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Efficient medium access control protocol for vehicular ad-hoc networks

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Efficient Medium Access Control Protocol For Vehicular Ad-hoc Networks

by

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ABSTRACT

Intelligent transportation systems (ITS) have enjoyed a tremendous growth in the last decade and the advancement in communication technologies has played a big role behind the success of ITS. Inter-vehicle communication (IVC) is a critical requirement for ITS and due to the nature of communication, vehicular ad-hoc network technology (VANET) is the most suitable communication technology for inter-vehicle communications. In Practice,however, VANET poses some extreme challenges including dropping out of connections as the moving vehicle moves out of the coverage range, joining of new nodes moving at high speeds, dynamic change in topology and connectivity, time variability of signal strength, throughput and time delay. One of the most challenging issues facing vehicular networks lies in the design of efficient resource management schemes, due to the mobile nature of nodes, delay constraints for safety applications and interference. The main application of VANET in ITS lies in the exchange of safety messages between nodes. Moreover, as the wireless access in vehicular environment (WAVE) moves closer to reality, management of these networks is of increasing concern for ITS designers and other stakeholder groups. As such, management of resources plays a significant role in VANET and ITS. For resource management in VANET, a medium access control protocol is used, which makes sure that limited resources are distributed efficiently. In this thesis, an efficient Multichannel Cognitive MAC (MCM) is developed, which assesses the quality of channel prior to transmission. MCM employs dynamic channel allocation and negotiation algorithms to achieve a significant improvement in channel utilisaton, system reliability, and delay constraints while simultaneously addressing Quality of Service. Moreover, modified access priority parameters and safety message acknowledgments will be used to improve the reliability of safety messages.The proposed protocols are implemented using network simulation tools. Extensive experiments demonstrated a faster and more efficient reception of safety messages compared to existing VANET technologies. Finally, improvements in delay and packet delivery ratios are presented.

DECLARATION

I certify that this thesis does not, to the best of my knowledge and belief:

(i) incorporate without acknowledgment any material previously submitted for a degree or diploma in any institution of higher education;

(ii) contain any material previously published or written by another person except where due reference is made in the text; or

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1. Niravkumar Shah, D.Habibi, and I.Ahmad, Multichannel Cognitive Medium Access Control Protocol for Vehicular Ad-hoc Networks (accepted), to appear in IEEE Conference Proceedings on VTC (IEEEVTC FALL-2012) , Quebec city Canada.

2. Niravkumar Shah, D.Habibi, and I.Ahmad, Efficient MAC protocol for VANET based on the IEEE 1609.4 (under review), to appear in IEEE Conference Proceedings on 1Telecommunications for Intelligent Transport Systems (ITST 2012) ,Taipei, Taiwan.

Chapter 1

INTRODUCTION

Over the last few years, Vehicular Ad-hoc Networks (VANETs) have been the focus of many automotive industries and academic research communities due to their distinct advantage and diverse applications. Research in this field has witnessed wide support from various governments and safety organizations; since a well established vehicular network provides an efficient transportation system, safety for passengers, and onboard passenger services as vehicles are becoming part of the next generation global internet of things. A recent study [1] suggests that, there are approximately 6.8 billion people in the world and by 2044 that number will grow to about 9 billion. This would result in many problems, one of which being the transportation system. As the total number of vehicles is expected to grow from 800 million cars today to 2-4 billion by 2050, global gridlocks and traffic jams will occur in many different places. People would not only be wasting their time stuck in traffic jams, but also the gridlock would stifle economic growth and the ability to deliver food and health care, particularly to people who live in city centers. As we have space to build new roads, the solution will definitely not be building more transportation systems, but in integrating the current ones to become smarter and more efficient. This would reduce congestion and consequently fuel consumption and enhance economic productivity. By the end of 2010, the World Health Organization (WHO) estimated that nearly 3,500 people died on the world's roads every day, and millions of people were injured or disabled every year [2]. Many accidents may be circumvented if the vehicles are able to communicate with each other, to warn passengers while driving. Safe driving applications and services may include emergency vehicle warning (sudden breaking, icy road or oil stain, approaching vehicle, stop sign warning for reckless driving, highway-rail intersection warning and others). Numerous applications and services included in the car would render driving more time-efficient, pleasant and entertaining. For example, applications such as searching directly for restaurants while calculating the shortest routes, general internet access, downloading

Emaps, sending emails, voice or video conversations with neighboring vehicles may all be some of the applications used onboard. Services might include finding parking spots and paying electronically. Toll services and payment, social networking and communicating with different service providers may be other services integrated in the network.

In general, VANET is going to be an integral part of our transportation system in the near future, because of the vital needs and benefits it provides once established. What makes VANET more promising and is a major driver for its rapid development, are the availability of low cost Global Positioning System (GPS), and the drop in cost, and the wide adoption of 802.11 as a wireless local area network (WLAN) [3]. Moreover, local regulatory entities such as FCC (Federal Communications Commission in the US), ETSI (European Telecommunications Standards Institute in Europe) and IC (Industry Canada in Canada) have all laid the cornerstone for the initiation of vehicular networks by allocating a unique spectrum the DSRC (Dedicated Short Range Communications - 5.9 GHz) for vehicular communication [4]. In this chapter, we first review the evolution of the wireless networks since introduction of the commercial cellular communication in 1991. Then, VANETs are discussed from the perspective of ad-hoc networks. We also discuss the current state of this technology, its standardization, its potential applications and motivation behind this research. Finally we conclude with research aims, our contribution and thesis Organization.

1.1 Evolution of Wireless Networks

Presently, wireless communications is the leading technology in telecommunications. This technology has shown tremendous amount of growth in a very short time period and has significantly impacted our way of life. Wireless networks have extended the services which were only available to the wire-line users to the mobile user. The evolution of wireless communications has been extremely rapid. In about two decades it has gone through four generations. The first generation wireless networks used analog communication with circuit switching technology. In circuit switching (CS), dedicated bandwidth is assigned to each call. The route of the call may consist of several hops and at least one of the hops is through a wireless network. The second generation wireless networks (2G) continued to use circuit switching technology, but they replaced analog channels with digital communication channels. The first two generations met the voice communication needs of mobile users, but they were not suitable for data communications. Since data is bursty, and in circuit switching the bandwidth is dedicated to a call, CS results in under utilization of network resources. The third generation wireless networks (3G) have been developed to meet the requirements of the mobile data communication users, and, at the same time, achieve higher network utilisation. The objective has been to provide Internet access to the users in order that they can browse web pages and have voice or video sessions while on the move. The third generation networks replaced CS with packet switching (PS) technology that allows dynamic sharing of bandwidth among different applications. This allows statistical multiplexing of information, and idle users do not consume network bandwidth since they are not generating any information. This technology has allowed introduction of several new services such as: video conferencing, IP telephony, video and audio streaming services.

Presently, fourth generation cellular networks are in development with the objective of providing high-speed Internet access. It is likely to appear after the successful deployment of 3G systems, as 4G is supposed to complement and replace 3G systems in different ways. The preliminary goal of 4G is to provide faster data speed greater than 2Mbps, and search for new spectrum for global standard. The main challenge in 4G is to provide a telecommunication environment where many types of wireless and wire-line systems can coexist and communicate with each other. Further, any peer-to-peer communication media becomes completely transparent to the users [5].

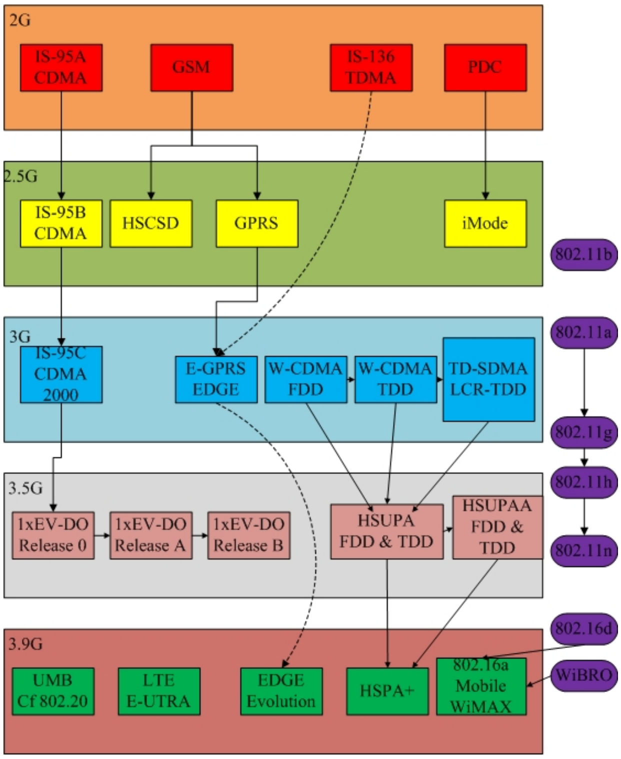

Figure 1.1: Evolution of Wireless Technology and Potential Application of 4G.

Different standards and technologies have been proposed for 4G, examples of which are: smart antenna technology, WIMAX topology, ad-hoc networks, OFDM WLAN etc. As an illustration of what may happen in a 4G communication, we can imagine a user who initiates a high quality video-conferencing from his cell phone to a friend while he is sitting

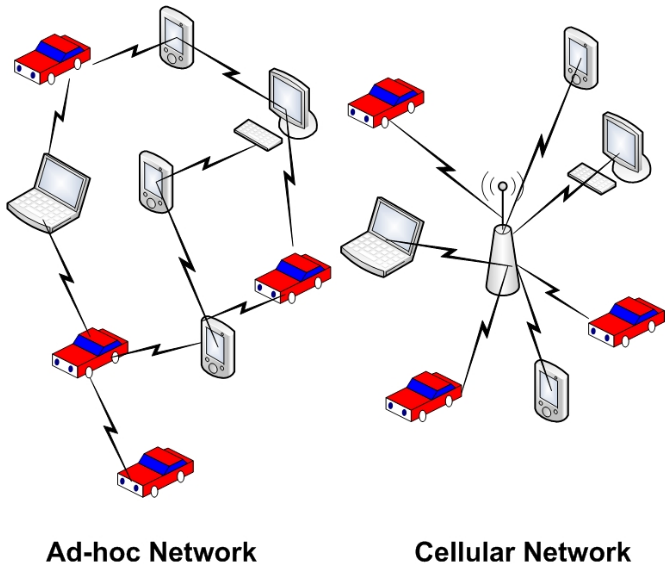

Figure 1.2: Ad-hoc Network versus Cellular Network.

in a café. This café may be served with a WIMAX or WIFI technology. On the other side, his friend may be sitting in a car which is served with vehicular ad-hoc technology or in a plane which is served with the satellite technology. In this example, not only are the end points served with different technologies, but the intermediate networks may be of different types such as, Ethernet, and ATM. Finally, all these changes and topologies are transparent to the end users. Fig. 1.1 shows the evolution in the wireless technology since the introduction of 2G systems and potential applications for 4G systems [6].

The key for success in the road towards 4G communications, is directly related to the success of all the relevant technologies as well as communications among them.

1.2 Ad-hoc Networks

Most recently, a new network research area known as ad-hoc networks has emerged in wireless communications which is presenting significant challenges to 4G communications. Mobile ad-hoc NETworks (MANETs) are instantly created by wireless mobile nodes; therefore, they do not have cell infrastructure such as base stations. These are forms of peer-to-peer networks with distributed control. In this type of networks, each node in addition to being the source or destination of the data, cooperates with other nodes for the transportation of the information the network. Thus, each mobile user acts as a store-and-forward node for the information that it receives from its neighbors. The ad-hoc networks may be stand-alone or may have interfaces to wire-line networks. Fig 1.2 compares the traditional cellular infrastructure with the ad-hoc scheme.

Among the wide number of applications of ad-hoc networks, the future applications can be classified based on the availability of traditional infrastructure-based cellular networks, as explained below [7].

- Infrastructure is not available. In some situations, implementing an infrastructure for communication is not feasible. The example could be deployment of an emergency response network for a search and rescue operation in an area where an earthquake has occurred. In this scenario, the ad-hoc network can provide communication among rescue teams on the scene.

- Infrastructure is available but it is inadequate. This is due to a traffic surge in emergency or changes in geographical distribution of traffic. The example is communications among drivers for finding a better route in transportation highways. In this situation, the cellular architecture is inadequate for providing the required information capacity, as it is saturated.

- Infrastructure is not necessary. When the traffic is local, the routing is not necessary through the network's infrastructure external to the location. For example, communications in a meeting room or a construction site can be handled with an ad-hoc architecture. Another example is the voice telephony inside a cell which is usually routed through the infrastructure which wastes the cellular capacity. Voice telephony may he provided through ad-hoc communications except when the end users are located at different cells.

Ad-hoc networking had originally been proposed for military applications, but recently, many commercial applications have also emerged. Some of the basic services which already implemented are Bluetooth technology, inflated device to device conferencing applications, and PC to PC ad-hoc communication. Although these technologies work in an ad-hoc manner, their applications are limited to one-hop communications.

1.3 Vehicular Ad-hoc Networks

A developing advanced ad-hoc network are Vehicular Ad-hoc Networks (VANETs), which visualise Inter-Vehicle Communications or equivalently Vehicle to Vehicle communication. VANETs are a type of MANET which constitutes of vehicles as the mobile nodes and the communication among them is in the ad-hoc manner. In VANETs, the nodes are highly mobile which is key feature that separates VANATEs from conventional MANETs, and make their behavior fundamentally different. The main differences can be classified as following:

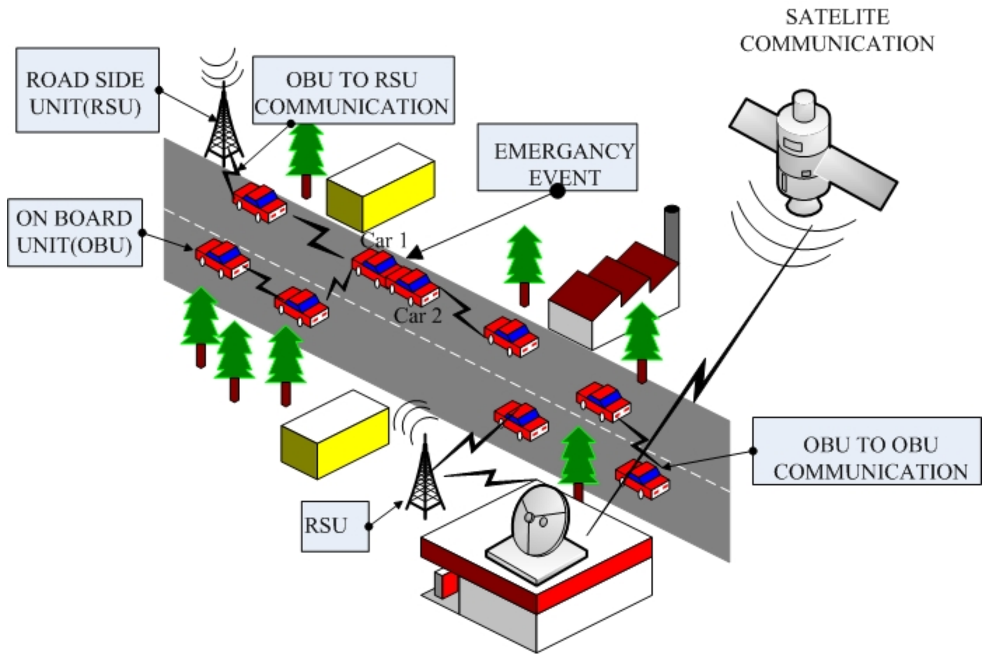

Figure 1.3: Vehicular ad-hoc Networking.

- VANETs have a highly dynamic topology and experience frequent fragmentation due to the fast motions of vehicles. This phenomenon results in a small effective network diameter.
- VANETs also have highly dynamic scale and network density. VANETs are the largest ad-hoc network ever proposed. Therefore, the issues of stability, scalability, reliability, and security are of great concern.
- The nodes' mobility is depend on a geographical pattern, for example a network of freeways or city streets.
- Vehicles have access to their battery and electrical system, therefore, power is not an issue.
- Driver's behavior is also another important issue. The drivers may react according to the data which they receive from the network and their behavior may influence the network topology.

These characteristics have important implications for design decisions in VANETs. The resulting challenges will be discussed, below. Fig 1.3 shows a schematic of vehicular communication in the streets of a city.

Although VANETs are the application of MANETs in vehicular environment, for simplicity reasons, we use the word "MANETs" to refer to the ad-hoc networks other than vehicular ones. This custom conforms to the literature and enables the authors to distin-

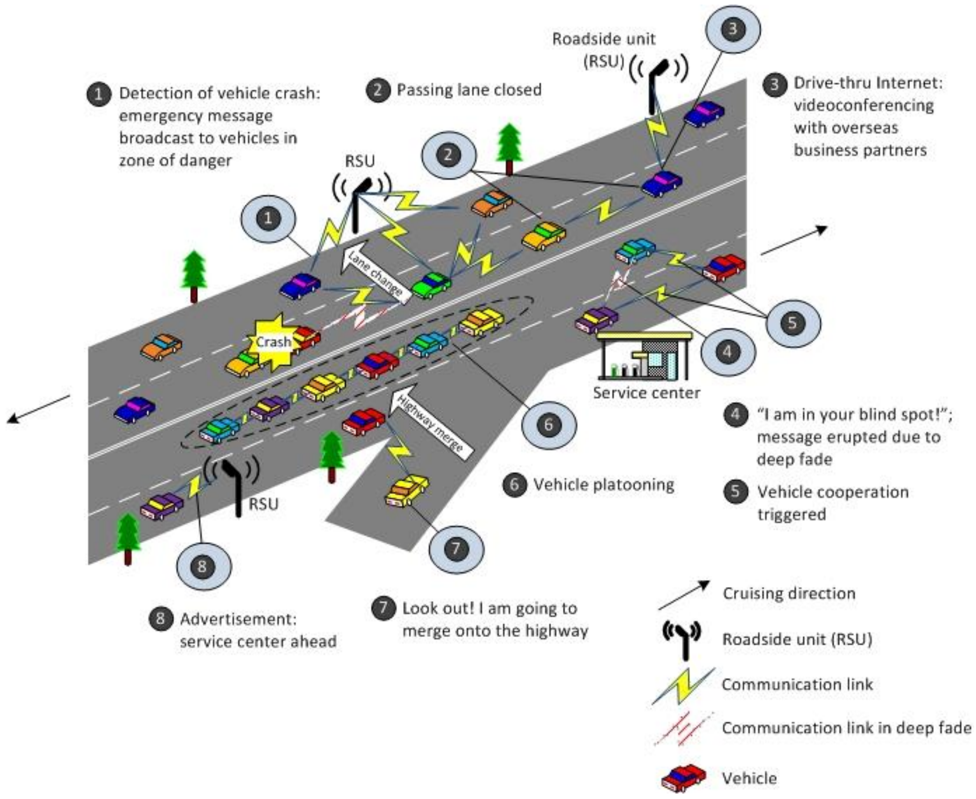

Figure 1.4: Example of Safety Applications in VANET.

guish these two types of services. However we employ ad-hoc networks to refer to both MANETs and VANETs in this study.

1.3.1 VANET's Applications

The main applications of VANETs are classified into two categories: safety and comfort applications [8]. The safety application is mainly to increase the driving safety. The safety applications may be classified into three groups according to their safety natures: assisting, informing and warning. Corporative collision avoidance and lane-changing assistant are the type of assisting application. Examples of informative safety applications are speed limit or work zone information. Finally, the examples for warning safety applications are obstacle, emergency or road condition warnings.

Periodic and event driven messages are the main safety messages which are communicated among nodes for safety applications.To prevent hazardous condition, beconing is used, which is described as periodic messages. The main content of these type of messages are position, direction and speed information. Moreover, it also provides information about drivers intention of source node. An occurrence of a potential hazard may cause an event driven messages to to be generated. For example, reckless high speed driving of neighbor car. This kind of event driven message also triggered the safety system actuator[8]. Fig 1.4 illustrates some safety applications for VANETs.

The comfort application category exists mainly to increase convenience of drivers and passengers and improve the efficiency of the traffic. The traffic informatics, providing desirable and less obstructive road choices, mobile IP, weather details, advertisement for near by businesses and commercial nodes, are types of comfort application. All these applications belong to the layer above the transport layers [9]. The main concern is to make sure these applications do not affect the performance of the safety applications which are time critical, and important applications of VANETs.

1.3.2 Motivation and Research Question

One of the most challenging parts in the design of a vehicular network lies in the design of an efficient MAC layer that considers both the highly dynamic nature of vehicles and the different QoS (Quality of Service) applications thus supported. Many proposed MAC protocols for VANETs consider one aspect but overlook others. We are in need of a MAC protocol that is capable of providing an integrated solution while dealing with different challenges simultaneously.

A MAC protocol for VANETs should be designed for both urban and suburban environments. Since each environment has its own characteristics, the medium contention in congested environments (downtown of urban cities) is much more demanding than suburban ones. Therefore the MAC protocol should easily adapt to different traffic conditions. Moreover, high mobility imposes a high multipath environment; with dynamic delay spread due to multiple reflections, scattering, diffraction and refraction. Therefore there exists a need in vehicular environments to assess the channel dynamically before initiating transmission, as many cars are competing for a limited spectrum resource in a network that is suffering frequent connections and disconnections.

On the other hand, there exists an imposed latency requirement for QoS applications and services. Data transmitted over VANETs can be classified as Safety or NonSafety with different considerations. QoS applications can be time-sensitive and latency-nontolerant and they range from Safety (collision warning), Realtime (video and audio) and NonRealtime (email, web surfing) applications. Safety messages must be sent within a certain upper threshold know as delay bound otherwise they reach their target late and are considered useless. An efficient medium access methodology ensures the prioritization of transmission by granting safety messages the highest priority to access the medium. Besides the above motivations, the auto industry is the second driving force behind this technology, desiring to so equip the vehicles, either for providing safety, gaining extra value or for implementing luxury applications. Toyota, BMW and Daimler-Chrysler have each launched important

Table 1.1: Examples of DSRC Applications and Requirements

Application	Allowable Latency(ms)	Priority
Intersection Collision Warning/Avoidance	100	Safety
Emergency Braking Warning / Avoidance	100	Safety
Cooperative Collision Warning	100	safety
Toll Collection	50	Non-Safety
Service Announcements	500	Non-Safety

projects for VANETs communications. Table 1.1 shows different applications with different delay bound requirements [10].

According to above discussions, existing MAC protocols for VANETs do not suit all of the above challenges, which raise the questions those are described below.

- Does a new MAC protocol have capabilities to prioritise traffic to ensure QoS ?
- Does a new MAC protocol have capabilities to mitigate interference in high multipath vehicular environment ?
- Does a new MAC protocol have capabilities to consider high mobility and maximizing available resource allocation by introducing a unique multichannel cognitive operation?

1.4 Research Aims

The potential of VANETs also bring many new challenges compared to traditional ad-hoc networks, which need to be addressed if VANETs are to succeed. The most successful standard for VANET is the IEEE 1609. Moreover, some important challenges facing the VANETs functionality are poor channel utilization and unreliability of the system for safety applications. The aim of this research is to address these challenges and answer the research questions. The research aimed to:

- Develop a multichannel Medium Access Control (MCM) protocol based on the IEEE 1609.4 using the cognitive radio concept to improve the channel utilization and ensure the reliability of the system for safety application, which will have capabilities to mitigate interference in high multipath vehicular environment, and to consider high mobility and maximizing available resource allocation

- Modify Enhanced Distributed Channel Access protocol to improve the reliability for safety application, which will have capabilities to prioritise traffic to ensure QoS.
- Develop a simulation model for IEEE 1609.4, which is close to real model to simulate close to real scenario for VANET.

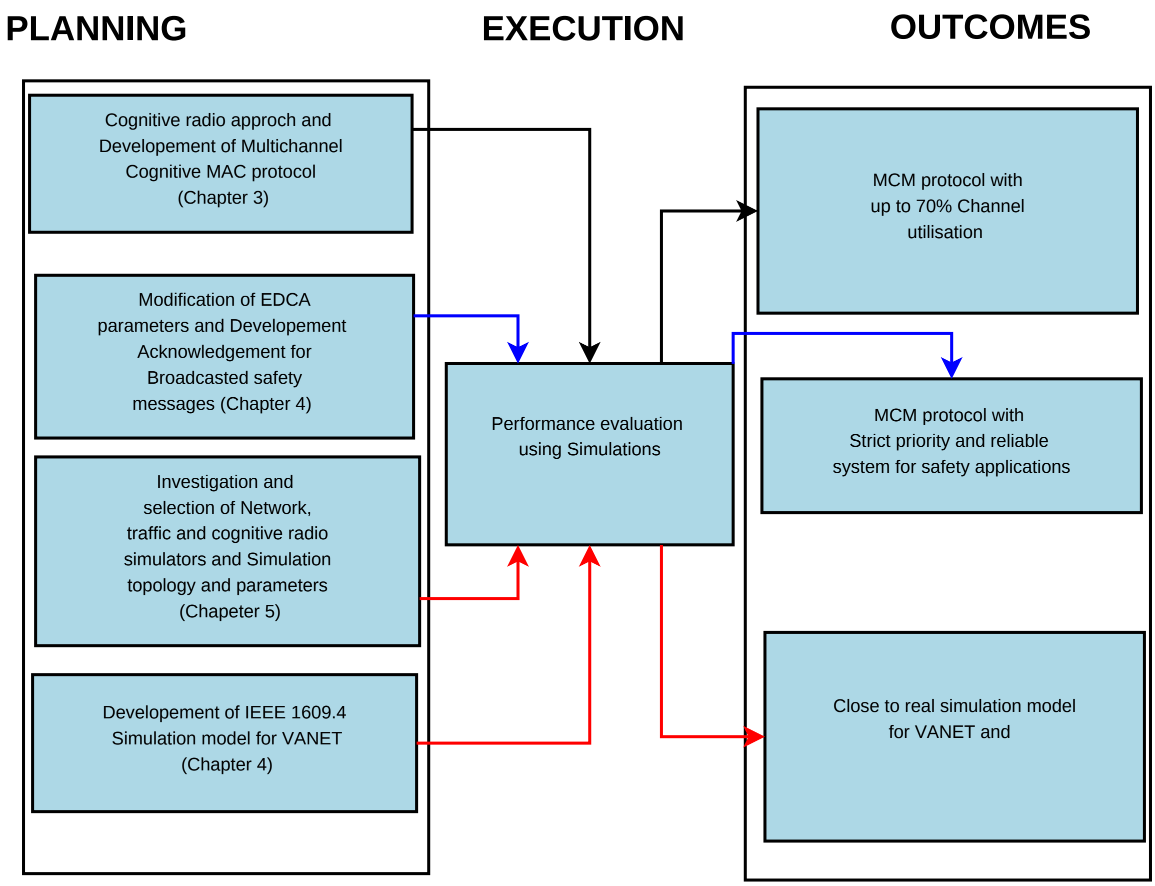

Figure 1.5: Research contribution.

1.5 Research Contribution

We have achieved the research goal by developing a new MCM protocol using cognitive radio technology, and prioritised channel access scheme. Moreover, we have develop the IEEE 1609.4 simulation model for VANET because the proposed MCM protocol is based on the IEEE 1609.4 MAC protocol. Our research contribution is shown in Fig 1.5.

1.6 Thesis Organization

The remainder of this thesis is organised as follows:

- Chapter 2 presents a literature review of the MAC protocols for VANETs, challenges and issues in VANET environment, quality of service (QOS) metrics, and the recent related work. In addition, it presents a brief overview of the mobility patterns and models, and cognitive radio (CR) technology.
- Chapter 3 presents the proposed multichannel cognitive MAC (MCM) to improve channel utilisation, and its algorithm and operation. In addition, it also presents the simulation systems and performance evaluation in-terms of channel utilisation, waiting time interval and control overhead. We conclude the chapter with the table which proves the superiority of our proposed protocol.
- Chapter 4 describes the proposed MCM to improve system's reliability in terms of safety applications. Moreover, it presents the improved priority access scheme, and the proposed algorithm for generating acknowledgments for broadcasted safety messages. Moreover, it also describes the developed IEEE 1609.4 model for NS-2. Finally, priority access scheme, and broadcast algorithm are thoroughly studied and evaluated through simulations and compared with present protocols.
- Chapter 5 presents the selection of simulators. In addition, it also describes the simulation systems, simulation topology and parameters.
- Finally, Chapter 6 gives concluding remarks of our work and outlines the possible future work.

Chapter 2

LITERATURE REVIEW AND RELATED WORK

In this chapter, VANET and different MAC protocol proposed for VANET are reviewed and briefly explained, and the issues it addresses are identified. Furthermore, different mobility patterns and models for VANETs and CR technology are reviewed and essential background knowledge about them and some related work are discussed.

2.1 Vehicular Ad-hoc Networks

2.1.1 Introduction

Since the first invention of mobile vehicles, governments and manufacturers have researched accidents to reduce the number of vehicle crashes in order to reduce costs, injuries and fatalities. The promising VANET technology complements this work with a research that focuses on preventing crashes on the first place. Accordingly, related governmental authorities initiated new projects to the study, research, development and standardization of VANETs. The 'Dedicated Short Range Communications (DSRC)' [11] is a pioneer ITS project dedicated to VANET standardization; with the acronym 'DSRC' becoming a worldwide name for any set of standards that aims to put VANET technology into life. The DSRC is concerned with communication links between vehicle-to-vehicle and vehicle-to/from-roadside units (RSU).

2.1.2 VANET characteristics

Although VANETs, Wireless Sensor Networks and Wireless Mesh Networks are special cases of the general MANETs, VANETs possess some distinguishable characteristics that makes it unique. These properties present considerable challenges and require a set of new especially designed protocols.

Due to the high mobility of vehicles, traveling at up to one hundred fifty kilometers per hour, the topology of any VANET changes frequently and unexpectedly. Hence the time that a communication link exists between two vehicles is very short, especially when the vehicles are traveling in opposite directions. One solution to increase the lifetime of communication links is to increase the transmission power, but increasing a vehicle's transmission range will increase the collision probability and degrade the overall throughput of the system. An alternative solution is to have a set of new protocols employing a very low latency.

Yet another effect of the high mobility of the nodes is that the usefulness of the broadcasted messages is very critical to latency. Assuming for example that a vehicle is suddenly stopping, it should send a broadcast message to warn other vehicles of the probable danger. Considering that the driver needs at least 0.70 to 0.75 sec to initiate his response [12], the warning message should be delivered at virtually zero seconds latency.

In VANETs, location of nodes changes very quickly and unpredictably, so that building an efficient routing table or a list of neighbor nodes will exhaust the wireless channel and decrease the network efficiency. Protocols that rely on prior information about location of nodes are likely to have a poor performance. Nevertheless, the topology of a VANET can be beneficial, because vehicles are not expected to leave the paved road, hence, the running direction of vehicles is predictable to some extent.

