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INTELLIGENT SYSTEM FOR HETEROGENEOUS VEHICULAR NETWORKS OPERATION BASED ON VULNERABLE ROAD USERS AWARENESS

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POR: **TOMÁS ANTONIO LARA ARAVENA**
FECHA: 2022
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SISTEMA INTELIGENTE PARA EL MANEJO DE REDES DE COMUNICACIÓN VEHICULAR HETEROGÉNEAS BASADO EN EL CONOCIMIENTO DE USUARIOS VULNERABLES

La seguridad de los usuarios viales vulnerables (VRUs por su sigla en inglés) es crítica dada su exposición. Se espera que la integración de VRUs en redes de comunicación vehicular mejore su seguridad. Sin embargo, la congestión de canal puede mermar la efectividad de aplicaciones para proteger a los VRUs. Trabajos previos han abordado este problema utilizando filtros de mensajes, cuyo efecto en la detección de VRUs permanece en cuestión.

Esta tesis propone un control de transmisiones para VRUs en redes de comunicación vehiculares heterogéneas. El sistema VRU Awareness-based Intelligent Beaconing System for Heterogeneous Networks (VARIATE) incorpora criterios de detección de VRUs y carga de canal para seleccionar una frecuencia de envío y red de acceso. VARIATE integra las tecnologías Dedicated Short-Range Communications (DSRC) y Cellular-Vehicle-to-Everything (C-V2X). El sistema utiliza aprendizaje de máquinas para estimar y utilizar métricas de detección.

VARIATE exhibe una mejora en la detección de VRUs comparado con las líneas base usando la mejor configuración encontrada. Se consideran mecanismos de selección aleatoria y codiciosos para las comparaciones. Los resultados muestran que C-V2X supera a DSRC en la detección de VRUs. Finalmente, VARIATE mostró mejoras sustanciales en latencia comparado con los mecanismos de mejor detección de VRUs.

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Vulnerable Road Users (VRUs) safety is one of the main concerns in vehicular networks due to their high death risk in traffic accidents. The VRU integration into vehicular communication networks could improve their safety. However, communication network congestion in dense scenarios may impair safety applications based on beaconing. Previous efforts have assessed this issue using message filtering mechanisms, yet their effect on VRU awareness remains a question.

This thesis proposes a VRU beaconing control mechanism for heterogeneous vehicular communication networks. The proposed VRU Awareness-based Intelligent Beaconing System for Heterogeneous Networks (VARIATE) incorporates VRU awareness and channel load criteria to control the beaconing frequency and radio access technology. VARIATE considers using Dedicated Short-Range Communications (DSRC) and Cellular-Vehicle-to-Everything (C-V2X). The system incorporates machine learning to predict VRU awareness and make awareness-based decisions.

Evaluations of the proposed system show that VRU awareness is improved when using the best configuration of VARIATE compared to heterogeneous benchmarks, precisely random and greedy mechanisms. We also observe that using C-V2X improves the awareness against using only DSRC in the access network. Also, we demonstrate there is a substantial improvement in latency when using the proposed system against the best-awareness modes while maintaining similar values of VRU awareness.

A Lorena, mi madre

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Glossary

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ITS	Intelligent Transportation Systems	1
CV	Connected Vehicles	1
C-ITS	Cooperative Intelligent Transportation Systems	1
RSU	Road Side Unit	1
VRU	Vulnerable Road User	1
PTW	Powered Two Wheeler	2
LIDAR	Light Detection and Ranging	2
LoS	Line of Sight	2
GIDAS	German In-Depth Accident Study	2
NLoS	No Line of Sight	2
V2P	Vehicle-to-Pedestrian	2
RFID	Radio Frequency Identification	2
TTC	Time To Collision	3
V2X	Vehicle-to-Everything	3
DSRC	Dedicated Short Range Communications	3
CCH	Control Channel	3
C-V2X	Cellular-Vehicle-to-Everything	3
AI	Artificial Intelligence	3
ML	Machine Learning	3
CBR	Channel Busy Ratio	4
VARIATE	VRU Awareness-based Intelligent Beaconing System for Heterogeneous Networks	7
Veins	Vehicular in Network Simulation	7
RAT	Radio Access Technology	8
AV	Autonomous Vehicle	9
V2V	Vehicle-to-Vehicle	10
V2I	Vehicle-to-Infrastructure	10
V2N	Vehicle-to-Network	10
V2VRU	Vehicle-to-Vulnerable Road User	10
ETSI	European Telecommunications Standards Institute	10
VLC	Visible Light Communication	10
PHY	Physical Layer	11
MAC	Medium Access Control	11
IETF	Internet Engineering Task Force	11

SAE	Society of Automotive Engineers	11
OCB	Outside the Context of a Basic Service Set	11
SCH	Service Channel	11
DCC	Decentralized Congestion Control	12
EDCA	Enhanced Distributed Channel Access	12
QoS	Quality of Service	12
DCF	Distributed Coordination Function	12
AC	Access Category	12
CW	Congestion Window	12
ACK	Acknowledgment	13
SIFS	Short Inter-Frame Space	13
3GPP	Third Generation Partnership Project	13
LTE-V2X	Long Term Evolution Vehicle-to-Everything	13
5G-V2X	Fifth Generation Vehicle-to-Everything	13
NR-V2X	New Radio Vehicle-to-Everything	13
FCC	Federal Communications Commission	14
D2D	Device-to-Device	14
UE	User Equipment	14
E-UTRAN	Evolved Universal Terrestrial Access Network	14
eNB	Evolved Universal Terrestrial Access Network NodeB	14
SB-SPS	Sensing-Based Semi-Persistent Scheduling	15
SC-FDMA	Single Carrier Frequency Division Multiple Access	16
TTI	Transmission Time Interval	16
RB	Resource Block	16
SCI	Sidelink Control Information	16
MCS	Modulation and Coding Scheme	16
TB	Transport Block	16
PSCCH	Physical Sidelink Control Channel	17
PSSCH	Physical Sidelink Shared Channel	17
RRI	Resource Reservation Interval	17
RC	Reselection Counter	17
CSR	Candidate Single-Subframe Resources	18
RSRP	Reference Signal Received Power	18
RSSI	Received Signal Strength Indicator	18
AU	Application Unit	19
OBU	On-Board Unit	19
CCU	Communication Control Unit	20
HMI	Human-Machine Interface	20
MANET	Mobile Adhoc Network	20
VANET	Vehicular Adhoc Network	20
UMTS	Universal Mobile Telecommunication System	21
E-UTRA	Evolved Universal Mobile Telecommunication System Terrestrial Radio Access	21
PLMN	Public Land Mobile Network	21

V2X AS	Vehicle-to-Everything Application Server	22
ProSe	Proximity Services	22
NR-RAN	New Radio Radio Access Network	22
URLLC	Ultra-Reliable and Low Latency Communication	22
HetVNET	Heterogeneous Vehicular Network	22
AP	Access Point	22
5G-PPP	5G Public-Private Partnership	23
ETSI ITS-S	ETSI Intelligent Transportation System Station	23
OSI	Open Systems Interconnection	24
SC	Service Center	24
CN	Core Network	24
RAN	Radio Access Network	24
HLL	Heterogeneous Link Layer	25
DL	Deep Learning	27
RL	Reinforcement Learning	27
CAV	Connected and Autonomous Vehicles	29
TR	Technical Report	29
TS	Technical Specification	29
FCOM	Functional Communication Requirement	30
OSYS	Operational System Requirement	30
OCOM	Operational Communication Requirement	30
OSEC	Operational Security Requirement	30
CPM	Cooperative Perception Messages	30
VAM	Vulnerable Road User Awareness Message	31
PSM	Personal Safety Messages	32
PCA	Pedestrian Collision Avoidance	32
P2C	Pedestrian-to-Cloud	33
V2C	Vehicle-to-Cloud	33
P2P Groups	Peer-to-Peer Groups	33
P2P GO	Peer-to-Peer Group Owner	33
OWR	Object Awareness Ratio	34
CBP	Channel Busy Percentage	35
B$_p$ER	Beacon Packet Error Ratio	35
PER	Packet Error Ratio	35
IPG	Inter Packet Gap	35
VAP	VRU Awareness Probability	35
PRR	Packet Reception Rate	37
WT	Waiting Time	37
PSR	Packet Sensing Ratio	37
CQI	Channel Quality Indicator	37
VHO	Vertical Handover	37
RRM	Resource Radio Management	37
CAM	Cooperative Awareness Message	37
DENM	Distributed Environmental Notification Message	37

