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A Simulation Study on the Performance Comparison of the V2X Communication Systems: ITS-G5 and C-V2X

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Abstract

Personal mobility and vehicular transportation system are undergoing a shift towards more reactive and intelligent transport infrastructure. Wide range of applications and use cases have emerged in the vehicular environment facilitated by various wireless communication systems. These applications can be broadly classified into road safety, traffic efficiency and infotainment services, each with its own set of functional and performance requirements. Interoperability and coexistence of multiple radio access technologies provide opportunities to meet the application requirement by capitalising on the strengths of each technology.

Two emerging Intelligent Transport System (ITS) technologies, namely Cellular Vehicle-to-Everything (C-V2X) and ITS-G5, are the focus of this work. A detailed qualitative comparison of the protocol stacks is provided along with performance evaluation of the standards. This work evaluates the performance of ITS-G5 and C-V2X for safety message application through simulation in a realistic highway scenario. The results indicate a superior performance by ITS-G5 in sparse vehicle density, delivering 80% of the beacons at a transmission frequency of 10 Hz. Moreover, ITS-G5 delivers beacons with less delay than C-V2X. C-V2X fares better for extremely dense networks in terms of delivering packets as well as inter reception time. It is inferred that appropriate resource allocation is vital in C-V2X to limit the transmission delay to within within 500 ms when delivering beacons to the destination node, without compromising on the packet reception ratio and inter reception time.

ETSI's recently proposed co-channel coexistence methods for encouraging spectrum neutrality, that allows C-V2X and ITS-G5 to operate in the 5.9 GHz, leads to co-channel coexistence issues between the two technologies. This work provides the skeleton of a combined framework which can be used to further study the coexistence challenges.

Sammanfattning

Personlig rörlighet och fordonstransportsystem genomgår en förskjutning mot mer reaktiv och intelligent transportinfrastruktur. Ett brett spektrum av applikationer och användningsfall har dykt upp i fordonsmiljön underlättad av olika trådlösa kommunikationssystem. Dessa applikationer kan i stort sett klassificeras i trafiksäkerhet, trafikeffektivitet och infotainmenttjänster, var och en med sina egna uppsättningar av funktionskrav och prestandakrav. Interoperabilitet och samexistens av flera radioåtkomstteknologier ger möjligheter att uppfylla fordonets nätverksapplikationskrav genom att utnyttja styrkorna i varje teknik.

Detta arbete fokuserar på två framväxande tekniker för intelligent transportsystem (ITS), nämligen 3rd Generation Partnership Project (3GPP) Cellular Vehicle-to-Everything C-V2X och ITS-G5. En detaljerad kvalitativ jämförelse av protokollstakarna tillhandahålls tillsammans med resultatutvärdering av standarderna. Detta arbete utvärderar prestanda för 802.11p och LTE-V2X för säkerhetsmeddelandetillämpning genom simulering i ett realistiskt motorvägscenario.

Resultaten indikerar en överlägsen prestanda med IEEE 802.11p i gles fordonsdensitet, vilket levererar 80% av paketen med 10 Hz fyrfrekvens. Dessutom levererar ITS-G5 paket med mindre fördröjning än C-V2X. C-V2X presterar bättre för mycket tätt nätverk när det gäller att leverera paket samt intermottagningstid. Det dras slutsatsen att lämpliga resursallokeringar (resursblock och MCS) bör göras för att begränsa förseningen i att leverera paket till destinationsnoderna inom 500 ms utan att kompromissa med paketmottagningsförhållandet och intermottagningstiden, särskilt för mycket täta nätverk.

ETSI: s nyligen föreslagna samexistensmetoder för samkanal för att uppmuntra spektrumneutralitet, som tillåter C-V2X och ITS-G5 att arbeta i 5,9 GHz, leder till samkanaliska samlivsfrågor mellan de två teknologierna. Detta arbete tillhandahåller skelettet i en kombinerad ram som kan användas för att ytterligare studera samexistensutmaningarna.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Dating back to the late 1800s, Karl Benz's model of gasoline engine sparked the beginning of an exciting era for automobile revolution. Ford Henry's mass production of cars not only set the standards for automobile manufacturing but also paved the way for the societal transformation around the world. With the advent of advanced information and communication technology over the last few decades, automobiles have evolved from a simple mechanical device to a highly complex and intelligent device that holds hundreds of sensors embedded. Enormous data gathering, processing, coupled with the need to improve road safety has sparked research in the area of vehicular communications. While in-vehicle sensors enable many functionalities, inter-vehicular communication promises additional benefits with respect to efficient route optimisation, improved road capacity and parking infrastructure utilisation [1].
Vehicle-to-everything (V2X) communication encompasses all communication capabilities such as vehicle-to-vehicle (V2V), vehicle to pedestrian (V2P), vehicle to network (V2N) and vehicle-to-infrastructure (V2I), see Figure 1.1.
Vehicular communication network aims at relieving modern cities from serious traffic congestion, safety and environmental impact. Broad range of infotainment services is another benefit of advanced wireless technology that aims to improve our working efficiency and provide an enriching experience associated with automobiles of the future.
There are two major wireless communication technologies that facilitate communication for connected vehicles. Dedicated short-range communications (DSRC) [2] in the US, also known as ITS-G5 [3] in Europe, is based on The Institute of Electrical and Electronics Engineers' (IEEE) 802.11p technology [4]. It refers to a wireless short-range exchange of information messages between the vehicle and the roadside at specific locations. Cellular communica-

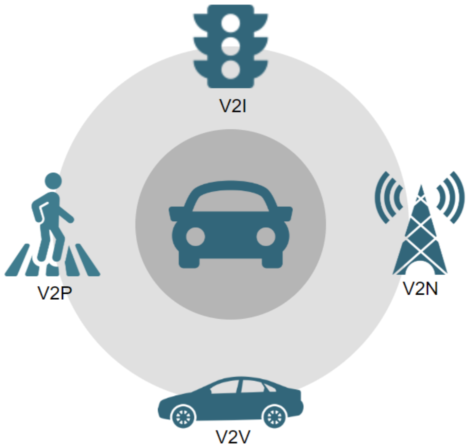

Figure 1.1: V2X components

tion network technology, such as Long-Term Evolution (LTE), although being a relatively new alternative to IEEE 802.11p technology, has been steadily and rapidly growing with specification for vehicular communication included in Third Generation Partnership Project's (3GPP) Release 14 [5] and Release 15 [6]. It also supports direct device-to-device (D2D) communication. LTE supports Cellular-based V2X (C-V2X) using classic cellular uplink/downlink communication, where a vehicle communicates with the base station to reach either back-end server or to connect to another vehicle.

The ability for C-V2X to provide reliable communication channel over large distances as compared to IEEE 802.11p has generated interest in studying these two technologies in combination, to create a reliable communication network in order to improve road traffic efficiency and safety. Experiments are generally limited by the number of automobiles as it would require extensive utilisation of resources and hardware to replicate a real world scenario. Simulations however have proved to be a budget friendly option to validate the effectiveness of a solution without over-utilisation of resources, cost and time. OMNET++ [7] and NS3 [8] are two commonly used discrete event simulators that support simulation of vehicle communication through supported model frameworks and extensions. LTE [9] and IEEE 802.11p [10] stacks have been implemented on OMNET++ and extensively used for simulating various networks.

1.1 Objectives

DSRC and C-V2X both have their pros and cons. IEEE 802.11p was primarily developed for its capability of carrying out distributed localised communication between vehicles in the absence of the roadside infrastructure. However, it suffers from drop in throughput under high congestion due to its basic physical layer and lack of protection mechanism from interference and collisions as a result of carrier sense multiple access with collision avoidance (CSMA-CA) at medium access layer (MAC) [1]. The main driving forces for using cellular network technology are Base Stations' (BS) large coverage area, high network capacity and mature technology. BS bridges the disconnections in a sparse V2X network and reduces the number of handovers as vehicles traverse a road segment.
The technology neutral nature of spectrum regulations in Europe means that C-V2X and IEEE 802.11p compete for the 5.9GHz spectrum. This has lead to the rise of several research challenges such as co-channel coexistence and adjacent channel interference [11]. Co-channel coexistence is referred to the communication scheme that allows two different radio transmitters (C-V2X and IEEE 802.11p) in a geographic area using the same frequency 5.9 GHz, to continue transmission without signal interference when transmitting packets in the same channel. 5G Automotive Association (5GAA) addresses the issue of co-channel coexistence between the two technologies at 5.9 GHz [12]. It proposes a spectrum sharing solution based on technology detection and dynamic channel selection to allow both technologies to operate safety-related Intelligent Transport Services (ITS) free from co-channel interference with the other technology. The question arises as to how effective is this solution when implemented in a specific network scenario, especially in high density vehicular scenarios. This work implements and utilises the highway scenario that uses comparable simulation parameters to evaluate the effectiveness of DSRC and C-V2X, individually as well as in an combined scenario. This project presents the qualitative and quantitative evaluation of DSRC and C-V2X when implemented independently. In addition to this, the objective is to implement a model to combine DSRC and C-V2X. This will provide a platform to kick start coexistence studies. Hence, the goals of this project can be summarised as the following:

- Carry out an in-depth functional and performance evaluation of DSRC and C-V2X using discrete event simulator OMNET++.
- Add a new implementation of co-existence model within OMNET++.

1.2 Research methodology

The research methodology employed in this work can be observed in figure 1.2.

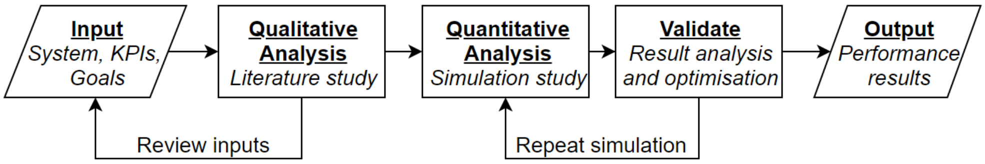

Figure 1.2: Research process

First stage includes problem identification and formulation respectively. These can be observed through the objectives stated in the Section 1.1. The current state-of-the-art system architectures for IEEE 802.11p and C-V2X are studied to identify the key performance indicators.
Qualitative analysis is the second research step to familiarise with the current state of feature functionalities, modes of operation, message types and research challenges in ITS-G5 and C-V2X. Literature study and related work is used to analyse and choose relevant performance metrics to represent the differences between the two technologies. Three vital performance metrics are chosen in this research to represent results. This acquired knowledge is passed onto next research step, i.e. quantitative evaluation.
Simulation environment that mimic real-world vehicular network is used as the primary tool to carry out performance evaluation. Evaluation for IEEE 802.11p and C-V2X are conducted independently with identical network characteristics such as route description, network map, and number of vehicles on the road. The results are validated and experiments are re-evaluated if necessary in order to perfect the simulation environment. The results obtained here are leveraged as baseline to compare the co-channel coexistence solution implemented in the next research step. Similar network characteristics are reused to implement coexistence solution that combines IEEE 802.11p and C-V2X. This would indicate the consistency and reliability of the overall system.

1.3 Report overview

The report is organised as below:
Chapter 2 gives a detailed description of the background on current state of vehicular communication standards ITS-5 and C-V2X. It also discusses the

scientific research conducted for the performance evaluation of DSRC and C-V2X.
Chapter 3 gives an overview of the simulation environment and the interaction between different components in the simulation.
Chapter 4 describes the experimental design setup and introduces the performance metrics.
Chapter 5 presents the simulation results for LTE-V2X and IEEE 802.11p comparison.
Chapter 6 discusses the results, limitations of the simulation and future work.
Chapter 7 presents the conclusion of the thesis work.

Chapter 2

Background

In this chapter, the vehicular communication is introduced, followed by detailed comparison of IEEE 802.11p and C-V2X stack.

2.1 Overview of Vehicular Network

Vehicular networks, also known as vehicular ad hoc networks (VANET), refer to applying the principles of Mobile ad hoc networks (MANET), spontaneously created network of mobile devices, to the domain of vehicles. Frequent link disconnections, intermittent connectivity and poor communication are some of the potential challenges faced due to the highly dynamic nature of VANET. The joined forces of information technology (IT) and automotive industry are accelerating the development of Cooperative Intelligent Transport Systems (C-ITS) that offers bountiful benefits, such as improved road safety, optimised transport efficiency, driver comfort, reduced travel times, new infotainment experiences for passengers, increased service reliability, reduced energy use thereby cutting down carbon emissions. Along with sensors and computing intelligence within the vehicle, the key component in the development is the vehicle-to-everything (V2X) communication. This allows a vehicle to communicate with nearby vehicles, pedestrians and road-side equipment (such as traffic lights, signs and internet gateway). 3GPP defines V2X as a branch of communication that encompasses vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-pedestrian (V2P) communication [5]. Good throughput, strict delay and reliable packet delivery are the core requirements for a safety transportation system.
The current V2X communication is based on one of the two major technolo-

gies: Dedicated Short Range Communication (DSRC) and cellular networks. DSRC, based on IEEE 802.11p is currently a de-facto standard. In the US, the alternative name for DSRC is wireless access in vehicular environments (WAVE). In Europe, DSRC V2X technology is referred to as ITS-G5 and is standardised as ETSI EN 302 663 [13]. To promote the development of DSRC technology, different spectrum management organisations, such as Federal Communication Commission (FCC) and EU commission have allocated 5.9 GHz radio spectrum band to be exclusively used for DSRC based applications. Various projects in Europe and the US have implemented ITS-G5 and WAVE respectively. Europe has fostered a healthy ecosystem for public-private partnerships, such as ERTICO-ITS [14], who develop, promote and deploy ITS through a variety of activities including European co-funded projects, innovation platforms and international events.
Although the simplicity and efficiency with which DSRC uses its radio spectrum makes it a very robust V2X short-range communication technology, its poor performance in high vehicle density scenarios has been a cause for concern for its widespread adoption. Limited mobility support, lack of advanced use cases support for fully automated vehicles, limited coverage range, latency and reliability are some of standing challenges faced by IEEE 802.11p. Lack of sufficient progress in solving standing issues in IEEE 802.11p and the recent advancement in cellular network technologies have motivated the research community to investigate cellular-based V2X communications.
C-V2X, initially defined as LTE V2X in 3GPP Release 14 [5], is designed to operate in several modes by leveraging existing cellular network infrastructure:

- Device-to-device enables V2V, V2I and V2P direct communication without relying for scheduling by network;
- Device-to-cell tower enables network resources, scheduling via existing operator infrastructure;
- Device-to-network is the Vehicle-to-Network (V2N) solution that uses cellular links to enable cloud services.

