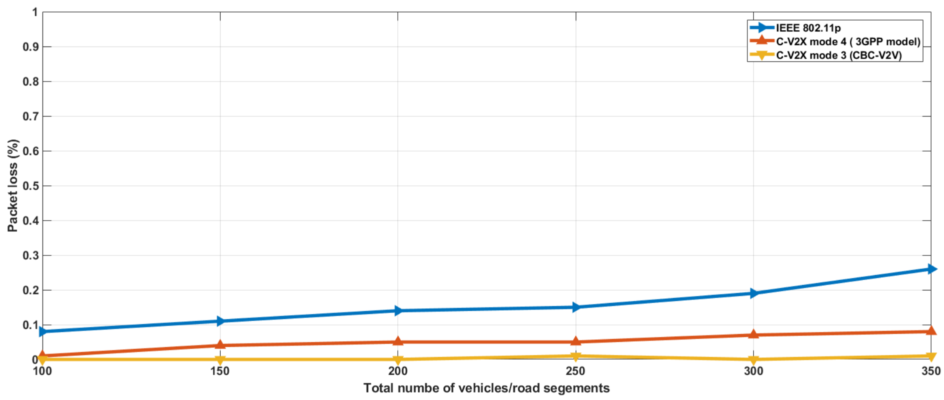


Figure 6.40: packet lost rate due to the collision experienced with periodic messages CAM (Constant size) for vehicle density/road segment and fading intensity (m=1)

A second type of packet loss is due to collisions as shown in Figs. 6.40 and 6.41. As shown in the figure, for higher traffic density the collision rate is higher for both C-V2X Mode 4 and IEEE 802.11p compared the CBC-V2V using communication Mode 3. In case of IEEE 802.11p, a higher transmission range and CBR results in an increase in the number of hidden nodes introducing higher contention resulting in a higher packet loss. C-V2X Mode 4 suffers some packet collisions at short distances even if the traffic density is low. These collisions are caused when several vehicles try to select new sub-channels around the same time. This type of collision is particularly present when the inter-vehicle distance is shorter At the short inter-vehicle distance,

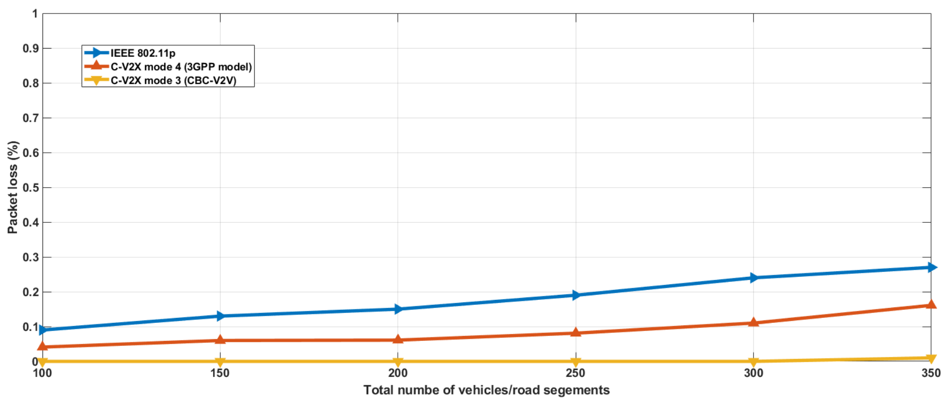


Figure 6.41: packet lost rate due to the collision experienced with periodic messages CAM (variable size) for vehicle density/road segment and fading intensity (m=1)