VoIP	Voice over IP	37
DV	Dual Interface Vehicles	38
SINR	Signal to Interference plus Noise Ratio	38
TVWS	Television White Space	38
DCM	Dynamic Communication Management	39
MEC	Mobile Edge Computing	39
RF	Random Forest	41
SVM	Support Vector Machine	41
KNN	K-Nearest Neighbors	41
CSI	Channel State Information	42
DRA	Distributed Resource Allocation	42
MADRL	Multi-Agent Deep Reinforcement Learning	42
DDQL	Double Deep Q-Learning	42
LSTM	Long-Short Term Memory	42
MBL	Maximum Beaconing Load	42
MDP	Markov Decision Process	42
DCA	Dynamic Channel Assigment	43
RL-CDCA	Reinforcement Learning-based Cooperative Dynamic Channel Assignment	43
CNP	Communication Node Pair	43
RLEB	Reinforcement Learning-based Exponential Backoff	43
PDR	Packet Delivery Ratio	46
NDP	Node Detection Probability	46
RVDP	Risked Vulnerable Road User Detection Probability	46
KAM	Knowledge About Me	46
ReLU	Rectified Linear Unit	54
MSE	Mean Square Error	54
RMSE	Root Mean Square Error	54

Chapter 1

Introduction

1.1. Motivation

The primary motivation of this thesis is to help improve the safety of road users through vehicular communications. Nowadays, private vehicles represent a threat to people's safety because of traffic accidents. Even though there are a variety of public transport options — with unequal development in each country — most road users prefer to use cars when commuting [1]. Moreover, the shared mobility tendency is not enough to reduce the number of circulating private vehicles. Actually, the vehicle number is expected to continue growing, only that with a slower pace (3.6% between 2011 and 2016 to 2% in 2030) [2]. The main problem related to the increasing number of cars is the high number of deaths caused by traffic accidents [3]. Statistically speaking, the *Global Status Report on Road Safety*, carried out by the World Health Organization (WHO) in 2018, indicates that annually 1.35 million people die in traffic accidents. To put this number in context, it represents the eighth leading cause of death worldwide. In the age range between 5 and 29 years old (considered young by WHO), traffic accidents represent the leading cause of death [4].

Considering the previous facts, both academia and industry are increasingly focused on developing Intelligent Transportation Systems (ITS). It is expected that these systems will bring benefits not only in terms of traffic accidents reduction but also the monetary and environmental costs that the increasing number of vehicles brings [5]. The development of vehicular communications is a critical element for the development of ITS and the successful reduction of accidents [6]. Vehicular communications, referred to as Connected Vehicles (CV) or Cooperative-ITS (C-ITS), allow wireless information exchange among road users. C-ITS comprehends the exchange of information among cars and between cars and any other type of nodes, such as Road Side Units (RSUs), the Cloud, and pedestrian handheld devices. The objective of this type of communication is to enable a set of road applications, such as safety applications, traffic optimizations, fuel consumption reduction, and many others [7, 8].

When analyzing the C-ITS development, we notice that not all road users are extensively included as active networks members. In particular, a relevant set of road users, named Vulnerable Road Users (VRUs), has not been fully included [9]. The definition of this set depends on the used reference; however, as stated in [10], we can consider that these users lack adequate protection mechanisms or are not capable of reacting to critical traffic situations.

In general, articles [1, 11, 12] and standardization documents [13] include in this set pedestrians, cyclists, motorcyclists, and Powered Two Wheelers (PTWs). In terms of government regulations, we can consider the definitions given by the Chilean and European legislation. According to Chilean law, VRUs are pedestrians and *ciclo* drivers (bicycles, scooters, skates, and others) [14]. The European Parliament defines VRUs as ‘non-motorized road users, such as pedestrians and cyclists as well as motorcyclists and persons with disabilities or reduced mobility and orientation’ [15].

Traffic accidents situations are particularly hazardous for VRUs. Moreover, according to the previously mentioned WHO report [4], VRUs represent half of the deaths in traffic accidents. Also, the efforts to improve VRU safety are not as successful as vehicular users’ death reduction experienced in the last years [9]. Nowadays, passive detection by vehicles is the basis of most of the mechanisms proposed to improve the safety of VRUs. These approaches use different techniques and sensors — video analysis, Light Detection and Ranging (LIDAR), proximity sensors, among others — to better understand a vehicle’s surroundings. Nonetheless, passive detection based on sensors is strongly affected by weather conditions and the requirement of Line of Sight (LoS) to operate correctly, which is not appropriate for different use cases as remarked by many authors [16–18]. For example, if we consider the use of cameras, we observe limitations in terms of geometry and range [19], along with LoS need. LoS is a critical factor in VRU safety applications design since, as stated by [20] (based on the German In-Depth Accident Study (GIDAS) [21]), 29.7% of all accidents between pedestrians and cars occur when pedestrians are crossing the street with No LoS (NLoS). Other impairments of the exclusive use of sensors are related to the economic and computational costs of having many different types of sensors in a car [22].

Different efforts intend to include VRUs as members of the C-ITS using Vehicle-to-Pedestrian (V2P) communications to overcome the limitation of passive approaches. The term V2P encapsulates the message exchange between vehicles and any VRU type. There are different approaches to enable this type of communication, depending on the used technology and the role of the VRUs — only transmit messages, only receive messages, or both. Among the many access technologies used, we can highlight the use of Wi-Fi [23], Cellular Network [24], IEEE802.11p/DSRC [25], and even Radio Frequency Identification (RFID) tags, Bluetooth or others, which are summarized in [26]. Despite these efforts, there is still a lack of research related to VRU specific apps in the C-ITS context [9, 27]. Also another relevant factor to be studied is the effect that the active inclusion of VRUs could have on the networks in terms of, for example, channel load [11, 26].

The approaches for VRU inclusion in C-ITS fit into two general categories. These two types of approaches are named active VRU and passive VRU. Each of these categories presents different advantages and disadvantages in different aspects. A *passive* VRU is a node that ‘waits’ for messages from vehicles before performing some task. These actions can be forwarding a message or other operation over the received information (e.g., collision probability estimation). On the other side, an active VRU is a node that participates in the C-ITS sending information in messages — e.g., position, speed, heading — usually in a systematic way or following a forwarding rule set.

Each of the VRU integration approaches has different advantages and disadvantages. On one side, an active system may have a better performance when compared to a passive one in several aspects. For example, an active approach can increase the total amount of packets received before a collision and the Time To Collision (TTC). On the other hand, the same approach can negatively affect channel congestion and battery consumption, particularly on handheld devices such as smartphones. In terms of congestion, there are serious concerns about the negative effect that the active integration of VRUs could have [26].

The consideration of the used access technology increases the doubt about the network performance under heavy channel congestion. Nowadays, the most studied technologies for Vehicle-to-Everything (V2X) are those based on the IEEE 802.11p standard, named Dedicated Short Range Communication (DSRC) in the USA or ITS-G5 in Europe. Despite the large number of works dedicated to studying this technology, there are concerns regarding the performance of the access mechanism in dense traffic scenarios. In this context, the integration of VRUs in the C-ITS comes to worsen the congestion that this technology suffers in its Control Channel (CCH), used by safety messages [28]. The situation can be even more critical in some countries, like the USA, with the announcement of the DSRC dedicated spectrum reduction and the encouragement of Cellular-V2X (C-V2X) technology [29].

Considering the congestion addition related to VRU integration in the C-ITS, new mechanisms for resource management must be developed to decrease the channel congestion. It is crucial to remark that the reduction of the channel load must not lead to a decrease in the awareness capacities (the ability of a node to detect other nodes). The awareness capacity is vital in VRU safety applications since it affects the environment's knowledge of a node and hence the ability to prevent traffic accidents. This thesis proposes using a heterogeneous network to control channel congestion without severely compromising awareness. The idea of heterogeneous networks is to use different access technologies for packet transmission. In the case of this thesis, we consider two access technologies named DSRC and C-V2X. In addition, Artificial Intelligence (AI), and more specifically, Machine Learning (ML), have shown different applications in C-ITS last years, which is the reason to consider these types of tools as an option for the management of heterogeneous networks.

1.2. Problem Statement

As stated in Section 1.1, several studies show the possible benefits of including VRUs as active members of the C-ITS. Among the advantages of this integration, the improvement of VRU safety is the main focus of this thesis. Nevertheless, integrating this large set of users as active communications nodes brings considerable challenges [26]. First, we consider the control of the channel congestion, studied in a substantial number of publications [17, 30, 31]. Second, VRU awareness maximization is an essential factor to consider. To this author's knowledge, at the moment of writing this thesis, there are no published works that assess the study of VRU awareness in the channel load reduction context. This factor is significant when designing safety applications oriented to VRU protection since the knowledge about VRU presence is crucial when performing collision avoidance actions. Previous work carried out during the development of this thesis showed a tradeoff between channel load reduction and VRU awareness when using channel load mechanisms. Although these mechanisms allow the network as a whole to reduce the channel load, the filtering of messages can negatively impact the VRU awareness [32]. The following two points synthesize the problem addressed in this thesis.