Although the major design challenge of protocols in wireless sensor networks is to minimise the power consumption, this is not a problem in VANETs. Nodes in VANETs depend on a good power supply (e.g. vehicle battery and the dynamo) and the required transmission power is small compared with power consumption of on-board facilities (e.g. air-conditioning). It is expected that as VANET is initially deployed, only a small percentage of vehicles will be equipped with transceivers. Thus, the benefits of the new technology, especially On Board Unit (OBU) to OBU applications, will not materialise for many years. Moreover, the limited number of vehicles with transceivers will lead to a frequent fragmentation of the network. Even when VANET is fully deployed, fragmentation may still exist in rural areas, thereupon, any VANET protocol should expect a fragmented network.

Concluding, the main characteristics of VANETs can be summarised as follows [13];

- High mobility of nodes
- No prior information about the exact location of neighbor nodes
- Predictable topology (to some extent)

- Critical latency requirement especially in cases of safety related applications
- No problem with power
- Slow migration rate
- High possibility to be fragmented
- Crucial effect of security and privacy

Finally, the key difference between VANET protocols and any other form of Ad-Hoc networks is the design requirement and resource management. In VANETs, the key design requirement is to minimise latency with no prior topology information. To fulfill the requirements for VANET, efficient MAC protocol design is necessary.

2.2 MAC protocols for VANET

MAC Protocols for VANET are considered crucial and important when measuring the network performance. The importance of MAC protocols in defining how each node shares the limited bandwidth in the network increases due to the special characteristics of the vehicular networks. Both high speed and fast topology changes make the process of sharing the bandwidth more difficult.

MAC protocols can be classed into two main types, centralised and decentralised. However in VANETs, due to the lack of a central coordinator, distributed MAC protocols are expected to provide a reliable communication, even though some VANET applications interact with infrastructure units, e.g. roadside units (RSUs)[14]. The majority of the protocols discussed in the literature are distributed. For VANET MAC, random access protocols are extensively researched. In random access protocols, the nodes contend to access the medium and should be aware of the collisions. On the other hand, contention-free protocols, e.g., Time Division Multiple Access (TDMA), Code Division Multiple Access (CDMA), Frequency Division Multiple Access (FDMA), determine which node should have access to the medium without any contention. There are some protocols that enable access to the medium by embedding the principle of schedule based MAC. For example, ADHOC-MAC uses a dynamic TDMA mechanism [15].

Historically ALOHA [16] is the main basic concept for random access protocols. The basic procedure for ALOHA is that nodes send the packet whenever they have them to transmit. Based on ALOHA, slotted ALOHA (S-ALOHA) [16] provides a better medium access mechanism by dividing the time into slots, and a node only transmits at the beginning of a time slot. While ALOHA and S-ALOHA allow nodes to access the medium whenever they have packets to send, carrier sense multiple access (CSMA) [16] protocols allow a node to send only if the medium is not busy. Thus, the node checks the status of the channel before transmitting, and if the channel is busy, it backs off for a random amount of time; otherwise, it transmits. CSMA with collision detection (CSMA/CD) [16] and CSMA with collision avoidance (CSMA/CA) [16]are both inherited from the original CSMA protocol. However, the latter is the one that is applicable in wireless networks. As Section 2.3 shows, several protocols for medium access in VANETs are based on the CSMA mechanism such as IEEE 802.11 and its derivatives.

2.2.1 Challenges and issues in VANET environment

There are several issues and difficulties that should be considered when designing a MAC protocol for VANETs. Some of these are classical problems and are present in other networks, e.g., hidden and exposed node problems; whilst other problems are present only in vehicular networks.

2.2.1.1 High Speed and frequent topology changes

In vehicular networks, the vehicles move very fast on the road. This causes frequent changes in the topology of the network. However, due to road geometry, the directions of the vehicles can be predicted to a certain extent. This issue should be handled carefully by the MAC protocol. For example, two nodes can communicate if they are in the transmission range of each other. If one node moves very fast, it will be out of the other node's range before completing the transmission. Due to high node density and high speed, the system performance can degrade dramatically. Another example is when vehicles move with speed of 120km or even 150km per hour, the probability of having frequent link disconnections increases. Therefore, the MAC protocol design should address mobility issues and estimate accurately the condition of the highly dynamic channel.

2.2.1.2 Lack of central coordination.

As mentioned previously, vehicular networks are considered a special case of MANETs with high speed. Therefore, it is difficult for a centralised MAC protocol to coordinate the medium access. Currently, distributed MAC protocols are proposed to enhance the performance of vehicular networks even though some applications may involve communication with roadside units. In those cases, where central coordination is used, either partially or completely, the network generally does not operate in an ad-hoc mode. However, the coordinator station can be considered as a node that operates in ad-hoc mode similar to any other vehicles moving on the road. As mentioned in Section 2.1, there are some protocols that are schedule-based, e.g., ADHOC-MAC uses Time Division Multiple Access (TDMA) [15]. Those protocols are mainly intended to work in a centralised mode, which makes it difficult to apply them to vehicular networks without major changes [17].

2.2.1.3 Scalability

In a distributed system that has very high mobility such as in vehicular networks, changes of network sise should be handled carefully. It is normal to have a situation where vehicle density is near the average. However, the vehicle density can suddenly grow significantly and becomes very large in a road segment. Operability in both sparse and high node density situations is very important for MAC protocols. An effective MAC protocol should be adaptive to various network information load and vehicle density. In this context, scalability can be defined as the ability to accept an increase in the number of nodes or elements in the network without suffering a noticeable decrement in performance or a complexity increment [18]. Vehicular networks can be considered to be a typical example of where scalability is required. Several studies on performance evaluations, some of which are mentioned in Section 2.3, show that some protocols do not work properly in a high node density and/or when the network is highly loaded with teletraffic. In such cases, the network may not provide the desired performance unless the MAC protocol is designed to address this issue.

2.2.1.4 Hidden and exposed node problem

One of the classical problems in distributed MAC is the hidden node problem. In the situation as shown in Figure 2.1a, node A is transmitting to node B; At the same time node C, that can not detect the transmission from node A, wants to initiate a transmission to the same receiver node, B. If C initiates the transmission, a collision occurs. This happens because both nodes A and C are out of each other's transmission range, while node B is placed in the transmission range of both A and C. In VANETs, due to the high speed mobility in vehicular networks, the hidden node problem is expected to happen more frequently.

Another problem is the exposed node problem. In Figure 2.1b, node B is transmitting to node A. However, node C, which is located in the transmission range of node B, wants to initiate a transmission, but it hears node B transmitting. Thus, C will not transmit in order to avoid collision.

The hidden node problem can be solved by using the request-to-send/clear-to-send

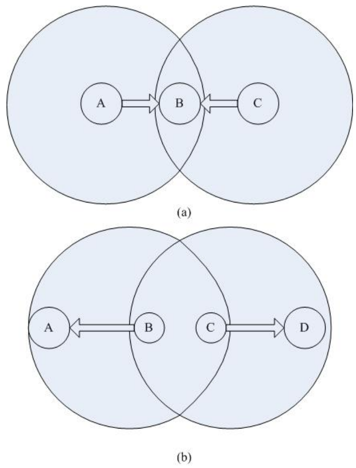

Figure 2.1: Hidden and exposed node problem

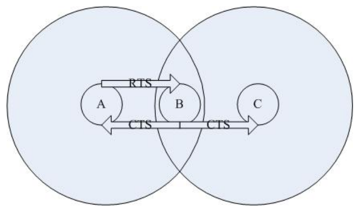

Figure 2.2: Solving hidden node problem using the RTS/CTS handshaking.

(RTS/CTS) handshaking as shown in Figure 2.2. Node A, which wants to transmit to node B, sends an RTS packet to inform node B that it wants to transmit. Node B responds to this request by broadcasting a CTS message to all the neighbors in its transmission range. Every node that hears the CTS should not start any transmission, especially the hidden node, C in this example.

2.3 IEEE 802.11 based MAC protocols for VANET

2.3.1 IEEE 802.11 standard

IEEE 802.11 [19] is a communication standard for wireless networks. The 802.11 works in two modes; centralised and decentralised. The basic group of 802.11 nodes communicate with an access point (AP) is called Basic Service Set (BSS). The BSS allows nodes to communicate with the AP and gain access to its services after having some authentication, association, and multiple handshaking steps. On the other hand, the ad-hoc mode allows the nodes to communicate with each other without any infrastructure and is called Independent BSS (IBSS). In vehicular networks, both modes are adopted with several modifications. Moreover, the IEEE 802.11 standard is often suggested for the implementation in vehicular networks due to the wide availability.

In IEEE 802.11, there are two methods to access the medium. Distributed Coordination

Function (DCF), based on CSMA/CA, is used to coordinate the medium access in the ad-hoc mode. The other function is point coordination function (PCF) which is used to control the medium access in a centralised mode. However, the majority of the protocols proposed for vehicular networks require operating in an ad-hoc mode especially for V2V communications. On the other hand, if the MAC protocol involves infrastructure units such as RSUs or uses a virtual grouping mechanism, then a PCF or PCF-like function can be used for access coordination.

One of the functions used to coordinate channel access and guarantee QoS requirements is the Enhanced Distributed Channel Access (EDCA), which is used in the IEEE 802.11e [20], and is considered an enhanced version of the 802.11 DCF. The EDCA is based on CSMA/CA. The main feature of the EDCA is that, when the channel is busy, the back-off mechanism differs. The back-off procedure is as follows. A node that will transmit, senses the channel first, and if the channel is busy, it will choose a back-off time sampled from a uniform distribution [0,CW](CW is the contention window size). If the channel is free, the back-off time will be decreased. Otherwise it will be doubled. The node will transmit when the back-off value reaches 0. The IEEE 802.11e prioritises messages by providing different Traffic Categories (TC) that are also called Access Categories (ACs).

2.3.2 IEEE 802.11p

The protocol IEEE 802.11p is an amendment of the IEEE 802.11-2007 protocol for wireless networks which focuses on the improvement of the performance of the CSMA/CA networks in highly mobile ad-hoc networks. It is the proposed standard of the DSRC (Direct Short Range Communications) in the vehicular environment by the IEEE organization. When taking into consideration the global success of the IEEE 802.11 standard, the derived IEEE 802.11p version has the potential of becoming a single global standard for the communications in Intelligent Transportation Systems (ITS)[16]. The design requirements of the standard are the following:

- Longer ranges of operation: target of approximately 1000m;
- High relative speed between nodes: up to 500km/h. Doppler effect has a high impact in the communication;
- Extreme multi-path environment;
- Operation of multiple potentially overlapping ad-hoc networks. High quality of service (QoS) and;
- Support for vehicular-oriented applications such as safety message broadcasting.

The implementation of IEEE 802.11p is easily understood in conjunction with the other amendments of the IEEE 802.11 protocol. The aspects of 802.11p which are common to the other IEEE 802.11 family protocols will be explained, providing a comprehensive insight into the protocol:

- The physical layer of the IEEE 802.11p protocol is based on that of IEEE 802.11a: similar orthogonal frequency-division multiplexing (OFDM) based modulation is used and the frequency allocation is at the 5GHz band;
- Medium Access Control (MAC) is that of IEEE 802.11: Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and;
- The Quality of Service (QoS) implementation has been adapted from the IEEE 802.11e protocol: Four Access Categories (ACs). Each AC has its own transmission queue with built-in priorities. IEEE 802.11p does not only implement features from other IEEE 802.11 protocols, as the design requirements are unique in the protocol family.

The main qualities which differentiate this protocol and which are required to meet the essential requirements of high speed and short communication intervals using exclusively the available resources, are:

- Dedicated frequency band (5.850 to 5.925 GHz);
- The channel bandwidth differs: 10MHz per channel instead of 20MHz;
- This implies the data rate is also halved, alongside the symbol and guard periods being doubled;
- Short Interframe Space (SIFS) times increased in order to prevent long-range issues;
- Polling-based Collision-Free Phase (CFP), present in other versions of IEEE 802.11, is not part of the 11p amendment as it would not be effective in a extremely dynamic environment. Therefore, no guarantee of timely delivered real-time data packets can be offered and;
- Introduction of the Wave operation mode: allows fast communication setup when certain conditions are met.

2.3.3 WAVE , DSRC and IEEE 1609 standards

WAVE, namely Wireless Access in the Vehicular Environment, defines a mode of operation for IEEE 802.11p devices in those situations where the properties of the physical layer are

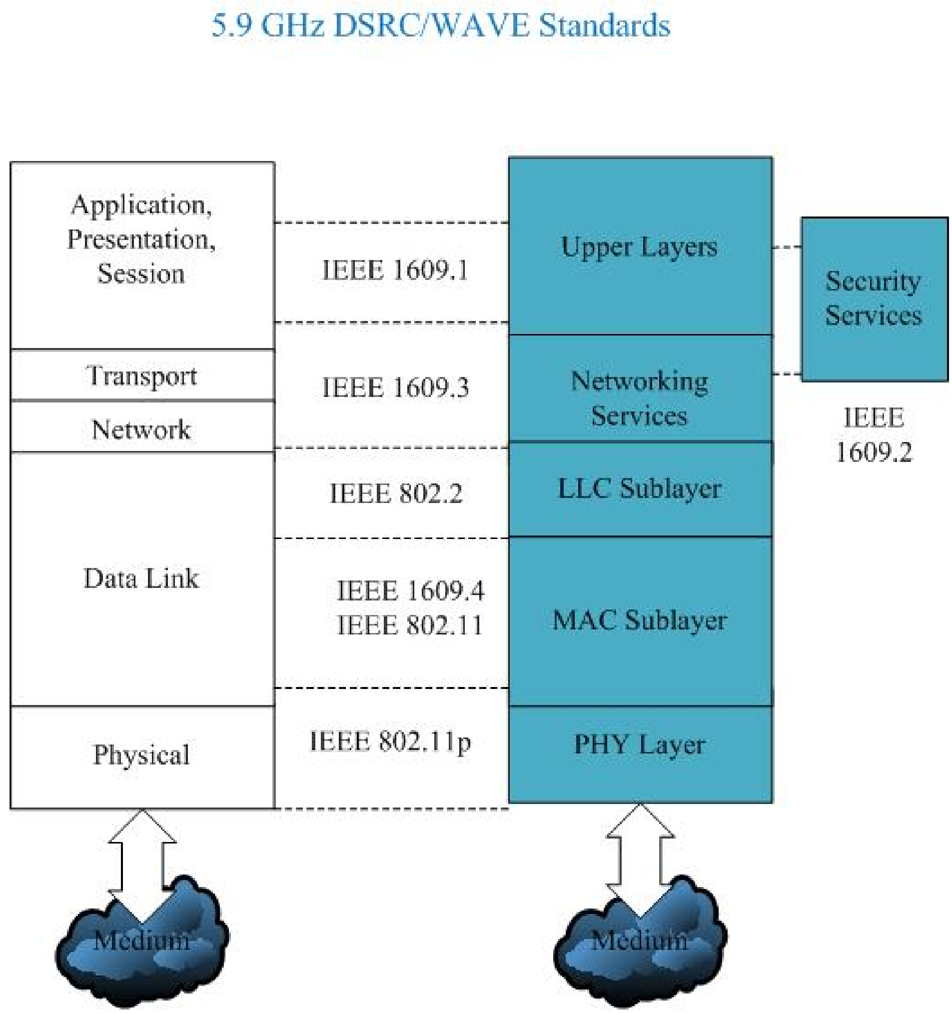

Figure 2.3: WAVE protocol stack

rapidly changing and where the duration of the communication exchange is remarkably short. The rapidly changing environment, and the nature of the information exchanged in vehicular networks, requires a system which can allow the nodes to actually complete the data transmission in a much shorter period of time than that required by other wireless protocols to authenticate and associate to join either a infrastructure or an ad-hoc network. The protocol stack for Vehicular communications is represented in Fig. 2.3 where it can be observed that the family of standards P1609.x provide an implementation of the higher OSI levels while it relies on the IEEE 802.11p protocol to provide the implementation of the lower levels.

- IEEE P1609.1 - Standard for WAVE - Resource Manager;
- IEEE P1609.2 - Standard for WAVE - Security Services for Applications and Management Messages;
- IEEE P1609.3 - Standard for WAVE - Networking Services and;

- IEEE P1609.4 (802.11p) - Standard for WAVE - Multi-Channel Operations.

When considering the communication requirements, WAVE defines an implementation of IEEE 802.11p for devices which is able to enable communication by defining the minimum set of parameters that will ensure interoperability between wireless devices which require to communicate in the previously mentioned conditions, called the WAVE mode. To work in a vehicular environment, the 802.11p MAC should simplify the BSS operations and reduce the amount of overhead needed to establish a communication link. Thus, WAVE mode stations operate in the same channel and communicate immediately without wasting time in association when joining the BSS. The joining process is done using a wild-card Basic Service Set Identification (BSSID), which is the name of the BSS at the MAC layer. This new BSS mode is known as WAVE Basic Service Set (WBSS) in which authentication and association are not required. Instead, a station can join the WBSS according to the WAVE advertisement or announcement. More information about WBSS is given in [21]. The IEEE 802.11p is supposed to provide prioritised channel access through the use of the EDCA by providing different Access Categories (ACs). The ACs ranges from 0 to 3, where AC0 and AC3 refer to the lowest and highest priority, respectively.

2.3.4 Related work review

The IEEE 802.11p has been extensively studied [22, 23, 24, 25]. However, to the best of our knowledge, there is no comprehensive evaluation that reflects the impact of mobility on the IEEE 802.11p MAC protocol performance, especially for the V2V communications. Moreover, very little work has been done on enhancing the performance of IEEE 802.11p via adaptation to the mobility factors.

The IEEE 802.11p is meant to provide reliable and efficient MAC for the high speed vehicular environment. In the literature, researchers are continuing to investigate and study the performance of the 802.11p, and 802.11p-based MAC protocols, and study their suitability for vehicular networks. It is known that 802.11 MAC is designed for low mobility and has some limitations especially in a high density scenario. Since the IEEE 802.11p is based on the original IEEE 802.11, it is normal for it or any other protocol based on 802.11p to inherit those limitations. In [22], the authors have studied the saturated performance of 802.11 MAC in a single-hop network. The study shows the delay requirement, which is below 100 ms, is satisfied while the PDR decreases dramatically when the number of nodes increases. The authors suggest that the reason for the failure on achieving the desired PDR rate (more than 99 per cent) is the high collisions due to the fixed short back-off window and hidden node problem. Several enhancements at the 802.11 MAC level are suggested such as repetition mechanisms, adaptive back-off, and dynamic adjustments of the contention window size.

The 802.11 Wireless LAN (WLAN) performance has been studied over different scenarios and with a reactive routing protocol in [26]. The performance indexes used to test the network performance are throughput and the signal to noise ratio (SNR). Experimental results show that the 802.11 throughput decreases dramatically in a high node density and large network. The recommended solutions are to modify the back-o mechanism, using a super frame structure, and using different inter-frame spacing system for different service priorities. In [27], the simulation results of 802.11p MAC in a highway scenario show that some nodes are forced to drop over 80% of its time-critical messages due to the long channel busy time. This can lead to serious failure in delivering safety messages.

In [28], simulation results of the IEEE 802.11p standard show that the fixation of the back-off window size does not guarantee the desired throughput in vehicular networks. Two algorithms for a dynamic back-off window size are proposed. In the centralised approach, the base station is assumed to know the number of transmitting nodes, and computes the optimal transmission probability accordingly. In the distributed algorithm, local medium information is needed for the vehicle to select the back-off time. Therefore, the number of current users is estimated by observing the current contending nodes. Both algorithms improve the performance over the 802.11 static back-off mechanism. However, the enhancement proposed is used for the V2I communication mode and even though the throughput has been improved, the computed contention window sizes are very large and can cause very long delays in transmission. Similar simulation results supported with analytical means show that the IEEE 802.11p suffers from an undesired decrease in throughput and an increase in delay in high density scenarios [23]. The study evaluates the collision probability, throughput, and delay in the performance evaluation, and focuses on WAVE message prioritization using the EDCA mechanism. It is mentioned that increasing the CW size in order to reduce the probability of collisions causes the throughput to decrease. An alternative is to shape the traffic while maintaining the number of high priority packets at a certain level. To achieve better performance, the author suggests using a re-evaluation mechanism for messages to reduce the number of high priority messages continuously. A similar study on the factors affecting the performance of the ad-hoc networks gives similar suggestions [29]. It is shown that increasing the network size, while maintaining the traffic load, leads to increased throughput. To apply this in vehicular networks, the number of potential neighbors should be considered. Aiming at multi-hop communications, Stibor *et al*: [25] evaluate the number of potential communication partners and the maximum communication time for vehicular ad-hoc networks using the IEEE 802.11p standard. The simulation is done for a highway scenario, and the results show that the number of neighbors varies and leads to different communications time between vehicles. It is shown that the number of neighbors should be used as an input parameter in multi-hop communications.

Other issues that the IEEE 802.11p should address are mentioned in [30]. To make the IEEE 802.11p work efficiently, some challenges should be addressed. These challenges are the stateless channel access, caching for handoff, and opportunistic frame scheduling. By operating in the WAVE mode, WBSS providers (e.g., APs) cannot keep track of the WBSS users due to the absence of authentication and association in the WBSS. Moreover, when a WBSS user moves out of a WBSS provider's range, the WBSS provider does not know that the WBSS user is not in its range anymore because there is no de-association process. The mobility of a WBSS user leads to its communication with multiple WBSS providers. Therefore, supporting fast handoff should be considered. In [31], a simulation framework that includes handoff mechanisms for the IEEE 802.11p is developed to study the behavior of handovers for the V2I communications. A solicitation-based IEEE 802.11p MAC protocol is proposed for roadside to vehicle communication [30]. The solicitation MAC protocol is based on a wired backbone for the WBSS providers, and introduces two new concepts. A new operation mode called WBSS user initiation mode (W-UIM), in which the WBSS user opportunistically solicits data frames for itself. A WAVE-poll frame is used to request the transmission from a WBSS provider. The other concept is that the adjacent WBSSs are virtually grouped and denoted as a WBSS-area.

A study in [24] shows that node speed is not a significant factor in terms of aggregate throughput, average delay, and packet loss rate. However, traffic load is shown to be a significant factor that affects the performance. From the simulation results, when the vehicle density increases, both aggregate throughput and average delay increases while the delay requirement is met. However, the simulation is done only for a one-lane road scenario.

2.4 QOS Metrics

The performance of any MAC protocol is measured through certain metrics that are specified for a certain application. For example, some protocols are intended to increase the capacity and maintain the delay at specific values, while other applications require delay to be minimised and maximising the available capacity for the transmission. In vehicular networks, depending on the application, certain QoS measures should be met. Generally, the following performance metrics should be considered by VANET MAC protocols:

- Packed delivery ratio: Usually, packet delivery ratio (PDR) requirements depends on the type of the application. The PDR should be larger than a certain threshold to provide a specific service. To achieve a good PDR that satisfies certain QoS, the hidden node problem, which causes unexpected collisions, should be addressed. Section 2.3.4 explains the hidden and exposed node problems. To achieve a desired PDR, two factors can be dealt with at the MAC level. They are collisions (which occur due to the hidden node problem) and transmission interference. Some performance metrics do not consider PDR. Instead, they consider the probability of packet reception, or alternatively, the probability of reception failure. Generally, PDR or packet loss rate (PLR), which is the complement of the PDR, is used as a measure of the transmission reliability of the MAC protocol. In some vehicular network applications, e.g., safety messages in safety applications, the packet delivery rate should be very high (>99%).

- Delay: An important requirement for vehicular communications is that a message should be delivered within a certain time. This time is known as communication delay bound, and can be defined as the maximum time duration between the generation and the successful reception of that message. In many cases, especially for safety applications in vehicular networks, if the message is delivered after the delay bound, it is considered useless. For example, in [16], it is mentioned that accident information should be delivered in a maximum of half a second to all desired destinations. Other specifications requires a maximum of either a 100 ms or 50 ms delay depending on the application. Consider the scenario where two vehicles are moving in opposite directions, the delay of transmission in this case should be very small. In such a case, the delay should be bounded by a limit that is called the deadline. After the reception deadline, the message is not considered fresh anymore.

- Channel Busy Time, Channel Utilisation: As mentioned in earlier, when a node is willing to transmit using a CSMA protocol, it may find the channel busy and backoff for a certain amount of time. This time is the channel busy time. Reducing the channel busy time results in better channel utilization. For vehicular networks, Xu *et al*: [32] have defined the channel busy time (CBT) for safety message communication within the dedicated short range communications (DSRC) spectrum range (DSRC will be discussed later in Section 2.5.2.4). The control channel is monitored for a certain time T_{inv}. During this monitoring time, the channel might be busy for some time, due to the transmission of other safety messages that might be delivered successfully or not. The transmission is assumed for a randomly chosen node and its neighbors who are located in the interference range of that node. If the total time of the transmission period is denoted by T_{total}, then the channel busy time can be defined mathematically as

$$CBT = \frac{T_{totat}}{T_{inv}} \tag{2.1}$$

- Fairness : At the MAC level, if the probability of transmission from each node that is transmitting using the same MAC protocol is equal, then the protocol is considered fair. However in vehicular networks, due to the high mobility and differences of speed, fairness is difficult to achieve. Therefore, a certain level fairness is usually defined as a goal. Although it is difficult to achieve complete fairness, it is preferred to allow a tradeoff between fairness and other QoS metrics in order to achieve better overall QoS in certain applications.

2.5 Different MAC protocols

This section describes different MAC protocols for VANET and their comparison.

2.5.1 Virtual grouping MAC

2.5.1.1 Cluster based MAC

Clustering has been proposed for ad-hoc networks. Clustering schemes can be used to manage the mobility and the quick changes in the network topology. In a vehicular environment, since vehicles sometimes move with similar speeds and in the same direction, dividing them into groups through clustering can help in controlling the medium access. Clustering is basically used by routing in mobile ad-hoc networks to handle the problem of flooding. However, in the medium access layer, clustering is used to handle the hidden node problem, provide better scalability, reduce the number of interfering nodes, limit the area of message dissemination, and provide fair access to the medium [33].

By using clustering techniques, an ad-hoc network can be handled by a centralised controller. This occurs by virtually grouping the mobile nodes into clusters. In each cluster, a Clusterhead (CH) is elected to act as a central controller that coordinates intra-cluster transmission. The other nodes in the cluster are considered cluster members, which are normal nodes, or cluster gateways. Figure 2.4 shows an example of a clustering structure. More information about clustering and cluster formation algorithms can be found in [34].

For vehicular networks, research on cluster-based MAC focuses on clustering formulation algorithms, improving the medium access through clustering, minimizing the cost by using a fewer number of transceivers, and avoiding the inter-cluster interference. The authors in [33] proposes a clustering medium access mechanism based on TDMA. The main function of the clusterhead is to manage the bandwidth assignment in the cluster. Through

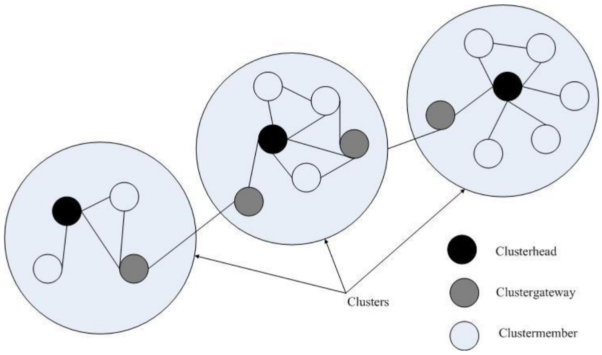

Figure 2.4: Clustering structure example.

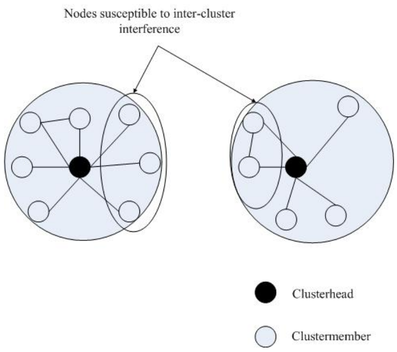

Figure 2.5: Example of inter-cluster interference.

simulation, the protocol is shown to be stable except for high dense traffic situations such as in rush hours. Su and Zhang propose a clustering-based multichannel MAC scheme in [35]. Their scheme integrates clustering with contention-free and contention-based MAC protocols. Each vehicle is supposed to use two transceivers that operate simultaneously. The clusterhead of each cluster has three functions to perform: 1) collection and delivery of safety messages within a cluster, 2) forwarding the safety messages to the neighboring clusters, and 3) coordinating the channel access for local cluster members with non-realtime communication flows. The contention-free MAC for communication within a cluster is TDMA, while the IEEE 802.11 is used for communications between clusterheads. The protocol is designed to provide QoS for the realtime data, e.g. safety messages, and provide an increased throughput for non-realtime data for a V2V communication scenario.

Based on the analytical model and the comparison with the IEEE 802.11 and V2V dynamic channel assignment (DCA) [35] through simulations, the proposed MAC scheme achieves both timely delivery of safety messages and high throughput for non-realtime traffic. A similar idea is proposed in [36], but using only one DSRC transceiver in each vehicle. The proposed protocol uses a clusterhead for the intra-cluster communication and cluster forwarder for the communication with backward clusters. Inter-cluster interference, that occurs to clusters close to each other as in Figure 2.5 or due to clusters overlapping, is handled with a simple algorithm.

2.5.1.2 Space division multiple access MAC

Space Division Multiple Access (SDMA) is proposed for inter-vehicular networks in [37, 38, 39]. The protocol is only theoretically investigated. The SDMA introduces a new concept of partitioning the geographical area into multiple divisions. Each of these divisions is mapped to a certain channel to achieve desired performance. To perform the mapping process accurately, the precise positions of the vehicles are assumed to be known. This can be done by using GPS devices.

The SDMA aims to reduce access collisions, and increase channel re-usability. However, many issues and challenges exist for the SDMA in vehicular networks. In [40], the suitability of SDMA in VANETs is investigated. For example, the partitioning process of the road depends on the road map. It is shown that SDMA is suitable for a highway scenario, but there are other scenarios that should be dealt with such as meshed road scenario [40]. Therefore, the SDMA should handle such a challenge when performing the partitioning and mapping processes.

2.5.1.3 Token ring MAC

In [41], a wireless token ring protocol (WTRP) is proposed for intelligent transportation systems. The protocol is evaluated and implemented on top of the IEEE 802.11 DCF. No mobility consideration is mentioned in the work. In [42], an extension of the WRTP with three implementations is proposed. The implementations are a simulator implementation, an application layer implementation that is platform-independent, and a kernel implementation which is a Linux link layer module built on top of the IEEE 802.11 DCF. In order to achieve reliable and fast communication for safety applications as well as QoS guarantee for data services, an overlay token ring protocol (OTRP) is proposed in [43]. The OTRP minimises the number of possible collisions, and transmits safety messages with high probability and low delay. Another advantage is the feasibility of implementation without complex hardware requirements.