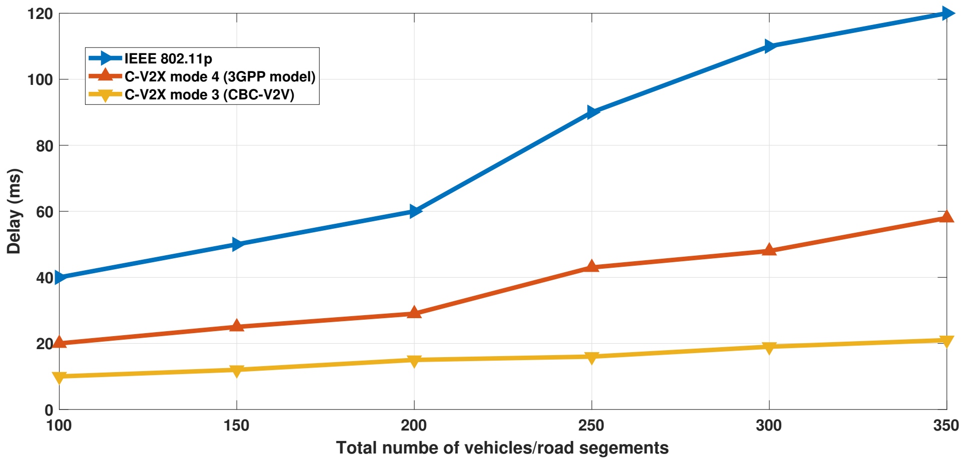


Figure 6.42: End-to-end delay experienced with periodic messages CAM (Constant size) for vehicle density/road segment and fading intensity (m=1)

during the channel sensing, vehicles will sense similar RSRP and RSSI levels. This could increase risk of packet collisions.

The end-to-end delay is shown in Figs. 6.42 and 6.43. In the case of the IEEE 802.11p, the backing-off time while channel sensing can significantly impact the end-to-end delay. A vehicle has to wait for the channel to be become idle. With C-V2X Mode 4, the average CAM latency is 120 ms for higher traffic density. Compare to the IEEE 802.11p and C-V2X Mode 4, CBC-V2V using Mode 3 offered a much lower end-to-end delay compared to the existing protocols. lower end-to-end delay is

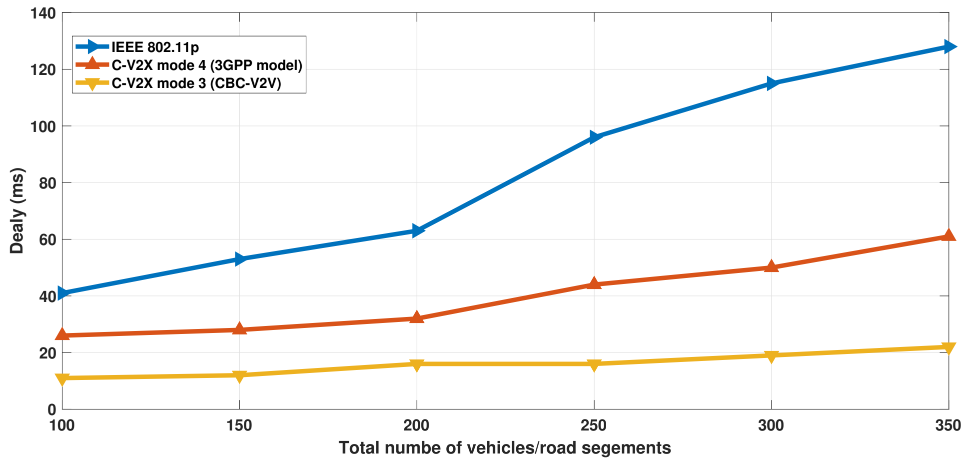


Figure 6.43: End-to-end delay experienced with periodic messages CAM (variable size) for vehicle density/road segment and fading intensity (m=1)

achieved due to the absence of any contention process in the LTE network. However, as shown in the figure, when the vehicle density increase, the end-to-end delay for CBC-V2V slightly increase due to the use of the round-robin packet transmission techniques.