High-density scenarios and standard radio access technologies: Nowadays, most road safety systems based on communications use direct communications technology (DSRC or ITS-G5) or the cellular infrastructure. The main problem related to the inclusion of VRUs as active communication nodes is the increase in channel load that this new set of nodes can add to the present congestion. Even now, doubts have been stated regarding the suitability of DSRC for supporting vehicular communications when the density increases. These doubts are mainly based on the congestion that affects the control channel — where safety packets are sent — of DSRC in present studies. [28]. Moreover, some works, such as the report developed by the European ITS-G5 Platform, have stated that nowadays, neither ETSI ITS-G5 nor Cellular Communications Systems can support the complete range of C-ITS services individually [33]. Other works sustain that current RATs cannot independently support the entire range of C-ITS applications. These works also express in favor of the parallel use of different RATs [34–36]. The previous facts show the high complexity that the integration of VRUs represents for the communications field.

VRU Awareness: With means to promote the inclusion of VRUs in the C-ITS environment, several works have been developed to overcome access technologies limitations. Previous works have mainly focused on channel saturation in high-density environments. Based on these problems, different authors have proposed systems that filter the VRU transmissions based on mobility or context conditions (e.g., [30]. Although these works evaluate the channel load when applying the transmission rules, VRU awareness is consistently not considered in the examinations. Not considering this criterion when designing filtering systems can harm its performance in terms of VRU knowledge, which directly impacts the ability of safety systems to protect VRUs. The use of fixed rules, only considering channel occupation benefits metrics as the Channel Busy Ratio (CBR) because of the reduction of the number of exchanged messages, but impact negatively the knowledge that vehicles have about surrounding VRUs [32].

1.3. Hypothesis

This section presents the hypotheses of the work developed in this thesis. The base of the formulation of these hypotheses is to consider the integration of VRUs as active members of the vehicular communications networks. This formulation considers the problems related to the additional VRU traffic, such as the increase in the channel load and the problems observed in the detection of VRUs when using existing access technologies independently. These challenges associated with VRU inclusion made us think of possible solutions that increase VRU awareness; this means the proportion of VRUs that vehicles can know through the exclusive use of communications. Based on the main objective of allowing the best possible detection of VRUs and considering the intelligent administration of heterogeneous networks, the following hypotheses are formulated:

1. When considering the inclusion of VRUs, the designed intelligent decision system for the operation of a heterogeneous network formed by C-V2X and DSRC allows the improvement of the general characteristics of the communication network. The system improves the metrics of VRU awareness (to be proposed), latency, and channel occupancy by at least 10% compared to the tested benchmarks. We propose this percentage as a goal of the designed system to consider a significant improvement.

2. Related to the objective of balancing the channel load and the awareness of VRUs, the proposed system must satisfy today's standard requirements. Specifically, we consider the condition of a maximum latency of 300 ms defined by ETSI for the case of non-obstructed communication [37]. Additionally, the intelligent system allows us to maintain a channel occupancy comparable to state-of-the-art, with a minimum value of awareness of 70% of the proposed metric. We consider this percentage as it is the worst value of the awareness metric studied in our previous work [32], for a fixed beaconing rate in a DSRC-based network.

1.4. Objectives and Scope

1.4.1. Overall Objective

The overall purpose of this thesis is to increase the safety of VRUs by helping their inclusion as active members of vehicular communication networks. This thesis aims to design a VRU beaconing control mechanism based on awareness and channel load criteria in a heterogeneous network context. Consequently, the proposed system will coordinate a heterogeneous network and will control VRU transmissions to improve the overall VRU awareness while controlling the global channel load. Additionally, the system will satisfy the standardized requirements for VRU transmissions, specifically regarding communication latency.

1.4.2. Specific Objectives

With aims to accomplish the overall objective, three specific milestones are defined. Here, the particular statements are formulated; through this formulation, the scope and boundaries of this thesis are also declared.

Obj. 1 To propose a set of metrics to measure node awareness. Particularly, a metric must allow the quantification of VRU detection.

Obj. 2 To design an intelligent VRU awareness-based system to control the VRU beaconing on a heterogeneous vehicular network. The heterogeneous network consists of DSRC and C-V2X access technologies and operates decentralized.

Obj. 3 To evaluate the proposed system against baselines mechanisms and analyze its performance in terms of the metrics of interest.

The accomplishment of Obj.1 is crucial to evaluate the proposed system in terms of *awareness*, the focus of this thesis. The formulation of the metric must reflect the ability to detect surrounding VRUs. Obj.2 represents the actual design of the beaconing control system. It shall be considered that the proposed approach is decentralized in its operation and looks to improve the values of VRU awareness, latency, and channel occupancy. The purpose of Obj.3 is to evaluate the proposed system. The fulfillment of this third objective is crucial for accomplishing the overall objective.

1.5. Methodology and Tools

The present section details the methodology and tools used for the design and development of the proposal. This thesis proposes a heterogeneous networks management system for VRU beaconing called *VRU Awareness-based Intelligent beaconing system for heterogeneous vehicular networks* (VARIATE). The system intelligently decides, based on the communication context of VRUs, between using DSRC or C-V2X for the beacon transmission and the beaconing rate to be used. Based on channel load and VRU awareness criteria, the system looks to reduce the channel load without severely sacrificing awareness capabilities. This last point is crucial in the formulation of this system since it is a commonly unconsidered criterion essential for the effectiveness of VRU safety systems. Chapter 4 describes the conceptualization and implementation of the system entirely. The following section presents the tools and frameworks used for the network simulation and the training of the intelligent system.

1.5.1. Tools

We consider the discrete event simulator OMNeT++ [38] to simulate the communication network. OMNeT++ is an open-source software built mainly for communication networking analysis. The simulations use this software along with the Vehicular in Network Simulation (Veins) [39] and OpenCV2X [40] frameworks. Veins allows the integration between the traffic simulator SUMO [41] and OMNeT++ (See Fig. 1.1), enabling the use of communications over mobile vehicular and VRU nodes. We use Veins to simulate DSRC and OpenCV2X for C-V2X. We create a new project to integrate both technologies in a heterogeneous manner using these frameworks. As the scope of this thesis is on the VRU side, we used the extension of Veins, VeinsPedestrian [42], for the simulation of pedestrians, bicycles, and motorcycles.

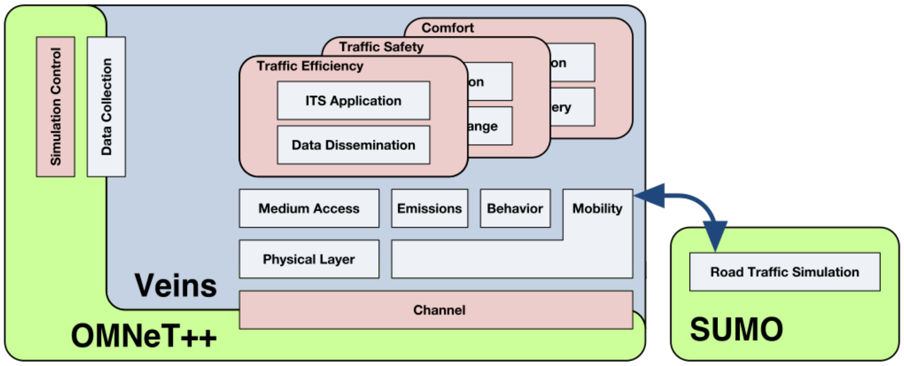


Figure 1.1: Diagram that shows the interaction between OMNeT++ and SUMO through Veins. Figure extracted from [39]

This thesis relies on the Python ™programming language for the ML models implementation and data processing. Python™is an open-source programming language created in 1991 and supported since 2001 by the Python Software Foundation [43]. Specifically, the distribution Anaconda ®[44] will be used for the programming of the intelligent agent. The Anaconda Individual Edition of Anaconda (open source) is used since it permits the quick use of many different Python ®libraries.

1.6. Contributions and Thesis Structure

This thesis proposes a new approach based on heterogeneous networks to contribute to congestion management in VRU-inclusive networks. The proposed system for the management of VRU beaconing is conceptualized considering the Radio Access Technologies (RATs) used and VRU awareness metrics. Maintaining high values of VRU awareness is critical since it directly affects the effectiveness of VRU safety applications. The mechanism proposed in this thesis uses two RATs to compose the heterogeneous network and several criteria to manage it. In terms of RATs, the system considers DSRC and C-V2X technologies. The design and evaluation of the proposed system consider criteria associated with channel load, general and VRU awareness, and latency. In addition, ML techniques are used to predict the awareness and include it as a variable in the selection mechanism.

We observe several contributions from this thesis work and proposed system. Regarding the proposed beaconing management mechanism, we observed that VRU awareness is improved compared to the only use of the DSRC and the tested heterogeneous baseline mechanisms. Another significant contribution is the transmitter-receiver latency reduction compared to the heterogeneous baselines and the C-V2X-only configuration (the best in terms of awareness). We also consider that this thesis document contributes to surveying state of the art in VRU inclusion in vehicular communication networks.