Collectively, C-V2X is the combination of shorter-range direct communication and longer-range network-based communication (V2N) transmission modes. Release 14 focuses on establishing data transport service for basic road safety service such as Cooperative Awareness Messages (CAM) and Decentralized Environmental Notification Messages (DENM). While Release 14 concentrates on supporting various V2X services by use of LTE technology, it had many future challenges. Release 15 [6] work specifies service requirements to enhance 3GPP support for V2X scenarios such as vehicle platooning, advanced driving, extended sensors and remote driving. 5GAA directs the advantages of C-V2X technology over IEEE 802.11p and also acts as a global, cross industry organisation of companies from automotive and technology to develop end-to-end solutions for future mobility. Overall, the 3GPP cellular technology that was predominantly used for mobile broadband services is now evolving to cover V2X related services and applications.

2.2 Dedicated Short Range Communication (DSRC) Based Standards

As discussed in Section 2.1, DSRC is an essential technology for realising V2X communication. DSRC operates over reserved radio spectrum allotted by different regulation bodies in Europe, US and Japan. Federal Communications Commission (FCC) has allocated 75 MHz of spectrum at 5.850 to 5.925 GHz frequency range. As illustrated in Figure 2.1, the total bandwidth in DSRC is divided into seven 10-MHz bandwidth channels mainly into Control Channel (CCH) and Service Channel (SCH), while the remaining 5 MHz is reserved as the guard band. CCH broadcasts short messages and is used for connectivity

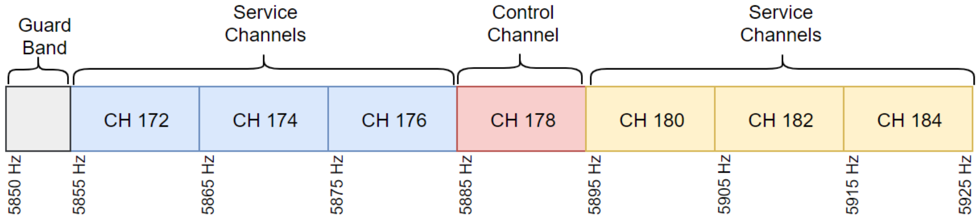

Figure 2.1: DSRC channels

management for road-safety applications, whereas the SSH is dedicated for the traffic efficiency and infotainment applications. On the other hand, the European Commission (ECC) has harmonised standards used for cooperative ITS within the European Union in EN 302 571 [15]. However, ITS-G5 introduces a fine grained service channel assignment which can be categorised into four types (see figure 2.2):

- **ITS-G5A**: Safety related applications
- **ITS-G5B**: Non-safety related applications

- **ITS-G5C**: Infrastructure-based broadband radio access networks in the 5.6 GHz frequency band
- **ITS-G5D**: Reserved for future ITS applications

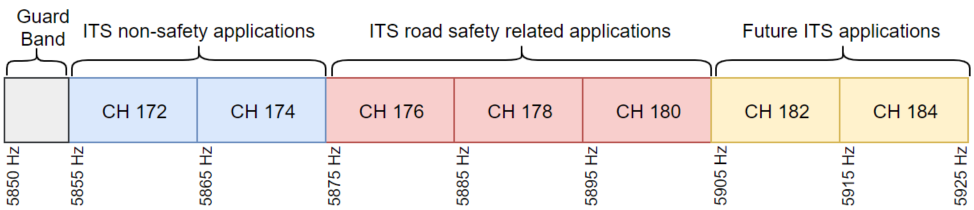

Figure 2.2: ITS-G5 channels

DSRC standards are developed by different standardisation bodies - ETSI in Europe, Association of Radio Industries and Businesses (ARIB) in Japan and IEEE in the US. Standards are developed for each layer of the networking protocol stack. This suite of protocols along the architecture for wireless vehicular communication is called Wireless Access in Vehicular Environment (WAVE). The WAVE protocol stack is therefore composed of several components at every layer of the stack, comprising of IEEE 802.11p at physical layer, IEEE 802.11p and IEEE 1609.4 at MAC sublayer, IEEE 802.2 at LLC sublayer, IEEE 1609.3 at Network layer, as seen in Figure 2.3. ETSI's ITS-G5 follows a similar approach to IEEE but supports new capabilities on top of existing WAVE components. It adopts the IEEE 802.11p at MAC and PHY layers but introduces selection of EDCA parameters based on its Decentralised Congestion Control (DCC). It also adds a 'Facilities' layer between the network and application layer of the stack (refer Figure 2.4). The upcoming subsections describe the different protocol layers in the DSRC stack and the noticeable changes in ITS-G5.

2.2.1 Physical Layer

IEEE 802.11p is essentially a 802.11-based standard adopted for the vehicular networking environment. DSRC and ITS-G5 both use the IEEE 802.11p standard for the physical and data link layers. 802.11p physical and MAC layer specifications are largely based on existing standards for 802.11a. This amendment of 802.11 introduces the reduction of the bandwidth in the physical layer from 20 MHz (earlier in 802.11a) to 10 MHz, thereby also reducing the data rate from 6-54 Mbps to 3-27 Mbps. These different transfer rates are supported by using different modulation schemes and coding rates. The receiver

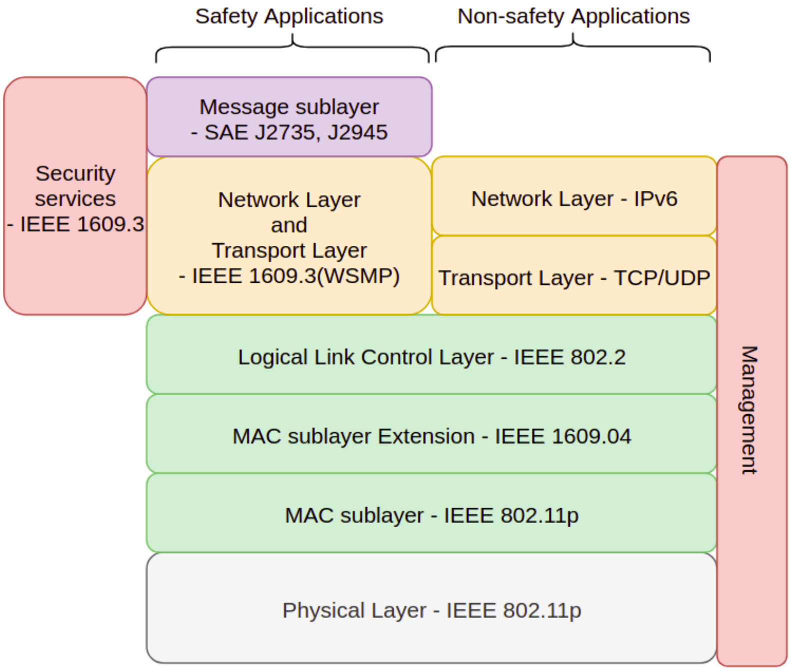

Figure 2.3: Layered Architecture for DSRC communication in the US

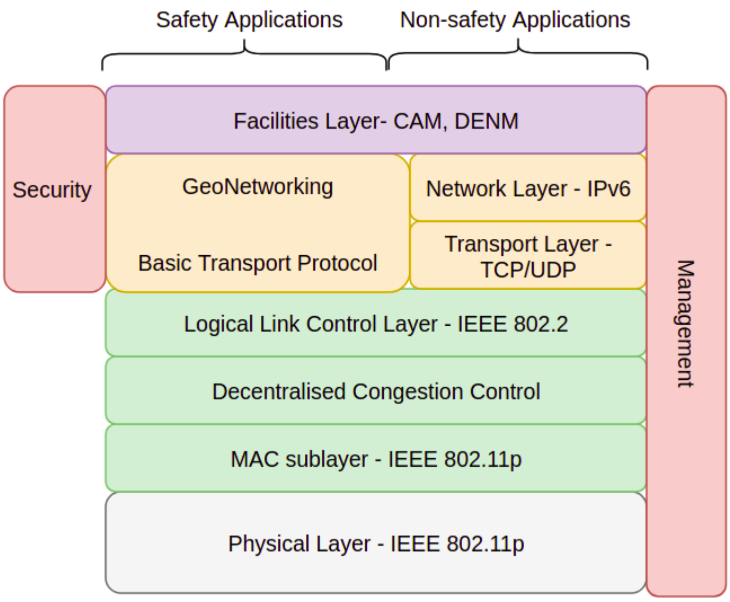

Figure 2.4: Layered Architecture for ITS-G5 communication in Europe

sensitivity is controlled by a set threshold and only signals above that threshold are accepted. There are different minimum values of sensitivity based on modulation scheme and coding rates. For example, 10 MHz channel with 16-QAM modulation and a coding rate of 3/4 requires the minimum sensitivity of -73 dBm. Table 2.1 shows different transfer rates used in ITS-G5, coding schemes, minimum receiver sensitivity in dBm.

Transfer rate (Mbits/s)	**Modulation scheme**	**Coding rate**	**Minimum sensitivity for 10 MHz channel spacing (dBm)**
3	BPSK	1/2	-85
4,5	BPSK	3/4	-84
6	QPSK	3/4	-82
9	QPSK	3/4	-80
12	16-QAM	1/2	-77
18	16-QAM	3/4	-73
24	64-QAM	2/3	-69
27	64-QAM	3/4	-68

Table 2.1: Receiver sensitivity for different transfer rates, modulation schemes and coding rates used by ITS -G5

ITS-G5 uses 52 orthogonal subcarriers in a channel bandwidth of 10 MHz, where 48 subcarriers are used for data and 4 are pilot carriers. The duration of an Orthogonal Frequency Division Multiplixing (OFDM) symbol is fixed to 8 μs, and consequently for different transfer rates the number of data bits per OFDM symbol varies. The format of the transmitted ITS-G5 packet, i.e. the physical layer convergence procedure (PLCP) protocol data unit (PPDU) is shown in figure 2.5. PLCP preamble is used for synchronizing the receiver. The signal field contains information about packet length and data rate of the data field. Data field consists of 4 subfields - service bits , PLCP service data unit (PSDU) bits, tail bits and pad bits.

2.2.2 Medium Access Control Layer

WAVE MAC layer can be subdivided into lower MAC layer and upper MAC layer. Lower MAC layer is responsible for channel access and the upper MAC

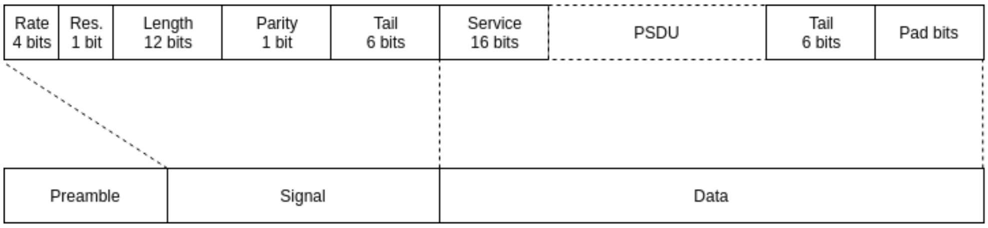

Figure 2.5: ITS-G5 packet format : PPDU

layer is responsible for channel coordination. DSRC and ITS-G5 use carrier sense multiple access with collision avoidance (CSMA/CA) where every node senses the shared transmission medium for the absence of traffic before sending its packet. This helps to avoid simultaneous channel access (collisions). Channel sensing mechanism detects header and decodes the packet length information in the signal field of PPDU Channel. RSSI threshold (energy detection) is the fall-back channel sensing mechanism in case the signal field cannot be detected.

A pure ad-hoc network employed by DSRC and ITS-G5 allows for exchange of data frames without any prior network establishment. Broadcast and Unicast are the two communication modes. Furthermore, data in 802.11p can be shared among different nodes without being part of the same Basic Service Set (BSS). In other words, communication occurs outside the context of BSS (OCB). BSS refers to units of devices operating on the same medium access characteristics such as radio frequency, modulation scheme, etc. Authentication, association and synchronisation and security between nodes are disabled in OCB mode of communication, thereby allowing for more efficient and less complicated communication.