2.5.2 Other MAC protocols

2.5.2.1 Ad-hoc MAC

ADHOC MAC [15] is a MAC protocol developed under the CarTalk2000 project to support inter-vehicular communications. ADHOC MAC uses a dynamic TDMA mechanism with slotted frame structure that is independent from the physical layer. The protocol is based on Reliable R-ALOHA (RR-ALOHA), which is an extended version of Reservation ALOHA (R-ALOHA). R-ALOHA is capable of coordinating the channel access in a centralised mode. RR-ALOHA aims to do the same thing, but in a fully distributed mode. The protocol is supposed to deal with the hidden and exposed node problems, provide a reliable single-hop broadcast service, and reserve additional bandwidth and QoS for real-time traffic as needed in the applications. An advantage of ADHOC MAC is that it can be adapted to work with the 802.11 physical layer by providing a frame structure. In [16, 22], several issues regarding ADHOC MAC are discussed. It is mentioned that the minimum time needed to successfully obtain the basic channel is greater than 200 ms in a static scenario. Moreover, several factors such as mobility and dense traffic may cause more latency in allocating and releasing slots. Another issue is the number of frame slots that should be optimised. It is known that frame size is related to other parameters such as network capacity. Thus, the number of vehicles in the same communication range must not exceed the number of slots in each time frame. In comparison with the IEEE 802.11, ADHOC MAC does not utilise the medium efficiently, and does not handle high mobility as the 802.11 does. Further information about ADHOC MAC performance can be found in [26].

2.5.2.2 Directional antenna based MAC

In VANETs, vehicles move according to road geometry. Therefore, the transmission of information, depending on the application, should be done in specific directions. For example, for a safety application that should warn vehicles of sudden braking, the information should be sent to the vehicles that follow the vehicle with the braking action. Other vehicles in front of the broadcasting vehicle are probably not affected by this braking action. This can be done by using directional antenna-based MAC protocols. For more information about MAC protocols with directional antennas, [44] is considered a good reference that provides a classification of MAC protocols with directional antennas, and discusses the challenges in their design.

Directional antennas are used to overcome some problems such as interference, hidden node and exposed node problems. In addition, increased transmission range, and reuse of channels are the main benefits brought by those protocols. Ideally, the transmission range is divided into x non-overlapping transmission angles each having a degree of 360/x. It is known that increasing x results in smaller antennas angles and narrower transmission range. One requirement in directional antenna protocols is the knowledge of the transmitter's and the receiver's active antennas during transmission. This can be done by having the neighbors' location information using a GPS, by neighbors location estimation, or by continuous neighborhood discovery. While the use of GPS devices incur extra cost and has some limitations, location estimation methods such as Angle of Arrival (AoA) may cause some errors [44]. On the other hand, continuous neighbor scanning are used in several protocols such as [45]. Furthermore, directional antennas can be classed as traditional directional or smart antennas [44].

For vehicular networks, several MAC protocols adopt directional antennas and achieve network performance improvement as in [46, 47, 48]. However, investigations of the performance and the suitability for VANETs show that, even though directional MAC protocols improve the performance by reducing collisions and increasing channel re-usability, complexity and difficulties of providing practical implementation are the major issues of directional MAC in VANETs. More information regarding directional antenna MAC performance can be found in [49].

2.5.2.3 Repetition based MAC

The idea of repetition-based MAC is proposed by Xu *et al*: in [50][32]. The aim of the protocol is to deliver safety messages in an ad-hoc mode with high reliability and low delay. In [32], several random access protocols for medium access which are compatible with the DSRC multichannel architecture are discussed and used in the design. The main advantage of the repetition is to have a better probability of reception. However, undesirable amount of reception may cause severe consequences. The main idea is based on repetition. The lifetime of a message is divided into several slots based on its useful lifetime and the transmission time. A variable number of slots are randomly chosen for repetition. A reception of at least one packet means that the message is successfully received within the limited delay. Otherwise, a failure of reception occurs. The main issue here is how to find the number of slots to be selected for repetition. Figure [2.6] illustrates the idea of repetition.

The repetition may overcome the collision problem, and the main advantage of this design is its simplicity. In this protocol, a MAC extension layer handles the generation and removal of repetitions. The MAC extension layer is between the logical link layer and the MAC layer.

Some proposals utilise optical orthogonal codes (OCC) to minimise the message loss probability, reach better probability of detection, and reduce the reception delay such as in [51]. The main idea is to use these codes to assure that a certain number of repetitions of every two nodes cause a collision. By knowing the number of collisions between the two nodes, it is obvious that using a larger number of repetitions will grantee a successful reception. The same concept is used in [52] to provide different QoS priority levels.

Another repetition based MAC is proposed in [53]. In this protocol, a distributed feed-

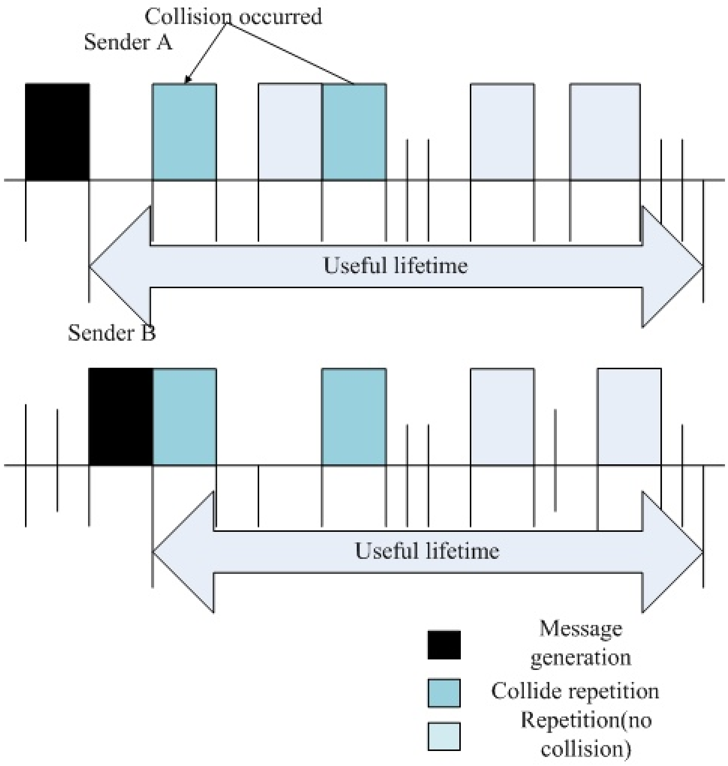

Figure 2.6: Illustration of the idea of repetition for two senders A and B.

back mechanism is used to optimise the number of repetitions. The feedback mechanism is used to broadcast information regarding the transmission and reception of messages through the network. According to the broadcasted information, an algorithm based on index coding is used to minimise the number of transmissions. It is shown through simulations that the protocol results in a lower message loss probability compared with the previous repetition-based MAC protocols, but close results in terms of average delay.

2.5.2.4 Multichannel MAC and Cognitive MAC

It is known that inter-vehicle communication systems are proposed for safety applications and traffic enhancements. However, non-safety applications, or commercial applications, have been proposed in the literature to provide effective use of the DSRC spectrum [54, 55, 56]. The best solution to provide non-safety realtime applications is through the multichannel communications. It has been explained in Section 2.4.2 that DSRC allows multiple channel communications by operating only one channel at a time. This is because there is only one radio used in DSRC. The difficult part of designing a multichannel MAC protocol is to provide the none safety communication while meeting the QoS of the safety communications. As discussed in Section 2.5.1, Su and Zhang propose a multichannel protocol that operates in two different radios simultaneously. This type of communication is considered a multichannel operating protocol, but it is also considered costly since each vehicle should be equipped with two transceivers.

Wang and Hassan propose a framework that performs periodic channel switching over DSRC to provide a concurrent safety and non-safety applications in [54]. It is found that, during rush hours of traffic, the non-safety applications can be extremely restricted to assure the QoS of the safety applications. An interesting conclusion is that using simple techniques can increase the commercial non-safety applications opportunities. Moreover, the authors suggested the use of an adaptive scheme to perform dynamic adjustments to the control channel interval to support the switching between safety and commercial applications.

In [56], multichannel single radio MAC is proposed to provide V2V and V2I communications. The protocol aims at providing concurrent safety and commercial services. The work is first presented with the basic idea in [55]. However, in [56], the authors extend their work with proof of theorems of the design, and performance evaluation with the IEEE 802.11 DCF used in the ad-hoc mode and PCF used in the centralised mode. The protocol is tested in three configurations: the DCF-only, the PCF-only in the hotspot area, and dedicated coordinating AP (DCAP) protocol configuration. The DCAP configuration is based on the DCF, PCF, and spatial division functions. These configurations are simulated using ns-2 in a four-lane highway scenario with high density of a vehicle flow. The DCAP configuration is shown to offer more consistent QoS than the other two configurations.

A cognitive MAC protocol for VANETs (CMV) based on cognitive radio management is proposed in [57]. In CMV, the protocol provides long-term and short term spectrum access which is applied in vehicular communications channels. The protocol is applied on DSRC channels. The cognitive radio management is used to improve the capacity in long-term spectrum access. For short-term access, the wideband spectrum pooling is used. The protocol showed a significant improvement in throughput compared with other multichannel protocols.

The IEEE 1609.4 draft standard for VANET [58] defines the sync interval which constitutes of control channel interval (CCH interval) and service channel interval (SCH interval) as shown in Fig 3.1. The IEEE 1609.4 standard defines the time division scheme for WAVE radios to alternatively switch between CCH and SCH during sync interval to support different applications concurrently [59]. The start of a sync intervals are synchronised with the Coordinated Universal Time (UTC) second and multiples of 100 ms thereafter. The sync intervals constitute of 100ms which has 50 ms CCH interval and 50 ms SCH interval [60]. According to WAVE, Wave Basic Service Set (WBSS) is defined by set of nodes which cooperates with each other, and consists of one provider (the node that has services to offer) that is WBBS initiator and one or more WBSS users. An example scenario is

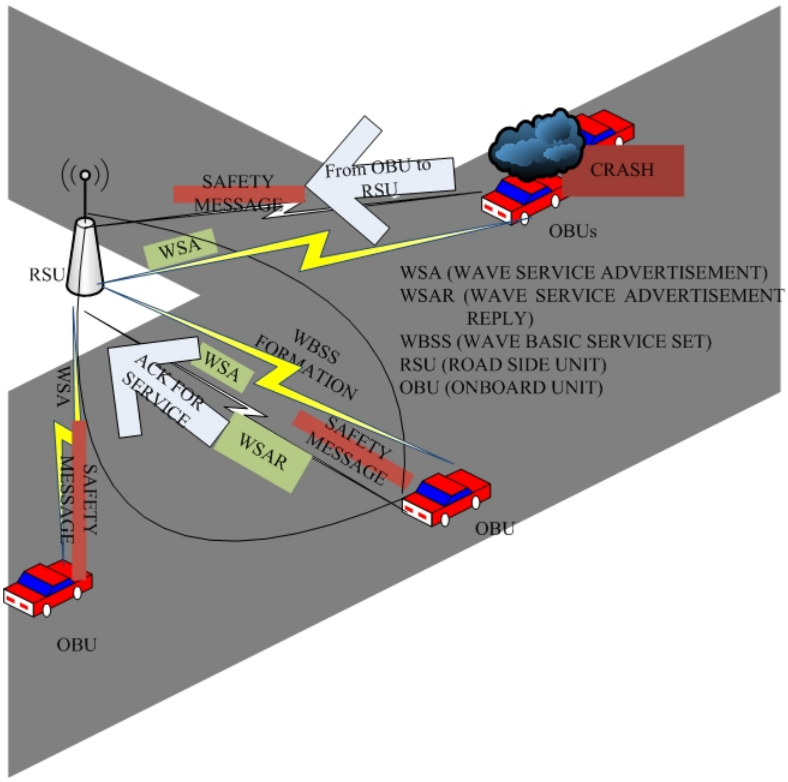

Figure 2.7: Example scenario for VANET.

shown in Fig 2.7

Several MAC protocols have been proposed based on IEEE 1609.4 standards to improve the protocol performance and reliability. The IEEE 1609.4 standard has been studied by Qi *et al.* [59] where the author shows that in IEEE 1609.4 standard the channel is heavily under utilised. The extended SCH interval has been proposed in [61], which increase the saturation throughput of the SCH but does not improve the reliability of the system for safety applications in terms of end to end (E2E) delay, throughput and jitter. Cognitive MAC protocol define by Seung *et al.* [62] which improves system throughput but degrades the performance of safety data delivery. The novel MAC protocol for vehicular mesh network by Yunpeng, Zeng and Stibor *et alia.* [63] enhances the performance of non safety application. Furthermore, the Hardware Constrained Cognitive MAC has been proposed in [64], which shows significant improvement in channel utilization and good performance for non safety users, but again the HC-MAC did not improve system performance for safety users. The above mentioned MAC protocols for VANET focus to improve the overall system performance only for IP services. However, none of them showed any improvement for safety related application, which is the most crucial application for VANET. In this paper we propose the novel mechanism that is based on IEEE 1609.4 and guarantee the reliability of the system performance for safety traffic with a better channel utilization.

As mentioned earlier, the CCH and SCH intervals are 50 ms each which forms one sync interval, so there are 10 sync intervals per second. This is motivated by a desire to map a sync interval to the generally assumed 10Hz vehicle safety messaging rate. It is possible that more than two providers try to access any of the six SCH. To avoid collision between WSA frames on CCH during the CCH interval random back-off scheme is being used. Moreover, when any provider listens to the successful WSA/WSAR handshake within the same CCH interval and also intends to broadcast WSA frames adjust it's SCH in order to avoid collision and if the successful WSA/WSAR handshake is conducted, the provider chooses different SCH during the SCH interval. Furthermore, if the provider fails to conduct WSA/WSAR handshake within the CCH interval then it has to wait until the next sync interval and then that node will make have to use larger CW size to make second WSA announcement. After the above mentioned management procedures, the vehicles will change into the SCH agreed by them, during SCH interval and start the data transmission. In addition, large amount of data required several sync intervals to complete the transmission.

2.6 Mobility Models and Patterns in VANET

The nodes' speed and direction of the speed are the main focus to study different cases on movement models. The mentioned characteristics are the main aim of the study to separate from any dubiousness in the working model. These models and its characteristics are mentioned and explained in [65, 66, 67, 68, 69, 70]. The reviews of these studies are further explored as follow:

According to [65], the VANET is highly untrustworthy, and to model architecture which carries the trustworthy V2V services depends on many different factors and parameters. These variable parameters and the affecting factors because of the involvement of different networks and route selection involving more then two nodes. Therefore, emphasizing on single network, concept of heterogeneous vehicular network (HVN) is proposed. The clusters of VANET with WMAN (wireless metropolitan area network) are incorporated with each other for observing different mobility patterns. The introduction of Mobility Pattern Aware Routing Protocol (MPARP) and HVN gave progressive outcome. The simulation results also show the credibility of enhancement in terms of packet delivery ratio (PDR), number of links break, and instant throughput and delay performances of the communication mediums. Similarly in [66], to utilise the metropolitan area and its mobile nodes with constantly changing speed and its direction, a different model was proposed. This model has achieved some significant results in C3 (car-to-car cooperation) project. The shape file of traffic information which have real traffic data and maps from some city, is used to simulate realistic scenarios. Routing capabilities of ad-hoc networks are simulated and emulated in the model named as STRAW (STreet RAndom Waypoint). The two key routing protocol DSR and AODV and the study of packet delivery ratio explains the heterogeneity of the vehicles on geographical networks such as highways. Different VANET's mobility modes such as Section Model (CSM), Stop Sign Model (SSM), Freeway, Manhattan, City and STRAW are compared in [67]. The comparison is done using different simulators and different mobility characteristics have been studied.

To develop and simulate different mobility models efficiently which have some real city traffic data for VANET, different simulators are studied in [68] . One of them is named as MOVE (model generator for networks). The main features of this tool is that it creates real traffic scenario for VANETs and does it with efficiency, accuracy and it is less time consuming. This tool is designed in JAVA and is based on traffic simulator called SUMO in which the different maps can be used and the mobile node's movement can be defined according to the users' need. Moreover, it is open source and provides a graphical user interface (GUI), which makes it very easy to use and accurate enough. However, SUMO has some problems with randomness of node mobility and it is only used with some network simulators such as ns-2 and Qualnet. In conclusion, this simulators open the gates for researchers working with the issues of mobility, speed, direction and velocity and also lest the users simulate a real scenario with the option of manually editing.

Another scope of realistic mobility model for VANET is described in [69], with multiple similarities of previous works on mobility issues. It is also focusing on real map usage for realistic results commented. The proposed model is applicable in ns-2 and therefore contributes the open research communities in the specified domain. The presented model is identifying and evaluating the work done by [68]. This similar work is already related with some further clarification and having suggestions to consider the mobility scenarios of residential and business area. Also partially done by [71] in their urban pedestrian flows models.

In [70], much of the focus was made on safety related problems faced by vehicular ad-hoc networks (VANETs), with certain limitations observed within the general traffic monitoring. In addition, another vehicular mobility model is proposed that reflects real world vehicle movement on road and performance of present network. The networking performance of VANET is directly affected by traffic rules, (physical) road layouts, and traffic regulations; keeping this fact in mind, processing of VANETs requires careful investigation. The observation enables us to identify the drawbacks of the MANET protocols. It is proposed that the MANET protocols be modified with certain changes, and an investigation undertaken to examine at large scale VANETs, phases of MAC protocols along with the incorporation of map information and road graph overlays.

2.7 Cognitive Radio Technology

Wireless communication has experienced exponential growth in recent years, so the use of the available spectrum resources has grown rapidly as well. The radio spectrum is limited and government departments such as the Federal Communications Commission (FCC) in the United States have total control over it and have the right to allocate it. As per the current laws regarding spectrum allocation, the spectrum bands are to be used only by the users assigned by the FCC, and SU can not use any licensed band. According to the National Telecommunications and Information Administration (NTIA)'s chart of these frequency allocations shown in Fig D.1in Appendix D, we can conclude that we are on the verge of having no free spectrum left [72]. However, according to the Fig 2.8, only certain part of the spectrum is highly used while some parts are sitting idle and so allocation of the spectrum is only one of the problems. The FCC has mentioned that about 15% to 85% difference in the utilised band, assigned to specific users due to their different geographic locations. For example, according to the experiment done in spectrum measurement in the New York city, the 30Mhz to 3Ghs range is only 13.1% occupied [73]. Due to rapid increase in the users and different technology, the spectrum assignment policy is no longer viable though it has been efficient in the past. Moreover, according to this policy, although the allocated band is idle, SUs are still not allowed to use that band.

Above mentioned features of the spectrum policies have made it clear that large sections of the spectrum are heavily under utilised and a new concept is needed to develop to accommodate new technology and the huge number of users within the limited available resources. A new communication algorithm is necessary to be developed so we can utilise the limited spectrum with high accuracies [74]. To solve this problem of under utilisation, the concept needed to be developed which allows SUs to find spectrum holes in the PUs band and use it in a way which does not affect the performance of the PUs. FCC has issued a Notice of Proposed Rule Making (NPRM-FCC 03-322 [75]) in which they assigned CR concept can be used to solve the problem of spectrum scarcity. Meanwhile, the Institute of Electrical and Electronics Engineers (IEEE) has also developed the standards and concept which uses CR technology. The IEEE 802.22 is a developed standard which defines PHY and MAC layers of CR technology which will allow SUs to use the spectrum allocated to TV bands [76].

CR [77, 78, 79] techniques are proposed to be good candidates that provide a facility for the PUs and SUs to coexist in same spectrum when possible, in order to solve the

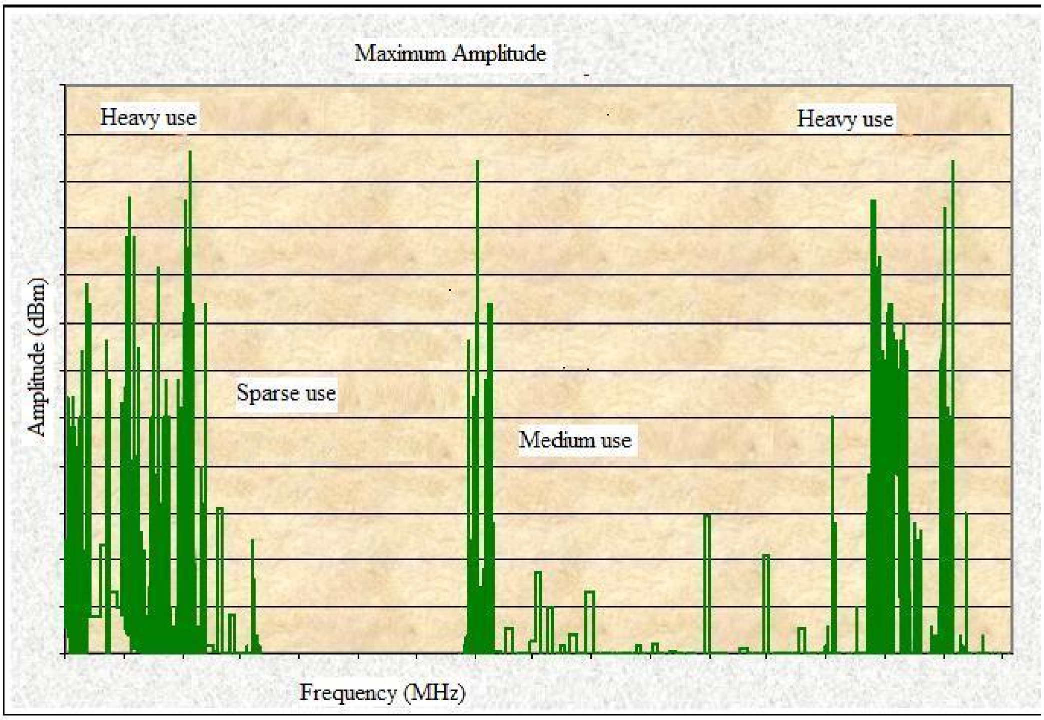

Figure 2.8: Spectrum allocation and spectrum usage and measurements from DARPA XG.

problem of spectrum scarcity. CR in terms of capabilities and functionalists are going to be described in more details in the following sections.

After defining the CR, we give here a brief picture on the basic tasks of CR. The CR, firstly coined by Joseph Mitola [77], which allow communication with the surrounding environment to gathered the required parameters which will help to use dynamic radio efficiently.. The cognitive cycle is defined as the process to use dynamic radio adaptively [77] and its shown in Fig 2.9. , The process of the cognitive cycles shown in Fig2.9, and described as follows:

- Spectrum sensing: A CR sense the frequency band , gather their required data, and finds the available spectrum known as spectrum hole.
- Spectrum analysis: The vacant spectrum is analyzed and their parameters are estimated.
- Spectrum decision: A CR decides the data speed, mode for transmission and required band. According to the data available, desirable spectrum is selected . Moreover, the spectrum characteristics and nodes' requirement is also considered in spectrum selection.

The first two tasks are carried out in the receiver of the cognitive system, and the last one is carried out in the transmitter as it can be seen in Fig 2.9. Through interaction with the radio frequency (RF) environment, the 3 processes of Cognitive cycle is described in

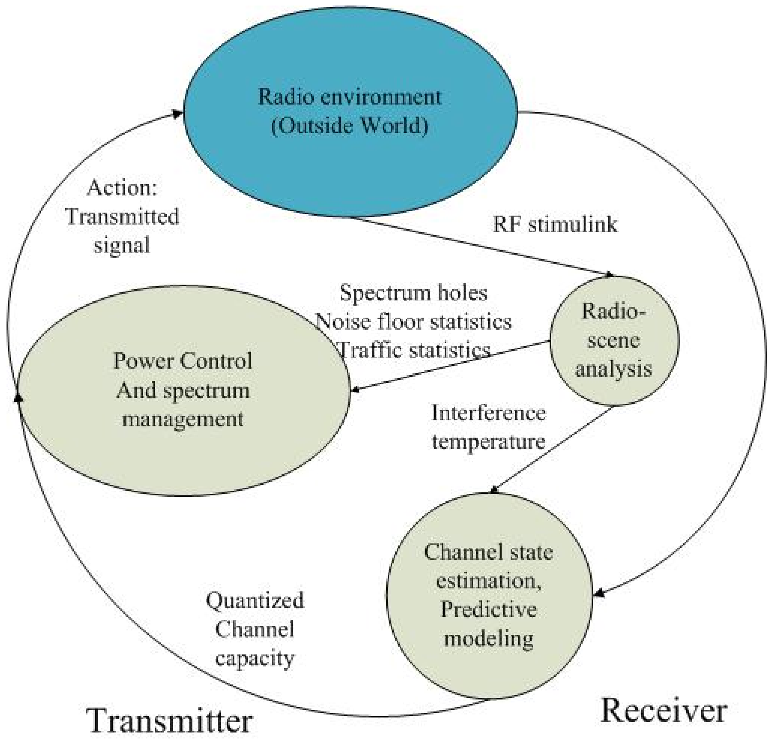

Figure 2.9: Basic cognitive cycle.

it's simple form in Fig 2.9. According to above mentioned concept, transmitter's cognitive module must work in accordance with the receiver's cognitive module. The feedback channel from receiver to transmitter is used to maintain this concept, which enables the receiver to send information to transmitter regarding the performance of the forward link between transmitter and receiver. It is apparent that CR is the feedback communication system.

2.8 Mobility Simulators

Mobility simulator classifications range from sub-microscopic to macroscopic depending on the level of detail of the simulation. This is reflected on the smallest entity considered by the simulator. Macroscopic simulators consider the whole traffic flow as the basic entity.

On the other hand, microscopic simulation considers the vehicle to be the smallest simulation unit. There are simulators which are in-between macroscopic and microscopic, referred as mesoscopic. The latter consider individual vehicles moving between queues, which are the main simulated entity.

There are also sub-microscopic simulators which consider not only each vehicle, but also the components of them, such as the engine or the gear-box, and their parameters. The different granularities are represented in Fig. 2.10.

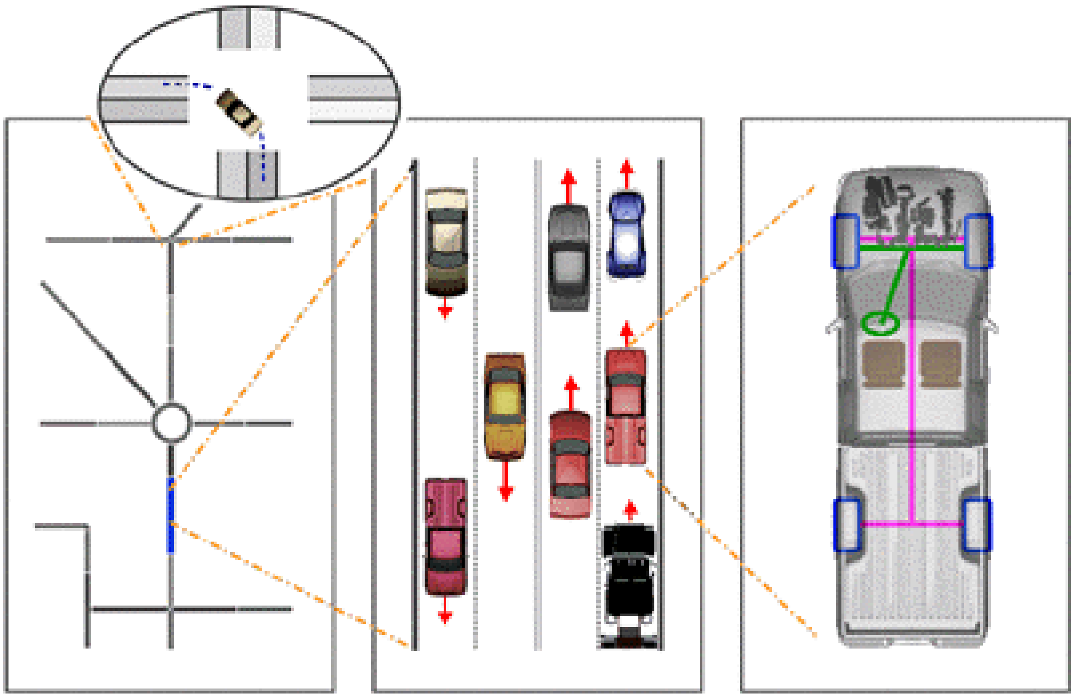

Figure 2.10: Mobility simulator categories. From left to right: macroscopic, microscopic, sub-microscopic (within the circle: mesoscopic).

For VANET simulations, where every individual vehicle will be considered a node and the simulation of the vehicle components and their status are not relevant, the most adequate approach to mobility simulation is microscopic. It provides enough resolution of the system as to provide realistic traces, but without the overhead of simulating sub-microscopic details which would not provide relevant information for this research.

2.8.1 CanuMobiSim

The Mobility Simulation Environment developed by the CANU (Communication in Ad-hoc Networks for Ubiquitous Computing) Research Group of the University of Stuttgart is a flexible framework for mobility modeling.

The framework is focused on user mobility models, as it integrates the spatial environment model, user trip sequences, and user movement dynamics. It includes parsers for geographic data in various formats, and in order to simulate movement dynamics, it provides implementations of several models from physics and vehicular dynamics. Additionally, the framework contains several random mobility models, like Brownian Motion or Random Way-point Movement.

It is available as a stand-alone java application, and consequently is possible to execute it in virtually any operating system.

2.8.1.1 VanetMobiSim

VanetMobiSim is a CanuMobiSim extension developed by Institute Eurecom and Politecnico di Torino which focuses on vehicular mobility with realistic automotive motion models at both macroscopic and microscopic levels. VanetMobiSim can import TIGER maps or randomly generate them using Voronoi tessellation. Also, it adds support for multi-lane roads, separate directional flows, differentiated speed constraints and traffic signs at intersections.

Mobility models which were not available in CamuMobiSim have been integrated, providing realistic car-to-car and car-to-infrastructure interaction. According to these models, vehicles regulate their speed depending on nearby cars, overtake each other and act according to the traffic condition.

2.8.2 BonnMotion

Developed by the University of Bonn, is a probably the most popular mobility scenario generator and analysis tool among MANET (Mobile Ad-hoc NETworks) researchers. It implements diverse mobility models which can be configured according to the scenario's needs. However, the only model directly related to VANET simulations is the Manhattan Grid. The scenarios can be exported for the network simulators ns-2, GloMoSim/QualNet, and MiXiM, network simulation software that will be introduced in the following section.

BonnMotion is well documented and its installation process proves to be simple. Being a java-based command-line software it is available for any operating system.

2.8.3 SUMO

Simulation of Urban Mobility [80, 81] is a microscopic open source traffic simulator based on the command-line which incorporates realistic traffic simulation algorithms, with the possibility to have different types of vehicles, different networks from the generated grid, spider-web or random artificial roads to be imported into VISUM, Tiger, OSM, etc. models|, and has a high speed performance. These features match the design criteria which considered that when the software was developed: "The software shall be fast and it shall be portable".

SUMO as the complete software package incorporates not only the mobility simulator SUMO, but also a bundle of applications to enhance the generation of networks as well as the import/export capabilities of the software. Another included application is GUISIM, which adds user graphic interface to the SUMO simulator.