This thesis consists of a description and analysis of the knowledge related to VRUs integration, the presentation of the thesis proposal for VRU transmissions management in heterogeneous networks, and the performance evaluation of the proposed mechanism. For this purpose, the thesis is organized as follows: The present chapter describes the motivation for this thesis; based on this motivation, it presents and describes the identified problem. The work's hypotheses, objectives, scope, and methodology are detailed. Finally, a summary of the contributions is given. Chapter 2 provides a revision of the theoretical basis of vehicular networks and the relevant aspects of the treated technologies and techniques. Chapter 3 provides a survey on the state of the art of VRU integration on C-ITS and heterogeneous networks; the chapter also describes several works that address wireless communication challenges using ML tools. Chapter 4 deeply describes the proposal of this thesis. The chapter also describes the simulation setups and the performed tests. Chapter 5 shows the results obtained from the simulations described in Chapter 4. The chapter discusses the results and provides the main conclusions of this work. Finally, Chapter 6 concludes this thesis and describes guidelines for future work.

Chapter 2

Background

The current section presents the most relevant elements of the theoretical basis needed by this thesis. First, Section 2.1 describes in general terms the vehicular communications paradigm. Second, Section 2.2 presents IEEE 802.11p-based RATs. Third, Section 2.3 presents the C-V2X RAT. Both sections 2.2 and 2.3 provide a detailed explanation of the access mechanisms of DSRC and C-V2X respectively. Fourth, Section 2.4 discusses topics related to the architecture of the networks. Fifth, Section 2.5 presents the concept of Heterogeneous networks and describes the main characteristics of the architecture of these networks. Finally, section 2.6 presents the needed tools and concepts of AI and ML.

2.1. Vehicular Communication Networks

Nowadays, encouraged by the advancement in urbanization, the use of private vehicles is a well-established behavior in society. Furthermore, the number of cars and other types of personal means of transportation will still grow in the following years [2]. Despite the benefits that these means of transport can bring in terms of transportation comfort, some issues arose from the expansion of vehicle usage. One of the main issues related to the use of personal vehicles and the increasing number of them is the growing number of traffic accidents [3]. Moreover, the continuous increase in the number of cars brings other impairments in terms of pollution (e.g., gaseous air pollutants such as carbon dioxide), noise, and fuel consumption [8].

At the moment of addressing these problems, the communication among vehicles (*Vehicular Communications*) appears as a key element required to enable a large set of applications related to different road actors, such as cars, pedestrians, buses, infrastructure elements, and others [7]. Among these uses, safety applications appear as an outstanding benefit, helping in aspects such as accident prevention, post-accident investigation, and traffic jams [3]. However, the benefits offered by vehicular communications are more diverse than the safety ones. Fuel consumption reduction, air pollutants decrease, driver assistance, and the offer of comfort services such as augmented reality and infotainment are additional applications enabled by vehicular communications. These benefits, along with the requirement for communication capabilities introduction in Autonomous Vehicles (AVs) [45] have made industry, network operators, academia, and governments invest in the deployment of these networks

[46, 47].

To implement these applications, vehicles and other types of nodes exchange information through messages. In general, we call this type of communication V2X. This term encapsulates different communication types such as communications between vehicles (Vehicle-to-Vehicle, V2V), between vehicles and infrastructure elements (Vehicle-to-Infrastructure, V2I), between vehicles and the network (Vehicle-to-Network, V2N), and the previously defined V2P communication [8, 48]. This thesis is focused on this last type of communication, which includes the communication between vehicles and different types of VRU — pedestrians, bicycles, motorcycles, and others. This type of communication is also called Vehicle-to-VRU (V2VRU) by organisms such as the European Telecommunications Standards Institute (ETSI) [13].

Different RATs have been considered to allow the deployment of vehicular communications. These technologies enable communication among different nodes in a vehicular network (vehicles, VRU, roadside elements, and others), showing different performances when used in various applications. In the extra-vehicular context — communication that occurs between elements outside vehicles — the following technologies are commonly considered [8]:

- IEEE 802.11p-based
- C-V2X
- 4G/LTE-A
- LTE-A Prose (3GPP Release 12/13)
- Wi-Fi
- Visible Light Communication (VLC)
- LTE-V2X/C-V2X

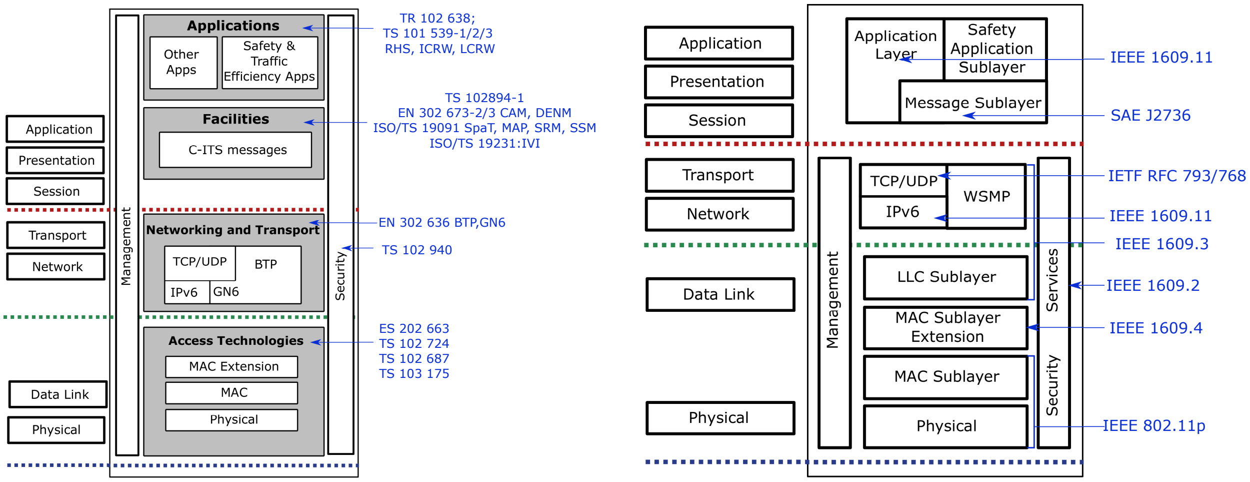
The subset of these medium access technologies used in this thesis will be described in more detail in the following sections. Section 2.2 describes the protocols stacks associated with IEEE802.11p-based technologies for Europe and the USA and describes the medium access mechanism of this standard. Section 2.3 introduces the most relevant aspects of C-V2X technologies.

2.2. IEEE 802.11p-based technologies

The terms *Connected Vehicles* and *Cooperative - Intelligent Transportation Systems* are used to refer to the protocols stacks used parallel in Europe and the USA for the deployment of ITS. The following two sections describe the protocol stacks and the medium access control mechanisms.

The protocol stack design points to the same objectives in both CV and C-ITS. These stacks support V2X communications, allowing the exchange of messages with low latency, and enabling safety and mobility applications. The protocol stacks are presented in Fig. 2.1 a) for CVs and Fig. 2.1 b) for C-ITS. The standards associated with each stack's component are presented for both cases. Also, the correspondence between the stacks and the OSI standard stack is presented on each figure's left side.

As seen from Fig. 2.1, several documents describe the protocol stack in each case. In the case of CV, the protocol stack relies mainly on IEEE documents superseded under the IEEE 1609 family and the IEEE 802.11p standard. The latter defines the Physical Layer (PHY) and Medium Access Control sublayer (MAC). Because of the inclusion of TCP/UDP and IPv6 support, the stack also includes Internet Engineering Task Force (IETF) documents. Society of Automotive Engineers (SAE) standards are also used. In the case of C-ITS, most standards are developed by ETSI (technical reports and specifications). ISO standards are also included in the C-ITS protocol stack.



(a) C-ITS

(b) CV

Figure 2.1: Protocol stack for IEEE 802.11p-based technologies. Based on [8]

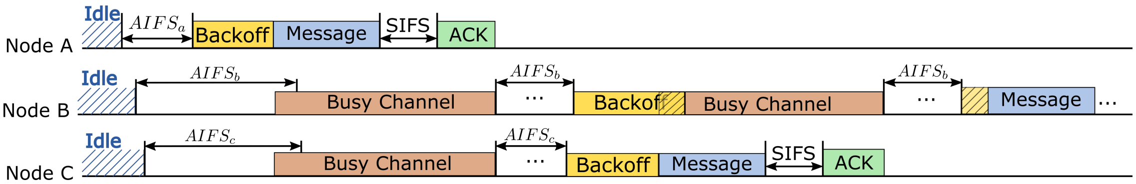
In terms of the access to the radio medium, Connected Vehicles' PHY and MAC layers rely on the IEEE 802.11p standard [49, 50] for the support of V2V and V2I communications. The design of this protocol intends to deal with high mobility, maximum speeds up to 200 km/h, and a communication range up to 1000 m (although a reasonable distance of 300 m is commonly considered [51]). The standard is an adapted version of the IEEE 802.11a standard for WLANs that allow vehicular nodes to operate without the overhead associated with device authentication. For this reason, the standard is said to work Outside of the Context of a Basic Service Set (OCB). It is also relevant to consider the IEEE 1609.4 standard [52], which defines the multichannel operation of VANETs. The operation of this multichannel mechanism is based on the division of time in a *Syncronization Interval* where there are slots for a CCH operation, Service Channels (SCHs) operation, and guard intervals [53]. In the case of C-ITS, the European equivalent to the IEEE 802.11p standard is called the ITS-G5. In this stack, the access layer (ETSI ES 202 663 [54]) includes layers 1 and 2 of the OSI model. Other documents of interest for these layers are the ETSI TS 102.724 [55], which defines part of the ITS-G5 MAC layer and the multichannel operation, and the Technical Specification ETSI

TS 102.687 [56], which defines the medium access mechanism through the *Descentralized Congestion Control* (DCC). Despite the previous description, Section 2.5.1 shows that C-ITS design allows the use of different access technologies in their protocol stack.