ITS-G5 MAC also employs a special backoff procedure to schedule the transmissions via Enhanced Distributed Channel Access (EDCA). EDCA is needed to support various kinds of services with different priority levels. In EDCA, every node maintains queues with different Arbitrary InterFrame Spacing (AIFS) values and congestion window (CW) sizes with the purpose of giving data traffic a higher priority. This increases the probability of a higher priority data packet to access the channel before data traffic with lower priority. Figure 2.2 maps the different user priorities to access category(AC) and uses the default values of AIFS number(AIFSN) and CW for each AC as stated in the QoS facility in IEEE 802.11-2012 [16] to come up with resulting AIFS values, according to Equation 2.1.

$$AIFS[AC] = AIFSN[N] \times aSlotTime + aSIFSTime \qquad (2.1)$$

AC refers to access category, AIFSN is the AIFS number, aSlotTime and aSIFSTime(short interframe space) have fixed values of 13μs and 32μs respectively.
The channel coordination is regulated by IEEE 1609.4 which describes multi-

User priority and traffic type	**Access category (AC)**	**CW$_{min}$**	**CW$_{max}$**	**AIFSN**	**AIFS**
6-Voice(VO) 7-Network control (NC)	AC_VO	3	7	2	58μ
4-Controlled load 5-Video(VI)	AC_VI	7	15	3	71μ
0-Best effort(BE) 3-Excellent effort (EE)	AC_BE	15	1023	6	110μ
1-Background(BK) 2-Spare(-)	AC_BK	15	1023	9	149μ

Table 2.2: Mapping of user priority and AIFS

channel wireless radio operations over IEEE 802.11. IEEE 1609.4 defines coordination between two channel types (SCH and CCH), channel routing by selection of proper channel and AC queue, time synchronisation and management services for channel switching.
ITS-G5 employs decentralised congestion control (DCC) methods specified in TS 102 687 [17] to limit the channel load and allow high priority messages to be received with reasonable probability. The transmission duty cycle of each ITS station is limited to $\leq 3\%$. Assuming that CAMs make up most of the transmissions, the average short CAM of 300 bytes takes 0.27 ms at 6 Mbits/s default transmission rate as compared to 0.67ms for average long CAM of 500 bytes. Taking 9 short CAMs and one long CAM per second into account, the channel will be occupied for 3 ms per second by a single ITS station resulting in 0.3$\%$ transmission duty cycle base load.

2.2.3 Network Layer

The Internet Protocol(IP) has become the default Layer 3 protocol in many networks today. The primary advantages that IP offers to higher layers is its ability to find a path to a node anywhere, based on its public IP address. Successful IP routing protocols are the backbone to driving the usage of IP connectivity to disparate devices sitting in different locations around the world who need to communicate. However, routing is not the primary issue in case of vehicular environment because many packets are sent directly over the air from the source to the destination. A lot of care needs to be taken to reduce the overhead associated with internet protocols since IPv6/UDP packet has a minimum size of 52 bytes. Therefore, a new Layer 3 protocol that is efficient for 1-hop transmission is designed by IEEE 1609, a family of Standards for WAVE. IEEE 1609.3 [18] networking layer defines the different networking services for WAVE. The protocol to exchange data using this lean protocol structure is termed as WAVE short messaging protocol (WSMP). It also encompasses support for management services namely channel access management, WAVE service advertisement, IPv6 configuration and Management Information Base (MIB) maintenance. Devices assume the role of either user (device monitoring the channel for potential data exchange), provider (transmitting device) or both.
The two types of WAVE messages are WAVE Short Message (WSM) and WAVE Service Advertisement Message (WSA). The format of WSM is designed to maximise the efficiency of WSMP because channel congestion is a significant concern in DSRC, especially on the channels used for Basic Safety Messages (BSM) (explained in Section 2.2.4). WSMP PDUs are addressed using Provider Service ID (PSID) and broadcasted on the selected channel whether SCH or CCH. The minimum WSM overhead is 5 bytes and rarely exceeds 20 bytes. The various fields in WAVE Short Message format (see figure 2.6) are described as follows:

1. **WSMP Version**: This mandatory field contains a 4-bit WSMP version number and 4 reserved bits. A receiver discards a WSM if it receives a WSM with version number higher than it was designed to support.

2. **Provider Service Identifier (PSID)**: PSID identifies the service that the WSM Data(payload) is associated with. In other words, the device forwards the WSM to the appropriate application layer process when the PSID is a match to the list of PSID on the device. PSID serves a purpose similar to a TCP or UDP Port.

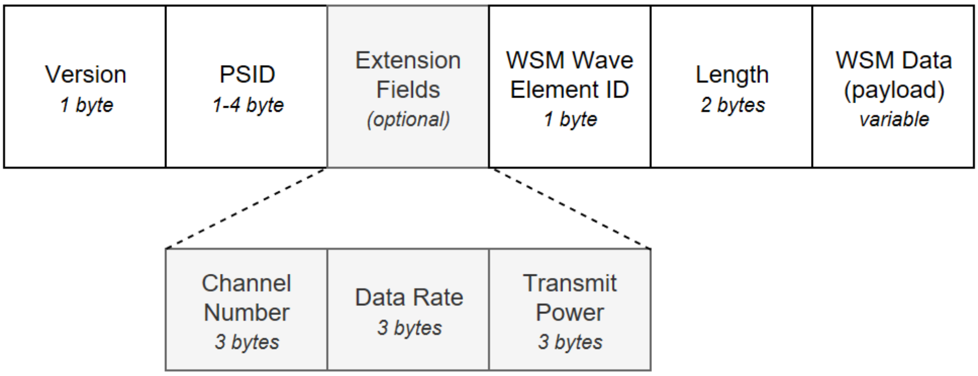

Figure 2.6: WAVE Short Message packet format

3. **WSM Extension Fields**: This optional field in current version of IEEE 1609.3 defines three extension fields namely Channel Number, Data Rate and Transmit Power Used.

4. **WSMP WAVE Element ID**: This mandatory one byte field marks the end of the extension fields and indicates the format of the WSM Data field.

5. **Length**: This final two bytes of the WSM header contain the size of payload in bytes. The valid range is 0-4095.

6. **WSM Data**: This is the payload of the WSM.

On the other hand, WSA provides information about one or more DSRC services that are offered in an area. Some of the examples for these DSRC services are traffic alerts, tolling, navigation, restaurant information, entertainment, and Internet access. In most cases, this information is provided by an RSU, but a vehicle can also send a WSA. WSAs are sent on the CCH during the CCH interval but are offered on one or more of the SCHs. One type of DSRC communication that is not considered a service is the broadcast of Basic Safety Messages (BSM).
ITS-G5 uses GeoNetworking routing protocol instead of WSMP. GeoNetworking is a routing protocol that provides packet delivery in ad hoc network without a coordinating infrastructure. By making use of the geographical position, it facilitates sending a packet to an individual ITS station or to a geographical target area (using broadcast or anycast) described by geometric shapes (circle, rectangle, ellipse; see ETSI EN 302 931) [19]. The GeoNetworking standard specifies several forwarding algorithms with increasing protocol functionalities and efficiency. A GeoNetworking packet is composed of three headers;

basic, common and extended. The extended header is specific for geo-unicast, geo-broadcast and has support for the definition of the geo-area. The separation of basic and common headers is for security reasons. A digital signature and certificate remains common throughout the connection interval and is therefore declared within common header. This enables decoupling from basic header fields that can be modified by a forwarder. An example would be that the hop-count value can be decreased by every forwarder without the need to regenerate the signature [20].
Basic Transport Protocol (BTS) multiplexes/demultiplexes facility-layer messages and provides a connection-less, unreliable end-to-end packet transport similar to UDP. It is similar to PSID in WSM.

2.2.4 Application Layer

SAE J2735 [21] specifies the message set, its data frames and data elements specifically for use by application intended to be utilised by 5.9 GHz WAVE communication systems. There are 16 message types but we focus on BSM in this work. A message consists of data elements and data frames. Data elements are primitive objects such as speed, heading, latitude, longitude, elevation, etc. Data frames are collection of data elements.

Basic Safety Message

BSM is the most important message in the SAE J2735 standard because it conveys the core state information about the sending vehicle to its neighbouring vehicles. Extensive research has been performed to test collision avoidance applications with BSM. A BSM message consists of two parts - Part I includes critical state information that must be sent in every BSM - Part II includes optional data types. Despite the specification of the message formats, SAE DSRC committee realised that it is vital to add additional rules in order to ensure interoperability of V2V safety applications. The motivation is to define additional constraints on a BSM sender so that the receiver will know enough to provide effective driver warning for collision prevention. BSM sending rate, sensor accuracy and BSM transmit power are some of the requirements to be included in this revised standard. Our work deals with two different BSM sending rates; 10 Hz covers lesser frequency transmissions and 20 Hz covers higher frequency transmissions.
In comparison to WAVE DSRC, ITS-G5 defines its message set in the facilities layer. This layer can be divided into three sub-layers:

- **Application Support**: It supports three kinds of messages :

  1. Cooperative Awareness Message (CAM): It is a periodic message, similar to BSM in WAVE, that provides node position and safety information to neighbouring ITS stations.
  2. Decentralised Environmental Notification Messages (DENM): It carries road hazard information and is triggered in an event-based manner.
  3. Service Announcement Message (SAM): This is similar to WSA in the way that SAM messages advertise services on control channel.

- **Information Support**: This sub-layer stores and maintains the Local Dynamic Map for cooperative perception. All the dynamic data received from other ITS nodes through CAM and DENM is stored in this layer so that applications can retrieve relevant data from the Local Dynamic Map.

- **Communication Support**: This sub-layer provides future-proof lower-layer independence by providing support for diverse access technologies (802.11p, VLC, LTE) and network protocols (IPv6 and non-IP).

2.3 C-V2X Based Standards

Having inherited decades of previous standardisation works by other organisations, 3GPP has actively stepped up its contribution to involve cellular network in V2X, starting with the first stage of specification in Release 14 [5] and clear road map towards further refinements in Release 15 [6]. To support V2V communication, 3GPP required modifications in the radio access network to exhibit some challenging requirements in terms of high reliability and low latency to be met under high-speed and high-density conditions. Message transfer latency was set to no longer than 100 ms with 20 ms latency in specific use cases. With message size upto 1200 bytes, 3GPP service requirements support up to 10 message transfers per second and in some cases message transfer rate can reach upto 50 Hz. 3GPP also supports communication at relative vehicle speed up to 500 km/hr.
Figure 2.7 illustrates the different communication capabilities of V2X communication. Short-range direct communications occur between vehicles (V2V), between vehicles and infrastructure (V2I) and vehicles and other road users

(V2P), such as cyclists and pedestrians. V2N comprises of long-range network communications which enable a vehicle to receiver information about the road conditions and traffic in the area, beyond the driver's line of sight. V2N occurs over the cellular LTE-Uu interface operating under the traditional licensed spectrum.

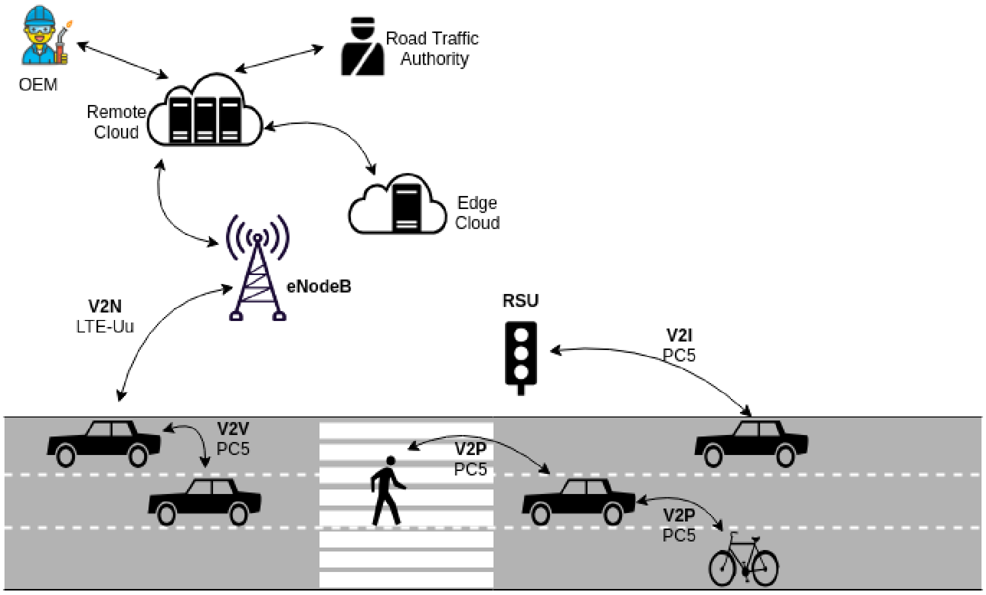

Figure 2.7: Communication modes in C-V2X

As mentioned before in Section 2.1, in-coverage and out-of-network coverage connectivity are two of the most important architecture enhancements provided by 3GPP for V2V communication. There are two communication modes called Mode 3 and Mode 4. In Mode 3, cellular network schedules the radio resources used by vehicles for direct V2V communication. In other words, Mode 3 operates only within the operators' eNodeB coverage area and the allocation of radio resources is supervised by the network. It is supported by LTE-Uu and PC5 interfaces. Mode 4 is an autonomous communication mode that functions in the absence of cellular network and supports direct communications between vehicles over sidelink interface called PC5. Sidelink/PC5 communication standards were introduced for proximity services (ProSe) in Release 12 and later modified in Release 14 as per vehicular communication properties and requirements. Mode 4 communication on the PC5 interface operates on 5.9 GHz band regardless of the presence of cellular network, i.e. both in and out of coverage area. This ensures ultra-high availability under all geographies regardless of the specific Mobile Network Operator (MNO). As

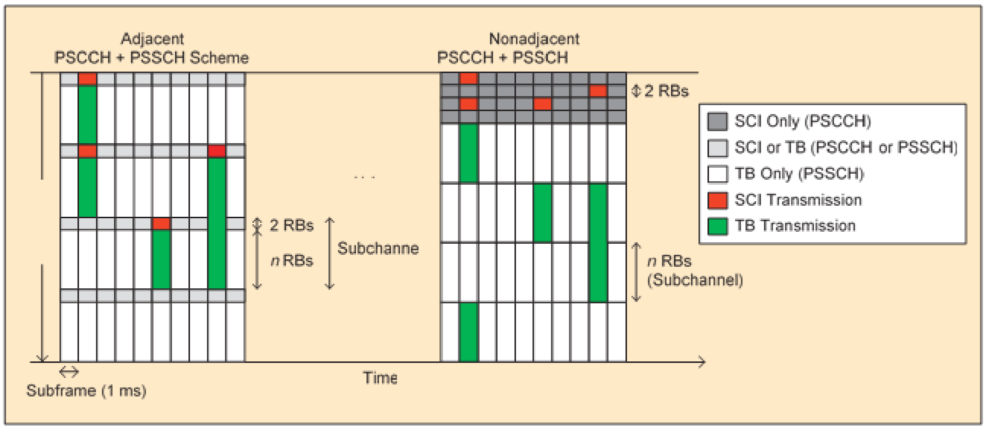

Figure 2.8: LTE-V2X sub-channelisation

a result, in Mode 4, vehicles can avail pre-configured resources without the network control, both in and out of eNodeB coverage.