It has installation packages available for Windows and Linux operating systems, but as it only uses standard C++ and portable libraries it is easy to compile and execute in any other operating system.

2.8.4 MOVE

MOVE [80] was originally developed by Feliz Kristianto Karnadi, Zhi Hai Mo and Kun-chan Lan. It provides a user interface for SUMO, but now it has evolved and it includes the interface for ns-2 and or QualNet.

2.8.5 Commercial Solutions

There are commercial solutions available for mobility simulation, the most relevant commercial software being Paramics, TSIS-CORSIM (Traffic Software Integrated System Corridor Simulation) and VisSim among others. However those have not been considered for this research as they are mainly oriented to very complex traffic simulation, and to traffic management. They provide results with a higher level of realism than that needed for this research, or in general any non-specific trace simulation.

2.9 Network Simulators

Some of the featured simulators offer not only network simulation capabilities, but network simulations from a more generic point of view. This potentially allows researchers to study the relation between nodes regardless of the nature of this nodes, as long as they are able to develop the modules representing the interaction of that node with its surrounding environment.

However, this feature is not relevant for this research and therefore will not be considered in our evaluations. Nevertheless it could be a determining factor for researchers who require to perform network simulations of different natures for their research, as this solutions would require the training for only one simulation environment.

2.9.1 Ns-2

NS-2 in its different versions is one of the most popular simulation environments for research. It has a hybrid approach to programming simulations with both C++ and an object-oriented version of Tcl scripting called OTcl. This duality can lead to confusion when not familiar with the system, but it proves to be very convenient once the user becomes acquainted with it. The modules are developed using C++, in order to provide higher simulation speeds by the use of compiled code.

C++ modules are configured and executed via OTcl scripts, which provide the description of the simulation environment and the configuration parameters for each module involved. This OTcl scripts are not compiled but interpreted by the ns-2 software. This makes the set-up of simulations very easy and convenient to batch, as there is no compilation needed to run the scripts, and these contain all the required configuration parameters for the C++ modules.

This duality becomes critical when it comes to develop or modify modules. The modules have two parts: one programmed using C++ and other OTcl. This is required to provide the usability features previously mentioned.

There is an All-in-One package available for most of the releases. These versions include the network simulator, network animator (NAM) and XGraph in the latest version available at the moment of the creation of the package. The installation is not quite straightforward if you are not using one of the systems supported out-of-the-box for that version, but is easy to find community-developed scripts to compile and install the software properly. The installation of extra modules may require additions and modifications in the configuration files in order to work, being usually simple and well documented.

There is an extensive documentation for the network simulator [82] and its modules, in addition to *.tcl example files provided in the distribution in order to both validate the installation of the simulator and learn how to script for the different areas of application of the simulator.

The disadvantage of ns-2 is mainly the limited scalability in terms of number of nodes being simulated, which is not a fixed limit, but depends on the simulation parameters. This fact is related with the lack of memory management of ns-2: it may require multiple times the amount of memory than some of its alternatives for similar simulations [83]. This is in part a consequence of the use of interpreted software (OTcl), which in 1989 when the ns project was born was a very convenient method to improve the simulation work flow. However, at present, when the compilation process is not time-consuming, it is considered an unnecessary legacy burden to carry when conducting large-scale simulations.

Another important disadvantage has already been introduced when we stated that ns-2 is in its different versions is the most widely used software: not all modules are updated and may not be valid for all the versions. There have been different points in the development where a number of modules stopped performing properly, so there are a considerable number of research projects utilising older versions as those are able to execute the modules required by the developers. Outdated versions lack general improvements and patches on different parts of the software [84] which may in influence the simulation results and their validity.

There is an extensive array of modules already implemented in the main distribution of the simulator which will be needed for our research. However there are protocols we require which are not yet implemented in the ns-2 system. There is a substantial number of contributed modules [85] for ns-2, among which we have selected three candidates to implement the WAVE/IEEE 802.11p protocol stack, these are described below.

2.9.1.1 Tongji University WAVE package

The WAVE package was developed by the Broadband Wireless Communication and Multimedia Laboratory (BWM Lab) of the Tongji University; it is based on the IEEE 802.11e EDCA and CFB Simulation Model for ns-2 by TKN research group of TU Berlin. The 802.11p QoS has been implemented using the 802.11e model and a supplementary QoS priority queue. The MAC layer has been almost completely implemented, but it is still a work in progress and at the moment the module lacks the implementation of handover procedures.

The module is only available for the ns-2.31 version of the software due to the dependency on the IEEE 802.11e module, which has not been updated to new versions of the ns-2 simulator.

2.9.1.2 Module 802.11p from the Sherbrooke University

This package [86, 31], which has been developed by the Sherbrooke University, is publicly available [87, 88] and offers the researchers the chance to simulate IEEE 802.11p without having to develop their own implementation. It has been developed for ns-2.31, but is easily adapted to be used at the 2.34 version of the software.

The version presented in the different papers published by the research team is based on a version of the module which does implement the different types of node, namely Base Station and Subscriber Station. However, the publicly available version of the module at the time of the research did not incorporate the different operation modes, critical for the handover research.

2.9.1.3 WAVEns-2 SourceForge Project

The WAVEns-2 project [89] is based on the ns-2.34 software and implements not only the 802.11p package from Sherbrooke University combined with 802.11e for QoS, but also includes the implementation of the IEEE P1609.x protocols by A. Cruz, from the Glasgow Caledonian University.

This is a work in progress which is actually focused on higher layers of the OSI model

(IEEE P1609.x), and only incorporates levels 1 and 2 by means of the Sherbrooke University package. This implies that the protocol P1609.4 has not yet been developed, and for physical and medium access control it has the same features of the Sherbrooke University module.

The installation and updating is very convenient (see Appendix E) and includes the 802.11p Sherbrooke University package adapted to ns-2.34. This is, at the moment of the research, the best candidate to implement the protocol P1609.4 for ns-2.

2.9.2 Ns-3

Even though ns-3 has been under active development since 2006, ns-2 has not stopped its development and presence in the research community. ns-3 is actually intended as an eventual replacement of ns-2. However, it is not an evolution of ns-2: it is a new simulator. There are a series of problems on ns-2 that ns-3 focused on solving, specifically:

- Interoperability and coupling between models;
- Lack of memory; and
- Management debugging of split language objects.

As ns-3 was intended by the developers to become such a breakthrough or revolutionary product by solving these problems, it required a completely different architecture than ns-2, so it lacks backwards-compatibility with it. There are plenty of community-developed modules which have not yet been developed for ns-3, and there are high likelihood that some will not be ported. This is the reason why ns-2 is still one of the reference simulators, and ns-3 is not yet very popular among researchers.

The main difference for researchers who do not require developing their own modules is the setup procedure: previously it was an OTcl script in ns-2 while ns-3 uses C++ with optional python bindings. The fact that python binding usage is not available for all the possible ns-3 installations is also to be considered. For the reasons here stated is clear that switching to ns-3 is a process of re-engineering the simulation scenarios rather than porting Tcl code to C++.

For developers the difference between using ns-2 or ns-2 is more drastic, not only because the APIs are not compatible, preventing from a direct implementation, but also as one of the aims of ns-3 is to improve the interoperability between modules. This is a feature that ns-2 lacks, where the interoperability requires the manual configuration and adoption of the different files by the user. This is the reason why the development has to follow a series of conventions and is encouraged to do it as part of the established development community via an available repository called Mercury. This ensures the interoperability and the validation of the different modules by as many developers as possible. Furthermore, some of this modules will possibly implemented in following All-in-One distributions.

According to the developers it is still a work in progress, but they consider it able to provide valid simulation results, and its use for research is encouraged. ns-3 has an extensive array of documentation for both users and developers [90, 91, 92].

2.10 Integrated Mobility and Network Simulators

Integrated simulators have the advantage of being able to modify the traffic parameters depending on the information traffic among the vehicles and vice versa. This can provide a higher level of realism for VANET simulations which focus on response to accidents or collisions and the improvements for those situations.

2.10.1 GloMoSim

GloMoSim (Global Mobile Information Systems Simulation Library) is a scalable simulation environment for wireless and wired network systems. It employs the parallel discrete-event simulation capability provided by PARSEC. GloMoSim currently supports protocols for purely wireless networks.

It had been widely used for network simulation but it now lacks the latest protocols (including IEEE 802.11p) as the last major version, GloMoSim 2.0, was released in December 2000. After that PARSEC stopped working on freeware software and the developers released a commercial version of GloMoSim: QualNet. However, it is still possible to download GloMoSim's source and binary code for academic research.

2.10.2 Estinet (NCTUns)

The approach to the simulation of the NCTUns (National Chiao Tung University Network Simulator) [93] is its main distinguishing feature: it is embedded on the kernel of the operating system in order to be able to simulate and emulate networks via the direct interaction with the system network protocol stack or use any application available to generate traffic. For that reason the only operating system supported by the developers for the latest NCTUns 7.0 is Red Hat's Fedora 14.

The installation in the supported system is well documented and straightforward even when performed over a virtual machine, a the method used to test this system for this research. Other Linux distributions such as Ubuntu may work with NCTUns as they use the same Linux kernel as Fedora. However, this other systems are not supported and the proper configuration must be checked using the validation tests provided.

The main drawback of this solution is the lack of flexibility in terms of module configuration and its very slow work flow. Estinet is completely based on a graphical interface, preventing the fast and convenient modification of parameters to run statistically independent simulations or changing configurations from one iteration to the next, in order to sweep the different simulation variables.

On the other hand, the graphical user interface [93] together with the demo videos [94] prove to be a very convenient way to allow the configuration of simulations with an almost non-existent learning curve.

2.10.3 OMNet++

OMNeT++ is an object-oriented discrete event network simulator. It can be further extended by means of modules, which may be nested unlimited times. Its framework offers the possibility to have its features and simulation capabilities expanded as long as it is possible to create the C++ code that implements the modules. This flexibility implies that OMNeT++ is not limited to network simulators, but any other kind of modeling that can be implemented using C++.

OMNeT++ is based on C++ modules, which are distributed and connected using NED topology description language. It can be executed via an IDE based on Eclipse platform, which is convenient for set-up and for running small simulations and also can be used via command-line, providing a fast and convenient simulation method for complex or batched simulations.

Some of the features of OMNeT++ are:

- hierarchically nested modules;
- topology description language;
- modules communicate with messages through channels; and
- flexible module parameters.

The installation is available for the main operating systems and it proves to be straightforward and hassle-free.

A critical disadvantage is the lack of mobility management as an integrated part of the simulator, requiring the installation of frameworks in order to provide that key functionality in VANET simulations. There is mainly one contributed framework available for

OMNeT++ which focuses in VANET networks, this is the MiXiM module, described in the next section.

2.10.3.1 MiXiM module

MiXiM (mixed simulator) [95] is a modeling framework for mobile and fixed wireless networks. It offers detailed physical and MAC layer models, such as radio wave propagation, interference estimation, radio transceiver power consumption and wireless MAC protocols, with IEEE 802.11p among others. However, it mainly focuses on the implementation of existing wireless network interface cards (NICs), a fact which constrains the researcher's configuration options in order to optimise the protocol using any available strategy.

2.10.3.2 INET Framework

The INET Framework [96] is an open-source communication networks simulation package for OMNeT++. The INET Framework contains modules for several wired and wireless networking protocols, including IEEE 802.11p. However, it focuses on the modeling of higher levels of the protocol architecture.

2.10.3.3 Mixnet: MiXiM + INET

MiXiM provides very detailed models of wireless NICs, but on the other hand it does not implement very sophisticated upper layers. As these are the layers for which the INET framework provides a lot of very detailed modules, Mixnet [97] combines these modules complementing their strengths.

2.10.4 Commercial Solutions

Most of the commercial software available for network simulation consider the simulators from an industrial research point of view, hence focused on issues such as support for certain devices, quality of human support, etc., which are less relevant for academic researchers. At the same time, these solutions usually lack the configuration possibilities in terms of protocol features, a key aspect for research. However, commercial solutions deserve to be mentioned, but will not be tested and therefore not evaluated as candidates for this research. Some of the most well-known network simulation frameworks are: MapleSim, simulator from the developers of the well-known Maple Mathematics software; NetSim; OMNEST, the commercially supported version of OMNeT++, required for commercial purposes; OPNET and QualNet, the commercial version of the previously mentioned GloMoSim.

2.11 Federated solutions

This solutions uses software integrating one of each kind of the aforementioned specialised simulators. This solutions implements the required features by means of at least two simulators which have compatible or translatable output/input files. In the VANET world any simulation would require the use of two specialised simulators: one for mobility and another for networking. Additionally this software may require the use of translation scripts for the mobility traces to be used as input for the network simulator.

2.11.1 SUMO/ns-2

This combination provides a common framework for research. As part of the SUMO project there is a trace translator tool called TraceExporter which provides researchers with the interface to combine the two systems. TraceExporter is easy to use but while testing a coding mistake was found which produced negative coordinates, probably produced because road width was not properly taken into account. This prevented ns-2 from using the translated traces. It was easily solved by means of adding an offset for all the coordinates into the translation code.

Rapid Generation of Realistic Simulation for VANET: This software [80] offers the users of SUMO and ns-2 or QualNet in a very easy to use java graphic interface. It is an evolution of the MOVE project which now includes interoperability with the network simulator. The mobility generation in this software is still referred to as MOVE. This software is still limited by the previously mentioned features of the simulation software it is based on, and furthermore, it does not allow all the potential of either of the software involved to be reached through its configuration wizards, specially in the network simulation aspect. It lacks the flexibility required to make complex simulations, but it may be convenient for scenario generation when the user is not yet confident with command-line configuration.

TraNS: TraNS (Traffic and Network Simulation Environment) is also a java GUI for SUMO and ns-2 interaction using the TraCI output interface provided by the developers of SUMO.

2.11.2 SUMO/Qualnet

Even if this combination will not be considered being a QualNet commercial solution, is to be noted as it is also implemented in the Rapid Generation of Realistic Simulation for

VANET software, with the same features as for the SUMO/ns-2 tandem.

2.12 MAC protocol for VANET

This section presents the comparison of different MAC protocol discussed above. Moreover, it summarise the requirements of MAC protocol to be considered as a complete solution for VANET. Finally, the research challenges are described.

2.12.1 Summary of existing MAC protocol

MAC protocols are designed to achieve better medium access and overcome some obstacles in the system, such as the issues discussed in Section 2.3 for vehicular networks. To compare MAC protocols, certain criteria must be considered. Here, the protocols are compared qualitatively. The issues each protocol solved are emphasised, and the limitations are pointed out. Since vehicular networks have their special characteristics, until now, there is still no comprehensive solution that is suitable for all situations, scenarios, and QoS requirements. The IEEE 802.11p standard at the MAC is one of the most promising protocols due the popularity of the 802.11 protocol. The 802.11p aims at providing a multichannel operation over DSRC with QoS support.

Since the 802.11p is amended from the original 802.11, it is obvious that it inherits its limitations. The 802.11p and 802.11p-based protocols perform better in a low node density, and tend to provide unstable results in a highly loaded situation. The hidden node problem is addressed by the carrier sensing mechanism. However, throughput and PDR are highly affected by a high node density. A logical explanation of what happens in a highly traffic loaded scenario with an 802.11-based MAC protocol is that as the channel busy time becomes larger, nodes have to wait longer time before retransmission. Moreover, when a node retransmits during the busy time, the contention window size increases due to the back-off mechanism. Therefore, the number of nodes in the network is a significant factor that affects MAC performance. Prioritizing messages is shown to cause decrement of throughput when the number of high priority packets increases. The frequent link disconnections can be dealt with by evaluating network state, which is not included in the IEEE 802.11p standard. To achieve better evaluation of the network state, node speed can be used to predict the duration of transmission, and help to adapt the medium access protocol.

ADHOC MAC reduces collisions, handles hidden and exposed node problems, and provides a reliable single-hop broadcast service. It also reserves additional bandwidth and QoS for real-time traffic. However, the performance of ADHOC MAC degrades with high mobility and node density. Moreover, the number of vehicles in the same communication range is restricted by the number of slots in the time frame. ADHOC MAC is considered independent from the physical layer and can work with the 802.11 physical layer.

Transmitting at a specific direction is done by directional antennas-based MAC. This type of MAC is used to increase transmission range and channel re-usability. In vehicular networks, directional MAC does not provide a feasible solution due to the complexity of implementation.

Clustering is used to handle mobility and frequent network topology changes. However, clustering is considered for average speed and similar direction mobility. Moreover, clustering provides better scalability, reduces interference between nodes in each cluster, limits the area for message dissemination, and achieves fair access to the medium. The problem with clustering is in deciding which node should be elected to be the clusterhead, and how to handle interference between nodes in clusters (intra-cluster interference) and among the clusters (inter-cluster interference).

The repetition based MAC protocols aim at a high probability of reception with low delay. A MAC extension layer is required to perform that. However, the number of repetitions and the generation process should be optimised. The SDMA and token ring based MAC protocols are based on grouping the nodes. While the SDMA aims at reducing access collisions and increasing channel re-usability, it is only theoretically studied, and no feasible implementation exists. Similarly, token ring protocols reduce the number of possible collisions, and deliver safety messages with a high probability and low delay. The advantage of token ring MAC protocols is that they can be implemented without high hardware complexity, but there are no practical implementations for VANETs.

2.12.2 Research challenges for VANET

The use of a multichannel solution addresses this issue and efficiently utilises the bandwidth and meets the QoS requirements compared to other mentioned MAC protocols, and can be considered a total solution, but with a non-avoidable complexity. The existing multichannel P1609.4 MAC protocols try to achieve the goal, but it fails to meet the requirements of the VANET and posses a greater challenge that is explained below. To transmit the larger data, the users required to go through more handshaking process in CCH interval until the completion of data transmission. All the nodes have to tune into CCH during CCH interval for resource management and contention and then they tune into agreed service channels in next interval to transmit the data. From the above explanation, it is apparent that CCH is not utilised in SCH interval and vice versa. In addition, large volumes of data can not be continuously transmitted as every node has to terminate their transmission during CCH interval. As shown in Fig 2.7 OBU has to terminate during CCH interval to contend for the channel to use it in SCH interval. As described in IEEE 1609.4, the nodes in VANET have to switch to CCH every 50ms to listen to safety messages and for network management processes (e.g., channel contention and negotiation and WBBS formation). Therefore, SCH is not utilised during CCH interval, which is 50% of every sync interval.The IEEE 1609.4 standard currently use the Enhanced Distributed Channel Access (EDCA) parameters defined in the IEEE 802.11 standard, which does not implement absolute priority system but only apply service differentiation within the different priority messages [98]. The EDCA mechanism is not suited for VANET because a low priority traffic may win the channel before higher priority traffic and may collide with a higher priority traffic, which makes the system unreliable. Moreover, all the safety messages are broadcasted in CCH without acknowledgment in the IEEE 1609.4 standard, thus the binary-exponential back-off technique can not be applied. The acknowledgments for safety messages are vital to employ binary-exponential back-off technique, so the lost data packets can be retransmitted to ensure the reliability of the system. It is very vital to simulate VANETs with close to real scenario. To achieve the goal, all different network, mobility and cognitive radio simulators are studied, and compared.

- This offers a research challenge in terms of how to increase the channel utilization, so that the available spectrum is fully used and reliability of the network for the safety related application can be preserved and improved. Moreover, selection of simulators and development of the IEEE 1609.4 model to mock the real scenario is another vital research challenge.

2.13 Summary of the Chapter

In this chapter, a literature review for MAC protocols in vehicular networks supported with related background, mobility model and CR was presented. First, the special characteristics of VANETs and their relation with medium access were discussed. Issues that should be addressed by VANET MAC were presented. After that, an overview of the existing MAC solutions for a vehicular environment were briefly introduced to provide a broad view of the existing solutions from the IEEE 802.11p standard, through virtual grouping mechanisms, multichannel utilization, and other enhancement techniques, and then, a qualitative comparison of the existing protocols was provided. Moreover, the brief overview of mobility models and CR technology was discussed. Finally, features of several mobility and network simulator were discussed, and a comprehensive comparison of them presented.

Chapter 3

PROPOSED MULTICHANNEL MAC PROTOCOL TO IMPROVE CHANNEL UTILISATION

In this chapter, We present our proposed Cognitive Multichannel MAC (MCM) in detail. We first outline the motivation behind our work and then We go through the system architecture and its operation.

3.1 Motivation

After examining the different related work, I find the following issues that should be considered in the efficient design of a MAC protocol for vehicular communications.

- The MAC protocol designed should be able to prioritise safety messages on behalf of non-safe messages. Moreover, not only should it prioritise safe messaging but also ensure their reliable transmission in case of facing contention on the medium. A dynamic solution should be available in case the medium is congested. Otherwise life-critical messages will miss their target;

- As vehicular networks are of ad-hoc nature then each vehicle should have enough knowledge and intelligence of its surroundings. The MAC protocol employed should be fault tolerant with respect to any topology changes. Any topological change should be accounted for directly. For example, if a vehicle is relying on an intermediate node to deliver a packet to the final destination and this node moves out of the network then it should be able to get notified directly and;

- As vehicular networks struggle from congestion in urban environments, it would result in an unstable, time-varying wireless channel. The MAC protocol designed should be able to assess the channel prior to transmission. Channel assessment for interference (Adjacent and Co-Channel Interference) would alleviate Layer 2 packet retransmissions in high multipath environments with dynamic delay spreads.

Those needs urged us to design a cognitive Multichannel MAC for VANETs able to address those issues as well as to achieve better MAC performance with respect to existing VANET MAC protocols.

3.2 Cognitive Radio Approach

There is a common belief that we are running out of usable radio frequencies because of the different wireless technologies being used nowadays. However actual spectrum usage measurements obtained by the FCC's Spectrum Policy Task Force shows that any given time and location, much of the prized spectrum lies idle [99]. So there exists a need to efficiently manage the frequency spectrum as it is a limited resource that is not scaling with the increasing demands of wireless technologies. In general, we have two types of spectrum access: dynamic spectrum access and static spectrum access [99].

- Static Spectrum Access (SSA) has been used for long time in most wireless technologies. In static spectrum access transmissions based on applications are assigned static frequencies and;

- Dynamic Spectrum Access (DSA) is a recent access technique where frequency selection is done on the fly due to different parameters. Advancements in antenna technologies had made this spectrum access feasible by introducing Cognitive Radios.

Cognitive radio, built on a software radio platform, is a context-aware intelligent radio potentially capable of autonomous reconfiguration by learning from and adapting to the communication environment [100]. While dynamic spectrum access is certainly an important application of cognitive radio, cognitive radio represents a much broader paradigm where many aspects of communication systems can be improved via cognition. Deploying cognitive radio in vehicular networks allows different channel selection dynamically while vehicles displace between different vehicular scenarios [100].

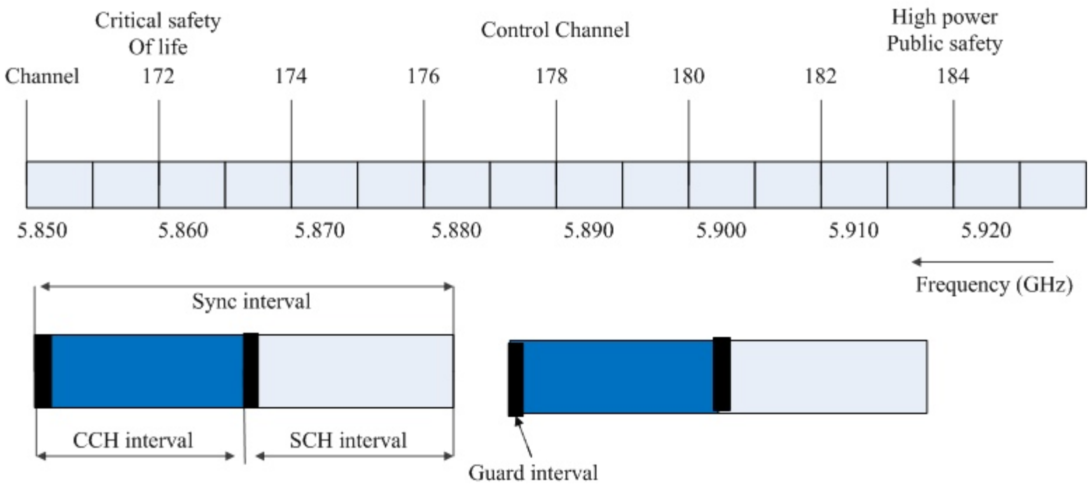

Figure 3.1: DSRC spectrum band.

3.3 Multichannel Operation in the IEEE 1609.4 MAC protocol

The main purpose of the proposed multichannel cognitive MAC (MCM) protocol is to improve channel utilization and transmission reliability of safety related data. To achieve the goal, the cognitive radio concept has been adopted within the MCM protocol. According to the concept of the cognitive radio, primary providers (PPs) are mapped as nodes with safety related data (e.g., emergency vehicles such as police cars, ambulance, fire trucks) and secondary providers (SPs) and secondary users (SUs) are mapped as commercial and general automobiles, where as primary users(PUs) can be any node in the system. In the following section, we will explain the operation of IEEE 1609.4 MAC protocol and its drawbacks. Moreover, the operation of the proposed MCM protocol is explained in section 3.3. Finally we will summarise the chapter.

As mention earlier, CCH and SCH intervals are 50 ms each which forms one sync interval, so there are 10 sync interval per second. This is motivated by a desire to map the sync intervals to the generally assumed 10Hz vehicle safety messaging rate [11]. There is a guard interval of 4ms at the start of the CCH and SCH intervals as shown in Fig 3.1, which takes care of radio switching and timing inaccuracies among the different nodes. During a CCH interval a provider intending to transmit some data, broadcast the wave service advertisement (WSA) frame. The WSA frame consists of the identification number of the WBSS, the SCH, that it intends to switch to and the MAC address of the user. A user who wants to join WBSS, acknowledges to the provider by a WSAR (WSA Response) frame. Once the WSA/WSAR handshake is finished both the provider and users will select the agreed SCH for data transmission, during the next SCH interval.

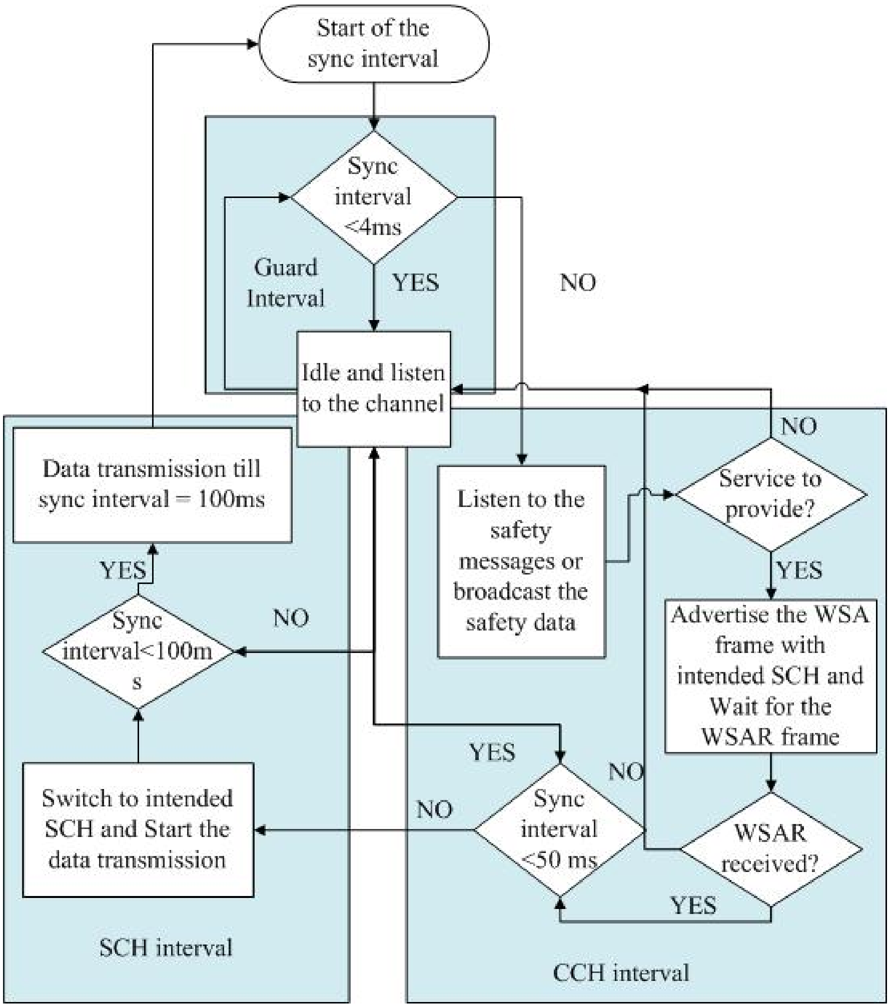

Figure 3.2: System flow diagram of the IEEE 1609.4 MAC protocol.

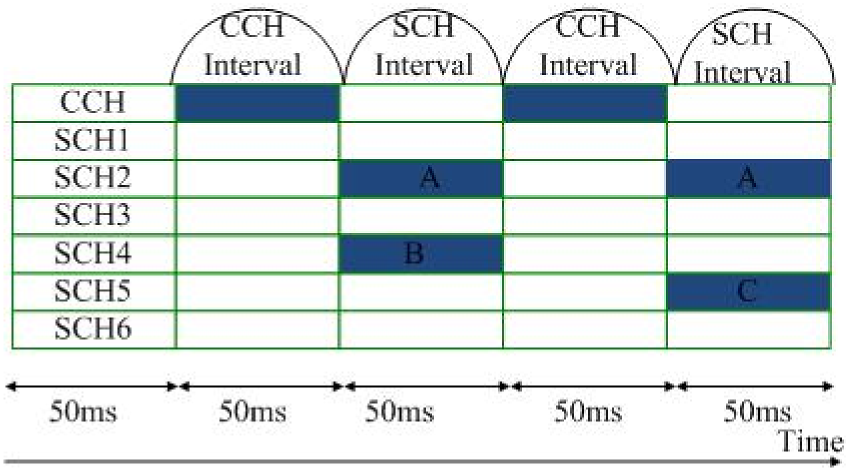

Figure 3.3: WBBS formation.

There can be multiple providers trying to compete for the any of the six SCH's access. To avoid collision between WSA frames on CCH during the CCH interval, a random back-off scheme is being used. Moreover, when any provider listens to the successful WSA/WSAR handshake within the same CCH interval and also intends to broadcast WSA frames adjusts it's SCH in order to avoid collision. If the successful WSA/WSAR handshake is conducted, the provider chooses a different SCH during the SCH interval. Furthermore, if the provider fails to conduct the WSA/WSAR handshake within the CCH interval then it has to wait until the next sync interval and then that provider will make another WSA announcement with larger contention window size. After the above mentioned contention and negotiation process, the nodes will switch to their corresponding SCHs in the SCH interval for data transmission. In addition, a large amount of data required several sync intervals to complete the transmission.