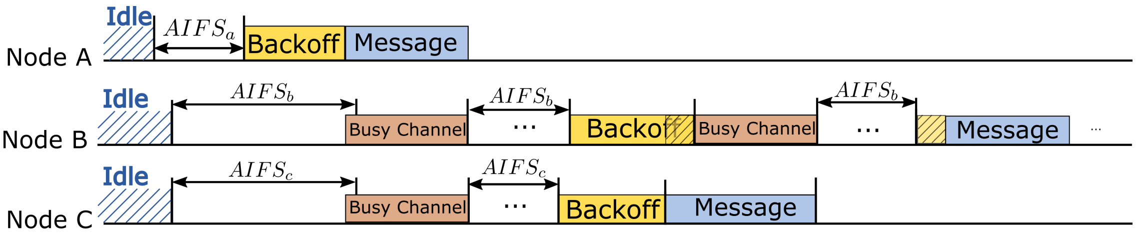
Despite the differences between the CV and C-ITS stacks, specifically between 802.11p and ETSI-G5 for the MAC and PHY layers, their key features remain the same or very similar. In terms of frequency usage, they both operate in the 5.9 GHz bands, with different channelization schemes. In terms of modulation, they both use OFDM. In the MAC layer, IEEE 802.11p and ITS-G5 use Enhanced Distributed Channel Access (EDCA) with CSMA/CA and include access categories to allow for data traffic prioritization [57]. In this thesis, we treat the problem of RAT. Due to this purpose, it is crucial to describe the access mechanisms of IEEE 802.11p and C-V2X in more detail. The following section presents the description of the IEEE 802.11p medium access mechanism.

2.2.1. Enhanced Distributed Channel Access (EDCA)

The IEEE 802.11p protocol uses the EDCA mechanism to control the access to the radio medium and support prioritized Quality of Service (QoS). The IEEE 802.11e standard [58] defines the EDCA mechanism as an evolution of the Distributed Coordination Function (DCF). EDCA defines four categories, each related to different QoS requirements. The categories are named *Voice*, *Video*, *Best Effort*, and *Background*. These Access Categories (ACs) divide the traffic into independent queues with different parameters giving them different priorities. The modified parameters are the Congestion Window (CW) minimum and maximum size and the number of time spacing between frames (AIFSN[AC]). Minimizing the values of the minimum congestion windows size (CW_{min}), maximum congestion window size (CW_{max}), and AIFSN[AC], the protocol gives differentiated priorities to different types of traffic. Also, if two (or more) queues decide to transmit a message at the same time, the queue with the higher priority gets the channel access [53, 59].



(a) General EDCA mechanism



(b) EDCA mechanism in beaconing

Figure 2.2: EDCA mechanism for acknowledge and unacknowledge transmissions. Figure based on [60].

In terms of the channel access mechanism, we can explain it based on Fig. 2.2 a). AIFS is calculated based on the AC of each queue being shorter in the messages with higher priority. Three prominent cases explain the operation of EDCA. First, focusing on node A, if the channel has been idle and still idle for a time AIFS plus a backoff time, the node is free to send its message and wait for the Acknowledgment (ACK) after a Short Inter-Frame Space (SIFS) time. In the case of nodes B and C, they detect the occupation of the channel by node A and wait to transmit a message; hence, they must wait until the channel is free to wait for an AIFS plus a backoff time. The idea of the backoff time is to reduce the probability that two nodes wait the same amount of time after a busy channel detection. This backoff time is a random number of time slots chosen in the interval [0, $CW[node]$], where $CW[node]$ is the instant upper limit of the congestion window. Every time that there is a collision (no ACK received), this limit must double until reaching the CW_{max}. As in the case of Fig. 2.2 a), node C finished its backoff sooner than node B; it can access the medium, while node B sense it as busy and freeze its backoff. After node C finishes its transmission, node B waits for AIFS and the backoff and can finally send its message [51, 59].

In the case of this thesis, we are interested in the operation of the safety beaconing mechanisms over IEEE 802.11p-based technologies. Both in the cases of ITS-G5 and IEEE 802.11p, there is a dedicated channel for the transmission of safety messages; hence, there is no internal competition between queues. Also, the beaconing of safety messages focuses on the rapid transmission of information rather than on a confirmed transmission. Because of this fact, the safety beaconing does not require confirmation, i.e., there is no ACK sending and reception in beaconing. As there is no confirmation in the communication process, packet collisions are not detected; hence, the congestion window is not doubled and stays fixed in CW_{min} [61]. The operation of EDCA in the case of safety beaconing is presented in Fig. 2.2 b).

2.3. Cellular - Vehicle-to-Everything (C-V2X)

The term C-V2X encapsulates the access technologies developed by the Third Generation Partnership Project (3GPP) for V2X communications. This denomination includes the access technologies developed since Release 14 (Rel.14) for the sidelink communication between vehicles and any other node type. In these terms, C-V2X includes both the Long Term Evolution V2X (LTE-V2X) technology developed in Rel.14, and its evolution Fifth Generation V2X (5G-V2X) — or New Radio V2X (NR-V2X) — established in Rel.16 [62, 63]. In the following two sections, the communication modes relevant to this thesis and the access mechanism of LTE-V2X are presented.

2.3.1. Description of C-V2X

Vehicular communications have been considered a key technology for the deployment of new safety applications [7]. They are also considered as essential support for the deployment of autonomous driving in advanced stages (levels 3 and 4) [63]. The previously presented standard IEEE 802.11p was developed by IEEE to enable this kind of communication. However, in previous years, a series of critics have arisen regarding the deployment and performance of the IEEE 802.11p-based system. In terms of deployment, in 1999, the

Federal Communications Commission (FCC) allocated 75 MHz to exclusive use by DSRC in the USA (between 5.850 and 5.925 MHz). However, in 2020, the FCC formally criticized the lack of massive technology deployment in the past twenty years. Because this reason, the Commission revoked the exclusive use of spectrum, leaving the lower 45 MHz for unlicensed use and the upper 30 MHz for ITS deployment but encouraging the use of C-V2X [29]. In terms of performance, different publications and organizations have questioned the suitability of IEEE 802.11p for vehicular networks. The performance issues are related to the collisions and scalability problems related to the MAC layer, based on CSMA/CA, which may affect its reliability and latency features, the limited transmission distance, and the lack of integration to the cellular infrastructure [63–67]. Even though the next generation of IEEE 802.11p is under development (IEEE 802.1bd) [28], it seems that standardization bodies tend to favor the use of C-V2X.

Cellular infrastructure used to support V2X communications has been studied for a long time, mainly for V2I. However, the use of the sidelink interface for the communication between devices (Device-to-Device, D2D) started with the publication of the Rel.12 of 3GPP, and the interest in using direct communications based on 3GPP standards began to grow since then [62]. As a result, in 2017, 3GPP published the first standard for direct V2X communications in Rel.14 [68]. This technology still uses LTE; hence, it was called LTE-V2X. With the development of the next generation of cellular communications (5G), 3GPP started to work on a new technology based on the 5G paradigm, 5G NR-V2X. The first release of 5G, Rel.15 [69, 70] points towards the development of 5G-V2X; however, this only made minor modifications to LTE-V2X but defines use cases and requirements for the most complex applications of V2X. These use cases have more stringent requirements, primarily in latency, reliability (under the Ultra-Reliable Low-Latency Communication, URLLC, requirements), and link budget. Rel.16 defined the new 5G NR-V2X specifications, and improvements are being developed and will be future presented in Rel.17 [62]. Some improvements in Rel.16 are the support for ultra-low latency applications, the use of the NR interface, and the ability for unicast and groupcast [63]. Despite these developments, as stated by [62] 5G NR-V2X appears as a complement to LTE-V2X to provide support to the more advanced use cases, while LTE-V2X continues to provide basic V2X safety.