6.7 Summary

This chapter introduced a novel prediction-based 5G-V2X communication protocol for transmitting safety messages on a highway road with entry point. We proposed a prediction-based protocol and an efficient channel structure for CAM message transmission. The proposed protocol offers low delay and performs significantly better than the hybrid LTE/IEEE 802.11p protocol. Simulation results show that the PMUJ offers higher QoS than do the IEEE 802.11p and other LTE networking architectures. We also compare the performance of our proposed CBC-V2V architecture with the IEEE 802.11p and C-V2X Mode 4 for CAM messages transmission of variable size for highway scenario.

Chapter 7

Conclusions and Future Work

7.1 Summary

Vehicle safety and reducing accidents is one of the major concerns of future intelligent transport systems. Using wireless communication between vehicles, many safety and non-safety applications can be realized. However, a number of challenges specific to the vehicular ad hoc network needs to be resolved before this technology can be effectively deployed for future road traffic systems. Multiple types of data traffic could be shared among vehicles in a vehicular network. Safety messages CAM and DENM need to be delivered to the target vehicles. The success of vehicular safety applications depends suitable wireless communication standard which can support mechanism for reliable and timely delivery of these messages. In past few year, two major communication standards IEEE 802.11p and 5G-V2X had been studied to meet the scalability and reliability requirement of safety applications. However, there is still a debate in academia and industry about which standard is suitable for successful deployment of vehicular safety application. The IEEE 802.11p is matured technology whereas the 5G-V2X standard is gradually evolving.

The IEEE 802.11p standard was designed for the rapid transmission of short-range basic safety messages. It cannot meet the higher bandwidth demands of different vehicular applications such as autonomous driving, multimedia services. As discussed in chapter 2, the major drawback of an IEEE 802.11p vehicular network are the scalability and lack of adequate Quality of Service (QoS) support. Introduction of the LTE-V or C-V2X standard to support V2X services, which improved spectrum utilization, efficiency and system capacity of a cellular system. However, the use of C-V2X for vehicular safety applications is still under investigation. It introduces some design challenges such as efficient and faster peer discovery mechanism to determine the proximity of the communication pairs, radio resource management, and power control mechanisms to avoid the collision and interference between D2D and regular LTE users. Although the C-V2X has a large bandwidth and can support high data rates, the amount of resources allocated for the safety applications is limited. This is due to the co-existence of Device-to-Device (D2D) communication and standard cellular services when the network is used for vehicular and standard telecommunication services.

It is necessary to reduce several major problems that exist in current communication standard. In this thesis, different techniques have been proposed that enhance the performance of vehicular communication to achieve the target of reliable, scalability and timely dissemination of safety messages. To reduce the network load in a vehicular network while maintaining vehicle safety, a cluster-based C-V2X named CBC-V2V, peer discovery model named ESPD and a new round-robin based techniques are proposed in Chapter 3. The proposed CBC-V2V architecture utilizes the sidelink communication channels where the proposed peer discovery model and the D2D multicast data packet transmission technique shown significant improvement in the term of resource utilization, data packet delivery ratio and end-to-end delay to meet the QoS requirement of safety services in VANET.

Propagation in a vehicular network can change very rapidly due to variable transmission conditions generated by movement of vehicles. Thus, if a fixed transmission power used by all vehicle radio then it will make difficult for multicast sender to transmit safety packet successfully to all recipients. In chapter 4 two new algorithms for cluster-based multicast vehicular networks are introduced. An advanced LTE Device-to-Device (D2D) cluster communication technique referred as LTE-DICV2V and a multicast power transmission control technique referred as CMTPC for C-V2X mode 3 communications are proposed. These algorithms support inter- and intra-cluster packet communications, offering a high packet delivery ratio for CAM messages. The LTE-DICV2V algorithm supports both inter- and intra-cluster safety packet distribution mechanisms. Whereas the CMTPC algorithm is a multicast packet transmission power control technique which is used by the LTE-DICV2V algorithm. Both algorithms are combined to improve the CAM packet success rate in clustered vehicular networks.