2.3.1 Physical Layer

LTE-V2X utilizes single-carrier frequency-division multiple access (SC-FDMA) and supports 10 MHz and 20 MHz channels. The standard specifies maximum transmit power and receiver sensitivity to be 23 dBm and -90.4 dBm respectively. Each channel is divided into 1ms-long subframes, so is the Transmission Interval Time (TTI). eNodeB allocates Resource Blocks (RB) to User Equipments (UEs) at every TTI of 1 ms. RB is the smallest unit of frequency resources that can be allocated to a user. 12 subcarriers of 15 KHz (total of 180 kHz) make up a RB. A group of RBs in the same subframe of 1ms is referred as a sub-channel in LTE-V2X.
Transport blocks (TBs) carry data over Physical Sidelink Shared Channels (PSSCH) and Physical Sidelink Control Channels (PSCCH) carry Sidelink Control Information (SCI) messages. PSSCH and PSCCH are transmitted on the same sub-frame albeit 3bB power spectral density boosting applied for PSCCH to make sure that control information does not become the bottleneck. A TB contains a full packet (e.g. CAM) to be transmitted. SCI includes the modulation and coding scheme (MCS) used for transmitting the TB, the RBs it uses and resource reservation interval for semi-persistent scheduling (SPS), explained in MAC subsection 2.3.2. LTE-V2X defines two sub-channelisation schemes (Figure 2.8):

- **Adjacent PSCCH + PSSCH** : The SCI and TB are transmitted in adjacent RBs.

- **Nonadjacent PSCCH + PSSCH** : RBs are divided into two pools where one pool carries only SCIs and second pool transmits only RBs. TBs use QPSK or 16QAM modulation schemes however SCIs are always sent using QPSK.

2.3.2 Medium Access Control Layer

When vehicles are under cellular network coverage, the network decides how to configure the V2X channel and informs the vehicles about V2X configurable parameters such as carrier frequency of the V2X channel, V2X resource pool, synchronisation references, the sub-channelisation scheme, number of sub-channels per subframe and number of RBs per subchannel.
Vehicles using mode 4 communication select their radio resources by using sensing with a semi-persistent transmission, which is similar to "frequency domain listen before talk". A vehicle reserves sub-channels for a few consecutive transmissions based on SPS scheme specified in Release 14 [22]. The reselection packet-counter is randomly chosen between five and fifteen. It decrements with every transmission. Once the reselection packet-counter reaches zero, the vehicle must request additional resources and the reselection counter is randomly chosen again.
Packets can be sent every 100 subframes, i.e., ten packets per second. The process of reserving sub-channels can be broken down in three steps :

- Measure received energy (RSSI) on resources that meet the latency requirement

- Rank resources based on received energy and shortlist 20% lowest relative energy RBs

- Choose one of the lowest relative energy resource for transmission

Release 14 defines *Channel busy ratio (CBR)* and *channel occupancy ratio (CR)* as two relevant metrics to reduce the channel congestion. These metrics are continuously calculated by the vehicle whenever it transmits or retransmits a packet. CBR provides an indication of the level of channel congestion and is defined as the number of subchannels in the previous 100 subframes that experience an average RSSI higher than the pre-configured threshold. On the other hand, CR quantifies the channel occupancy generated by the transmitting vehicle and is defined as the number of subchannels that the transmitting vehicle utilises during a period of 1000 subframes. The decision of choosing either past or future subframes for CR calculation is left to the vehicle, although atleast 500 past subframes must be considered for CR calculation. As per the standard, a CBR can be divided into 16 CBR intervals. For each interval, a vehicle cannot overshoot its CR_{limit}. This CR_{limit} for each CBR interval varies according to the packet priority. If the CR exceeds the CR_{limit}, the vehicle must reduce its CR below CR_{limit}. Although the standard does not specify the range of these CBR intervals or values of CR_{limit}, it provides several possible mechanisms to reduce CR_{limit}, such as packet dropping, modifying the number of transmissions per packet, reducing the number of subchannels reserved, and reducing the transmission power.

2.3.3 Network Layer

C-V2X employs standard compliance stacks such as IEEE 1609.3 [18] and ETSI TC-ITS similar to DSRC standard as explained in section 2.2.3.

2.3.4 Application Layer

The application layer is the top–level applications suite which provides information, alerts and warnings to drivers. C-V2X standard allows flexibility to employ application suite based on either SAE, ETSI and IEEE standards, similar to the ones explained in the Section 2.2.4.

2.4 Coexistence study

ETSI recently provided information to ECC concerning the co-frequency coexistence of LTE-V2X and ETSI ITS-G5. The commonalities and differences of the spectrum access mechanisms and their sharing capabilities have led to specific proposals. This section cites the different proposals as a result of the study conducted by ETSI [23].
One of the primary requisites to ensure a non-interfering operation of distinct radio technologies together is to achieve orthogonality in time, frequency, space and/or code domain. There are two approaches to achieve this orthogonality:

1. A-priori agreement;

2. Infrastructure based and/or ITS-Station (ITS-S) based decision making.

2.4.1 Coexistence solutions requiring an A-Priori Agreement

A-priori agreement refers to an agreement between all stakeholders to come up with an agreeable parameters for respective systems that comply to regulation requirements (including in particular the principle of non-segregation of the ITS spectrum) and to achieve orthogonality over time, space, frequency and/or code domains. Several solutions are possible with their own advantages and disadvantages :

Coexistence based on sharing at the physical layer

Code Division Multiple Access (CDMA) approach assigns orthrogonal codes to distinct systems and technologies. Orthogonal Frequency Division Multiple Access (OFDMA) and Time Division Multiple Access (TDMA) assign resources and transmission burst allocations respectively to implement sharing mechanism in physical layer. All these approaches will require coordination of physical layer of distinct technologies (intra-technology coordination) because the existing systems typically have physical layer resources shared among components of a single technology. Therefore, either one or all of the concerned technologies (ITS-G5 and LTE-V2X) will require modifications at the physical layer. Another major disadvantage of this approach is that the channel access schemes of the respective technologies may have inherent limitations which exclude some of the available physical layer sharing approaches. Listen Before Talk(LBT) channel access mechanism in 802.11p may be disadvantageous in the possibility of using the channel in the presence of LTE licensed spectrum.

Coexistence based on geographical sharing

As implied by the title, the usage of only a single technology is authorised in a given geographic area. Service continuity is ensured by handover mechanisms. Separation between such geographical areas will require signal strength based separation or even GNSS geo-fencing. In practice, multi-technology ITS stations are needed to work in all geographical areas. RSU and/or Cellular Infrastructure may need to disseminate control messages to vehicles indicating which orthogonality solution is applied by which system for a given time, frequency band and geographical location. Some of the major disadvantages of this approach are that the vehicles will need to adapt to the locally applicable technology, frequency/area planning will be needed, and geographical map will need constant updates as new roads are constructed.

Coexistence based on preferred channels

This solution proposes to split the currently available 5.9 GHz spectrum so that LTE-V2X and ITS-G5 can operate without interference in the same geographic area. The proposal is to be implemented in 3 phases and comprises a spectrum use, based on technology detection and dynamic frequency/channel selection.

1. Phase 1: Allocate 10 MHz channels for LTE-V2X and ITS-G5 according to the proposal made in [24] as illustrated in Figure 2.9.

2. Phase 2: Maintain the allocation of preferred channels and additionally, allow for a shared use of the middle channel (5885-5895 MHz) by applying appropriate orthogonality solution such as detect and vacate mechanism (outlined in the subsection 2.4.2) and illustrated in Figure 2.10.

3. Phase 3: Apply shared use of all channels only when detect and vacate mechanisms are implemented in both C-V2X and ITS-G5 as illustrated in Figure 2.11.

The key advantage of this solution is that it does not require any modifications of the related technical specifications. One major disadvantage is that use cases such as platooning will not work with Phase 1,2 and 3 because it requires a separate channel with low data-traffic on it (no CAMs and no DENMs).

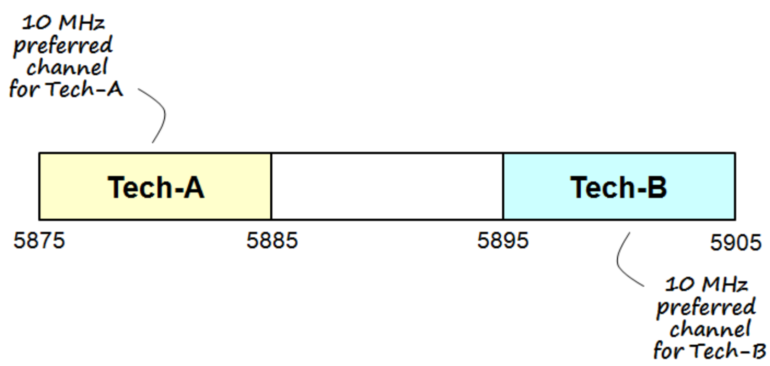

Figure 2.9: A-Priori Agreement on Preferred Channels : Sharing of 5.9 GHz ITS Safety band

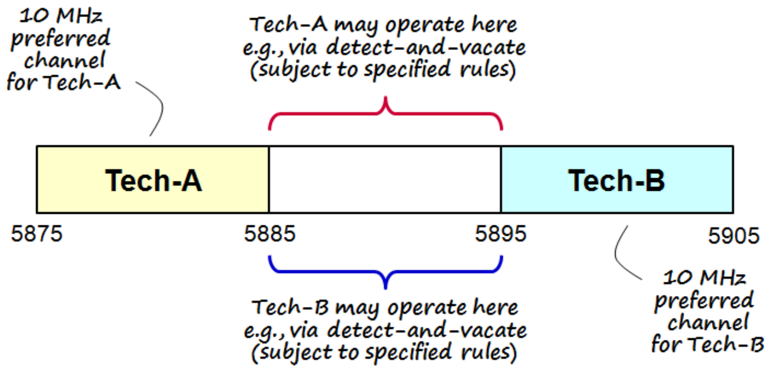

Figure 2.10: A-Priori Agreement on Preferred Channels : Sharing of 5.9 GHz ITS Safety band complemented by mutual detect and vacate mechanism

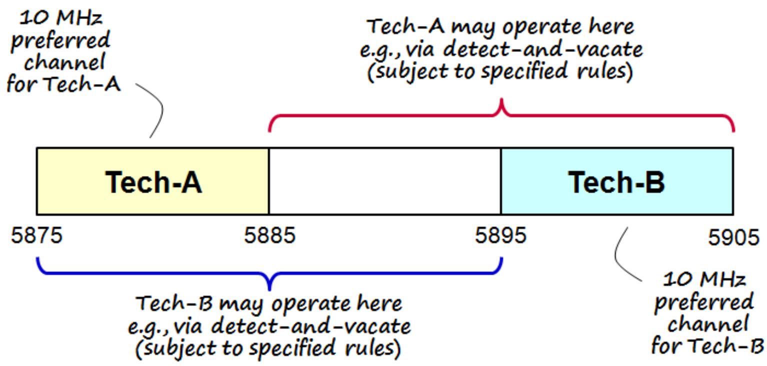

Figure 2.11: A-Priori Agreement on Preferred Channels : Sharing of 5.9 GHz ITS Safety band complemented by mutual detect and vacate mechanism extended to lower and upper 10 MHz channels

2.4.2 Coexistence solutions based on infrastructure decision making

Infrastructure based decision making is achieved by RSU and/or Cellular Infrastructure providing scheduling information as signals to the vehicles. The ITS-S (i.e. vehicles) based decision making is achieved through an appropriate radio channel sensing mechanism.

Coexistence using Detect-and-Vacate Mechanisms

Figure 2.10 and Figure 2.11 act as per the following rules for their respective Preferred Channels:

- In case that an ITS transmission of different technology is detected, the

ITS-S switches to another radio channel.

- In case that an ITS transmission of identical technology is detected, the ITS-S may decide to use the radio channel with the same technology
- In case that the radio channel is unoccupied, the ITS-S may use the channel appropriately.

Phase 3 achieves the most effective usage of the band, especially if only one technology is present/detected in the same geographical area. Hidden node problem poses a significant challenge in Phase 2 and Phase 3 since Detect-and-Vacate mechanism relies heavily on ability to detect the transmissions. Moreover, a careful detection mechanism is needed in order to avoid likelihood that one technology is disadvantaged, by means of not having the possibility to use a channel on an equal basis. Moreover, results from other studies show that a pure energy detection is not enough because the detection range is shorter than the range of interference. This will result in interference from an ITS-S because it is not aware of the presence of other ITS-S using another technology.

2.5 Related Work

[25, 26, 27, 28] provide comparisons between IEEE 802.11p and infrastructure LTE for cooperative awareness messages. One of the early efforts in evaluating the performance of IEEE 802.11p and LTE was carried out by Mir et. al [27]. The authors compare both technologies in terms of delay, reliability and scalability by varying beacon transmission frequency, vehicle density and vehicle average speed. They use LENA module in NS-3 to simulate LTE technology and 5x5 Manhattan grid as the road network in SUMO. The results indicate that IEEE 802.11p offers acceptable performance for sparse network with under 50 vehicles. It is found that LTE meets most of the application requirements in terms of reliability and delay; however, this study uses infrastructure-based scheduling and downlink unicast message dissemination. The authors do warn that downlink unicast is only appropriate for small number of vehicles (less than 100) in the cell. The authors in [29] focus on the performance of high-density truck platooning for C-V2X and IEEE 802.11p, to measure reliability and latency with CAM reception rate and inter-truck spacing. This evaluation is carried out using Nokia's interval 3GPP system simulator and Poznan Univserity of Technology's IEEE 802.11p simulator. The authors find that both Mode 3 and Mode 4 in C-V2X provide superior performance with respect to IEEE 802.11p, albeit for only 20 platooned trucks.