This thesis is based on the use of LTE-V2X defined in Rel.14 [68] of 3GPP using the simulation tool developed in [40]. Hereafter we use the notation C-V2X to denote LTE-V2X technology. This release presents three ways of communication in the vehicular context. The modes are presented in the following:

- **Communication over LTE-Uu:** LTE-Uu is the interface between the User Equipment (UE) and the Evolved Universal Terrestrial Access Network (E-UTRAN) NodeB (eNB). This type of communication is the most common in cellular communications nowadays. The transmitter node sends messages to the eNB through the LTE-Uu (uplink) when using this interface. The eNB can then directly send this message to the receptor through LTE-Uu (downlink) if they are in the same cell; otherwise, the message is passed to the cellular infrastructure. The main advantages of this type of communication are the more extensive range of communication, its efficient resources allocation, and the connection to the Cloud [28]. This mode operation is presented in Fig. 2.3.

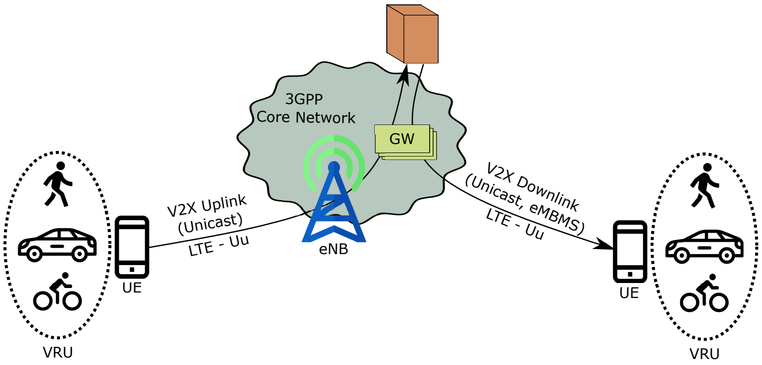
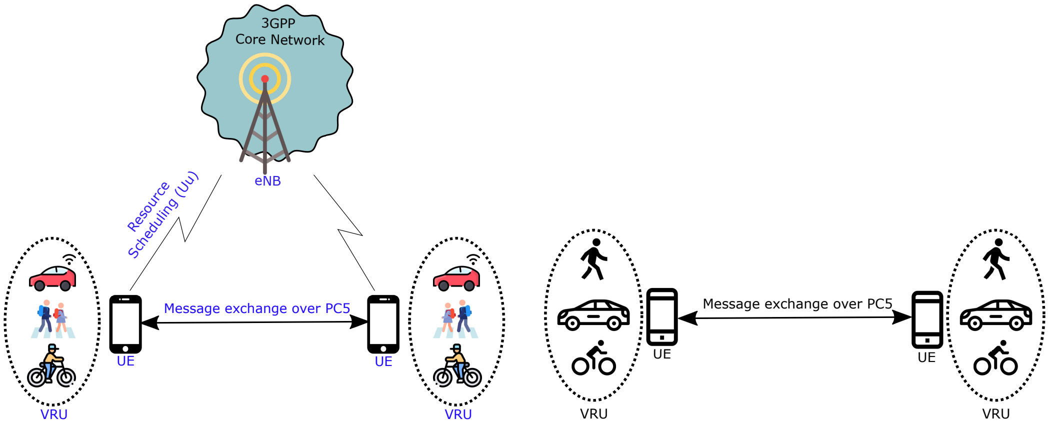


Figure 2.3: V2X communication using LTE-Uu interface

- **Communication through PC5:** PC5 interface connects UEs directly through the sidelink. In this way, UEs can exchange messages without passing through the eNB [68]. In this way, PC5 allows the communication both under network coverage (inside LTE network coverage, supported by E-UTRAN) and with no coverage (UE out of network coverage). These communication modes are denoted as Mode 3 and Mode 4, respectively [67]. The modes are graphically represented in Fig. 2.4 and described in the following:
    - **Mode 3:** In this mode, even though communications use PC5, the schedule of resources is done by the network. Specifically, the serving eNB delivers the communication parameters to each UE. Hence, it is clear that this communication mode is only possible under network coverage. Even though the limitation of network coverage, there are some advantages in this communication mode compared to Mode 4. The advantages come mainly from the computational capabilities and the knowledge of a general network state that allows a more efficient allocation of resources.
    - **Mode 4:** In this mode, UE can operate both under coverage and without coverage of the network. In this case, the used resources are selected using a mechanism of sensing and scheduling named Sensing-Based Semi-Persistent Scheduling (SB-SPS). In this way, vehicles under coverage can receive communication parameters from infrastructure, while those out of coverage get their resources autonomously. Because this communication mode does not require network coverage, it is considered the default mode for safety applications [71].



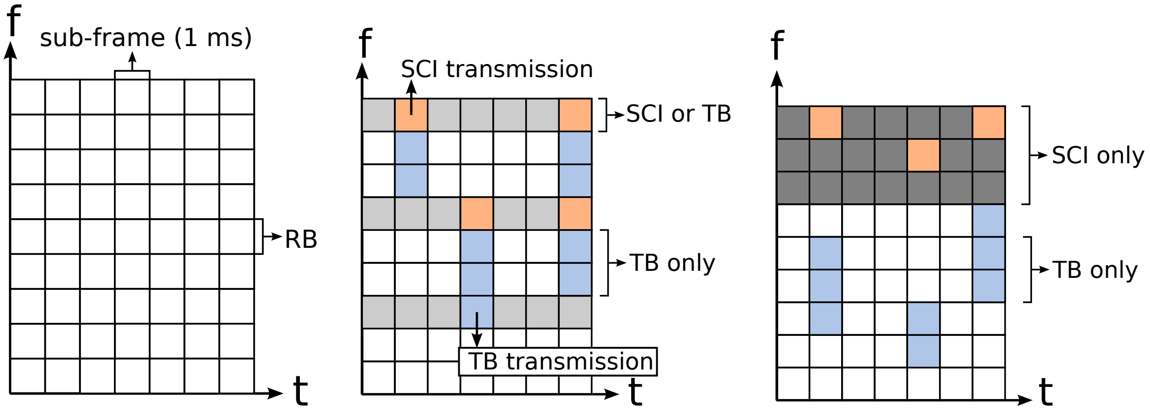
(a) Mode 3 (b) Mode 4

Figure 2.4: Communication over PC5

2.3.2. Channel aspects

The description of channelization is essential for describing the access mechanism of LTE-V2X (SB-SPS); hence, this subsection describes its main aspects. Regarding physical layer features, C-V2X uses Single Carrier Frequency Division Multiple Access (SC-FDMA) as resource distribution. The nodes may use channels of 10 or 20 MHz. QPSK and 16-QAM modulations can be used depending on the channel quality [62, 71, 72].

The Resources in C-V2X are divided by frequency and time domains. Fig. 2.5 (a) presents the division in time and frequency. The time is divided into sub-frames of 1 ms long, the same as the Transmission Time Interval (TTI). In the frequency domain, the available bandwidth is divided into Resource Blocks (RBs). RBs have 180 kHz each, equivalent to 12 OFDM subcarriers of 15 kHz. The distribution of RBs depends on the type of information. C-V2X distinguishes between control and data information. Control information is sent with a Sidelink Control Information (SCI) packet. It contains information such as the used Modulation and Coding Scheme (MCS) and the number of RBs associated with a Transport Block (TB) transmission. Each SCI uses a fixed number of 2 RBs in the same subframe. On the other hand, data information is carried in TBs. TBs encapsulate a complete packet, and the number of RBs can vary according to the size of the packet. It has to be noticed that a TB and its associated SCI must be sent in the same subframe [62, 71, 72].



(a) Distribution of resources (b) Adjacent PSCCH + PSSCH (c) Nonadjacent PSCCH + PSSCH

Figure 2.5: Communication over PC5

C-V2X also defines two types of subchannels. Sub-channels are a variable number of RBs in the same subframe [72]. C-V2X defines two subchannels: the Physical Sidelink Control Channel (PSCCH) and Physical Sidelink Shared Channel (PSSCH). PSCCHs are used to transmit control packets (SCI), while PSSCHs are used to transport TBs. There are two possible distributions of RBs called adjacent or non-adjacent modes. In the adjacent mode, the RBs occupied by the SCI are next to the RBs occupied by the associated TBs. In non-adjacent mode, SCIs are grouped in an RBs set while the associated TBs are distributed in the remaining RBs. The TBs and their associated SCI must be in the same subframe in any mode. Figs. 2.5 (b) and 2.5 (c) represents the adjacent and non-adjacent modes.