The explained mechanism fails to meet the requirements of the VANET and posses a greater challenge that is explained below. In order to transmit the data in more then one sync interval, the provider has to go through the WSA/WSAR handshaking process in every CCH interval until the transmission is finished. Fig 3.3 shows how three WBSS A, B and C are initiated by their corresponding provider and are established to conduct the data transmission. All the nodes have to tune into CCH during the CCH interval for resource management and contention and then they tune into the corresponding SCH during the SCH interval for data transmission. From the above explanation, we can observe that the standard mechanism causes three major problems as shown in Fig 3.3, and that leads to under utilization of available resources: i) all CCH intervals in the SCH are not utilised by any nodes. ii) all SCHs are not utilised during CCH interval which is 50% of every sync interval. iii) large data can not be continuously transmitted as every node has to terminate their transmission during the CCH interval. As shown in Fig 3.3 WBSS A has to terminate during the next CCH interval to contend for the channel to use it in the SCH interval.

3.4 Operation of MCM protocol

The main purpose of the proposed multichannel cognitive MAC (MCM) protocol is to improve channel utilization and transmission reliability of safety related data. To achieve the goal, the cognitive radio concept has been adopted in the MCM protocol. According to the concept of the cognitive radio, primary providers (PPs) are mapped as nodes with safety related data (e.g., emergency vehicles such as police cars, ambulance, fire trucks) and secondary providers (SPs) and secondary users (SUs) are mapped as commercial and

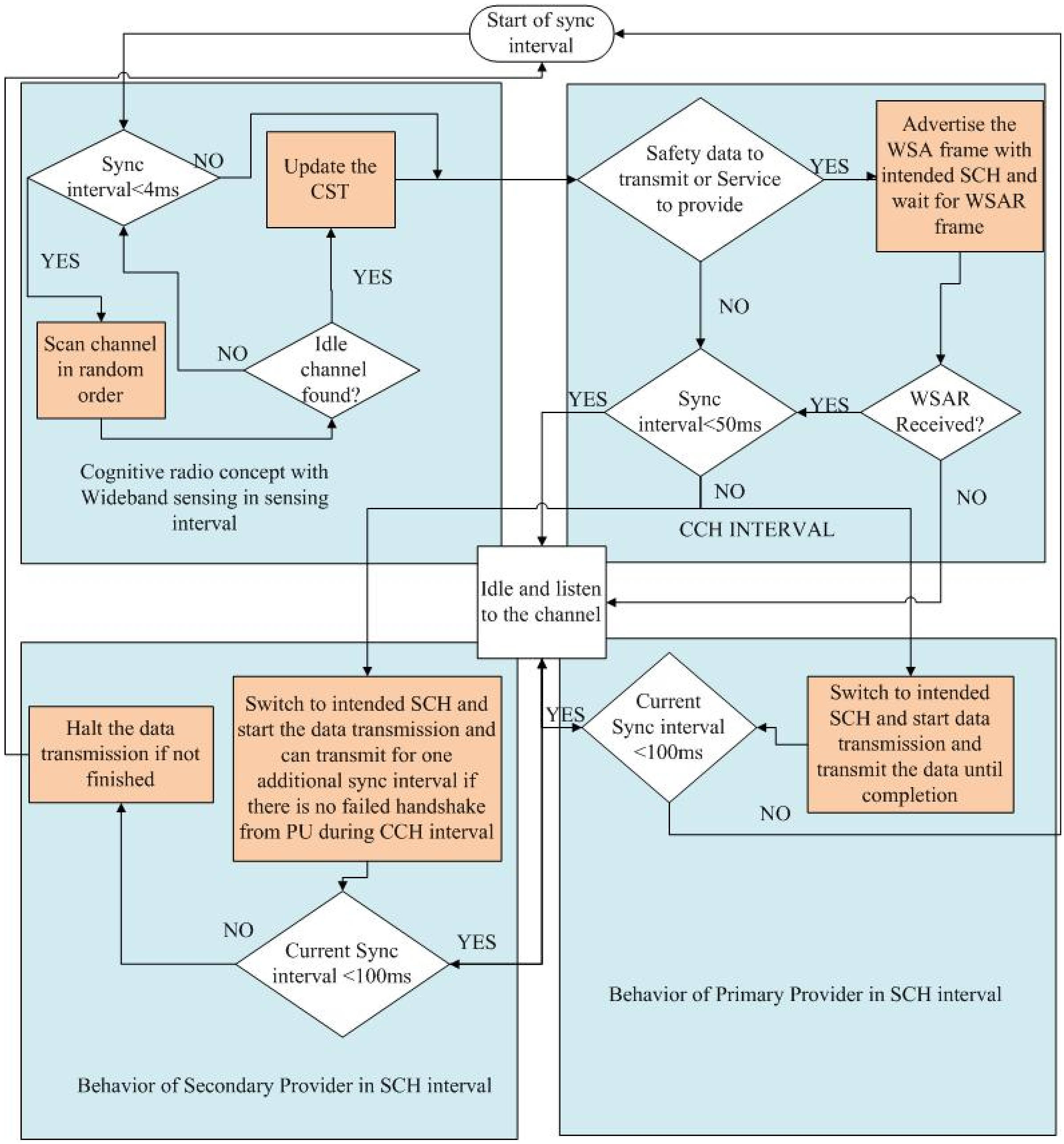

Figure 3.4: System flow diagram of the proposed MCM protocol

general automobiles, where as primary users (PUs) can be any node in the system.The system flow diagram for the IEEE 1609.4 and the MCM protocol is presented in Fig3.2 and Fig 3.4, respectively.

In the MCM protocol, all the nodes are required to perform wide-band spectrum sensing [101] to utilise the cognitive radio concept which is presented in the flow chart as summarised in Fig 3.4. As shown in Fig. 3.4 the operation is divided in four section.

3.4.1 Sensing Interval

Each node senses the spectrum across all six SCHs using its radio trans-receivers and update the spectrum condition at the beginning of each CCH interval. Once all the nodes

Frequency Channel	Access Category Priority Level	Countdown Duration Of Transmission	Reservation Field

Figure 3.5: Channel State Table.

go through the sensing phase, they establish their own Channel Status Tables (CST) which have the channel information for all six SCHs.

3.4.1.1 Channel state table (CST)

As shown in Fig. 3.5, CST stores the ongoing neighboring communications between neighboring vehicles in every vehicle in its database. Neighboring vehicles continuously update their channel transmission by sending control frames on the dedicated control channel. CST stores the following information for every ongoing transmission:

- Frequency Channel: The frequency channel being used by the corresponding communication link.
- AC Priority Level: The Access Category of the data being sent on that channel highlighting the QoS.
- The interference information: This is associated with each node over each channel. Several kinds of interference information are needed: Channel that has minimum interference,Current interference value over a specific channel and historical interference information.
- The traffic information: Current and historical traffic information

3.4.2 Design overview of CR MAC/PHY

The proposed MCM protocol has the following functionalities to support cognitive radio technology. The detail information and simulation codes is provided in Appendix A.

- CR single-radio multi-channel simulation environment ;
- Interface for channel decision ;
- Interface for transmission power decision ;
- Interference information ;
- Traffic information ; and
- Channel utilisation information.

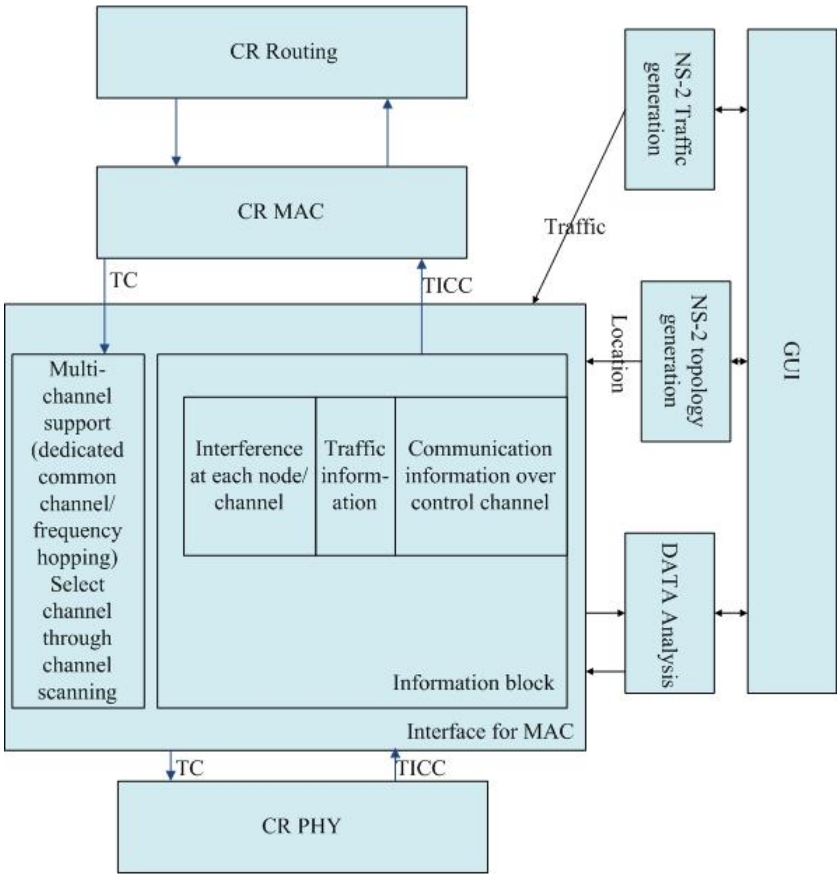

Figure 3.6: High level design of CR MAC/PHY.

The high level design for MAC is shown in fig 3.6. To provide the MAC and PHY algorithm a multi-channel environment, multi-channel is needed at each radio. The design includes single radio multi-channel , which is visible to both the MAC and PHY layers. In this design, multiple channel objects are created through the TCL library. Nodes can be switched to different channel objects during the simulation process.

3.4.2.1 Single radio multi-channel MAC design

Figure 3.6 shows the high level software design for single radio multi-channel support for the MAC and PHY layer. The components with the blue colour are modified in proposed MCM protocol to support the functionality mentioned above. Starting from the DSA, the interface parameters are as follows.

- TC (Transmission power and Channel selection)

After CR MAC makes the decision, which includes the transmission power and Channel selection, the simulator will send down the information through the multi-channel support functional block provided by proposed design. Before the multi-channel support functional block is introduced, the MAC layer is only aware of a single channel.

- TICC(Traffic information, Interference information over specific Channel, Communication information over common control channel)

The physical layer will provide the traffic information, interference information and communication information to the upper layer through the Information Block shown in fig 3.6.

3.4.2.2 Interface for channel decision

The channel decision from CR MAC has been set through the interfaces provided as follow, which reflects the channel that the receiver is using to receive packet. A new field channelindex_ is added into the packet header. After CR MAC makes channel decision, this decision can be stored into this field. In our design, multiple channel object pointer is used to index the channel object. Hence, it is appropriate to use channel index derived in CR MAC to differentiate channel, which helps to achieve conflict free or reduce interference among neighboring nodes. channelindex_ defined in the packet header can carry this information from CR MAC to the wireless physical layer.

3.4.2.3 Interface for transmission power decision

A packet will be transmitted using the default transmission power if the transmission power is not specified in simulation script. However, as the CR MAC may control the txpower over each channel to control the interference to primary users or nearing neighbors, it is necessary to provide an interface, which can control the txpower during the simulation.

To determine the txpower, the CR MAC algorithms need to know the identity of sender and receiver. As the sender and receiver has negotiated the channel decision, and thus the power control algorithm compute the txpower over the negotiated channel.

3.4.2.4 Interference information

The interference information is associated with each node over each channel. Several kinds of interference information are needed:

- Channel that has minimum interference;
- Current interference value over a specific channel;
- Historical interference information.

Besides obtaining the channel with minimum interference, the interference information over each channel around can be obtained through the ITfile generated by the simulator. The format of the ITfile is as follow. We can obtain their information through ITfile according to the format shown in fig 3.7.

ITfile format			
Timestamp	Nodeid	Interference	Channel id

Figure 3.7: ITfile format

3.4.2.5 Traffic information

For our CRMAC, it is necessary to use the sensing traffic information to predict the future traffic information in the neighborhood, and derive the best user strategy. The interface are in the two formats:

- Obtaining the current traffic information
- Obtaining the historical traffic information.

The historical traffic information is stored in the Trafficfile. We can obtain this information based on the format shown in fig 3.8.

Trafficfile format		
Timestamp	Nodeid	Traffic information

Figure 3.8: Traffic file format.

3.4.2.6 Channel utilisation information

- Current channel utilization information
- Historical channel utilization information.

The historical channel utilization information is stored in Chanfile. We can obtain this information based on the format shown in fig 3.9.

Channelfile format		
Timestamp	Nodeid	Channel utilisation

Figure 3.9: Channel file format.

Table 3.1: Channel Assessment Properties

RSSI	Rx Sensitivity	Threshold(%)	Signal Strength	SNR Signal Quality(%)
30	-30 dBm	100	70 dB	100
25	-41 dBm	90	60 dB	100
20	-52 dBm	80	43 dB	90
21	-52 dBm	80	40 dB	80
15	-63 dBm	60	33 dB	50
10	-75 dBm	40	25 dB	35
5	-89 dBm	10	10 dB	5
0	-110 dBm	0	0 dB	0

3.4.2.7 Dynamic spectrum access

The Dynamic Channel Allocation Algorithm selects the best available channel with low interference and noise levels. If the Cognitive Radio Assessment reveals an available DSRC channel with optimum conditions then it is directly selected for the incoming transmission. However, if all available DSRC channels are being used by neighboring vehicles then an assessment for the level of noise and interference on each channel is made. If at least one channel is above the threshold then this channel is selected and checked by comparing it with the CST. This channel is then reserved by the vehicle for the upcoming transmission.In our simulations, we set the threshold s to 0.5 considering 1 as clear channel assessment. This threshold is the RSSI (Received Signal Strength Indicator) which is proven to be suitable for wireless networks as it has also been used in Air Magnet Site Surveying tool [102] As shown in Table 3.1, the RSSI of a selected channel should be greater or equal than 15 [103]. This number indicates that the channel has a Signal to Noise Ratio (SNR) above 33 dB and a strong signal strength. If all channels suffer from high interference and noise levels then the QoS of the message to be sent is investigated. If the message to be sent is safety then CST is checked to assess if all occupied channels belong to safety transmissions. If this is the case, then the vehicle has to wait for the end of the first transmission.

3.4.3 Control channel interval

The CST indicates whether the channel is available during the desired intervals. As mentioned above, each provider needs to go through a channel contention and negotiation process during the CCH interval. A provider advertises its WSA frame during CCH interval for channel access and the negotiation process. The SCH which the provider is targeting to switch to is decided based on its own CST. Once all interested users acknowledge the WSA frame with a WSAR frame, the handshake process is complete and the provider is ready to send it's data in the next SCH interval.

3.4.4 Behavior of primary provider in service channel interval

In the proposed MCM protocol, the PPs are given the opportunity to transmit all of their data until it is finished, and as long as they have the possession of the SCH. In other words, the PPs can transmit their data for more then one sync interval without going back to the CCH during the next CCH interval. PPs do not need to go through the channel contention and negotiation process again during its data transmission. Once they finish their data transmission, they go back to normal sync interval and channel switching process. They can start the data transmission again by following the same process. The behavior is explained in Fig 3.10 where PPs go through the channel contention process and complete the handshake during the CCH interval and transmit data during the next four sync intervals.

3.4.5 Behavior of secondary provider in service channel interval

In the MCM protocol, SPs always have lower priority for channel access and they follow the same process as the PPs for data transmission. In the case where the SPs have larger volume of data to transmit once they win the channel, they can transmit for one additional sync interval as long as handshakings from the PPs in the CCH interval are successful. The behavior is explained in Fig 3.10. All the nodes other than PPs are ready to listen to the CCH during the next CCH interval, so the failed handshake from PP is clearly visible. Assuming there is no failed handshake in the fifth sync interval, all the SPs can extend their data transmission for an additional sync interval. If there is a failed handshake from one of the PPs during the CCH interval, the SP only transmits its data in the upcoming SCH interval and then goes back to the CCH during the next CCH interval and starts all over again. This allows the PPs to have a upper hand and to win channel as they need. The ability of nodes to transmit data for more than one sync interval (through the use of cognitive radio) without the need to go back through the whole process of channel

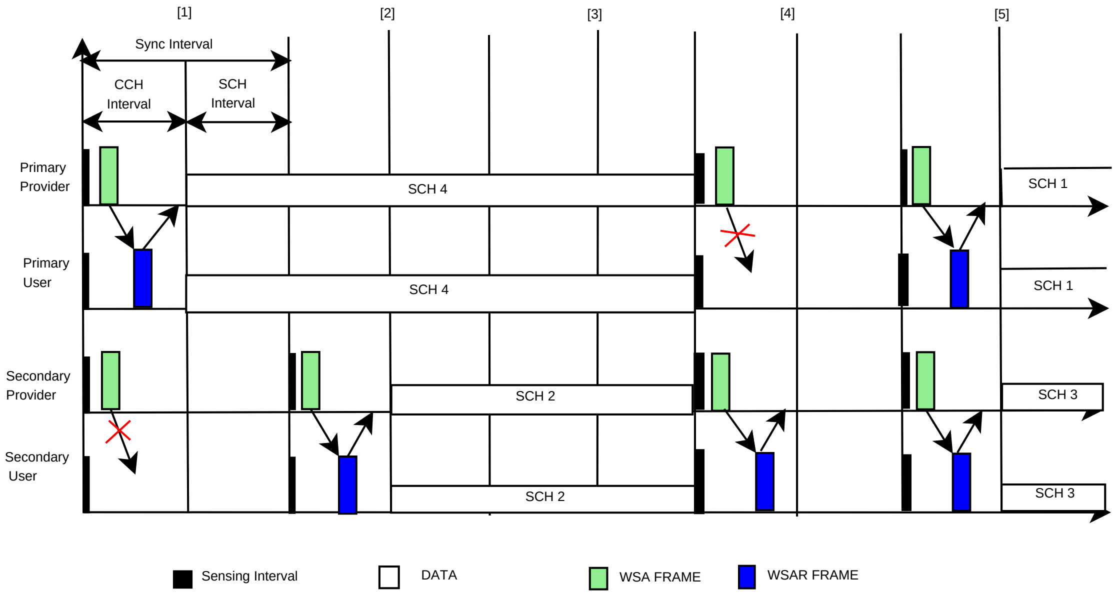

Figure 3.10: The operation of MCM protocol.

contention and negotiation again, certainly improves the channel utilization, which is a key innovation in the proposed MCM protocol.

Finally, We have summarise the operation of MCM protocol in pseudo code shown in algorithm 3.1, where NUC is number of unused channel and LUC is list of unused channel.

3.5 Performance Evaluation for Channel Utilisation

The simulation is explained in detail in chapter 5. This sections presents the effectiveness of MCM protocol briefly. Performance evaluation of the proposed MCM protocol was carried out through simulation and results were analyzed against the IEEE 1609.4 standard. We adopted the parameters defined in the IEEE 1609.4 standard [104], The topology used in the simulation is shown in Fig 3.11. The simulation was conducted in two phases: i) in the first phase, we evaluated the system performance in-terms of channel utilization, number of waiting time slots and control overhead at different traffic arrival rates (i.e. Y=2, 8, 20 frames/sec) to show how the MCM protocol performs against the standard 1609.4 standard, and ii) in the second phase, we monitored the reliability of safety messages in terms of frame error rate (FER),

3.5.1 Channel utilisation

As shown in Fig 3.12, the MCM protocol consistently achieves higher channel utilization at various traffic arrival rates. The MCM protocol achieves up to 70% channel utilization whereas the IEEE 1609.4 standard achieves a maximum of 40% channel utilization as the load is increased. This is because the MCM protocol efficiently uses SCHs during the CCH

Algorithm 3.1 Pseudo code for the operation of the proposed MCM protocol.

```
Initial state

01.Initially: NUC:= 0, LUC:= 0, Send_flag:= 0

Sensing phase:

02. Start of Sync interval
03. IF Sync interval < 4ms
04.     Sense the channel using wide band sensing
05. IF Channel i is idle // update the Channel Status Table (CST)
06.     NUC:= NUC + 1  // Update the CST by adding the number of unused ch
07.     LUC(NUC):= k   //Update list of unused channels.

Channel negotiation phase:

08. IF CCH interval > 4ms and node have safety data to transmit/service to
09.     Broadcast WSA frame and wait for WSAR frame

Transmission phase (primary provider)

10. UPON receiving WSAR
11. IF source address is correct and CCH interval > 50ms // negotiation su
12.     Send_flag:=1  // permission to send if the outgoing queue is empty
13. IF the outgoing queue is not empty
14.     Send_flag:=0  // wait for a permission to send
15.     Contend to send data to the destination node using
        binary exponential backoff and EDCA
16. ELSE
17.     Send_flag:=1  //permission to send
18. IF Send_flag:=1
19.     Switch to intended SCH
20.      Start the transmission and transmit until completion
21. ELSE
22.     Remain idle and listen to Channel till the completion of Sync inte
23. UPON completion of Sync interval
24.      Return to initial state

Transmission phase (secondary provider)

10. UPON receiving WSAR
11. IF source address is correct and CCH interval > 50ms // negotiation su
12.     Send_flag:=1 // permission to send if the outgoing queue is empty
13. IF the outgoing queue is not empty
14.     Send_flag:=0 // wait for a permission to send
15.     Contend to send data to the destination node using
        binary exponential backoff and EDCA
16. ELSE
17.     Send_flag:=1  //permission to send
18. IF Send_flag:=1 and Sync interval < 100ms
19.     Switch to intended SCH
20.     Start the data transmission
21. ELSE
22.     Halt the data transmission
23 UPON completion of Sync interval
24.     Return to initial state
```

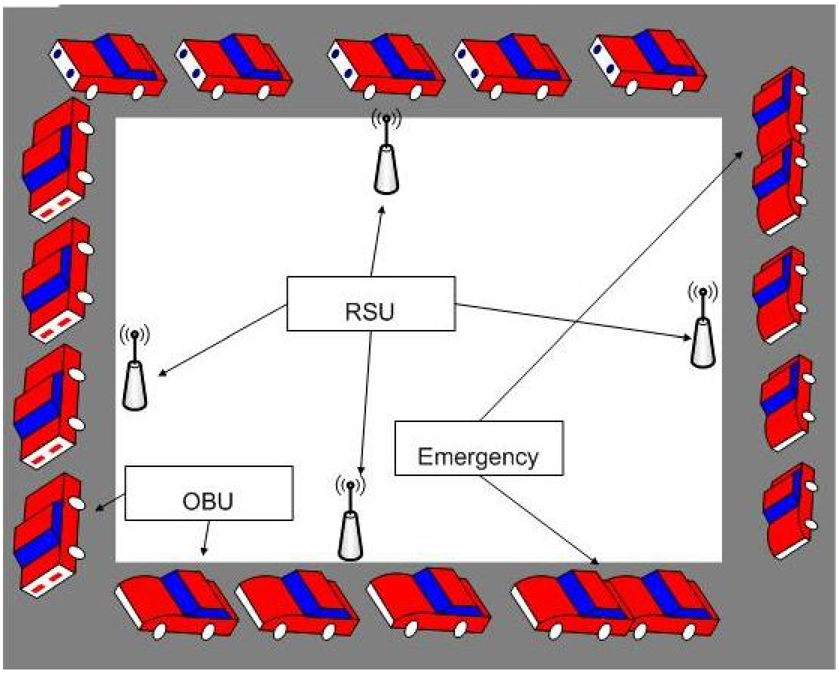

Figure 3.11: Simulation Topology.

interval for data transmission while, in the IEEE 1609.4, channel utilization is very poor as the number of nodes increases because of the severe frame collisions.

3.5.2 Waiting time slots

Fig 3.13 shows the waiting time period (i.e., 1 waiting time slot = 1 SCH interval = 50 ms) at three different frame arrival rates as a function of number of providers. It is observed from the Fig 3.13 that the MCM protocol provides much lower waiting time than in the IEEE 1609.4. A provider in the MCM protocol on average, has to wait 5 intervals less than the providers in the IEEE 1609.4 in case where Y=2 frames/sec and there are 50 providers in total.

3.5.3 Number of overhead

Fig 3.14 shows the amount of control overhead with respect to the number of providers at different frame arrival rates. The control overhead is calculated as an average number of handshaking from a provider within the sync interval. When the number of providers is high, every node has to go through the contention and access control process and as a result, the number of WSA/WSAR handshakes increases. As the number of providers increases, the MCM protocol shows large amount of control overhead as compared to IEEE 1609.4 in case of Y=2, 8 frames/sec. However, at high arrival rate (e.g., Y=20 frame/sec), both the MCM and the IEEE 1609.4 show degraded performance in terms of control overhead. This is because, providers have to frequently rebroadcast their handshake frames because

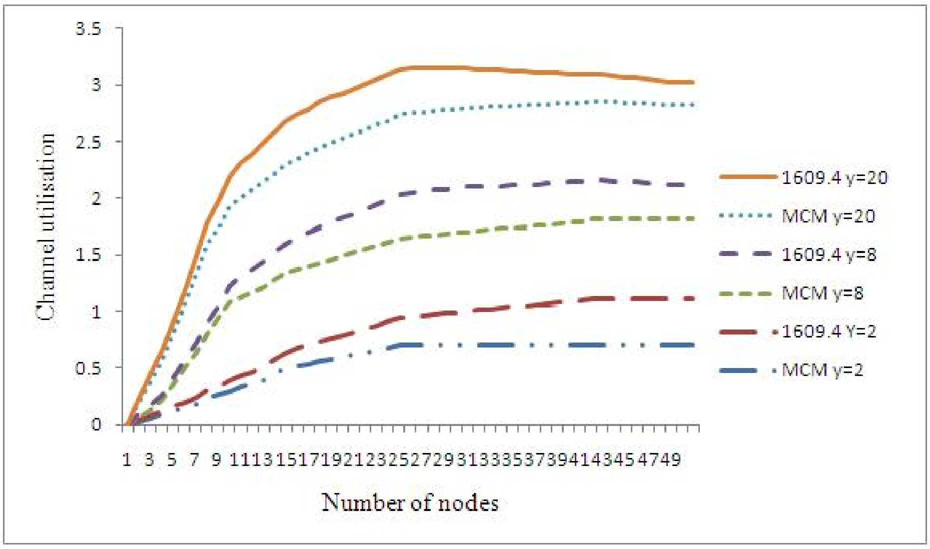

Figure 3.12: Channel utilisation vs Number of nodes.

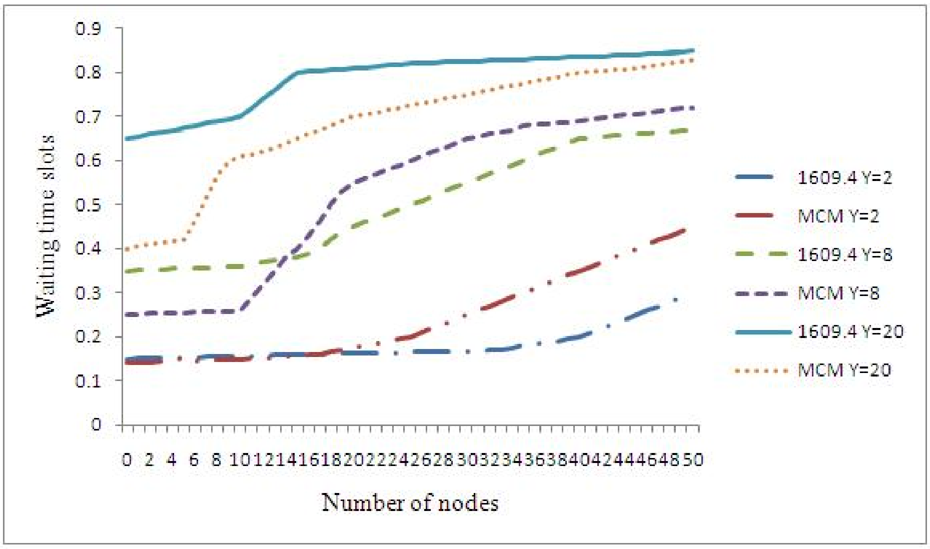

Figure 3.13: Waiting time slots vs Number of nodes.

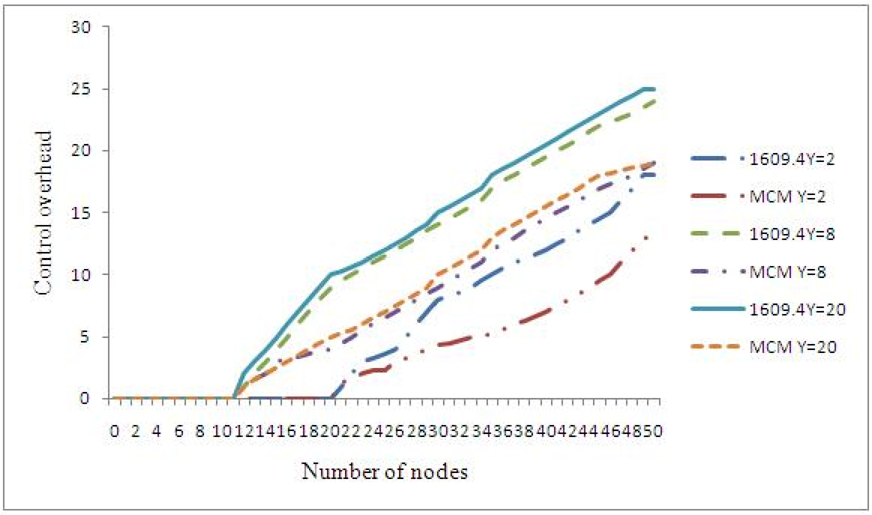

Figure 3.14: Control overhead vs Number of nodes.

the system has very high traffic causing a large number of collisions. The MCM protocol still maintains lower control overhead because the WSA/WSAR handshake is not needed for the extended intervals of data transmission.

In conclusion, the MCM protocol improves the channel utilisation up to 70% which ensures the reliability of the system for safety application, provide capabilities to mitigate interference in high multipath vehicular environment, and maximise available resource allocation. As mentioned earlier, safety messages must be sent within a certain upper threshold know as delay bound otherwise they reach their target late and are considered useless. Our protocol reduces the waiting time interval significantly to ensure that the delay bound conditions are satisfied. Performance evaluation parameter is shown in table 3.2.

Table 3.2: Summary of performance evaluation

Parameter	IEEE std 1609.4	MCM protocol
Maximum Channel utilisation	40%	70%
Maximum Waiting Time	1.25s	1s

3.6 Summary

In this chapter, we have presented the Proposed MCM protocol and its operation via flow chart, and outlined the changes made to the IEEE 1609.4. In addition, we have discussed the cognitive radio technology and its algorithm which have been used to develop the MCM protocol. We have also presented the algorithms to collect information like interference, traffic and channel utilisation. Finally we have concluded this chapter with performance evaluation of our protocol. It is obvious that MCM protocol improves Channel utilisation and also a reliability if the system for safety application. Although, there is still a room for further improvement to ensure that the safety messages have the highest priority. Moreover, it is vital to identify lost safety data packets to implement the binary-exponential back-off technique, so we can reduce the large number of collisions occurs due to high amount of traffic load. The further improvement in our protocol is explained in next chapter.