[30] compares LTE-V2V in-coverage and out-of-coverage with IEEE 802.11p using packet reception ratio and update delay. These performance parameters are computed for a highway scenario with awareness range from 50 m to 500 m and different packet size (190 bytes, 300 bytes). Results highlight that LTE-V2V in-coverage achieves 10% better packet reception ratio and 10 times lower update delay than IEEE 802.11p for 190 bytes CAM packets. For 300 byte CAMs, LTE-V2V outperforms IEEE 802.11p by 26% improvement in packet reception ratio. However, IEEE 802.11p guarantees lower update delay at higher than 100 m. The authors conclude that the adoption of technology is dependent upon the specific application requirements and that there is not an optimal technology for every condition. Paper published by Avino et. al [31] evaluates the Intersection Collision Avoidance (ICA) application for both candidate technologies as a function of penetration rate (PR). By considering different penetration ratios (10%, 20%, 50%, 100%) and two transmission channel models (simple and realistic), the authors investigate the effectiveness of ICA, i.e the percentage of collisions that can be avoided. Only a very high PR detected over 85% possible collisions. With 100% PR, 802.11p and C-V2V detect same number of collisions. The transmission of ICA messages along with BSM actually brings an average improvement of 5% in the number of correctly detected collisions.

Chapter 3

Simulation Environment

Different technologies have been implemented as a simulation framework in the recent years. Various simulator platforms such as NS3 or OMNeT++ exist which are capable of simulating distributed networks. Although IEEE technology stack for 802.11p has been the first to be implemented into the simulation frameworks, the evolution of cellular technology for V2X communication has lead to simulation framework implementations for LTE. OMNet++ has stacks for LTE and 802.11p. OMNeT++ has been chosen as the main platform for this work because it offers a wide range of freedom to customise and merge IEEE 802.11p and LTE implemented frameworks to investigate the coexistence issue. A short introduction in the upcoming subsections highlights the concepts of the frameworks Veins and SimuLTE.
In order to avoid confusion between the different terms that will be used in the later sections, the following clarifies these terms beforehand:

1. Platform refers to the whole system, i.e. OMNeT++ along with the features such as the framework SimuLTE and Veins.

2. Framework refers to implementation of protocols, modules, layers or the whole stack. SimuLTE, INET, Veins are recognised as relevant frameworks.

3. Module refers to features or models that provide the implementation of different protocols, libraries, channel models, etc.

3.1 The OMNeT++ framework

OMNeT++ [7] is considered to be a discrete network simulator platform, with an extensible, modular, component based C++ library and framework, primar-

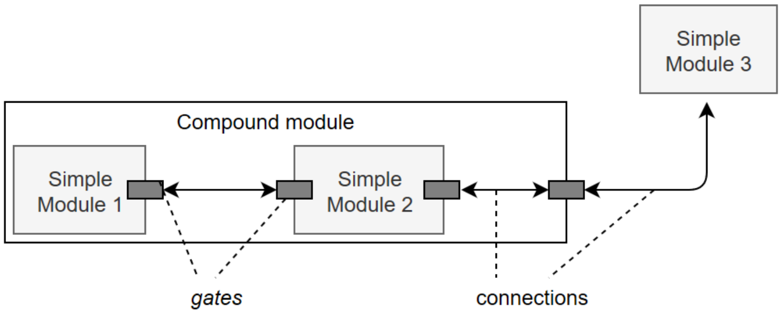

Figure 3.1: OMNeT++ Module Connection

ily for building network simulators. OMNeT++ has gained a widespread popularity in the scientific community since it is free for academic use. It provides all the basic tools and libraries for creating and performing one's own simulations. In this work, we make use of interactive simulation runtime graphic user interface called *Qtenv* and command line interface called *Cmdenv* which provide great debugging options and improved simulation speed respectively. Moreover, ability to create our own statistic parameters within the modules is a great way to capture results at specific points in the simulation. This feature helps to analyse the data and investigate the results.
OMNeT++ allows one to keep a model's implementation, description and parameter values separate. The implementation (or behaviour) is coded in C++. The description which includes gates, connections and parameter definition, is written in Network Description File (NED). The parameter values are written in initialisation (INI) files.

3.1.1 Modules

The basic OMNeT++ building blocks are *modules*, which communicate with each other through messages. These message are usually sent and received through *connection* linking the modules' interfaces called *gates*. Modules can be either *simple* or *compound*. Simple modules implement model implementation (or behaviour) and consist of three functions - initialisation function, event handler function and finalisation function. Initialisation function initialises the module before the start of the simulation. The event handlers are triggered when a module receives a message. A module can also send messages to itself. Connections are characterised by bit rate, delay and loss rate and cannot bypass a module hierarchy. With reference to Figure 3.1, simple module 3 cannot connect to module 2 without connecting to compound module gates first.

3.1.2 Network Description File (NED)

NED manages the connections between the modules. NED is a declarative language that exploits inheritance and interfaces and allows one to write topologies, for example, a tree structure describing the connections and the flow of messages between different components in the car module. The management of the connections, structures, the collection of results and many other functions are facilitated by NED files. For illustration purposes, Figure 3.2 shows the graphical contents for LTE-D2D Nic interface implemented for the car module.

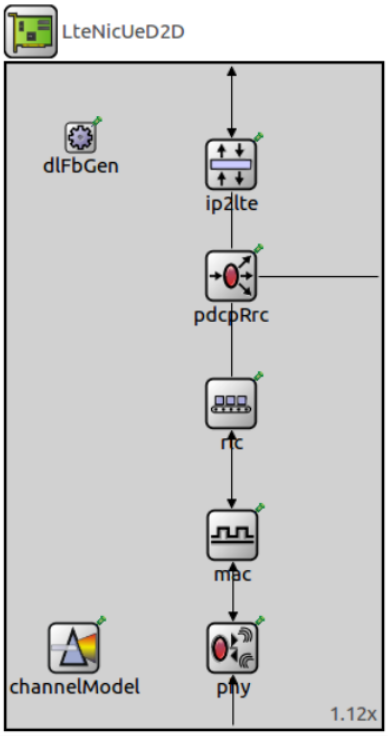

Figure 3.2: Snippet of LteNic module for D2D UE

3.1.3 Initialisation File (INI)

INI files contain the values of the parameters that will be used to initialise the model. In other words, it sets the parameters or configures the behaviour of the simulation. This is an easy way of setting and changing parameters of the simulation scenario from within one file instead of changing each parameter values in the respective module files. In case of our simulations, we define details such as execution of simulation in graphical or command-line interface, debugging options, size of the playground and parameter values such as transmit power, data rate, modulation scheme, RBs and number of UEs.

3.1.4 Result Analysis

OMNeT++ provides a graphical user interface for analysis which offers us a wide scope to investigate the data captured. We capture the results as vectors and scalars. Scalars record aggregated data at the end of the simulation and vectors record data values as function of time. Scalars and Vectors are instantiated as a combination of NED files, C++ header and C++ source files before the simulation run. We filter out the results into datasets by filtering and sorting. We extract the datasets in csv format and generate plots.

3.2 INET

INET is considered as the main protocol library for OMNeT++. It is composed of modules that implement OSI layers, transport protocols TCP and UDP, network stack of IPv4 and IPv6 and other wireless protocols for wired and wireless links. INET is an open-source framework which is updated constantly by the OMNeT++ community. Other frameworks used in this work (SimuLTE and Veins) need INET as a part of their system. Since the simulations are performed by transferring of messages between various modules in one or more frameworks, INET framework makes it easier to overcome the challenges of communication models in OMNeT++ by supporting different components such as routers and switches. Abstraction of these components allow easy to use off-the-shelf protocol features in the simulation scenario.

3.3 Veins

Veins [10] is an open source simulation vehicular network simulation framework that implements the IEEE 802.11p stack for DSRC in OMNeT++. Veins offers an interface of collaboration between OMNet++ and Simulation of Urban Mobility (SUMO) simulator. In this work, Veins serves as the basis for application-specific simulation code and SUMO provides the environment to

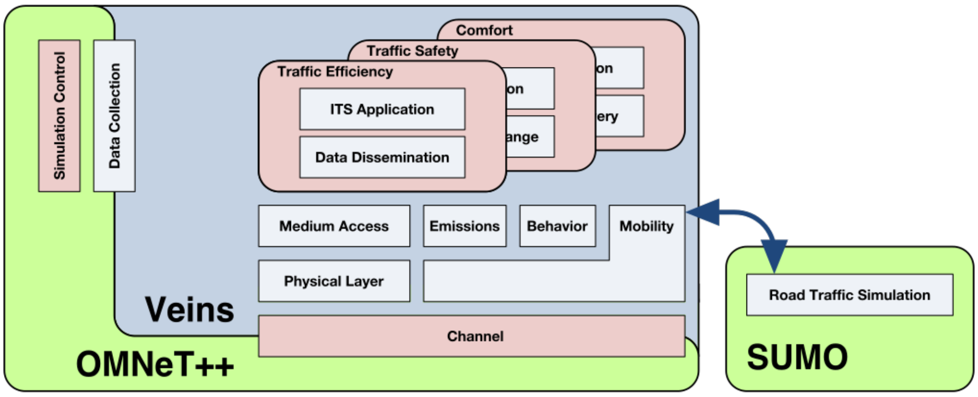

Figure 3.3: Veins Architecture and its interaction with SUMO

simulate road traffic. Both work in parallel to run a simulation scenario. Connected via a TCP socket, OMNeT++ communicates the logic to Sumo and retrieves simultaneous feedback updates for all events on the performed scenario. Traffic Interface Control (Traci) is the standardised protocol for intercommunication between SUMO and OMNeT++. This allows bi-directional coupling of road traffic and network traffic. The architecture of Veins and its relation with SUMO is illustrated in Figure 3.3.
Veins comprises of various modules that model lower protocol layers according to the various protocol standards defined by IEEE 802.11p and IEEE 1609 WAVE specifications. It employs QoS channel access conforming to EDCA and accurately captures modulation and coding scheme. Veins offers the possibility of switching between CCH and SCH, which is useful for our work when its comes to only utilising channel designation for BSM messages. At the application layer, it handles WSM messages and allows periodic beaconing for sending BSM and WSA.

3.4 Simulation of Urban Mobility (SUMO)

SUMO [32] is also an open source and road traffic simulation package designed to handle large road networks. In this work, it is primarily used to model road traffic. The modification of map scenarios with new vehicles and their attributes is done using XML files. The framework supports a large amount of traffic specifics such as route finding, visualisation, network import and visualisation. Vehicles' mobility can be set independent of each other and each vehicle can be setup with a specific configuration. SUMO can be run using Graphical User Interface or command-line for faster simulation. The frame-

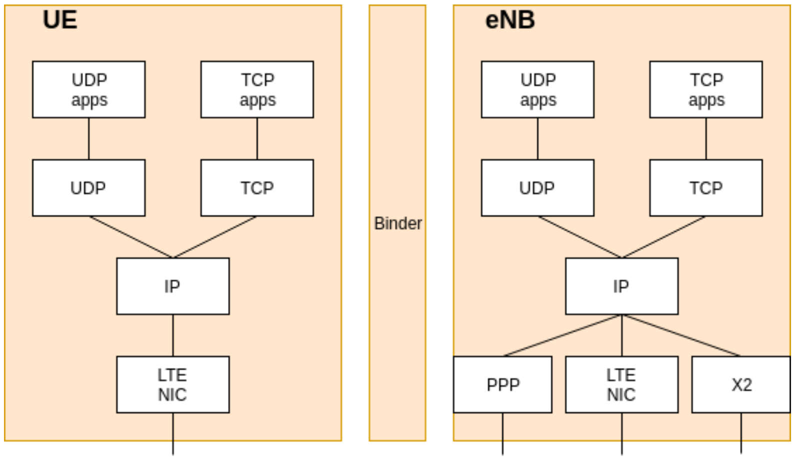

Figure 3.4: UE and eNodeB module structure

work provides many traffic specific parameters such as traffic lights, streets, directions of the street and many other environmental specifications. Importing realistic maps by making use of OpenStreetMap files is one of the most important feature of SUMO so that simulations could be performed for certain streets with the assistance of Veins and other frameworks. OpenStreetMap file is converted into a package of files that SUMO understands. Various applications such as Netconvert, Netgen, Duarouter, etc are available with SUMO to create use case specific network file, that is then fed to Veins framework. This work uses a 1000m stretch of highway road map with 4 lanes. Different number of vehicles are generated with maximum attainable velocity.

3.5 SimuLTE

SimuLTE [33] is an open source OMNeT++ library developed by Computer networking group at the University of Pisa in Italy that implements LTE stack. Developed in C++, SimuLTE uses the same module structure as OMNeT++ and simulates the data plane of the LTE, LTE-Advanced Radio Access Network and Evolved Packet Core. Some of main features that SimuLTE implements are VoIP GSM Adaptive Multi-rate (AMR), video streaming , real time gaming and File Transfer Protocol (FTP). This framework supports communication with the Frequency Division Duplexing (FDD) mode with heterogeneous eNodeBs (macro, micro, pico etc). We utilize the macro eNodeB for our experiments.
Figure 3.4 shows the structure of three main nodes in SimuLTE. eNodeBs

and UEs are compound modules those can be connected with each other and with other nodes (e.g. routers, applications, etc.) in order to compose networks. Binder node stores reference to all the nodes. This information is handy to compute the inter-cell interference perceived by a UE in its serving cell and thereby locate the interfering eNodeBs. As can be seen from Figure 3.4, UE and eNodeB are further composed of modules. SimuLTE re-uses the UDP/TCP and IP modules from the INET package and connects them to the LTE stack. TCP and UDP applications (TCP App and UDP App) enable multiple applications per UE. This work uses two UDP Apps for each UE, one for sending D2D multicast messages and the other for receiving them. The LTE NIC in UE and eNodeB implements the whole LTE protocol stack, as one submodule per layer, namely Packet Data Convergence Protocol (PDPC), Radio Link Control (RLC), MAC and PHY (refer Figure 3.5). UEs and eNodeBs perform different operations within the protocol stack. This is achieved by exploiting the inheritance paradigm of OMNeT++ to structure each submodule with common operations, those are extended with functionalities specific for the UE and the eNodeB, respectively.