2.3.3. Sensing-Based Semi-Persistent Scheduling (SB-SPS)

This section describes the resource reservation mechanism used in Mode 4 of LTE-V2X in more detail. For the reservation of resources, the nodes using Mode 4 use the SB-SPS algorithm described in Rel.14 [73, 74]. The base idea of this algorithm is to select subchannels that are not occupied by other vehicles. The nodes send information using the SCI to learn what RB will be occupied. Two main features are included in each SCI associated with a TB. First, the Resource Reservation Interval (RRI) informs other nodes that the resources previously occupied by the target node in t will also be used in the $t + RRI$. Second, nodes include the Reselection Counter (RC) in their SCIs. The RC counts the number of consecutive packets that will be sent using the same resources. The RC is decremented by one each time a new packet is sent, and when it reaches zero, the node must reserve new resources with probability $(1 - p)$, where $p \in [0, 0.8]$. Nodes use these two variables to estimate which resources will be occupied.

When a new packet arrives from the upper layers, the node must select new resources in three cases. First, if the new packet (TB) does not fit the selected resources. Second, if the resources exceed the latency associated with the packet (latency is related to beaconing frequency). Third, if the RC has reached zero and the node must select new resources for the next packet or packets (with probability $1 - p$). The reservation of resources can be divided into three main steps. Each step is described in the following, based on [71, 72]:

1. The node identifies a Selection Window. The Selection Window is a time interval between the packet generation time and the maximum latency allowed by the packet. The maximum latency of a packet depends on the message frequency in an inverse proportion. In this window (see Fig. 2.6), the node identifies the group of Candidate Single-Subframe Resources (CSRs). CSRs are a group of resources in the same subframe where the TB and its associated SCI fit.

2. The node creates a list, L_1. This list contains all the possible resources that it can reserve. To determine the resources that the node can reserve, it uses a Sensing Window (see Fig. 2.6) that is a time window of one thousand subframes before the reservation attempts (1 s). L_1 contains all the CSRs identified in 1) except the ones that have the following two conditions:

   - In the Sensing Window, the node has received SCIs informing the node that another network participant will use those resources in the Selection Window or its next Reselection Counter packets.
   - The node sense an average Reference Signal Received Power (RSRP) over the resource greater than a given threshold

   The node also excludes the resources in frame f_i used for its own transmission in the past frames f_j, where f_j depends on the transmission frequency. At the end of applying these filters, L_1 must contain at least 20 % of the CSRs selected in step 1). If not, the procedure of step 2) is repeated, increasing the threshold by 3 dB.

3. The node creates a new list L_2. L_2 contains the resources from L_1 that have the lowest average Received Signal Strength Indicator (RSSI) measured over the Sensing Window (See Fig. 2.6). L_2 must contain the 20 % of the CSRs detected in step 1). From L_2 the CSRs to be used by the node are selected randomly.

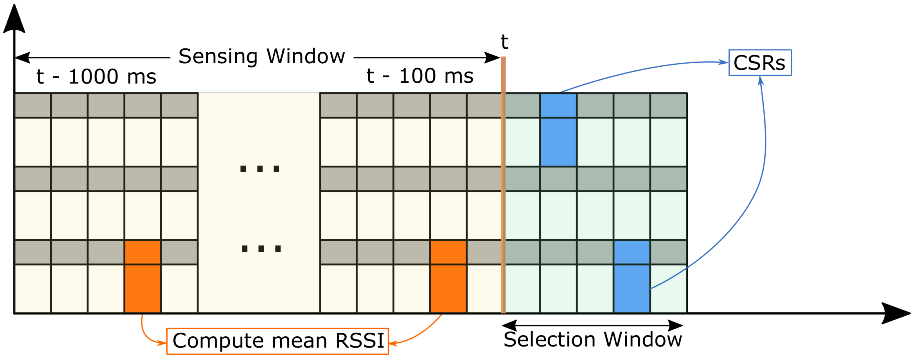


Figure 2.6: Notation for the SB-SPS description

2.4. Network Architecture

The present section describes the main elements of the vehicular networks architecture. Only the architecture of those technologies used in this thesis (C-V2X and DSRC) will be detailed. First, section 2.4.1 describes the reference architecture for systems that use DSRC (based on IEEE 802.1p) and C-ITS (based on ITS-G5). Section 2.4.2 presents the reference architecture associated with C-V2X.

It is worth noticing that the 5G paradigm includes both of these architectures. The 5G networks include in their conception the use of a heterogeneous architecture, where the network itself is composed of different networks working together to supply various applications and services. Fig. 2.7 presents an example of a 5G network where a variety of technologies are integrated.

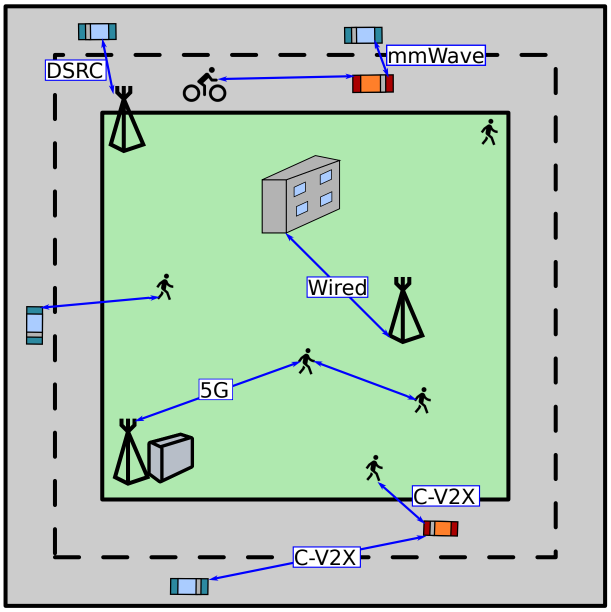


Figure 2.7: Example of 5G paradigm architecture

2.4.1. Reference Architecture of DSRC and C-ITS

To describe the architecture of vehicular networks based on DSRC, the main components of these systems must be presented. Typically, the elements can be cataloged as Applications Units (AUs), On-Board Units (OBUs), or RSUs. The following presents a brief description of each component [3]:

- **OBU:** It is a radio device, usually installed in a vehicle, that allows the information exchange between the communication node and other network components such as other OBUs or RSUs. The main actions that OBUs allow in terms of communications are wireless network access, routing, congestion control, information security, and others. OBUs communicate to other OBUs or RSUs using different technologies providing communication capabilities to the AUs.
- **AU:** It is a device that, through the communication capabilities of an OBU, uses the applications developed for the vehicular environment.

- **RSU:** It is a device located on the streets or in specific places such as intersections. These devices possess radio communication capabilities that allow them to communicate with mobile nodes and network infrastructure. RSUs can provide several services to the vehicular communications environment. For example, they can act as relays to increase the communication range of other nodes or as an infrastructure element that allows Internet access to AUs.

The architecture of a vehicular network can be separated into four *domains*. The domains are illustrated in Fig. 2.8 and are described in the following:

- **In-Vehicle Domain:** The Intra-vehicular domain is composed of all of those elements that allow the connection between the internal devices of a vehicle. These elements may also incorporate the information coming from an OBU (external data). This domain comprises a Communication Control Unit (CCU), an OBU, and a Human-Machine Interface (HMI). The CCU is the device that controls the communication layers from Physical to Network. HMI allows the driver to use the capacities of OBU and CCU.
- **Adhoc Domain:** The Adhoc domain is a subcase of the Mobile Adhoc Networks (MANETs) called Vehicular Adhoc Networks (VANETs). This domain includes communications created among mobile nodes. In general, this is considered the communication between vehicles; however, we also incorporate VRU communications in this thesis. Fig. 2.8 presents the domains, also showing the case of VRU communications.
- **Infrastructure Domain:** This domain includes the wireless infrastructure, the wired network backbone, and all the intermediate elements. The wireless infrastructure can be RSUs, eNBs, WiFi hotspots, and others. The wired and wireless sections of the infrastructure connect themselves to allow the interaction between the In-Vehicle Domain and the Service Domain.
- **Service Domain:** It is the top layer of the architecture. It provides services to the vehicles using the infrastructure.

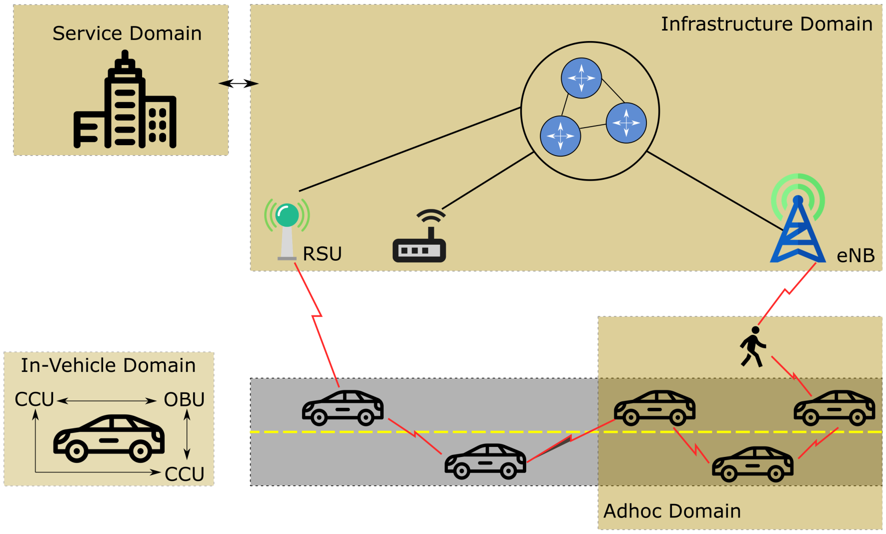


Figure 2.8: Illustration of the domains

2.4.2. Reference Architecture of C-V2X

Figs. 2.4 and 2.3 present the synthesized architecture of the network associated with C-V2X. However, this section gives a more detailed description of the architecture of the access networks applied to V2X communications in cellular networks and the involved equipment. The architecture of C-V2X, including PC5 and LTE-Uu links, is schematized in Fig. 2.9. The diagram of Fig. 2.9 is a modified version of the architectures presented on Rel. 14 [75] and Rel. 15 [76].