Chapter 4

PROPOSED MULTICHANNEL MAC PROTOCOL TO IMPROVE THE SYSTEM RELIABILITY FOR SAFETY APPLICATION

In this section, the WAVE MAC protocol (EDCA) is described briefly, in order to create a basic understanding of the key problems. The two key innovations, establishment of the strict priority and acknowledgment of the safety messages which enables the use of binary-exponential back-off for retransmission to reduce the collisions are described in the subsection 4.2 and 4.3 respectively. Finally we discuss the performance analysis of all the key innovations.

4.1 EDCA Protocol in WAVE

The MAC protocol in the IEEE 1609.4 utilises the IEEE 802.11e EDCA Quality Of Service (QOS) extension [105]. The EDCA mechanism defines different Access Categories(ACs) in all nodes with their specific AIFS and CW sizes to provide service differentiation capabilities. The parameters used in EDCA are defined as follows: i) AIFS is defined as the minimum time interval that the wireless medium has to be sensed idle in order for a node to decide that it is free. ii) CW is defined as a random number generation window for the back-off mechanism. iii) TXOP limit is defined as the longest time interval during which a WAVE device can transmit one or several frames [105]. To accommodate the large frames in order to be transmitted in one TXOP, frame fragmentation is used. The duration of AIFS is defined as follows:

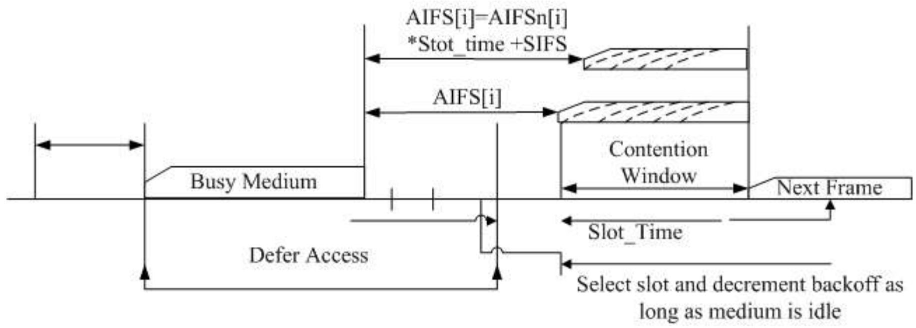

Figure 4.1: Timing relations: EDCA

Table 4.1: EDCA Parameters used in IEEE 1609.4

	Default ECDA Parameters		
AC[i]	CWmin	CWmax	AIFSN
0	15	1023	9
1	7	15	6
2	3	7	3
3	3	7	2

$$AIFS\,[AC] = SIFS + AIFSN\,[AC] \star (slot\,time) \tag{4.1}$$

SIFS (short IFS) is defined as the time that separates the frame exchanges like data frame and its ACK. The AIFSN[AC] (AIFS number) is defined as the minimum number of slots to wait before starts the back-off counter. Slot time is the duration of physical layer time slot. Table 4.1 shows the values of the EDCA parameters used in WAVE. As shown in fig 4.1, the node with higher priority messages will know earlier that the medium has been freed because it has smaller AIFS which will give them advantages over lower priority messages. The above mentioned concept is not enough to establish strict priority, while the proposed novel MAC protocol will establish the absolute priorities between different ACs.

4.2 Implementation of Strict Priorities

For channel contention resolution between the RSU (node with higher priority frame) and the OBU (node with lower priority frame) in the proposed MAC protocol, we use the EDCA mechanism with strict priorities (i.e., OBUs must not get channel access ahead of RSUs and their frames do not collide). In EDCA, for a given access category, the minimum time

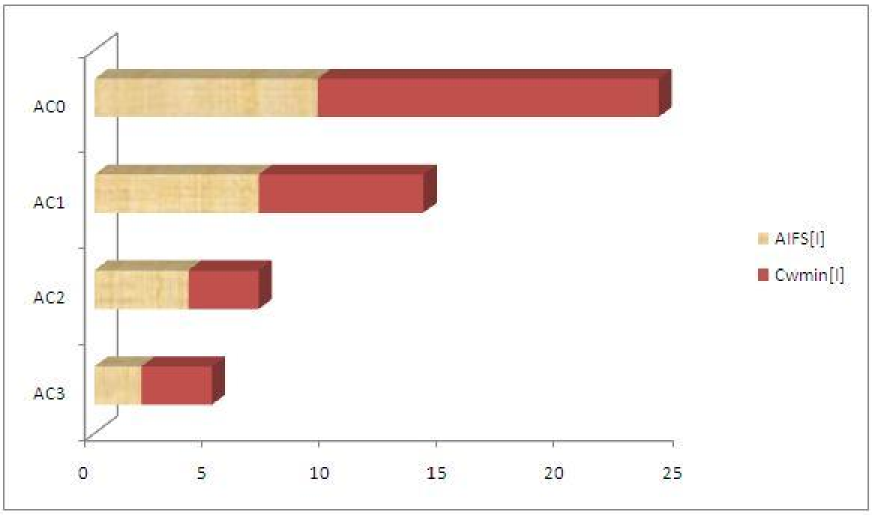

Figure 4.2: Default AIFS and CW values for different ACs.

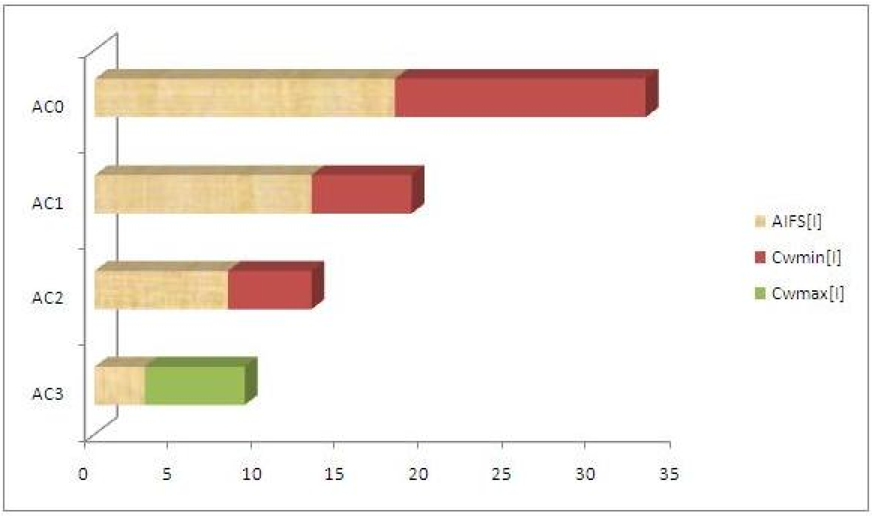

Figure 4.3: Modified AIFS and CW values for different ACs.

Table 4.2: EDCA Parameters used in Proposed MAC

AC[i]	Modified ECDA Parameters CWmin	CWmax	AIFSN
0	15	1023	19
1	7	15	12
2	3	7	9
3	3	7	2

period that a node needs to sense the wireless medium in order to determine if it is idle, is larger than the AIFS plus the largest possible back-off interval of all ACs corresponding to higher-priority frames [106]. According to the concept mentioned above, the waiting time period in the worst case to transmit the highest priority frame belonging to class i is AIFS[i] plus the largest possible back-off interval. For lower priority frames belonging to class i-1, the waiting time period to transmit in a best case is AIFS[i-1] assuming the random back-off interval is zero. In order to establish the strict priority, the waiting time interval for higher priority frames must be less than the lower priority frames. If we use the default parameters of standard EDCA, the condition mentioned is not satisfied. According to the proposed mechanism, AC[3] frames (i.e., safety data) have strict priorities over AC[2] frames. While the rest of the categories (i.e., category 1-0) are not for safety related messages, they can still have priorities, but we do not need to establish the strict priorities (i.e., wide variation in AIFS and CW) among them. Table 4.2 shows the parameters used to establish the strict priorities and fig 4.2 and, 4.3 shows the timing relations between different ACs for default and modified parameter respectively, so that AIFS[2]= AIFS[3]+CW$_{max[3]}$, AIFS[1]= AIFS[2]+CW$_{min[2]}$, and AIFS[0]= AIFS[1]+CW$_{min[1]}$. We have used CWmax in the first equation to accommodate the acknowledgment and retransmission for the highest priority frames belongs to AC[3]. This concept is explained in detail in the next section. It is noteworthy that the main aim is to reduce delays and frame losses for higher priority frames by establishing strict priorities, however it will increase the E2E delay for lower priority frames.

4.3 Safety Message Acknowledgment

It is vital to employ the binary-exponential back-off technique to reduce the large number of collisions occurs due to high amount of traffic load. In order to implement the mentioned technique, we need to identify the lost data packets, so that they can be retransmitted. In WAVE, all the safety messages are broadcasted in CCH without acknowledgment, thus the binary-exponential back-off technique can not be applied. The proposed novel MAC protocol allows to sending of minimum overhead acknowledgment for safety messages which corresponds to AC[3]. To utilise this concept we use cluster based scheme, of which there are two types of clustering scheme: i) Active CLustring (ACL), ii) Passive CLustring (PCL). ACL requires some signaling protocol for exchanging additional messages among neighboring nodes to select cluster heads (CH) and gateways (GW). Moreover, periodic advertisement of cluster information is very vital in ACL. However, in ACL large amount of overhead is generated and association and disassociation to and from clusters affects the stability of the network due to the highly dynamic nature of VANET. The PCL is easy to implement and is virtually overhead free [107] and has the best performance among all clustering protocols in case of high mobility and time constrained network [108], like VANET, therefore, in our proposed MAC protocol, we have used the PCL.

4.3.1 Passive Clustering

Passive Clustering is a cluster formation protocol that does not use dedicated protocol-specific control packets or signals. Conventional clustering algorithms, as earlier discussed, require all of the participating network nodes to advertise cluster dependent information repeatedly. Moreover, most of the existing clustering schemes require the execution of a separate clustering phase prior to any network layer activity (e.g., routing). With passive clustering, we avoid all the above limitations. By monitoring user data packets that piggyback some predefined cluster information, we can build impromptu "soft state" clusters for mobile wireless networks. Thus, the cluster infrastructure can be constructed as a by-product of user traffic, without any dependency on the routing protocol, for example. In passive clustering, each node collects neighbor information from the MAC sender address carried by the incoming packets, and can construct clusters even without collecting the complete neighbor list. This is an innovative approach to clustering which virtually eliminates major cluster overheads the time latency for initial clustering construction as well as the communication overhead for neighbor information exchanges. Instead of using protocol specific signals or packets, cluster status information (2 bits for four states: Initial, Clusterhead, Gateway, and Ordinary-node states) of a sender is stamped in a reserved field in the packet header. Sender ID (another key piece of information for clustering) is carried by all the existing MAC protocols and can be retrieved from the MAC header. Since in flooding the MAC packets are transmitted in broadcast (instead of unicas0 mode, every node receives and reads the packets (in a promiscuous way), and thus participates in passive clustering. Due to its passive nature, passive clustering does not introduce any control packets dedicated to the protocol. In other words, it is "control overhead free" [107].

As mentioned above, in PCL all the nodes have four states 1) initial, ii) cluster head, iii) gateway, and iv) ordinary node. All the nodes starts with the initial state and analyze its neighbours' status to determine its role from the four state mentioned. Moreover, nodes use 2 bits in MAC sub-layer header of all outgoing frames for cluster status information (CST) and sends it with the data. CST is used by receiver to identify its own status by counting the number of CHs and GWs which are in the communication range. As per our proposed protocol, every gateway node will select one of the CHS to his home CH. We have modified the CST and add the information about its own home CH.

The proposed MAC protocol uses this section of VANET as clusters, and identify the CHs. When they receive the broadcasted safety message correctly from any of the cluster member then they will send the acknowledgments. Every cluster ha designated cluster member (Assigned by CH) to send acknowledgment when safety message is send by CH. To reduce the probability of interference with another Custer, the GW is not assigned as a designated cluster member.

4.3.2 Analysis of proposed MCM protocol

The simulation sysytem is explained in detail in chapter 5. This sections presents the effectiveness of MCM protocol briefly. Performance evaluation of the proposed MAC protocol was carried out through simulation and results were analyzed against the IEEE 1609.4 standard. We adopted the parameters defined in the IEEE 1609.4 standard [104],The topology used in the simulation is the same as the one used to anayse the MCM protocol for channel utilisation in chapter 3. We denote ACe[0-3] as an existing EDCA categories and AC[0-3] as the modified ones. We analyze the performance in-terms of E2E delay, jitter and Frame error rate (FER). In addition we use four different scenarios as explained: i) Firstly, we have two AC[3] nodes (RSUs) and one OBU besides the RSU and traffic generated by RSUs are 10% and traffic generated by OBU [AC[0-2]] varies from 20% to 100%, ii) The second scenario is the same as the first one but we use ACe[0-3] instead of AC[0-3] , ii) Thirdly, We vary the AC[3] traffic load only from 10% to 100%, and iv) The fourth scenario is the same as the third one but for ACe[3].

4.3.2.1 E2E delay and Jitter

- One hope E2E delay for the all frames for AC[1-3] is shown in fig 4.4. The key observation is that the E2E delay for AC[3] frames is 0.4ms and its remains approximately same throughout the simulation even for 100% traffic load while delay for other ACs increase with traffic load.

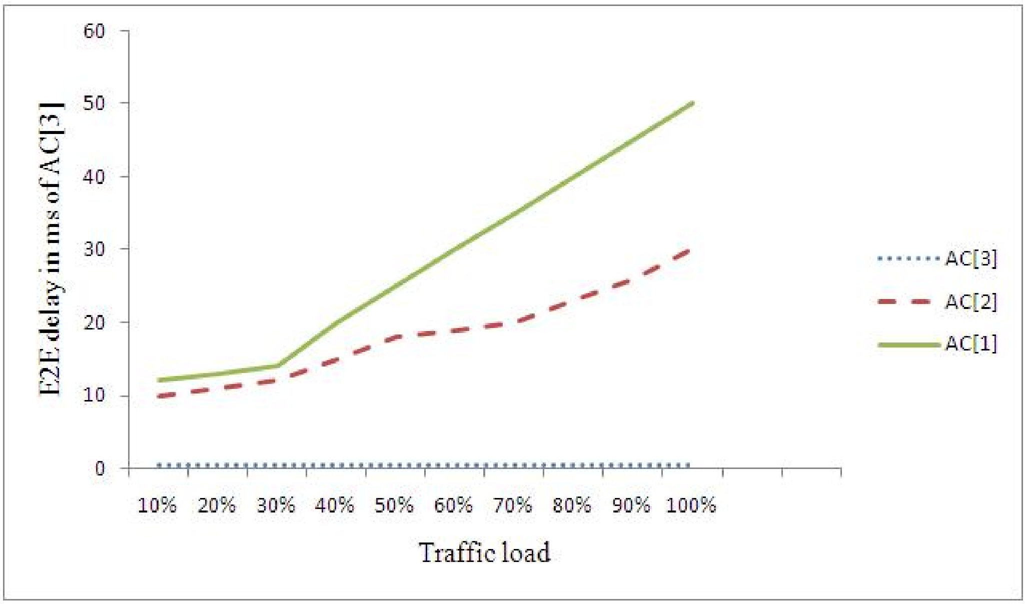

Figure 4.4: E2E Delay in ms of AC[1-3] Vs. Traffic Load

- One hop E2E delay for AC[3] and ACe[3] is compared in fig 4.5, and it is generated using the first two scenarios. The E2E delay for exiting EDCA protocol increases with traffic load and reaches up to 0.72ms while the E2E delay remains considerably lower throughout the simulations and reaches to 0.5ms which proves the superiority of proposed MAC protocol in-terms of E2E delay.

- One hop E2E delay for AC[3] and ACe[3] is compared in fig 4.6, and it is generated using the last two scenarios. The E2E delay for the existing EDCA protocol increases with traffic load and reaches up to 4ms while the E2E delay for proposed MAC reaches up to 7ms. The E2E delay for the proposed MAC protocol in this scenario remains higher throughout the simulation because the lost frames are retransmitted, and so the E2E delay for successful transmission is higher. It is noteworthy that, the maximum delay should be less than 10ms (Which is 7ms in our case) for VANET to be reliable.

- Jitter for AC[3] and ACe[3] is compared in fig 4.7, and it is generated using the first two scenarios. The jitter for exiting EDCA protocol increases with traffic load

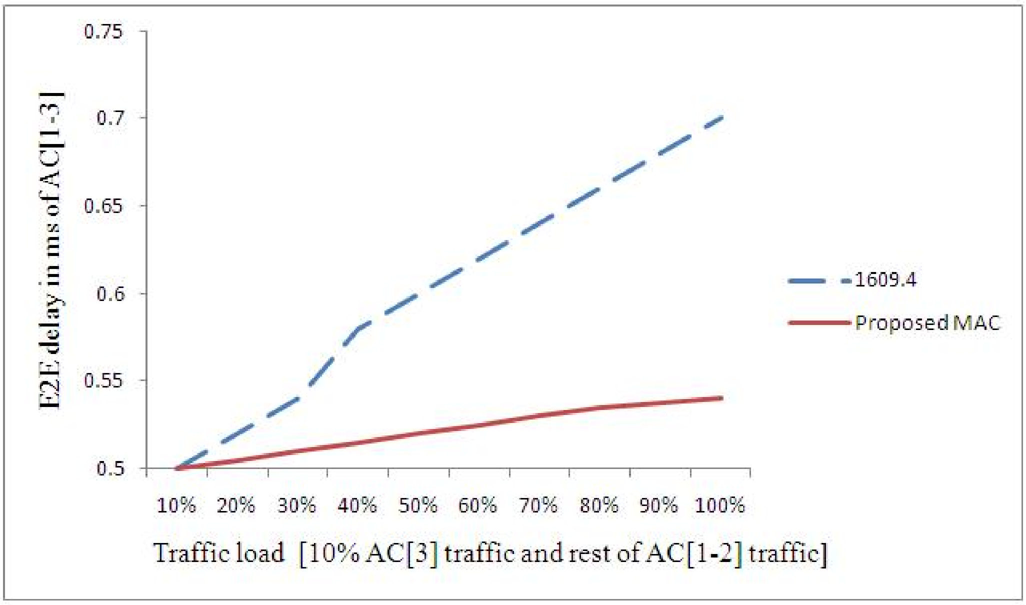

Figure 4.5: E2E Delay in ms of AC[3] vs. Traffic load [10% AC[3] Traffic and rest of AC[1-2] Traffic].

and reaches 0.22ms while the E2E delay remains considerably lower throughout the simulations and reach to very low value of 0.04ms, which proves the superiority of the proposed MAC protocol in-terms of jitter.

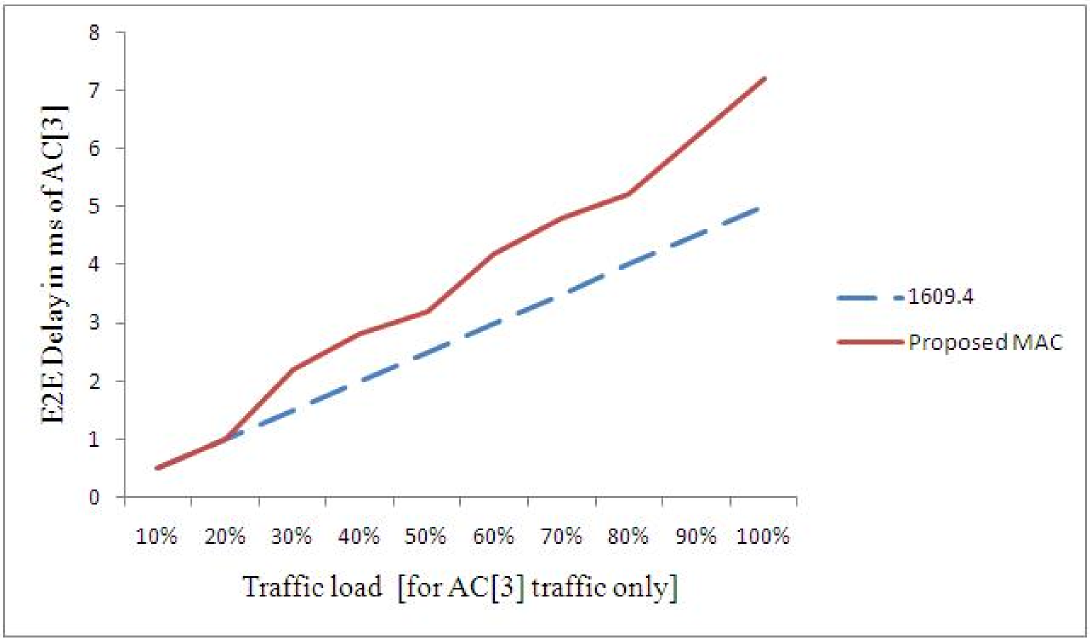

Figure 4.6: E2E Delay in ms of AC[3] Vs. Traffic load [For AC[3] traffic only].

4.3.2.2 Frame error rate

FER is defined as the ratio of the frames that are never successfully received because the maximum retransmission is reached, to the ratio of the frames transmitted.

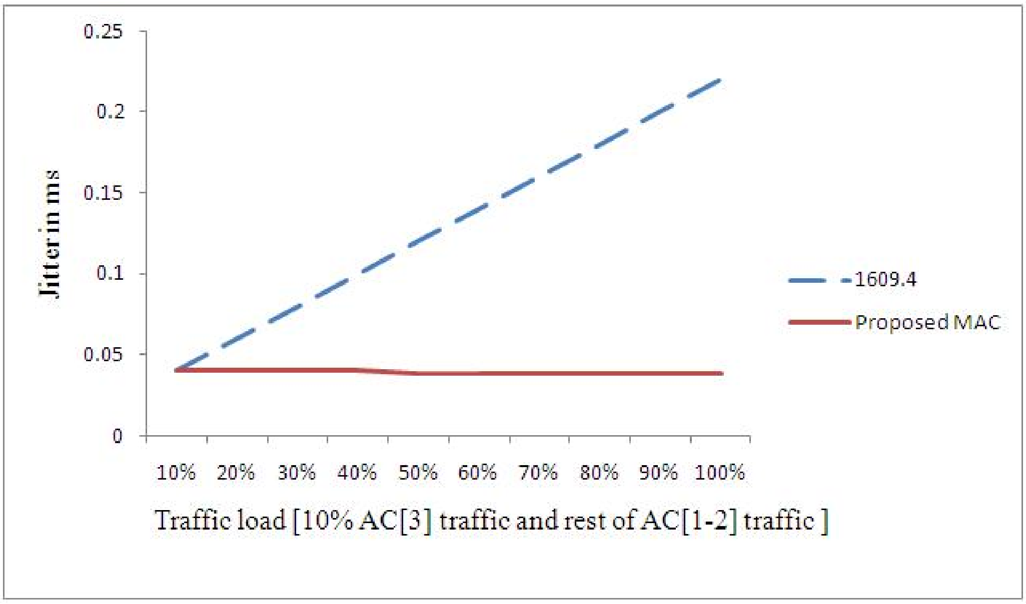

Figure 4.7: Jitter in ms Vs. Traffic load [10% AC[3] Traffic and rest of AC[1-2] Traffic]. Jitter.

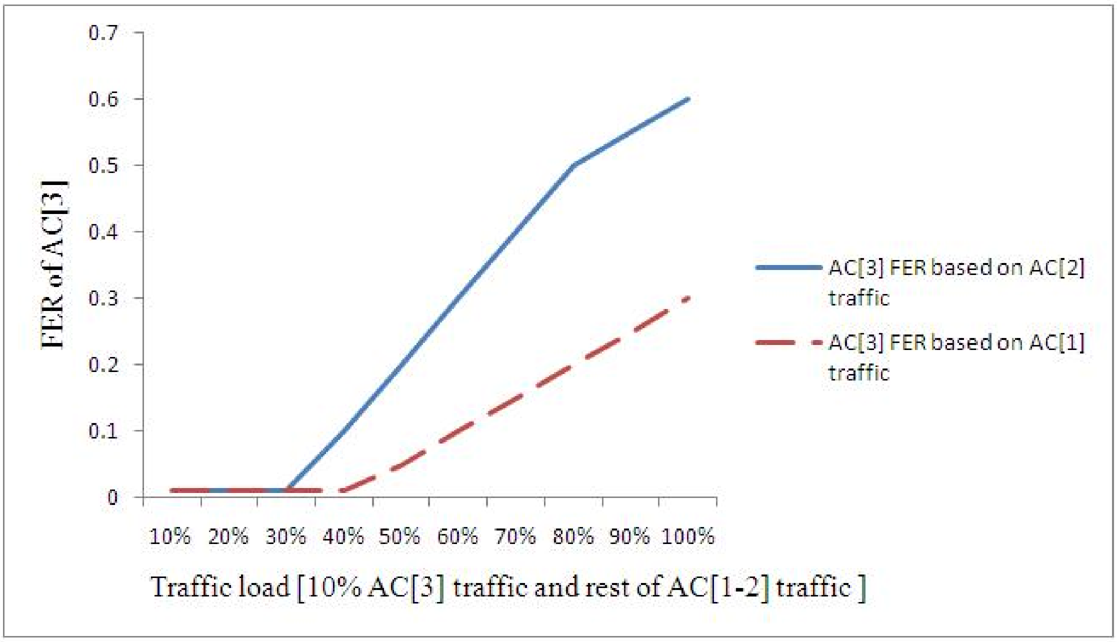

Figure 4.8: FER of AC[3] Vs. Traffic load [10% AC[3] Traffic and rest of AC[1-2] Traffic].

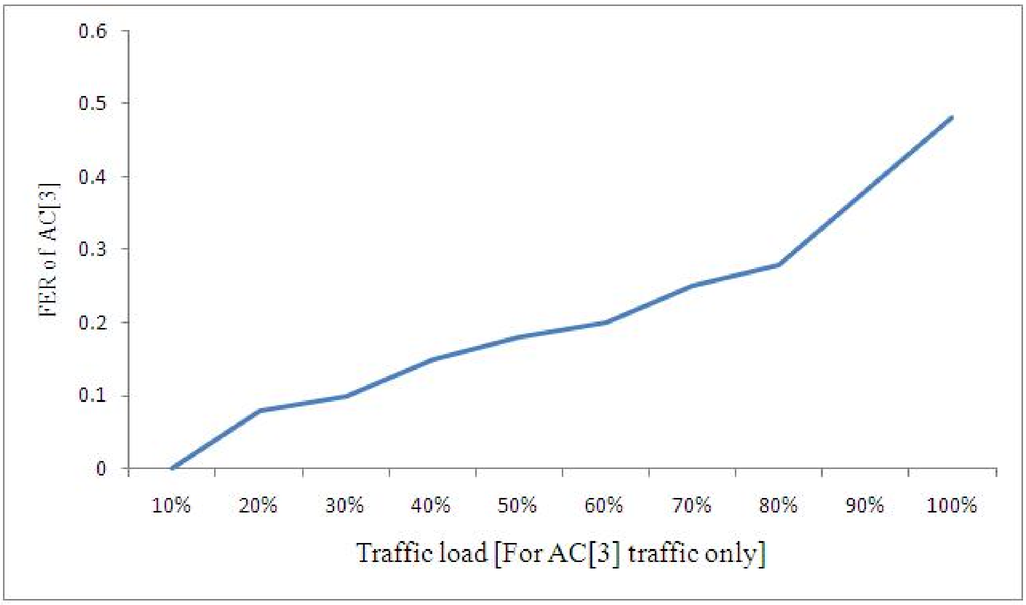

Figure 4.9: FER of AC[3] Vs. Traffic load [For AC[3] Traffic only].

- The FER of AC[3] (highest priority frames) is compared with other ACs which is shown in fig 4.8, and it is generated using the first two scenarios. It is observed that the FER is almost zero for all ACs when traffic load is below 30% and it increases after that. The reason is that the lower priority users will use all the bandwidth left by AC[3] and so, it is likely that the AC[3] frames generates when the channel is busy. Moreover, AC[3] frames are not generated at the same time but will be transmitted at the same time as the channel becomes available thus causing the collisions. In addition, it is noted that the presence of AC[2] frames causes higher FER than the AC[1] frames.

- The FER of Ac[3] in the third scenario is shown in fig 4.9. It increases with the traffic load and reaches the maximum value of 0.5%. In the proposed MAC protocol, all the lost frames are successfully retransmitted by the PCL method and so, the losses remain very low.

- The FER for AC[3] and ACe[3] is compared in fig 4.10c, and it is generated using the last two scenarios. The FER for AC[3] increases with the traffic load and reach to the maximum value of 0.6% while it reaches up to 25% in the case of ACe[3] which proves the superiority of proposed MAC protocol and the mechanism of PCL for sending acknowledgments for broadcasted frames and successfully retransmitting the lost frames with minimum overhead.

In summary, An efficient medium access methodology ensures the prioritization of transmission by granting safety messages the highest priority to access the medium to meet the

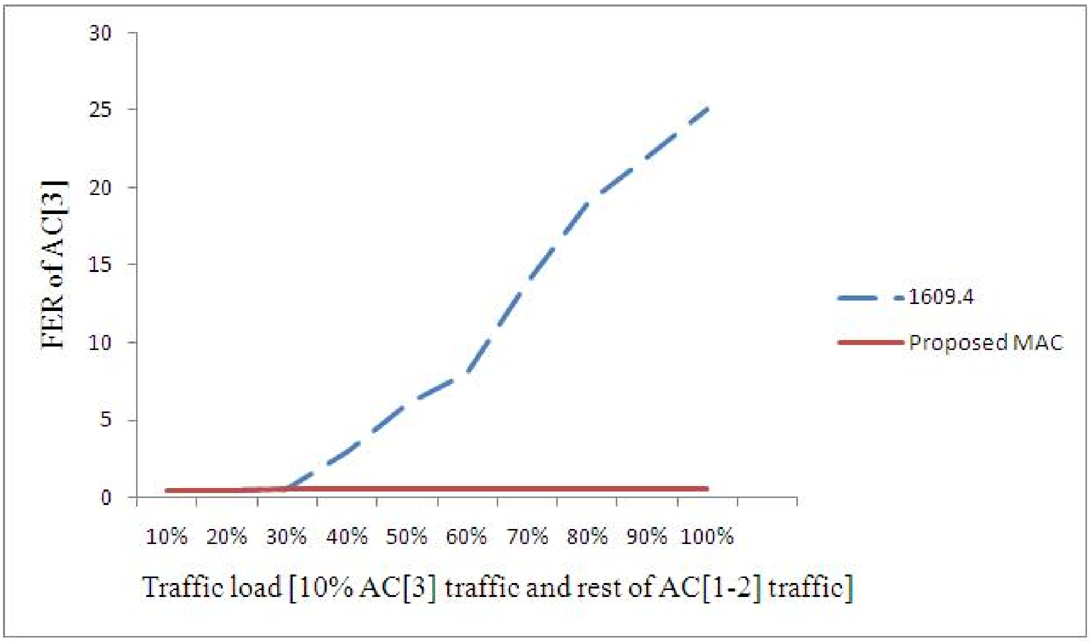

Figure 4.10: FER of AC[3] Vs. Traffic load [10% AC[3] Traffic and rest of AC[1-2] Traffic].