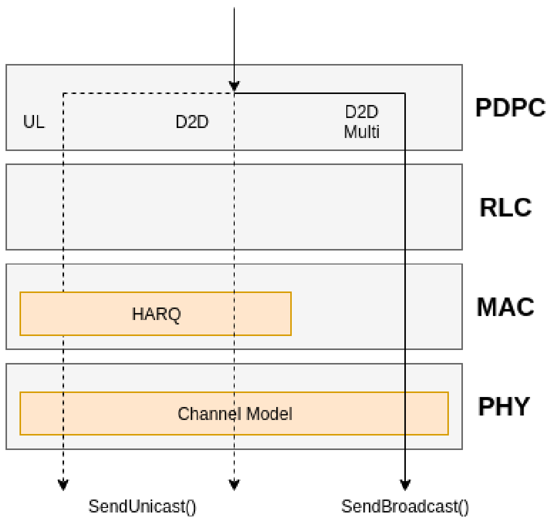

Figure 3.5: Data flow within sender UE's protocol stack

ChannelModel class within the PHY layer of LTE NIC, models the air transmissions between LTE NICs. When a new message arrives, ChannelModel computes the Signal-to-Interference-and-Noise Ratio (SINR) perceived by the node. In order to do this, it retrieves information about the usage of RBs for all the nodes in the network from Binder and decides if the message can be successfully decoded or not. Apart from this, ChannelModel also computes

and reports the Channel Quality Indicator (CQI) of the UEs. eNodeB uses this information to schedule operations. SimuLTE employs a realistic implementation of ChannelModel which takes path loss and fading effects into account. SimuLTE provides D2D capabilities with one-to-one and one-to-many direct communications between UEs. With reference to Figure 3.5, data flows received by LTE NIC module are forked at the PDCP level when they arrive from hte upper layer, based on the transmission direction (UL, D2D or D2D_-MULTI). In the case of D2D_MULTI, each packet also contains the identifier of the multicast group that this packet is addressed to. In D2D-Multicast, packets cannot use Hybrid Automatic Repeat reQuest (H-ARQ) functionalities at the MAC layer. H-ARQ buffers at MAC layer help to store MAC PDU until it is received correctly or the maximum number of retransmissions is reached. Once the packet arrives at PHY layer, *sendBroadcast()* function sends a copy of the message to all the UEs within the transmission range of the sender. The receiver UE then verifies whether this packet contains the multicast group it is subscribed to and then decodes it.
For more information about the framework SimuLTE, refer to the book titled Simulating LTE/LTE-Advanced Networks with SimuLTE [9] or the article [33].

Chapter 4

Simulation Setup

This chapter describes the simulation setup with the focus on some of the contributions of this thesis. The chapter is divided into the following subsections - combining Veins and SimuLTE frameworks, experimentation setup, performance metrics and the coexistence model.

4.1 Combining Veins and SimuLTE framework

One of the most important steps in getting started with simulation study in this work is to choose the compatible frameworks since the main objective is to eventually combine IEEE 802.11p and LTE into one framework. Initially, VeinsLTE was chosen as the framework as it was created by integrating three popular frameworks Sumo, Veins and SimuLTE into one simulation package. However, VeinsLTE framework lacks some of the latest modules that exist in Veins and SimuLTE. These additional new modules have been contributed by different authors by offering a more realistic view for simulation. Moreover, the lack of support for forward and backward compatibility led to installation issues. For these reasons, VeinsLTE has not been used for our simulation.
Owing to the dependencies involved in installing SimuLTE compatible framework with IEEE 802.11p, compatible version of Sumo v0.30.0, INET v3.6, Veins v5.1.1 and SimuLTE v1.0.1 were installed individually on the operating system Ubuntu 16.04. Individual modules within this respective Veins and SimuLTE frameworks have been adapted as per the simulation configuration and reused for computing performance metrics discussed later in the subsection 4.3. Furthermore, coexistence of 802.11p and C-V2X is enabled by implementing a new project within OMNeT++ that utilises INET's 802.11 stack and SimuLTE together.

4.2 Experimentation setup

In order to compare 802.11p and LTE-V2X, it is imperative that experiments are run for a comparable scenario. The first step performed to achieve this is by considering the same road network with exactly the same vehicle generation and route definition. We consider a 1000 m stretch of a highway, composed of four lanes and traversed only by vehicles with vehicular network communication capabilities (figure 4.1). Once the highway map is setup, SUMO is configured to generate vehicles on each highway lane. In order to accommodate all the vehicles within 1 km and have sufficient time to compute their performance for 10 s of simulation time, the maximum vehicle speed is chosen to be 30 kmph. This value is obtained by adding the time it takes to generate 70 vehicles (i.e 105 s) to the simulation time of 10 s. Vehicle density is calculated as the number of vehicles per lane within 1 km and varies from 10 vehicles/lane/km to 70 vehicles/lane/km. We consider four vehicle densities in our simulation to emulate different traffic conditions:

- 10 vehicles/lane/km represent low vehicle density scenario
- 30 vehicles/lane/km represent moderate vehicle density scenario
- 50 vehicles/lane/km represent high vehicle density scenario
- 70 vehicles/lane/km represent extremely high vehicle density scenario

In order to bring the highway simulation close to real life situation, the vehicles are generated at the maximum speed so as to mimic their entry into highway lanes. The output files from sumo are accessed by both veins and SimuLTE to read the attributes such as vehicle position and speed.

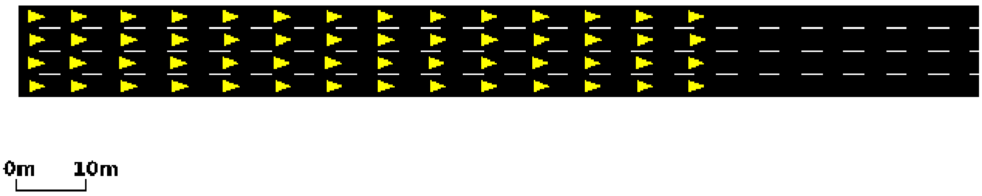

Figure 4.1: A screenshot of simulation of four highway lanes

The next step is to configure the simulation parameters within OMNET++ so we can compare the performance of IEEE 802.11p and LTE-V2X by varying the beacon frequency and increasing the vehicle density on the constructed highway map. The beacon frequency for BSM messages recommended by FCC is 10 Hz. For certain applications such as platooning, beacon frequency can reach up to 20 Hz. Hence, our experiments are conducted for 10 Hz (i.e, 100 ms beacon transmission interval) and 20 Hz (i.e, 50 ms beacon transmission interval).

For IEEE 802.11p-based vehicular network, we utilize Veins project for OMNeT++. All vehicles communicate directly using single-hop broadcast without any assistance from the RSU. All the experiments are conducted with 6 Mbps bit-rate, which has been the default data rate considered by IEEE during the standardisation process. By considering a fixed bit-rate, the transmission process is simplified and the vehicles only need to select the transmission frequency and power. Receiver sensitivity is set to -82 dBm for 6 Mbps data rate, as seen in Table 2.1. For propogation modeling, we use Nakagami fading channel using 5.9 GHz radio because it is a generalised distribution that can model line-of-sight (LOS) and non LOS fading environments unlike Rayleigh's which is not favoured for LOS distributions. All vehicles are configured to transmit BSM messages of size 300 bytes using UDP-based BSM application.

For LTE technology simulations, we utilize SimuLTE's D2D communication stack [34]. D2D-Multicast configuration in simulte makes use of LTE sidelink mode 3 for V2V communication to send CAM messages. This closely replicates how IEEE 802.11p broadcasts BSM. D2D communication allows UEs in promixity to exchange data directly using the sidelink (SL) path. This avoids two-hop path through the eNodeB, thereby reducing latency and saving resources. In this one-to-many mode of communication, the sender UE transmits data using a MAC-level identifier for the group of UEs that should receive the message. However, eNodeB still controls the allocation of resources in a semi-static way by a predefined CQI for all vehicles. It is important to note that H-ARQ feedback and retransmissions are not supported for D2D-Multicast. Therefore, H-ARQ reduction parameter is set to 0.2.

The evaluation has been done under the URBAN_MACROCELL scenario. Each CAM is 300 bytes at the application layer (excluding extra headers introduced at lower layers). SimuLTE comes with a realistic channel model that takes into account inter-cell interference, path loss, fading effects, shadowing, anisotropic antenna gain and noise figure. Pathloss and shadowing are used together with the SINR to estimate the BLER (Block Error Rate) for each received packet. This BLER value is used together with a random number to decide whether the packet is correctly decoded or not. Our simulations consider a single 10 MHz channel at 5.9 GHz carrier frequency. UEs transmit with a power of 15dB and the channel is affected by Jakes fading model. The 300 bytes packets are coded with a MCS using QPSK and 1/2 code rate (CQI 6). This study considers sub-channels of 12 subcarriers. The 10 MHz channel has 50 RBs of 180 kHz per sub-frame. The transmission method between the vehicles is single-hop multicast. UE noise figure is set to 7 dB. Antenna gain for UE and eNodeB is 18db and 0 respectively. Table 4.1 summarises the simulation parameter settings for the IEEE 802.11p and LTE standards.

Parameter	**Value**	
Vehicle density(vehicles/lane/km)	10, 30, 50, 70	
Vehicle speed	30 kmph	
Beacon Transmission Frequency	10, 20 Hz	
Highway length	1000 m	
Highway lanes	4	
Simulation Duration	10 s	
Vehicular traffic (packet size)	300 Bytes	
	IEEE 802.11p	**3GPP C-V2X**
Frequency	5.9 GHz	5.9 GHz
MCS/CQI	QPSK, R=1/2	6
Fading model	Nakagami fading	Jakes
Maximum Transmit Power	23 dBm	15 dBm

Table 4.1: Configuration parameters chosen according to IEEE 802.11p and 3GPP C-V2X

4.3 Performance Metrics

The load on the channel increases with increase in highway traffic intensity, making it challenging to provide reliable communication due to the potential interference between transmissions of different vehicles. The main objective of this study is to investigate the impact of traffic intensity on latency and reliability requirements of IEEE 802.11p and LTE-V2X. In order to do this, we refer to the following set of metrics:

4.3.1 Packet Reception Ratio (PRR)

Packet Reception Ratio is computed as the ratio of the number of received packets and the number of transmitted packets during the simulation. It illustrates the efficiency of the protocol to deliver packets to its destination. Higher the PRR, the greater is the guarantee for more reliable communication. For the simulation carried out in Veins,

$$PRR = \frac{receivedBSM}{receivedBSM + SINRLostPackets + TXRXLostPackets} \tag{4.1}$$

Algorithm 1: Packet reception ratio pseudocode

```
Result: Returns successfully and unsuccessfully received BSM
        messages
Input: Message msg
Output: scalars SINRLostPkt, TXRXLostPkt and receivedBSM
Function HandleLowerMsg(msg):
    if msg.errorCode = BITERROR OR
     msg.errorCode = COLLISION then       /* Packet not
     received due to biterrors */
     | SNIRLostPacket++
    else
        if msg.errorCode = RECWHILESEND then
         /* Packet not received due to sending
         while receiving */
         | TXRXLostPacket++
        else                        /* Packet received */
         | receivedBSM++
        end
    end
return
```

For IEEE 802.11p in Veins, *Decider80211p* module decides whether the received packet is properly decoded on the receiver. When the error codes returned are either *BITERROR*, *COLLISION* or *RECWHILESEND*, respective scalars *SNIRLostPackets* and *TXRXLostPackets* are incremented and the packets are not forwarded to the application layer. If the application layer successfully receives the packet from the MAC layer, the scalar *receivedBSM* is incremented within the *BaseWaveAppLayer::handleLowerMsg()* function.

4.3.2 End to End Delay

This performance metric refers to the time taken for a BSM/CAM message to be transmitted from sender node's application layer to the receiver node's application layer. Therefore, it includes channel access delay, transmission time and propagation delay. In this work, end-to-end delay is computed as the sum of the mean delays recorded for all vehicles over the total number of vehicles.

Algorithm 2: End-to-End delay pseudocode

Result: Returns end-to-end delay for each received BSM message
Input: Message msg
Output: vector E2EDelay
Function `populateWSM`(msg):
  $msg.Timestamp \longleftarrow simTime()$
  $msg.SenderAddress \longleftarrow senderId$
  $msg.ReceiverAddress \longleftarrow rcvId$
  $sendPacket(msg)$
Function `HandleLowerMsg`(msg):
  $StartTime \longleftarrow msg.Timestamp$
  $StopTime \longleftarrow simTime()$
  $E2EDelay := StopTime - StartTime$
return *E2EDelay*

BaseWaveAppLayer::populateWSM() packs the IEEE 802.11p packet with a timestamp field along with other fields and populates it with current timestamp. When the packet is received at the application layer, difference between the time of arrival and time of creation is computed. After the computation of the delay for both technologies, the implementation for automated analysis of delay over simulation time is done using vectors.