For multi-hop safety message transmission such as DENM, Chapter 5 present a multicast communication architecture to distribute the warning messages using two communication protocols referred to as the Clustered Multi-hop Multicast Protocol (CMMP) and the Clustered Multi-hop Broadcast and Multicast Protocol (CMBMP) Both protocols use distributed resource allocation techniques in a LTE network. To improve the performance of our C-V2X-based cluster architecture at highway intersection scenarios, Chapter 6 a new procedure for trajectory prediction and collision detection at a road intersection and assists the cluster formation and reformation at road intersection scenarios. The proposed schemes exploits both mobility related metrics such as moving direction, relative velocity, relative distance and metrics related to communication link quality. We also compare the performance of proposed protocol CBC-V2V in communication Mode 3 with the IEEE 802.11p and C-V2X Mode 4 standard by conducting an comparison study considering single hop safety message with constant and variable size in highway scenarios.

7.1.1 Potential Future Research

The main focus of this thesis is to improve the reliability of vehicular safety application. Several techniques to performance of safety messages transmission used in the vehicular communication are presented. Some of the proposed solutions in this thesis are well suited for both highway and city scenario. The urban traffic scenario has different vehicle connectivity and movement characteristics than the highway scenarios. Therefore, the proposed cluster-based architecture CBC-V2V and proposed peer discovery model ESPD in chapter 3 and the direct-inter cluster communication LTE-DICV2V combining with the adaptive transmit power control techniques CMTPC in chapter 4 for single hope safety message transmission such a CAM require further investigation for city scenario. In chapter 5, we focused on the transmission of multi-hop warning safety messages such as DENM in highway scenario. For such purpose we developed two communication protocols named as the CMMP and the CMBMP. The performance of the CMMP protocol is analyzed in both city and highway scenario however the CMBMP protocol require further investigation in city scenario.

The chapter 6 present a proposed prediction based protocol named PMUJ to improve the stability of our cluster-based architecture named CBC-V2V and reliability of the CAM safety messages transmission in different road structure such highway with entry and exits points. However, the proposed PMUJ require further investigation for multi-hop safety message transmission such as DENM in both road structure such as city and highway with entry and exit points. The chapter 6, also present a performance comparison of proposed CBC-V2V using C-V2X mode 3, 3GPP C-V2X mode 4 and the IEEE 802.11p standard for periodic CAM messages of constant or variable size in highway scenarios. Further work require to investigate the performance comparison for periodic CAM messages and aperiodic DENM saftey messages transmission in both city and highway scenario.

In vehicular ad hoc network, different applications have different requirement. In this thesis, periodic safety message and event driven warning messages are two main type of data traffic are considered. Further development of proposed solutions in this thesis require to support the many other applications and services such a traffic management, infotainment and potentially future electric vehicle management systems. Future vehicular networks supporting a number of application could require an integrated networking solution that use various access technologies. A cluster-based opportunistic heterogeneous network by integrating the different wireless access network such as a C-V2X and the 802.11p standard where the transmission of data packet happen based on the best available network may be a good platform that can meet various demanding communications requirements of vehicular services.

Autonomous vehicle are currently attracting the attention of researcher and engineers. The penetration of V2V devices is the key factor to enabling cooperative ITS. The US National Highway Traffic Safety Administration (NHTSA) had studied the possibility of implementing regulation to require V2V devices in new light vehicles. However, regardless of the level of such deployment, legacy vehicle will not have access to V2V devices, and future VANET should consider mixed environments in which vehicle equipped with ITS system operates among legacy or old vehicles without ITS system. However, the major issue of mixed environment in which a ITS enabled vehicle can not communicate with vehicle which is not equipped with ITS. The main research question is: How to design and configure communication protocol and methods to enable the V2V messaging in mixed environment where V2V aware node and non-aware nodes (i.e., legacy vehicle, pedestrians and cyclists) co-exist. Thus, the proposed solutions in thesis require further investigation to meet the requirement of V2X communication in mixed environment.

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