QOS and delay requirements.

4.4 IEEE 1609.4 Model in ns-2

The simulator used to model the IEEE 1609.4 is ns-2.34[104]. In this version, a completely overhauled IEEE 802.11 simulation engine and implementation is introduced [109]. The module based design of IEEE 802.11 MAC and PHY is shown in fig 4.11. The changes and new modules to emulate the IEEE 1609.4 are shown in blue colour. To model the time division operation of the IEEE 1609.4, we have to disable the radio at proper times to which is corresponding to Guard, CCH and SCH intervals as shown in fig 3.1. Channel switch timer module takes care of channel switching timing and event generation in ns-2. Moreover, at the start and end of every CCH interval, the channel switch module signals the channel state manager in the MAC layer, thus the channel state manager declares if the channel is busy or available. In addition the PHY get the information about the channel switching event by the channel switch timer, and so the PHY drops all unfinished transmission at the start of the guard interval. In this paper, the guard, SCH and CCH intervals are modeled as 4ms, 46ms and 46ms respectively.

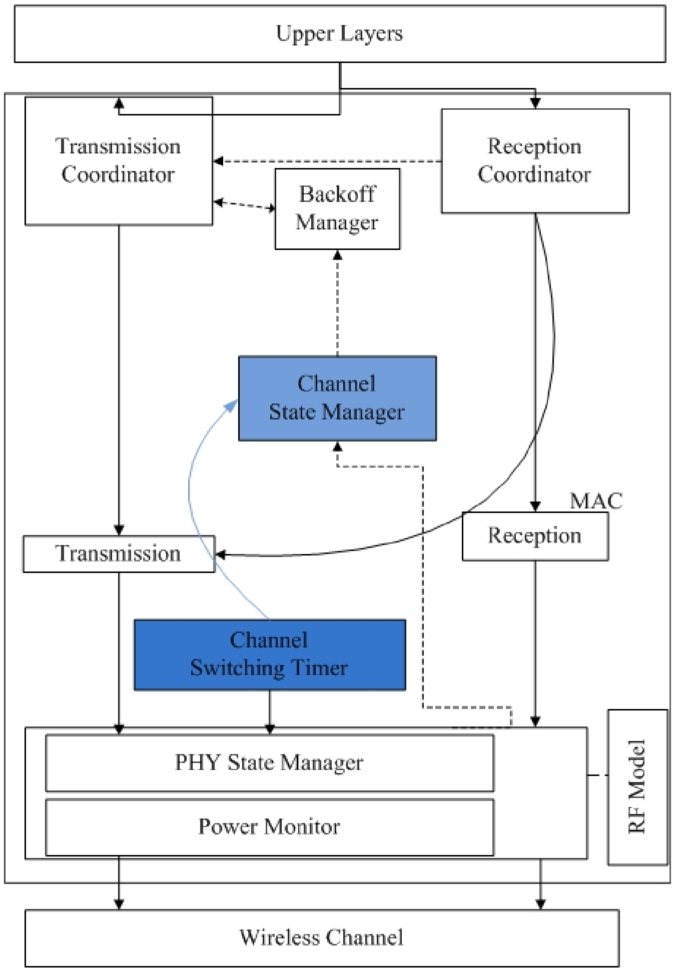

Figure 4.11: Module based design of the IEEE 1609.4.

4.4.1 Important changes made to model the IEEE 1609.4

4.4.1.1 The MAC layer

- mac1609.4 : To achieve the functionalists of MAC protocol we have created a new class called mac1609.4 which is a subclass of MAC class in ns-2. This abstract class contains the elements of RSU and OBU. In addition, it stores MAC Management Information Base (MIB) and PHY MIB. It has the functionality to use dynamic MAC addresses and work as an interface with other layers to send and receive packets.

- 1609.4packet : It is an simulation object which provides packets that meet requirements of the IEEE 1609.4. For example an additional field has been added to indicate whether the OBU is in WAVE mode and it also indicates how the OBUs will behave and what kind of services are available to them. Moreover, the priority field is also added to establish priorities between different packets i.e safety packets, IP packets.

- 1609.4timers : We have created a different timer to support different WAVE timing functionalists. For example, Wave timer, WAVEbecontimer, WAVEbackofftimer, WAVEdefertimer, WAVEprobetimer, WAVERxtimer, and WAVETxtimer.

- 1609.4RSU : This is a subclass of a class mac1609.4 and includes the information about different OBUs connected, information regarding the channel that is being used, information about neighbor RSUs, and data regarding the handover.

- 1609.4OBU : This is also a subclass of mac1609.4 and has the information of OBUs and RSU connected , current state of the OBU and information regarding handover.

4.4.1.2 The PHY layer

- OFDMphy : The class called OFDMphy and the corresponding object has been created to use OFDM properties into the PHY layer of IEEE 1609.4 (which is IEEE 802.11p). It is a subclass of the abstract class WirelessPhy. It has a function to modify the modulation (BPSK , QPSK or QAM) rates used and status of OFDM. In ns-2, the parameters like frequency and transmission power can be configured via TCL simulation script, same can be applied to the new modulation parameters. To support the functionalists mentioned, we have created corresponding TCL bindings. According to the allocated bursts by MAC layer, different modulation can be used based on distance and interference, which also cause effects on data rate and transmission time.

- OFDM Timers : Some timer are needed to model OFDM which are currently not present in IEEE802.11 model, thus these timers have been created.
- Channel : A Multichannel model has been created for OBU and RSU to support 1 CCH and 6 SCH. The CCH has been implemented to support safety and managements frames while the implementation of SCH to support data frames. As shown in fig 4.11, a new simulation object Connection Manager has been created for RSUs and OBUs to help keep a track of the connections (i.e. the MAC address of destinations and the channel used by destination node) they have. TCL binding for the channel objects has been created, so it can be configured via TCL simulation script.
- The advantages of creating TCL bindings for different objects is to reduce code complexity when generating different simulation scenarios.

4.4.2 Analysis of IEEE 1609.4 simulation model

Performance evaluation of the IEEE 1609.4 communication model is done using three different modes: i) First mode does not use any channel switching and 100% of CCH for safety messages. ii) In the second mode the applications are not aware of channel switching and keep generating messages and do not worry about CCH interval. We call this partial channel switching. iii) Thirdly, we use IEEE 1609.4 channel switching concept where no safety messages are generated during the SCH and Guard intervals. The simulation parameters are shown in table 3.11. and the topology used in the simulation is shown fig 3.11. To analyze the performance of the system we use two different scenario. In the first scenarios the payload size is 100 bytes and communication range is 300m and the safety message generating frequency is 3,5,and 10 Hz, while in the second scenario, the payload size is 200 bytes and communication range is 500m and the safety message generating frequency is 3,5,and 10 Hz.

- Fig 4.12, 4.13, and 4.14 shows message reception probability as a function of distance for the first scenario. As shown in fig 4.12, the partial switching method suffers from higher collisions even at 0 distance, while there is a minor difference in the curve for the no channel switching and IEEE 1609.4 channel switching mode. The reason being that this is the least stressful simulation scenario, as we increase the message generating frequency the gap in the curve between second and third mode increases, which is expected and behaves as a real model.

- Fig 4.15, 4.16, and 4.17 shows message reception probability as a function of distance for the second scenario. As per the expectation, the gap in the curve between the

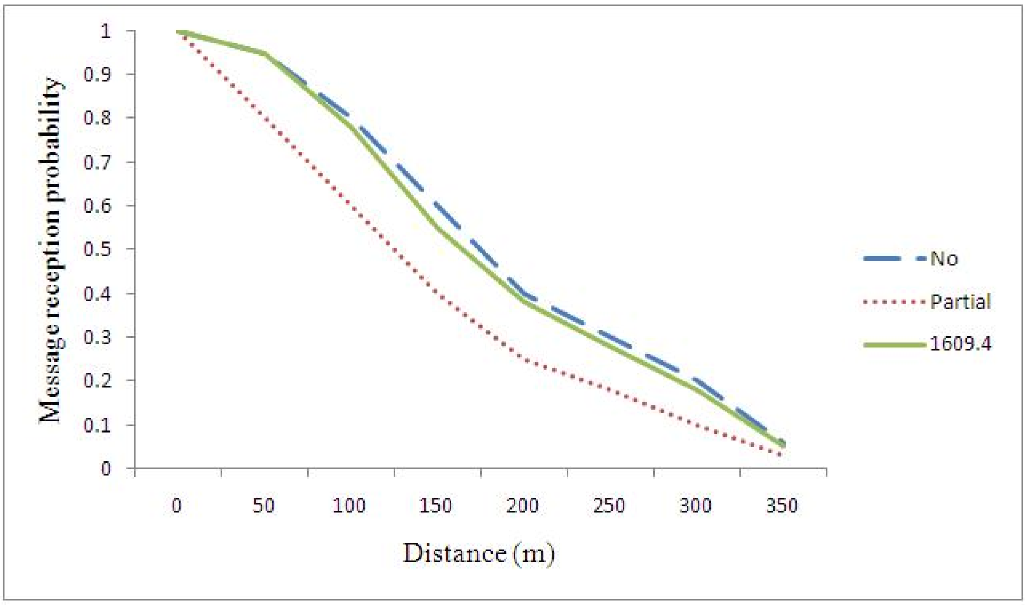

Figure 4.12: Message reception Probability Vs. Distance (m) [100 bytes, 300m, 3Hz].

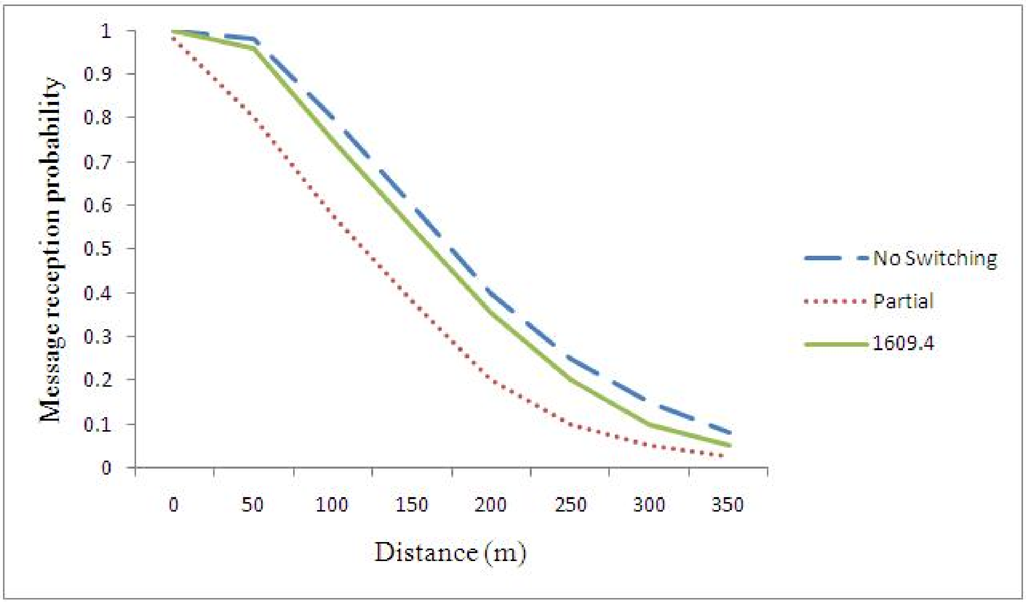

Figure 4.13: Message reception Probability Vs. Distance (m) [100 bytes, 300m, 5Hz].

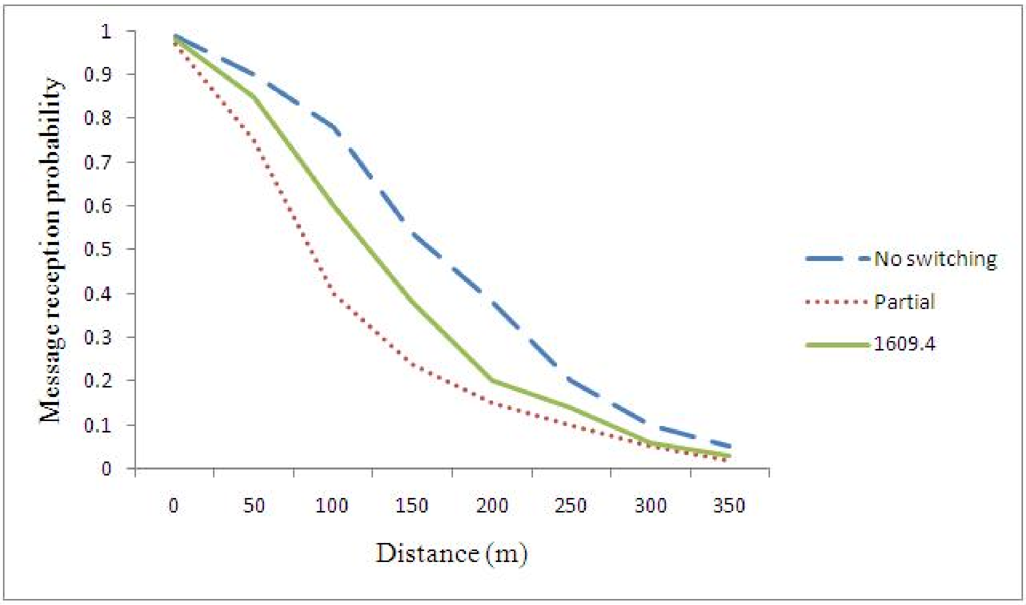

Figure 4.14: Message reception Probability Vs. Distance (m) [100 bytes, 300m, 10Hz].

second and third mode increases. As shown in fig 4.17, the curve for partial channel switching and the IEEE 1609.4 switching crosses each other. The reason is that in the case of partial switching, more then half of the safety messages collide in the first half of the CCH interval but the remaining CCH interval is open for the rest of the safety messages. However, all the safety messages are generated within the CCH interval in the IEEE 1609.4 channel switching mode, and so they have to compete within that interval, thus causing poor reception performance. In a nutshell, the reception performance is very poor for all modes in the case of very high traffic load. Moreover, the safety communication is not reliable even though the IEEE 1609.4 channel switching is turned on, which proves the channel is under utilised.

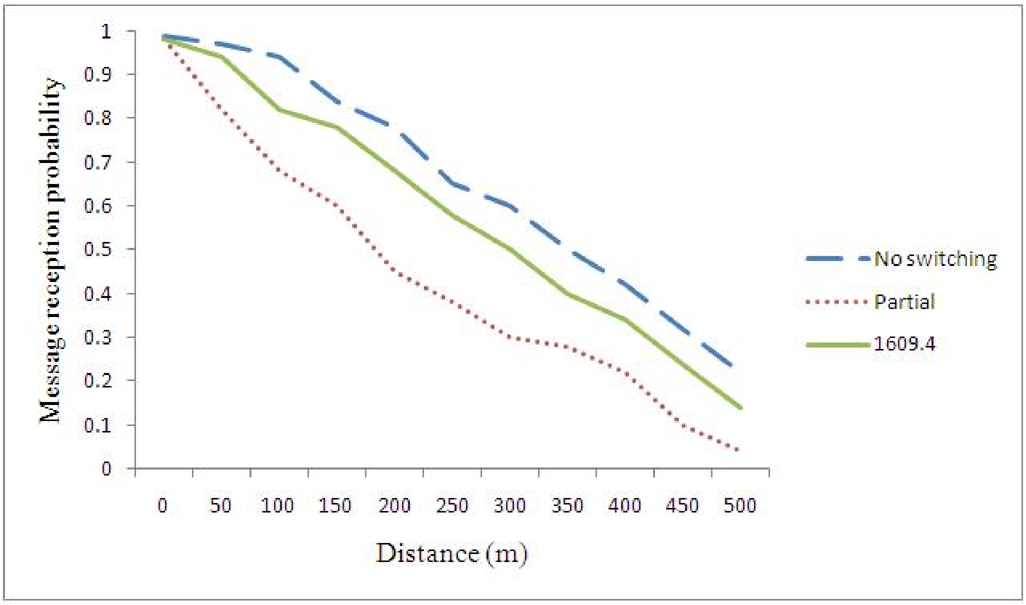

Figure 4.15: Message reception Probability Vs. Distance (m) [200 bytes, 500m, 3Hz].

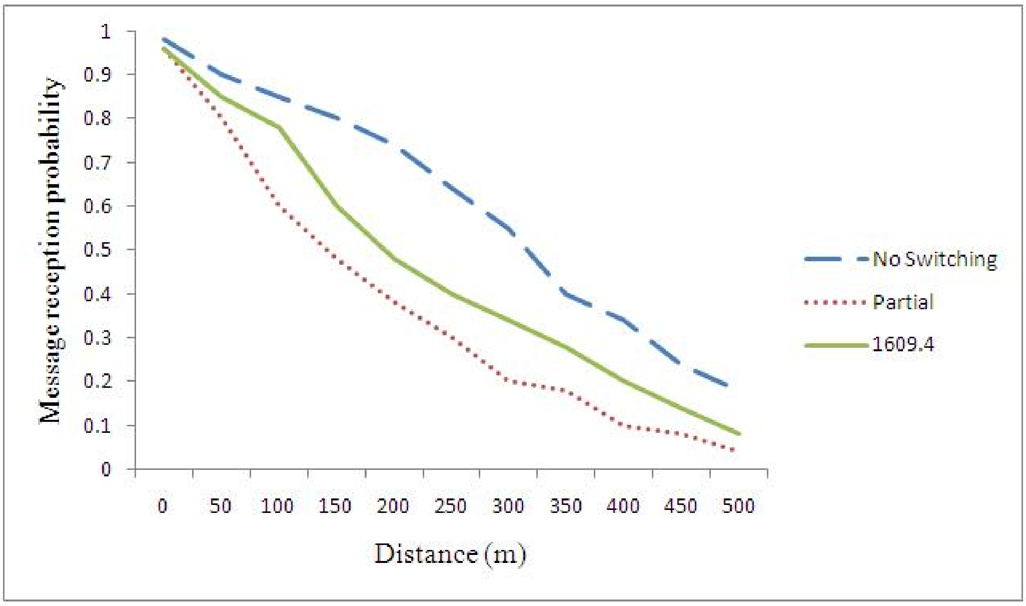

Figure 4.16: Message reception Probability Vs. Distance (m) [200 bytes, 500m, 5Hz].

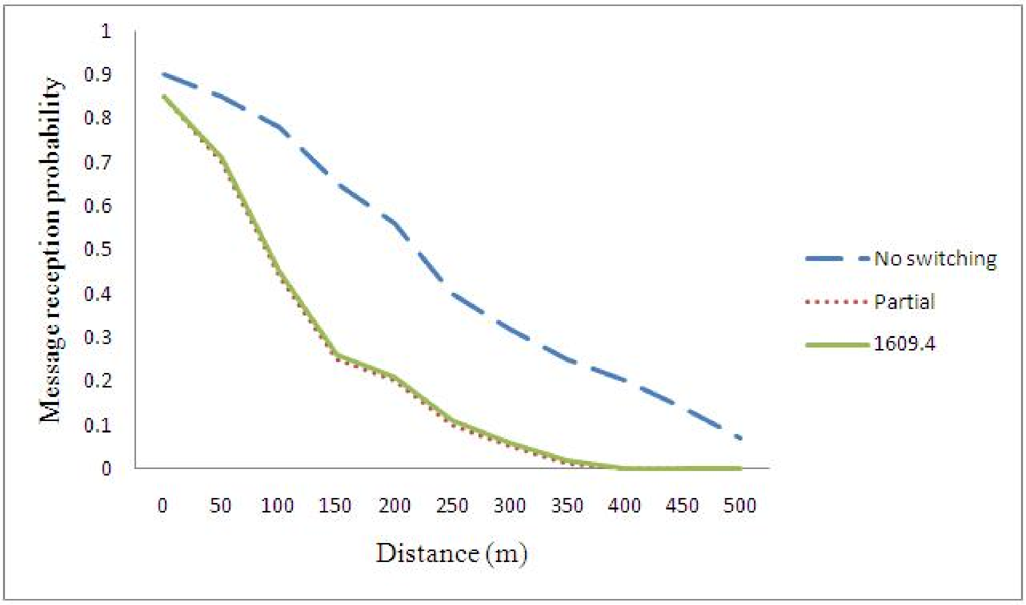

Figure 4.17: Message reception Probability Vs. Distance (m) [200 bytes, 500m, 10Hz].

4.5 Summary

Firstly, the EDCA protocol in WAVE and its limitations are presented briefly. In addition, the proposed parameter changes for establishing the strict priority and its effects on the MAC protocol are discussed. Secondly, proposed scheme for safety message acknowledgment and PCL is presented. Thirdly, we have discussed the performance evaluation of our MCM protocol. Finally, we have presented the developed IEEE 1609.4 model and performance evaluation for the IEEE 1609.4 simulation model in-terms of message reception probability as a function of distance.

Chapter 5

SIMULATION SYSTEM

There are three main techniques for analyzing the behavior of a system: Analytical Modeling, Computer Simulations and Real Time Physical Measurements. Analytical Modeling may be impossible for complex systems such as this research, and Real Time Physical Measurements would require a very long time to be performed and a considerable investment in equipment and resources. Computer Simulation is the only reasonable approach to the quantitative analysis of both traffic and computer networks for this research.

Computer Simulation may be based on the Discrete Event Simulation (DES) approach, which is based on a event scheduler and only calculates the impact of those events, or Continuous Simulations, which simulates the whole system for all the instants simulated. For example, the simulation of one car moving at a certain speed along a road without obstacles can be either simulated continuously, or by configuring an event corresponding to the next instant that the vehicle has to modify its movement, saving a considerable amount of simulation time and computer resources. Consequently, when possible computer based simulators use the DES approach.

Diverse simulation environments have been tested in order to recommend the best option for the optimization of the handover in 802.11p environments. In this chapter they will be presented and analyzed alongside their advantages and disadvantages. Even though the simulators share a main set of features, each one has its own distinctive characteristics, which will be the parameters which will determine the best option for our simulation requirements.

The node mobility simulation, which is very important for realistic VANET simulation results, can be either integrated in the same software suite as the network simulator or, on the other hand, be based on a federation of different software which can interact properly by means of trace translation, etc.

5.1 Selection

Based on the description of features described in chapter 2 and the previously mentioned suitability for this research there are two simulators which have been discarded, namely BonnMotion and GloMoSim. Even though CanuMobiSim itself is not suitable either, when used with its extension VanetMobiSim will be taken into account as trace simulator. The main aspect where realism is required in order to optimise the IEEE 1609.4 is the network model, while at the first steps of the optimization the mobility model can be simple and become more complex for validation and the implementation of optimization techniques not based on parameters.

5.1.1 Network simulators

The priority in the choice of simulation environment is the network simulator. The most relevant network simulator features in order to select the most appropriate for this research are:

- Ease of use;
- Flexibility Mobility features ;
- WAVE Module: Availability and adequacy of WAVE/IEEE 802.11p modules for the platform. This includes the configuration possibilities in order to setup the parameters in order to optimise them, as well as the handover capabilities of the model, key to achieve realistic results for our research;
- Other modules: Availability of models which may enhance the realism of the simulation and/or be required for further research in the topic;
- Performance: This has been differentiated between big and small simulations, as there may be an important gap depending on the simulator. For our research the number of vehicles required to have valid results will not require a big simulation, but further research using the same simulation system to study e.g. other protocols may require a considerable amount of nodes; and
- Workflow: How easy is to generate different simulations, and how easy is to batch the simulations in order to (i) make statistically uncorrelated simulations when random variables are present and (ii) vary the values from one simulation in order to sweep a parameter among an interval of interest.

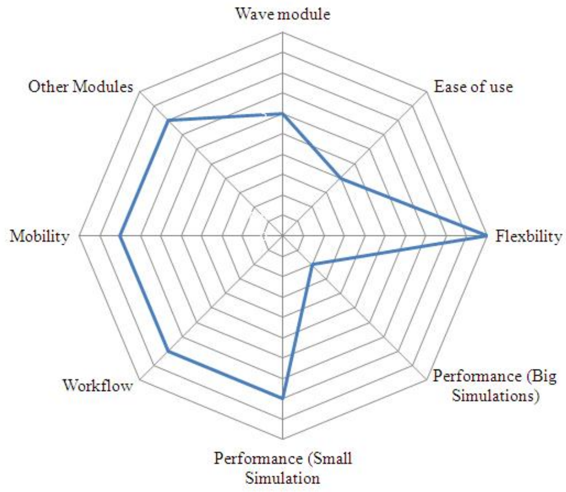

Figure 5.1: ns-2 features chart.

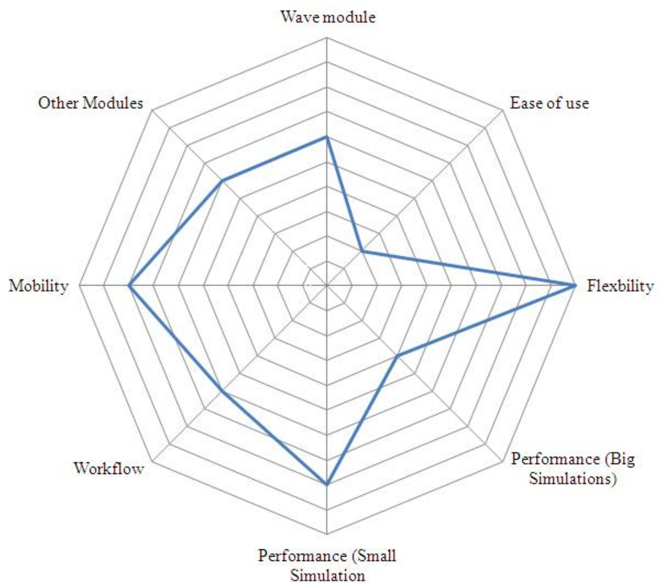

Figure 5.2: ns-3 features chart

After the installation and testing of ns-2, ns-3, ESTINET and OMNeT++, the evaluation of the candidates according to this features are illustrated as charts in figures 5.1 and 5.2 to 5.3 and 5.4.

Considering the simulations required in order to achieve the goal of this research, and based on the descriptions and feature charts, the choice of simulation environment is either ns-2 or ns-3. However, the simulation environment choice may differ for other research, as there are VANET simulations for which this solutions would not be adequate due to the lack of synchronised mobility and network models. Those features are critical in simulations such as the performance of accident-response and mobility patterns depending on the VANET data flow. Taking in consideration our goals, the simulation framework that will be used for this research is ns-2.

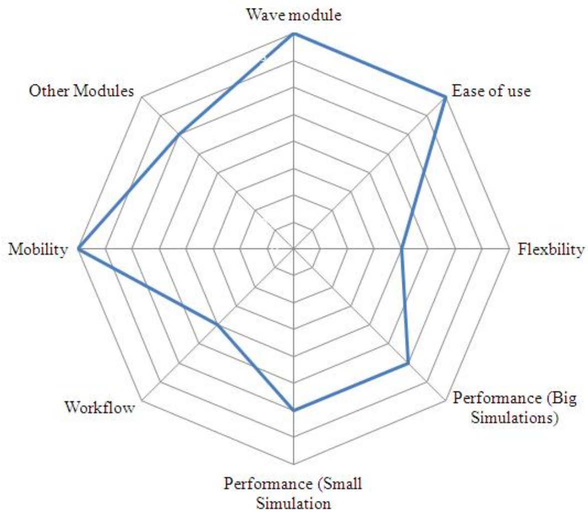

Figure 5.3: ESTINET features chart.

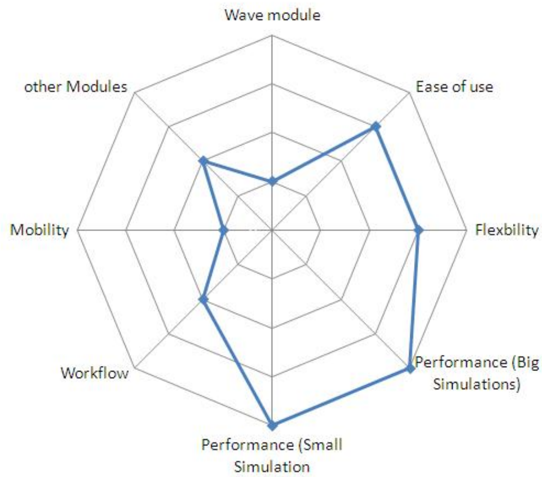

Figure 5.4: OMNET++ features chart

5.1.2 Mobility Simulator

The choice of traffic simulator for our research has been reduced to two candidates: SUMO and VanetMobiSim. For the simulations required for this research, complex mobility simulations are not required, and both systems have a set of features which exceed our requirements. Both frameworks provide a wide array of configurations, including both real and artificial layouts, multi-lane roads, influence of traffic signs, etc. and can export their mobility traces as ns-2 format. Hence, the choice of traffic simulator is not critical between our two candidates and it will become a choice of the researcher who may even choose one simulator or the other according to each particular simulation requirements.

CRCN is based on ns-2 and the fact is that ns-2 is the most viable candidate for our research, the simulators we chose are ns-2/SUMO/CRCN.

5.2 Cognitive Radio Cognitive Network (CRCN) Simulator

5.2.1 Background of CRCN

Cognitive radio network is a new emerging research area recently. It enhances the existing software-defined radio [72], whose physical layer behavior is largely defined in software. Cognitive radio has the following characteristics [73]. First, it is aware of its environment and its capabilities. Second, it is able to independently alter its physical layer behavior based on its previous experience and its current environment. Finally, it is capable of performing the complex adaptation strategies according to the cognitive cycle shown in [74]. With these capabilities, when spectrum environment changes around cognitive user, it is capable of sensing these changes and independently changing its physical layer settings such as transmission power, channel selection and etc to meet some constraints or QoS requirements of the users.

Cognitive radio gains popularity in the research area because it enables the current fixed spectrum channel assigned by FCC to be utilised by the new users. For example, most of the spectrum assigned to TV channels are idle most of the time, while wireless network users share a small range of spectrum, 2.4 G Hz and 5G Hz. When there are many wireless users at a time, the network is congested because of the limited number of channels. With the spectrum opportunities [75] provided by the cognitive radio network, the wireless network users are able to share the idle spectrum for TV channel, on the condition that it does not interfere with the normal TV channel.