4.3.3 Inter Reception Time (IRT)

Inter reception time is defined as the time difference between two consecutive received packets from the same sender. Since beacons are transmitted at regular time intervals in the simulation, IRT is essential to observe the effect of increasing car density on timely information exchange. This helps to evaluate the reliability of the network in delivering packets to destination vehicles when subjected to higher vehicular densities. Algorithm 3 shows the pseudocode for Inter Reception Time at the application layer.

Algorithm 3: Inter reception time pseudocode

```
Result: Returns inter reception time for every sender-receiver pair
Input: Message msg
Output: vector IRT
Function HandleLowerMsg(msg):
    prevTimestamp :=
      SenderDetails(receiverId, senderId, timestamp)
    if prevTimestamp! = NULL then
        startTime ⟵ prevTimestamp
        IRT := simTime() − startTime
    end
IRTDictionary[Index,Timestamp]  /* Dictionary containing
  Timestamp for every sender-receiver pair */
  Function SenderDetails(receiverId, senderId, Timestamp):
    primaryKey = receiverId ∗ 100000 + senderId
    IRTDictionary.Index ⟵ primaryKey
    if IRTDictionary[Index] ≠NULL then
        prevTimestamp ⟵ IRTDictionary[Index]
        IRTDictionary[index] := Timestamp
    else
        IRTDictionary[index] := Timestamp
    end
  return IRT
```

To compute Inter Reception Time, it is vital to track the every BSM/CAM packet's origin at the vehicle receiving the packet. A new C++ class *ReceiverStatic* stores and retrieves the previous timestamp for the packet sender-receiver pair in the IRT Dictionary. *BaseWaveAppLayer::handleLowerMsg()* calls the *SenderDetails* function by passing identifier for the sender vehicle, receiving vehicle and the current timestamp. If no timestamp entry is found for the sender-receiver pair in the dictionary, a new entry with the current timestamp is added. If a timestamp entry for the currently received packet is found in the dictionary with a matching key, it returns the stored timestamp back to wrapper class *BaseWaveAppLayer* for the computation of Inter Reception Time and updates the dictionary with the new timestamp value for the sender-receiver pair.

4.4 Coexistence Model

The spectrum sharing solution proposed by ETSI [23] and 5GAA [12] can be realised through the framework implementation done as part of this work. We provide an sample combination of LTE-V2X and IEEE 802.11 such that each vehicle has two interfaces to transmit packets on a particular interface as per desired logic. This implementation integrates code from SimuLTE's LTE-V2X project with INET's 802.11. Combining 802.11p of Veins with LTE of SimuLTE is a very complex process as it involves merging two independent stacks. Although VeinsLTE project combines these two frameworks, the lack of backward compatibility, installation support and up-to-date protocol stacks is the reason why it is recommended to stick to 802.11 INET model of WLAN. IEEE 802.11 WLAN is a very close approximation of IEEE 802.11p.
This project integrated code from SimuLTE *car* project along with *Alert-Sender* and *AlertReceiver* that sends packets from both WLAN and LTE simultaneously. CAM message of size 300 bytes is triggered by the AlertSender UdpApp on the sender UE. Owing to the time constraints, the decision making algorithm that selects the interface on which this packet will be forwarded is absent. Hence, in the current implementation, the sender UE simultaneously forwards this packet on both interfaces(WLAN and LTE) using the different wireless LAN identifiers. Receiving vehicle receives the CAM message from whichever framework that happens to deliver the message first. Simulation specific parameters similar to IEEE 802.11p and LTE-V2X simulations are applied here. Performance metrics (IRT, End-to-End delay and PRR) are implemented to observe how the coexistence model fares in same highway scenario as IEEE 802.11p and LTE-V2X.

Chapter 5

Results

The simulation study carried out in this work examines the impact of varying beacon transmission frequency (or number of beacons sent per second) with increase in vehicle density. Simulation results are obtained as per the performance metrics discussed in Section 4.3.

5.1 Evaluation Results for IEEE 802.11p

Figures 5.1, 5.2 and 5.3 present the results for Packet reception ratio, End-to-end Delay, and inter reception time for IEEE 802.11p.
Reliability is an important factor when evaluating the performance of vehicular communication, which is characterised by packet reception ratio in our work. As seen in Figure 5.1, the ratio of BSM packets received decreases when the transmission frequency and the number of vehicles increase. At beacon transmission frequency of 10 Hz, sparse networks of vehicle density 10 and 30 exhibit better performance with 92% and 86% packet reception respectively. As the network load increases, denser networks with 50 vehicles/lane/km and 70 vehicles/lane/km result in 72% and 54% PRR respectively. In contrast, vehicles at 20 Hz experience more packet loss than 10 Hz. It can also be observed that for the same vehicular density, BSM reception is better for 10 Hz than 20 Hz. As the vehicular density increases, the gap between the PRR for 10 Hz and 20 Hz widens. More packet loss at 20 Hz can be attributed to congestion at the MAC layer contention based queue. With the increase in the network size, along with more packet transmissions per second, the channel gets saturated with traffic. Furthermore, lack of centralised coordination of the common channel among the vehicles contending for the access to the channel is another major contributing factor towards the performance degradation. In

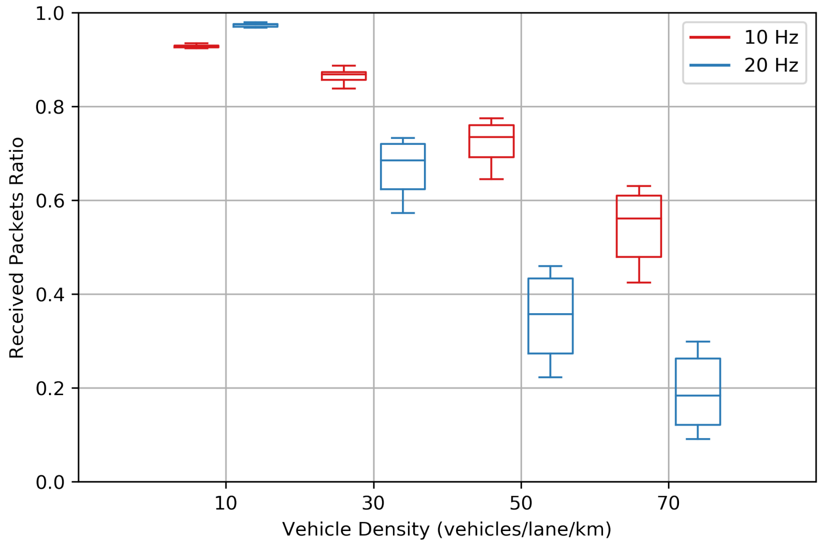

Figure 5.1: Packet reception ratio vs vehicle density at 10 Hz and 20 Hz beacon transmission frequency (Hz) for IEEE 802.11p

the case of 20 Hz beacon transmission frequency, one astute observation is that packet reception ratio halves from 0.67 to 0.35 when vehicles density increases from 30 to 50.

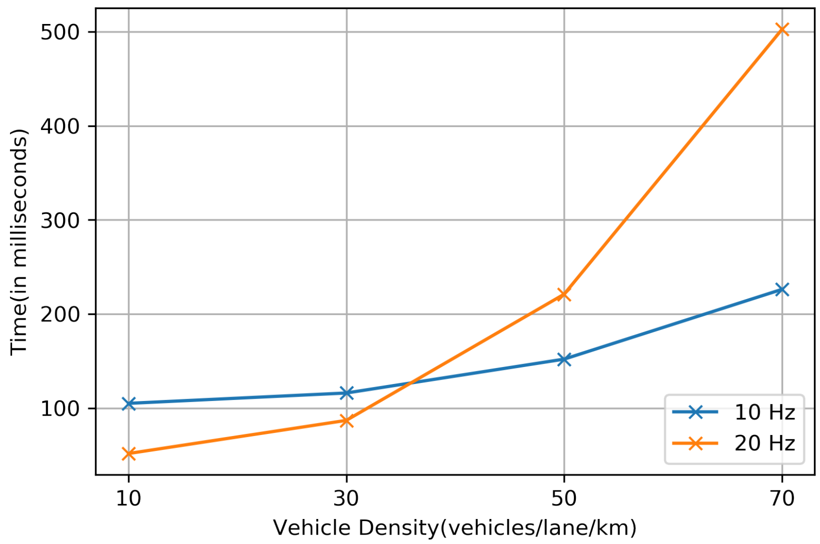

Figure 5.2: Inter reception time (ms) values by varying vehicle density and beacon transmission frequency (Hz) for IEEE 802.11p

Reliability can be further analysed by computing the overhead time it takes for a beacon to arrive at the destination, subject to channel congestion with increase in vehicle density. IRT complements the PRR analysis by quantifying the increase in reception time of consecutive beacons as few packets are lost during transmission. For example, in an ideal scenario where sending vehicle transmits a beacon at a periodic interval of 100 ms, the receiving vehicles must receive it every 100 ms. However, as the network density increases, the congestion in the network leads to longer delays than 100 ms. As observed from the Figure 5.2, IRT rises more rapidly for beacon transmission frequency 20 Hz with increase in vehicle density when compared to increase in IRT for 10 Hz. At 10 Hz, IRT is observed in the range of 104 ms (10 vehicles/lane/km) to 226 ms (70 vehicles/lane/km). At 20 Hz, IRT ranges from 51 ms to 502 ms. These results complement the trend observed in the Figure 5.1 where PRR decreases severely for 20 Hz. For instance, it can be inferred that for 19% PRR (70 vehicles/lane/km at 20 Hz) corresponds to an IRT of 502 ms. This means that there in an extra delay of 452 ms for each BSM to be delivered to the destination vehicle.

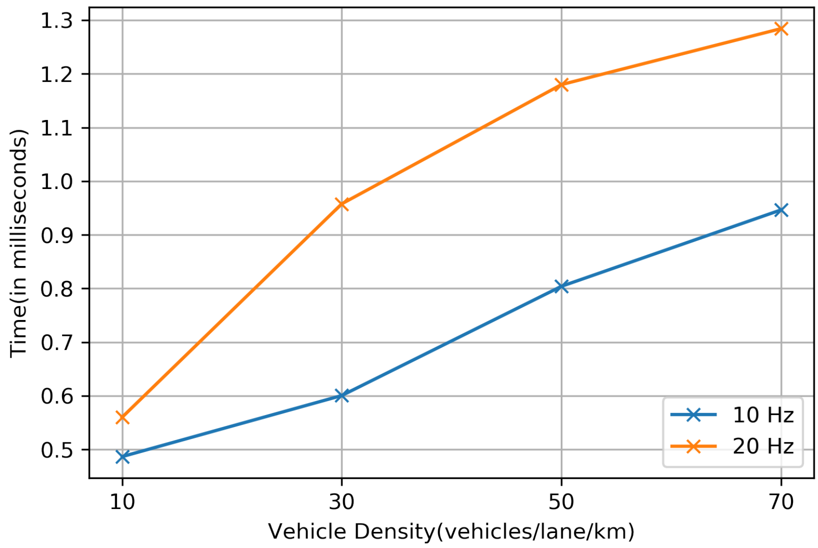

Figure 5.3: End-to-end application layer delay (ms) values by varying vehicle density and beacon transmission frequency (Hz) for IEEE 802.11p

Figure 5.3 depicts the average end-to-end application layer delay of successfully transmitted BSM messages at respective vehicular densities. Vehicular networking applications are time-critical and hence, it is imperative that the end-to-end delay must be between 100 and 500 ms. The general observation at the first look depicts that delay increases when the transmission frequency and the vehicle density increase. The delay for 10 Hz and 20 Hz beacon transmission frequency tends to be fairly linear increase as the vehicle density increases from 10 to 70 vehicles/lane/km. Successfully transmitted BSMs take only 1.3 ms to be delivered to the destination nodes even at a vehicular density of 70 vehicles/lane/km. In conclusion, the delay received for a beacon packet size of 300 bytes is well below the upper limit of 500 ms.

5.2 Evaluation Results for 3GPP LTE-V2X

Figures 5.4, 5.5 and 5.6 depict the results for Packet reception ratio, inter reception time and End-to-end Delay for 3GPP LTE-V2X, respectively.

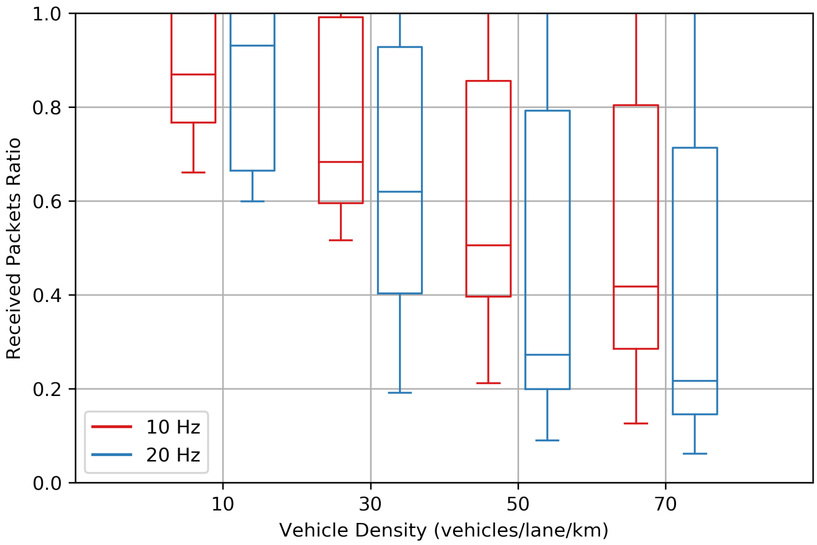

Figure 5.4: Packet reception ratio values by varying vehicle density and beacon transmission frequency (Hz) for LTE D2D

Similar to IEEE 802.11p, we observe that the packet reception ratio gradually decreases with the increase in vehicle density. PRR fares better at 10 Hz beacon transmission frequency than at 20 Hz for all vehicle densities except 10 vehicles/lanes/km. This is an outlier case for our experiment.
When comparing the PRR results to IEEE 802.11p, LTE-V2X fares poorly at 10 Hz and 20 Hz beacon transmission frequency. Looking at the median values obtained in the Figure 5.4 for 20 Hz, LTE-V2X fares poorly for vehicle densities 10, 30 and 50, but marginally outperforms IEEE 802.11p at 70 vehicles/lane/km.

We can also observe that the range of PRR increases with increase the vehicle density. As the vehicle density increases, collisions during transmission due to high Block Error Rate (BER) induced due to interference from neighbouring bands results in low PRR. Static CQI indicator also plays an adverse affect on PRR results. Since eNodeB exploits CQIs reported by UEs for the D2D links and utilises this information to allocate RBs, it overloads same RB to multiple D2D flows and allocates RBs on an assumption of CQI rather than the actual CQI perceived by vehicles, thereby resulting in even more collisions.

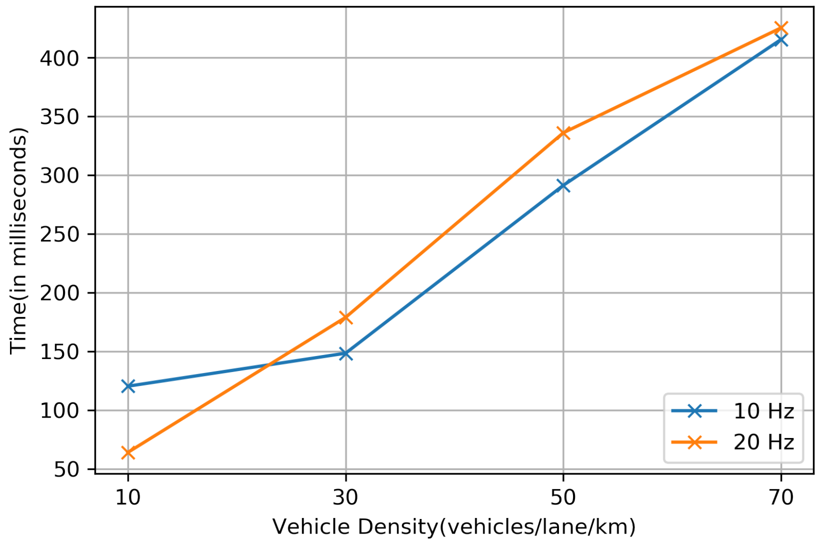

Figure 5.5: Inter reception time (ms) values by varying vehicle density and beacon transmission frequency (Hz) for LTE D2D

Figure 5.5 depicts the average inter reception time for D2D Multicast communication in LTE-V2X. The rise in IRT for CAM transmissions at 20 Hz is much sharper than those at 10 Hz. We observe that transmissions at 20 Hz surpasses the ones at 10 Hz at 30 vehicles/lanes/km for LTE-V2X whereas in case of IEEE 802.11p, 20 Hz surpassed 10 Hz at 50 vehicles/lane/km. This is consistent with the low PRR value observed for LTE-V2X, which is directly proportional to the increase in IRT for LTE-V2X.
Keeping in line with the better PRR observed for 70 vehicles/lane/km at 20 Hz in Figure 5.4, it is observed that LTE-V2X has better IRT (425 ms) than IEEE 802.11p (502 ms).
End-to-end application delay for LTE-V2X increases many folds with the increase in vehicular density. For 10 Hz, the delay ranges from 24 ms to 5.7 s.

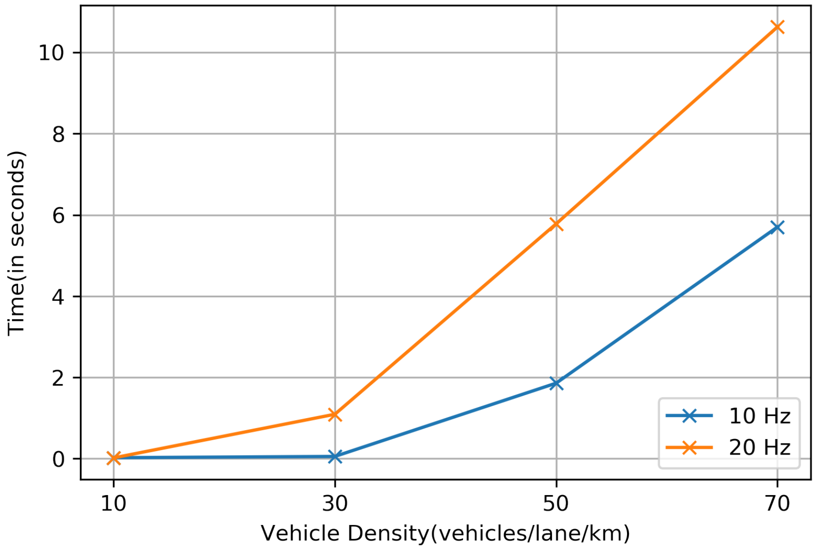

Figure 5.6: End-to-end application layer delay (s) values by varying vehicle density and beacon transmission frequency (Hz) for LTE D2D

For 20 Hz, the rate of increase is much sharper with delays reaching 10.6 s. In comparison to IEEE 802.11p where end-to-end delay is in the order of milliseconds, successful transmission in LTE-V2X at 6 CQI takes place in order of seconds for higher vehicle densities 50 and 70. Clearly, more transmissions come at the cost of higher resource consumption. The number of allocated RBs per broadcast should increase as the number of UEs increase [35]. Since we have fixed the number of RB to 50 (calculated for 10 MHz), only a certain number of devices who request transmission can be granted RBs by the eNodeB. This results in extremely high waiting time for packet transmission in dense network conditions.

Chapter 6

Discussion

The conducted analysis helps us to derive some key insights into the potential of IEEE 802.11p and LTE-V2X.

For the highway scenario simulated in this work, the results clearly show that increasing the beacon frequency from 10 Hz to 20 Hz results in higher packet loss, increased inter-reception time and more delays in transmitting BSM/CAM messages. Saturation of traffic channel is the major cause for this behaviour. The channel saturation is exacerbated when vehicle density crosses 50 vehicles/lane/km.

Although IEEE 802.11p achieves better average PRR than LTE-V2X for lower density vehicle simulations, range of PRR in LTE-V2X suggests that there are few vehicles that receive 100% of the transmitted packets. There is no simulation scenario in IEEE 802.11p where maximum PRR achieved is 100%. For the LTE scenario, much of this higher PRR is attributed towards infrastructure-assisted scheduling that enables nearby transmissions with higher probability. Whereas in case of IEEE 802.11p, lack of centralised coordination of the common channel plays a major role in increased collisions. On the other hand in LTE-V2X, we observe that some vehicles suffer tremendous packet loss. Upon further exploration of the decoding process of the packet at the receiver node, it is observed that a transmission is classified as unsuccessful when its error probability is smaller than a random error extracted ranging between 0 and 1. The computation of error probability is dependent on the Block Error Rate (BER) and the channel band selected for transmission. BER is a function of number of used RBs, CQI and Signal-Noise Ratio (SNR), thermal noise, noise figure and interference. Higher the band number used for transmission, more likelier it is for BER to multiply, thereby increasing error probability. Increase in vehicle density leads to higher band number selection for transmission.

IRT complements the PRR results by giving insights into the overhead delay observed by vehicles in receiving time critical periodic information. For beacon transmission frequency of 10 Hz, IEEE 802.11p has significantly lower IRT than LTE-V2X for all vehicle densities. For beacon transmission frequency of 20 Hz, the effects of channel congestion and exponential increase of packet collision is visible in IEEE 802.11p at highest vehicle density of 70 vehicles/lane/km.

End-to-end delay is computed for transmissions which are successful. Results show that LTE-V2X experiences more delay than IEEE 802.11p for respective vehicle density and beacon frequency. LTE-V2X has most delay accruing at the radio link control layer. This is reflective of the time it takes for the transmitting vehicle to be granted RBs by the eNodeB because only a certain number of vehicles can be allocated RBs at a time. It is therefore imperative to increase the number of RBs to accommodate more transmissions. Adaptive RB allocation is not implemented in SimuLTE. Another major reason for higher delay is the choice of MCS employed (CQI 6 in our case). MCS significantly affects the number of allocated RBs. Lower CQIs occupy more RBs to transmit the same packet and vice versa. Lower CQIs ensure higher robustness at the expenses of higher transmission overhead. By performing some more experiments by varying the CQI, we observe that end-to-end delay reduces many folds with higher CQI but it also results in higher packet loss. It is hence important to achieve a good trade-off in terms of allocated resources and reliable coverage. CQI 6 is chosen for our experiments to have a comparable scenario where MCS of LTE-V2X and IEEE 802.11p have same data rates.

Implementation of coexistence model is done using IEEE 802.11 and SimuLTE where a BSM is transmitted at the same time using both technologies. The motivation is to analyse which interface is able to transmit quickly and the conditions that favour choice of one interface over the other. It is observed that nearly 95% of the messages reach the destination first using IEEE 802.11 and the other 5% using LTE. This is majorly due to the fact that in our LTE scenario, the vehicles first request the eNodeB for channel allocation before transmitting CAM. In 802.11, the decentralised transmission strategy happens to allocate the channel before LTE. To mitigate other factors like interference due to two technologies functioning within the same spectrum, it is important to limit the technologies to separate bands as per Phase 1 coexistence proposal on preferred bands.

6.1 Limitations

The limitations of our work are listed below:

- Experiments for IEEE 802.11p are performed for data transfer rate of 6 Mbps which employs QPSK modulation and a coding rate of 1/2. This setting is employed in order to match with the modulation scheme in LTE. Other transfer rates can lead to different simulation results.
- SimuLTE employs MCS as per CQI table in TS 36.213 [36], which defines the mapping of each CQI to a modulation scheme. This mapping table has been updated for Release 12 and beyond. It now contains 256-QAM modulations for CQI ranging from 12 to 15 which is not available in the current available SimuLTE framework.
- Since D2D-Multicast comes with its own limitations which disables real time CQI reporting for vehicles, a fixed CQI is enabled instead of automatically adjusting MCS. If CQI is reported back to the sender, it would allow the sender to adapt the MCS as per the actual channel quality experienced by the receiver. This would highly improve the resource utilisation.
- Simulation experiments that are run for evaluating the coexistence model currently do not provide tangible inferences that would suggest improvements on our performance metrics. Two of the observed limitations are interference caused due to two technologies functioning in the same spectrum without channel segregation; both LTE and 802.11 interfaces on the vehicle emitting the same packet instead of only one interface.

6.2 Future Work

SimuLTE's D2D-Multicast configuration allows vehicle to broadcast messages to all the receiving vehicles using a single hop mechanism. The new library called "Multihop D2D" should be evaluated to compare the improvement in protocol performance in LTE. [35] argues that network controlled D2D communication is fast and reliable from a resource consumption standpoint when packets are relayed in a multihop fashion.
Another interesting study would be an exhaustive performance analysis of LTE D2D Multicast communication based on the combinations of MCS and RBs. This would provide insight as to how the SINR at the UE and the scheduling

algorithm employed can affect the optimal MCS and the allocated RBs for a particular vehicular density scenario.
The implementation of a model where LTE and IEEE 802.11 can function simultaneously has opened up some new possibilities for future work in the V2V space, especially for implementation of coexistence based on preferred channels. In order to implement Phase 1, one of the major areas to focus is the decision making to transmit the packet using either LTE-V2X or IEEE 802.11p interface. Choosing one of the interfaces will determine the channel on which CAM/BSM will be transmitted. One way to implement the decision algorithm is by predicting the quality of channel. This can be tricky and requires metrics that determine channel strength. Another way to select the technology for transmission is to determine whether the vehicle destined to receive the packet lies in the transmission range of the vehicle transmitting the packet. CBR can also be used to determine whether a congested channel needs to switch packet transmission to another channel. In Phase 1, switching channels will result in use of other technology. Implementation of Phase 2 and Phase 3 will use the same prediction logic along with the ability to allocate Channel 178 for transmissions. The project can witness a fruitful end when simulation carried out with different network settings (vehicle density and beacon frequency) for coexistence between IEEE 802.11p and C-V2X can result in efficient channel utilization and successful deployment of products/services in real world V2X use cases.

Chapter 7

Conclusion

This work evaluates the performance of ITS-G5 and LTE-V2X via simulations by varying beacon transmission frequency and vehicle density. The results obtained infer that IEEE 802.11p is much more suited for sparsely dense network than LTE-V2X at lower beacon frequency of 10 Hz. LTE-V2X has better mean PRR and IRT for extremely dense highway scenario, albeit resulting in few seconds of delay to transmit CAM.

Initially, the difference in protocol stacks for DSRC (IEEE 802.11p and ITS-G5) and C-V2X is discussed and relevant performance metrics are chosen. OMNeT++ simulation platform is utilized to carry out simulations with comparable scenario. Different degrees of performance degradation is observed in terms of PRR, IRT and end-to-end delay for both technologies when vehicular density and beacon transmission frequency is increased. IEEE 802.11p outperforms LTE-V2X at beacon transmission frequency of 10 Hz for all vehicle densities. Limitations of setting fixed CQI in D2D Multicast configuration is deduced as the major reason for drop in packets in LTE-V2X. It is also inferred that more RBs must be allocated as per increasing vehicle density and beacon intervals to adequately accommodate for increased transmissions. At 20 Hz beacon frequency, LTE-V2X achieves better IRT than IEEE 802.11p at 70 vehicles/lane/km. Although LTE-V2X achieves better performance in terms of IRT, end-to-end delay is recorded in the order of seconds.

We additionally provide an implementation for coexistence model to achieve a simulation scenario where IEEE 802.11 and LTE-V2X can simultaneously transmit packets.

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