5.2.2 Motivation

As cognitive radio research is emerging, more and more researchers are looking forward to a simulator that is suitable for cognitive radio. However, there is no existing simulator that is suitable for the demand of cognitive radio simulations. Many researchers implemented their algorithms for cognitive radios on existing network simulator such as ns-2 [85], OPNET [110], QUALNET [111]. However, since these simulators are created for the ordinary wireless network, researchers can not easily implement their cognitive radio algorithms over those simulators. Hence, there is a demand to extend existing simulators to support cognitive radio simulators. We make use of existing ns-2 to extend it to support cognitive radio network simulation.

5.2.3 Why based on ns-2?

There are several reasons to base on ns-2 for the development of cognitive radio simulators. First, ns-2 is open source software. Any contributions to ns-2 are accessible by people around the world. Second, ns-2 provides an interface for users to configure different network protocol at each network layers, which is essential for simulation. Third, ns-2 already provides many radio models, such as 802.11, 802.16, 802.15.3, 802.15.4. Users can make use of these radio models for cognitive radio network simulations. Finally, ns-2 has incorporated with different topology and traffic generators, which enable users to create different simulation scenarios.

5.2.4 CRCN simulator overview

This cognitive radio cognitive network (CRCN) simulator is a software based network simulator for network-level simulations. It is based on open-source ns-2 (network simulator 2). CRCN simulator supports performance evaluations for the proposed dynamic spectrum resource allocation, power control algorithms, and the adaptive Cognitive Radio (CR) networking protocols including the CR MAC and the CR Routing protocols. This simulator uses ns-2 to generate realistic traffic and topology patterns. For each node in this simulator, a reconfigurable multi-radio multi-channel PHY layer is available by customizing the spectrum parameters such as transmission power, propagation and so on.

The architecture block diagram for this simulator is illustrated in Figure 5.5. The CRCN simulator enables the interface parameters transmission between different layers, as shown in arrows with blue color. Users just need to replace their own Routing and MAC algorithms according to ns-2 protocol design requirements with the existing one in the CRCN.

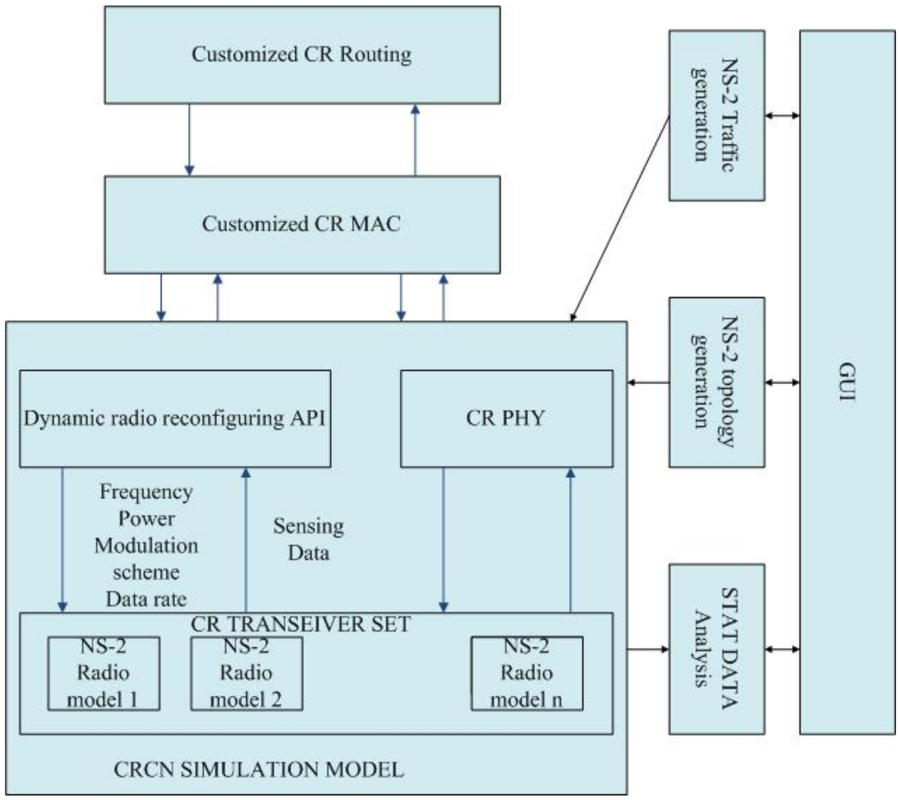

Figure 5.5: CRCN architecture block diagram.

5.2.5 Functionality overview

- CR Routing/CR MAC algorithms

Several exemplary algorithms for CR Routing and CR MAC are given in the CRCN simulators. These algorithms illustrate how to use the functionality provided by this simulator. Also, these algorithms provide simulation environment for CR networking protocols. Users can replace these components with their own algorithms, and test the performance of their designs.

- Performance Evaluation for CR algorithms

This simulator contains several evaluation metrics for performance evaluations of the algorithms at different layers. Currently, the evaluation metric include summate, interference.

- Graphical User Interface (GUI)

A user-friendly GUI is provided to define simulation scenarios. Users can select the different network protocols, different topology and traffic model and so on. Also, users can start the simulation and see the simulation result through this GUI.

Table 5.1: Functionality Overview

Support for CR Routing	Support for CR MAC	Support for CR PHY
Multi-radio multi-channel support	Multi-radio multi-channel support	SINR and SNR physical model
Single-radio multi-channel support	Single-radio multi-channel support	-
Interface to select radio	-	-
Interface to select channel	Interface to select channel	-
Heterogeneous radio and spectrum environment	-	-
Information needed during routing process	Information needed during dynamic spectrum access	-

5.3 Simulation Scenario

There are some general parameters in any given simulation which will determine the environment characteristics and will influence in the results of the simulations. For the optimization of channel utilisation, and the need for the reliability of safety messages in order to be valid; it is required that the parameters have a minimum impact in the results.

The design of the simulation may eventually reduce the level of realism of the results of the simulation, but will allow fast batched simulations to define the values, which will then be applied in more complex scenarios where the optimised values will be validated. The selection of the non-strictly IEEE 802.11p parameters defining the environment for the simulation and their descriptions are:

- Node layout and movement pattern: The layout is as seen in fig 3.11. There are 0 to 200 vehicles at a distance which varies from 100m to 1000m proceeding along the straight way at random speed between 40 to 80km/h. The road has five infrastructure nodes at a distance of 1000m. This layout has been chosen to make the simulations with multiple vehicles in order to make a more realistic physical layer response for different vehicle load. The implementation is quite complex, thus the choice is to implement it directly on the SUMO and link it with ns-2 later. Regarding the traffic simulation and mobility, I used SUMO which is a microscopic traffic simulator [81]. SUMO performs simulations of vehicle movements in real word maps adhering to multiple lanes, speed limits and traffic lights.

- Car-Following Model: For SUMO parameters, we have to set a Car-Following Model. The model developed by Krauss in 1998 is a microscopic, space-continuous, car-following model based on the safe speed paradigm: A driver tries to stay away from the driver in his front at a distance and a safe speed that allows him to adapt to his leader's deceleration [112]. The model assumes the driver to have a reaction time τ of about one second.

The model uses the following parameters [112]:

1. A: the maximum acceleration of the vehicle
2. B: the maximum deceleration of the vehicle
3. Vmax: the maximum velocity of the vehicle
4. l: the length of the vehicle
5. e: the driver's imperfection in holding the safe speed (between 0 and 1)
6. Vsafe: Safe velocity computed using the following equation: V safe(t) = V$\star$L(t) + $\frac{g(t)-VL(t)\tau}{\frac{V}{B\star V}+\tau}$

Where:

– VL(t) : Speed of the Leading Vehicle in time t

– g(t): Gap to the Leading Vehicle in time t – τ :

– τ: The Driver's Reaction Time (usually 1s)

- Routing Protocol: there are a variety of available ad-hoc routing protocols in ns-2, namely DIFFUSION/RATE, DIFFUSION/PROB, DSDV, DSR, FLOODING, OMNIMCAST, AODV, TORA and PUMA. However, in our simulation, as we configured the topology with multiple mobile nodes, for the analysis of our model it is more convenient to use any ad-hoc routing protocol and we have chosen AODV as its very easy to implement and reliable.

- Radio Propagation Model: as the simulation environment is meant to be simple and does not simulate urban environment, there is no need to add simulation complexity by using a highly realistic propagation model as shadowing or Nakagami, which would only increase the simulation time without any significant value added to the results [113]. We will use the two-ray-ground reflection model, which is more suitable for this simulation as it considers both the direct path and the ground reflection, which for VANET simulation is more realistic than the Free Space model without adding significant simulation time. It must be remarked that the ns-2 implementation of the two-ray-ground uses Friss-space attenuation (α/r^2) when the distance is short and an approximation to two-ray-ground (α/r^4) for longer distance [114]. This is because two-ray models do not provide good results for short distances because of the oscillation caused by the constructive and destructive combination of the two rays.

- Link Layer: in ns-2 is implemented by a Queue and a LL object in order to provide configuration flexibility. There are two LL objects: LL and LL/Sat for wireless satellite systems. We will use LL, oriented for not satellite wireless. The queue for our simulation where QoS priority is taken into consideration|, will be Queue/DropTail/PriQueue.

- Antennas: Omni-directional antennas with unity gain (for both transmission and reception) which are centered in the node and 1.5 meters above it.

5.4 Simulation Parameters

The WAVE standard fixes a series of parameters for both IEEE 1609.4 physical layer (PHY) and medium access control layer (MAC) in order to ensure interoperability; In table [5.2] the PHY parameters are described, while the standardised MAC IEEE 1609.4 parameters involved in the simulation are the ones in the table [5.4].

5.5 Summary

In this chapter, Different ways to analyse the system were presented. Moreover, we have discussed selection criteria for mobility and network simulator. Secondly, we have justified our choice of simulators. Finally we have presented the simulation scenario, topology and parameters.

Table 5.2: IEEE 1609.4 PHY parameters

Parameters	Description	Value
Transmission Range	Maximum communication range between OBU and RSU	1000m
CSThresh	Wireless interface sensitivity	-85dbm
Data Rates	in Mbps	3 to 27
Frequency	-	5.9GHz
Modulation Scheme	Modulation is set according to different data rates	Table [5.4]
Channel	Physical medium	Wireless
Bandwidth	-	10MHz
PowerMonitorThresh	Power monitor sensitivity	-102dbm

Table 5.3: OFDM Signal structure depending on BW

Data Rate	Modulation	Encoding Rate	Bits per sub-carrier	Bits per symbol(Coded)	Bits per symbol (Data)
3	BPSK	1/2	1	48	24
4.5	BPSK	3/4	1	48	36
6	QPSK	1/2	2	96	48
9	QPSK	3/4	2	96	72
12	QAM-16	1/2	4	192	96
18	QAM-16	3/4	4	192	144
24	QAM-64	2/3	6	288	192
27	QAM-64	3/4	6	288	216

Table 5.4: MAC layer parameters

Parameters	Description	Value
CWmin	Minimum Contention Window for congestion control	Table [5.2]
CWmax	Maximum Contention Window for congestion control	Table [5.2]
AIFSN	Arbitary Inter-Frame Space Number	Table [5.2]
AIFS	Arbitary Inter-Frame Space	Table [5.2]
Slot Time	in micro seconds	13
SIFS	Short Inert-Frame Space in micro seconds	32
Bandwidth	-	10MHz
Short Retry Limit	Retry limit for short MAC layer frames	7
Long Retry Limit	Retry limit for long MAC layer frames	4

Table 5.5: The Simulation Parameters used for the analysis of IEEE 1609.4 simulation model

Parameters	Values
Simulator	ns-2.34
Number of OBUs	up to 200
Number of RSUs	5
Data Rate	3 Mbps
Simulated Area	2000*400 squaremeter
Communication Range	300 and 500m
Message generating frequency	3,5 and 10 Hz
Fading Model	Two way round

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Due to the inherent characteristics and diverse challenges facing vehicular networks, existing MAC protocols are not suited to meet VANET's requirements. In this thesis, a new multichannel cognitive MAC protocol is introduced, followed by an enhancement mechanism of EDCA and safety message acknowledgment for improving the performance of MAC's contention and reservation in vehicular networks. The proposed protocol together with the enhancement mechanism were both evaluated with ns-2 and simulations showed improvement for the MAC in-terms of Channel utilisation, waiting time interval, delay, jitter, and frame error rate.

First, a background discussion of MAC protocols is presented. Moreover, MAC design guidelines were highlighted. Following a top down approach, diverse multiple access schemes were explained and then the most suitable protocols for VANETs were discussed. From the perspective of using different MAC architectures, overviews of the existing MAC solutions for a vehicular environment were briefly introduced. This provided a broad overview of the current existing MAC protocols for VANETs. Finally, a qualitative comparison between different existing protocols was provided. I then proposed a new Multichannel Cognitive MAC (MCM) tailored for vehicular communications. The proposed MCM protocol increases the channel utilization for both primary and secondary users due to extended transmission time periods, while maintaining the reliability of the data transmission for safety applications. MCM ensures QoS by granting safety messages a higher priority, and improves the channel utilisation up to 70% with the use of cognitive radio technology. Moreover, MCM assesses the channel prior to transmission messages which are always sent on the best available channel to mitigate high interference and multipath problems. Those features make the proposed protocol MCM more suitable for VANET environments.

Moreover, we have designed the additional modules in ns-2 which are required to simulate the IEEE 1609.4 for realistic scenarios. Performance analysis using different channel switching shows that the IEEE 1609.4 standard is not reliable for safety communication and the channels are underutilised. In addition, we have proposed an Enhanced EDCA and Safety message Acknowledgment; which is a new MAC enhancement mechanism added on top of EDCA, a MAC Layer mechanism, tailored for vehicular communications incorporating mobility, QoS and integrates them into the MAC to mitigate VANET challenges. The proposed MAC protocol has different AIFSN values for different ACs, in order to establish the strict priorities, and to develop the mechanism to send acknowledgment for broadcasted safety messages confirming that they have been successfully received; the lost frames being retransmitted using the binary-exponential back-off technique. We analyzed our proposed MAC protocol and compared it with the developed IEEE 1609.4 MAC protocol, The analysis showed that our MAC protocol reduces the delay, jitter and losses for the safety messages even in the extreme conditions. The tradeoff has been an increase in the delay for lower priority messages, but it is noteworthy that lower priority messages can tolerate the delay as they are not related to safety applications, and so they do not have time constrained.

6.2 Future Work

Although this thesis provides a comprehensive study and evaluation from various perspectives, there are still some open issues and several research directions that can be pursued to improve the performance of proposed MCM protocol.

- Multiple Hops: The proposed MAC protocol and the enhancement mechanism are both for one hop transmission. Future work may expand the operation of both of them to consider multiple hops.

- Heterogeneous Networks: Work can be done to provide a MAC handover process between different heterogeneous networks such as cellular networks or WLANs from one side and vehicular networks from the other. Moreover, the MCM architecture of having multiple channel can be helpful in the handover process and may facilitate such convergence implementations.

- Fuzzy adaptiveness: It is very difficult to quantify speeds in real world environments as they are always fluctuating. Moreover, in reality, it is difficult to determine if the relative speed is very high or very low. There is always a fuzzy region between the different classes of relative speed. Therefore, to avoid crisp assignment and to translate the knowledge from uncertain form to a meaningful output, fuzzy logic based soft computing is expected to give better quantification.

- Joint analysis: In our work, we assume a routing protocol that is not based on the mobility factors. A more thorough model should benefits from the same evaluation in a cross-layer design with the upper and/or lower layers. For example, a joint routing and MAC performance analysis based on mobility metrics, such as relative speeds and positions, is expected to provide better end-to-end delivery and QoS provisioning.

- Mobility index: There is a mobility impact on the performance of VANETs. The impact is proven to exist. However, a more precise measure that can indicate the mobility state of the node in the network according to its current state would help to enhance the MAC performance. This measure should provide different communication priority for the vehicles based on their mobility and provide better fairness.

- Secure MAC protocol: Designing of a security mechanisms to secure VANETs against abuse, and designing of efficient medium access control (MAC) protocols so that safety related and other application messages can be timely and reliably disseminated through VANETs. Design of the secure communication protocol, which will have time-stamp, digital signature, and trust certificate to guarantee the freshness of the message, message authentication and integrity, message non-repudiation, and privacy and anonymity of the senders.

- Wireless channel fading model: It is infeasible to use real vehicles for the large scenario in different conditions to develop new algorithms and protocols for VANET. A wireless channel is unsteady and lossy, so simulators for VANET require a model of these characteristics. It is vital to investigate requirement for adequate radio propagation and mobility models for VANET as these two factors play an important role to adopt the protocol suitable for vehicle communication.

- Realistic Simulation Model: Realistic V2V channel modeling has become a crucial issue in Intelligent Transportation Systems (ITS) networks. V2V channels are known to exhibit specific features which imply the design of new simulation models. A study on the main physical features of such wireless time and frequency dispersive channels are a key research area. Moreover, the importance of a realistic channel and physical layer modeling in vehicular networking needs to be addressed.

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Appendix A

COGNITIVE RADIO ALGORITHMS

A.1 CR MAC

This section presents the modification and different algorithms of MAC layer to support CR technology and wideband sensing.

- Component 1. Define the channel number in TCL script

Seven channels are available in the network

Algorithm A.1 Define Number of Channels.

```
set val(channum) 7 ;#
```

- Component 2. New channel objects according to the interface number provided in Component 1.

Algorithm A.2 Tcl scripts to define New Channel Object.

```
for {set i 0 } { $i < $val(channum)} {incr i} {
set chan_($i) [new $val(chan)] ; #new channel objects
}
```

- Component 3. Configure the multiple channel option

Algorithm A.3 Tcl Script to configure multi-channels.

```
$ns_ node-config -adhocRouting $val(rp) \
- ChannelNum $val(channum)\ ;# configure channel number
-channel $chan_(0) ;#configure the first channel object
```

- Component 4. Assign the channel objects to the channel array of the simulator.

Algorithm A.4 Tcl scripts assigning channel objects.

```
for {set i 0} {$i < $val(ni) } {incr i} {
$ns_ add-channel $i $chan_($i) ; # initialise the channel array with chann
```

A.1.0.1 Interface for channel decision

The channel decision from CR MAC has been set through the interfaces provided as follow, which reflects the channel that the receiver is using to receive packet. A new field channelindex_ is added into the packet header. After CR MAC makes channel decision, this decision can be stored into this field.

Algorithm A.5 Module packet.h:.

```
struct hdr_cmn {

int channelindex_;

}
```

The code as follow should be added in the sendDown function for wirelessphy. In our design, multiple channel object pointer is used to index the channel object. Hence, it is appropriate to use channel index derived in CR MAC to differentiate channel, which helps to achieve conflict free or reduce interference among neighboring nodes. channelindex_ defined in the packet header can carry this information from CR MAC to the wireless physical layer.

Algorithm A.6 Module WirelessPhy: Interface for channel decision in MAC.

```
void WirelessPhy::sendDown(Packet *p)
{

// Send the packet //
channel_->recv(p, this);
//send packet over the channel specified by channel index.
multichannel[hdr_cmn::access(p)->channelindex_]->recv(p, this);
}
```

As our MAC is for single-radio and multi-channel network, the above code change is enough to differentiate different channels for MAC protocols. Moreover, to avoid collision, random back-off scheme is being used.

A.1.0.2 Interface for transmission power decision

Packet will be transmitted using the default transmission power if transmission power is not specified in simulation script. However, as CR MAC may control the txpower over each channel to control the interference to primary users or nearing neighbors, it is necessary to provide an interface, which can control the txpower during the simulation.

Algorithm A.7 Module Mobilenode: Interface for obtaining the transmission power from CR MAC.

```
Class PacketPr{ public:

//Obtain CR MAC decision according to different input parameters.
double getMACPr(int receivernode);
double getMACPr(int receivernode, int channelindex);

}
```

Then, we have added the following interface for controlling the maximum transmission power and obtaining CR MAC power decision.

Algorithm A.8 Module WirelessPhy: Interface for channel decision in MAC.

```
int WirelessPhy::sendUp(Packet *p) {

double MACPr= (MobileNode*)node()->PacketPr_.getMACPr();
//if the Pr is within the limit range of user, assign MACPr to Pr.
Pr=MACPr;

}
```

To determine the txpower, the CR MAC algorithms need to know the identity of sender and receiver. As the sender and receiver has negotiated the channel decision, and thus the power control algorithm compute the txpower over the negotiated channel.

A.1.0.3 Interference information

The interference information is associated with each node over each channel. Several kinds of interference information are needed:

- Channel that has minimum interference

Interface for obtaining channel number with minimum interference around one node. We have used the following method to obtain channel number which has minimum interference.

Algorithm A.9 Module Mobilenode: obtain channel with minimum interference.

```
Class PacketPr{

//return the channel id with minimum interference.
int ChannelwithMinimumIf{ return chanwithminiIf;}

}
```

- Current interference value over a specific channel

We have used the following method to obtain interference value. Please note the interference value is sometimes too small and so, it has been scaled by some factor to see the result

Algorithm A.10 Module Mobilenode: Interface for channel decision in MAC.

```
Class PacketPr {

//obtain the interference information for current node.
double getInterference(int channelno);

}
```

- Historical interference information.

To obtain the historical information of node i, we have added the following option to select whether to record interference on node i in simulation script by the user.

We have used the corresponding API into their algorithm to obtain the information.

Algorithm A.11 TCL script: add the interference option.

```
for {set i 0} {$i < $val(nn) } {incr i} {
set node_($i) [$ns_ node]
$node_($i) set SingleIfMultiChan 1 ;
$node_($i) set recordIfall 1 ; # enable interference information collectio
$node_($i) random-motion 0 ;# disable random motion
}
```

If this option is added, the interference information about node i is provided. Besides obtaining the channel with minimum interference, the interference information over each channel around can be obtained through the ITfile generated by the simulator. The format of the ITfile is as follow. We can obtain their information through ITfile according to the format shown in fig A.1.

ITfile format			
Timestamp	Nodeid	Interference	Channel id

Figure A.1: ITfile format

A.1.0.4 Traffic information

For our CRMAC, it is necessary to use the sensing traffic information to predict the future traffic information in the neighborhood, and derive the best user strategy. The interface are in the two formats:

- Obtaining the current traffic information

We have used the following function to obtain traffic information

Algorithm A.12 Module Mobilenode: obtain traffic information.

```
class PacketPr {
public:

int getTrafficCount() {return trafficcount;}

}
```

We can access this function through the pointer to mobilenode. For example, in the MAC , we can access traffic information like the following way.

Algorithm A.13 Module Mobilenode: obtain traffic information.

```
int traffic= ((MobileNode*)(netif_->node()))->PacketPr_.getTrafficCount();
```

- Obtaining the historical traffic information.

The historical traffic information is stored in the Trafficfile. We can obtain this information based on the format shown in fig A.2.

Trafficfile format		
Timestamp	Nodeid	Traffic information

Figure A.2: Traffic file format.

A.1.0.5 Channel utilisation information

To obtain the channel utilization information, we have added the following codes in the MAC layer.

- We have added the timer definitions in the CRMAC.

Algorithm A.14 Module mac1609.4.h: add timers for channel utilization .

```
//Timer for channel utilization
class ChanUtil_Timer : public TimerHandler {
public: ChanUtil_Timer(mac1609.4 *a) : TimerHandler() { a_ = a;} void expi
protected:
mac1609.4 *a_;
};
```

Algorithm A.15 Module mac1609.4.h: add timers for calculate channel utilization.

```
//Timer to Calculate channel utilization
class CalChanUtil_Timer : public TimerHandler {
public: CalChanUtil_Timer(mac1609.4 *a) : TimerHandler() { a_ = a;}
void expire(Event *e);
protected:
mac1609.4 *a_;
};
```

- The timer functions' implementation in the CRMAC

Algorithm A.16 Module mac1609.4.cc: add timer functions' implementation.

```
//Timer for recording channel utilzation
void ChanUtil_Timer::expire(Event *)
{ a_->ChanUtil_Calculate();
//Traffic timer expires for every node or the node specified
resched(0.01);
}
//Timer for calculating channel utilzation
void CalChanUtil_Timer::expire(Event *)
{
a_->CalChanUtil_Calculate();
//Traffic timer expires for every node or the node specified
resched(1);
}
```

- We have also added the timer definitions in the mac1609.4

Algorithm A.17 Module mac1609.4.h: add timers variable in mac1609.4mac class

```
Class mac1609.4{

friend class ChanUtil_Timer;
friend class CalChanUtil_Timer;

public: FILE *fp;
ChanUtil_Timer ChanUtil_Timer_;
CalChanUtil_Timer CalChanUtil_Timer_;
void ChanUtil_Calculate(); //function for recording channel utilization
void CalChanUtil_Calculate(); //function for calculating channel utilizatio
void resetChanUtil() {chanutilcount=0;}
int getChanUtil(){return chanutilcount;}

private:

int chanutilcount;

}
```

- We have defined the timer functions' implementation in the mac1609.4 class as follows:

Algorithm A.18 Module mac1609.4.cc: add the related function implementation as defined in mac1609.4 class.

```
void mac1609.4::ChanUtil_Calculate()
{
//if mac is not idle
if(!is_idle()){
//increase channel utilization counter
increaseChanUtil();
}
}
void
mac1609.4::CalChanUtil_Calculate()
{
if (((fp = fopen("Chanfile", "a")) != NULL) )
{
fprintf(fp, "%lf %d %lf\n" ,NOW,((MobileNode*)(netif_->node()))->nodeid(),
fclose(fp);
resetChanUtil();
} else {
printf("fail to open file");
}
}
```

Appendix B

WORD-WIDE VANET PROJECTS

USA

- DSRC: http://www.leearmstrong.com/DSRC/DSRCHomeset.htm
- California PATH: http://www-path.eecs.berkeley.edu/
- DynaMIT: http://mit.edu/its/index.html
- ITS Research; Program http://www.ivhs.washington.edu/
- CITranS: http://citrans.pti.psu.edu/ CISR http://www.cisr.gwu.edu/
- TIDE: http://www.njtide.org/ ODU_VANET; http://www.cs.odu.edu/~vanet/index.html

Europe:

- AIDE: http://www.aide-eu.org/
- Car to Car; http://www.car-2-car.org/
- CarTALK 2000: http://www.cartalk2000.net/
- CVIS; http://www.cvisproject.org/
- FleetNet: http://www.et2.tu-harburg.de/fleetnet/index.html
- Invent; http://www.invent-online.de/
- Network on Wheels; http://www.network-on-wheels.de/
- SEVECOM; http://www.sevecom.org/
- SAFESPOT: http://www.safespot-eu.org/pages/page.php SmartPark http://smartpark.epfl.ch/
- WATCH-OVER: http://www.watchover-eu.org/

- WILLWARN: http://www.prevent-ip.org/en/prevent_subprojects/ safe_speed_and_safe_follo

Japan:

- ITS Consortium: http://www.its-jp.org/english

Appendix C

VANET SIMULATION PROGRAMS

Network Simulators

- NS-2: http://www.isi.edu/nsnam/ns/
- GloMoSim:http://pcl.cs.ucla.edu/projects/glomosim/
- QualNet: http://www.scalable-networks.com/
- OPNet: http://www.opnet.com/
- Estinet: http://nsl.csie.nctu.edu.tw/nctuns.html
- MATLAB: http://www.mathworks.com/

VANET Mobility Generators

- VanetMobiSim: http://vanet.eurecom.fr/
- CanuMobiSim: http://canu.informatik.uni-stuttgart.de/mobisim/
- Simulation of Urban MObility: SUMO from http://sumo.sourceforge.net

Joint Mobility and network simulators for VANET

- TraNS: http://trans.epfl.ch/
- MOVE: http://www.csie.ncku.edu.tw/~klan/move/index.htm

Appendix D

NTIB'S SPECTRUM ALLOCATION CHART

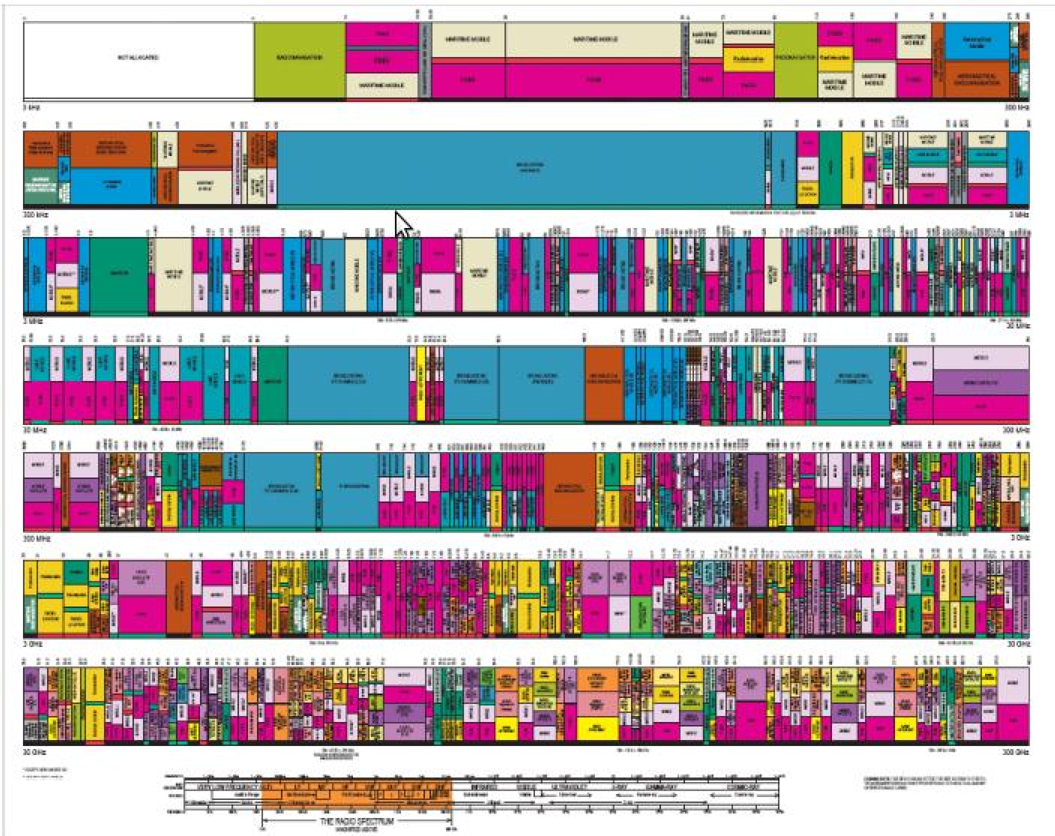

Figure D.1: Spectrum allocation and spectrum usage and NTIB's spectrum allocation chart.

Appendix E

INSTALLATION GUIDE FOR WAVENS PROJECT

The easiest installation method for ns-2.34 is by means of the all-in-one package, as it includes not only the ns-2.34 package but also some software that will allow the visualization of traces, creation of graphics, etc. After the installation and for the purpose of t research work, consideration should be given to substituting the original ns-2.34 directory with the one of the WAVEns project [89], available from the svn repository using the following command:

```
svn co https://wavens-2.svn.sourceforge.net/svnroot/wavens-2
wavens-2
```