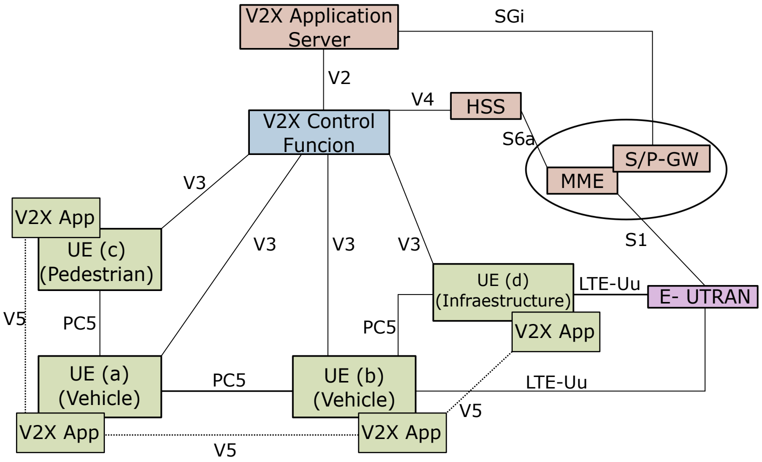


Figure 2.9: Reference architecture for C-V2X. Figure based on [75].

As seen from Fig. 2.9, the C-V2X architecture possesses many elements dedicated to the operation of vehicular networks. However, it is worth noticing that the nodes use the same kind of device, called the User Equipment, independently of their type (pedestrian, vehicle, and others). The infrastructure elements and the interfaces between them are presented in the following [76, 77]:

- **Functional Entities:**
  - *User Equipment (UE):* The UE is the device that allows the user to access all the network services. This equipment is a wireless device since, according to 3GPP, the interface between UE and the network is a radio medium.
  - *Evolved Universal Terrestrial Access Network (E-UTRAN):* E-UTRAN is the evolution of the radio interface Universal Mobile Telecommunication System (UMTS). This entity includes Evolved UMTS Terrestrial Radio Access (E-UTRA), the UE, and eNBs, equivalent to the base stations. E-UTRAN's objective is to evolve the 3G UMTS radio-access network improving the spectral efficiency, data rates, frequency flexibility, and bandwidth [78].
  - *V2X Control Function:* This is the logical function used to control all the actions related to the network that allow V2X communications. There are two ways the V2X Control Function can operate with the UEs. First, it can provide UEs with the parameters needed to establish the V2X communication. This allows the connection between the UE and the Public Land Mobile Network (PLMN). Second, V2X Control Function can provide the UE with the parameters it will need when operating outside the context of E-UTRAN (i.e., direct communication).

  - *V2X Application Server (V2X AS):* V2X AS has several functions for the sending and reception of information to and from UE processing it in different ways. Two applications are relevant for this thesis; On one side, the sharing of parameters for V2X communication over PC5 to the V2X Control Function; On the other side, the direct sharing to UEs.

- **Interfaces:** Called Reference Points. This item will present the interfaces relevant for the V2X communications [76].
  - *PC5:* Also called *sidelink*. PC5 Is the reference point between UEs for the direct Proximity Services (ProSe) communication between V2X devices.
  - *LTE-Uu:* It is the traditional interface between UE and E-UTRAN. In this case, it is the access, through the radio medium, to the cellular network infrastructure.
  - *V3:* It is the reference point between UE and V2X Control Function in the specific PLMN. This connection is possible for devices exchanging messages between PC5 or LTE-Uu.
  - *V5:* Reference point between V2X applications in different UEs.

The architecture and components of the LTE-V2X and C-V2X are very similar. These similarities are mainly because the C-V2X technology is still in development at the time of this thesis writing. The fulfillment of the most complex parts is still under development. Cases such as platooning, advanced driving (cooperative maneuvers), Extended sensing (sharing of sensors information), and remote driving have more restrictive requirements. The new radio medium, New Radio - Radio Access Network (NR-RAN), is expected to accomplish Ultra-Reliable and Low Latency Communications (URLLC). URLLC considers more stringer requirements such as latency values of less than 3ms for the advanced driving use cases and reliability of 99.999% with minimum communications ranges of 1000 m.

2.5. Heterogeneous Vehicular Networks

2.5.1. General Aspects

For the purposes of this thesis, we define a Heterogeneous Vehicular Network (HetVNET) as a network that integrates different medium access technologies in a vehicular context. This integration aims to fulfill the communication requirements of a diverse set of services offered by the VANETs and ITS. Different access technologies may constitute an HetVNET, such as DSRC, LTE, C-V2X, mmWave technology, and others [79, 80].

The concept of *Heterogeneous Networks* is not exclusive to the vehicular context. Nowadays, commonly used devices such as smartphones and Access Points (APs) are often equipped with multiple RATs that allow them to stay connected under different contexts and requirements; maybe the most common example is the use of LTE and WiFi by smartphones. The use of heterogeneous networks is expected to grow as new technologies are continuously introduced. There are mainly two cases for multiple access technologies on a device. First, the technologies may cover different scenarios but share the same radio spectrum, such as

WiFi and Bluetooth. Second, the technologies may cover similar use cases but operate on separated spectrum bands. Independent of the relation between technologies, heterogeneous networks present several challenges, mainly due to their operational characteristics. As technologies are seen principally as competitors, there is a lack of coordination between them in terms of coordinated management, spectrum coordination, seamless handovers, and others. These problems lead to the inefficient use of the different available technologies [81].

The motivation to incorporate heterogeneous networks into the vehicular environment comes mainly from the limitations of the most commonly considered access technologies. Each of these technologies presents its particular advantages and drawbacks. The most popular access technologies considered for the operation of vehicular communications networks correspond to the IEEE 802.11p-based technologies (DSRC in the US and ITS-G5 in Europe). This technology presents a wider grade of deployment and analysis among ad-hoc vehicular technologies. The main advantages of IEEE 802.11p are its low cost, the maturity of its study, the wider deployment, its specific design for direct communications, and the low over-the-air latency [35, 79]. However, the exhaustive study of this technology has exposed several drawbacks. The principal negative aspect that affects this technology is its lack of scalability. Several studies have shown that the technology presents issues in scenarios of intense congestion related to its unbounded delay (due to its CSMA-based MAC mechanism) [5, 82]. Other works points toward the limited throughput [83, 84] — now even more limited due to spectrum reduction [29] — and coverage that offers DSRC, especially in urban scenarios with high buildings [5, 35]. Another widely extended technology and the commonly considered most attractive alternative to DSRC corresponds to cellular systems (called here Long Term Evolution, LTE). This technology also has advantages, such as its long coverage range [83, 85], high-capacity [83], and high penetration rate [79]. However, the same as DSRC, it presents many drawbacks. In the case of LTE, the disadvantages come mainly from the fact that its centralized architecture may add a large amount of delay to the communication, which is critical, particularly in safety applications [79, 85]. Another technology that appears as a new alternative, specifically for high data rate applications, corresponds to the mmWave technology (based on the IEEE 802.11ad standard [86]), which allows the use of high-throughput links but only at short distances with LoS conditions [35].

As seen from the previous description, each access technology presents benefits and drawbacks. Most technologies have competed to have the best performance under severe conditions; however, different works propose a different perspective, considering the advantages and flaws of each access technology. As stated by works such as [79, 82] the scope of the vehicular network implementation should be changed from a homogeneous and competitive approach to a diverse (heterogeneous) one. Under this approach, different technologies coexist, contributing their best features to satisfy the different QoS requirements of the different vehicular applications (from safety to entertainment). In addition to this motivation, several entities have favored heterogeneous networks. For example, the 5G Vision developed by the 5G Public-Private Partnership Group (5G-PPP Group) states that the 5G networks must be a heterogeneous set comprising different wireless technologies existing now or in the future [87]. Moreover, the European ITS-G5 platform has recently concluded that at the moment, neither ETSI ITS-G5 nor cellular systems could provide the full range of services conceived by C-ITS independently [33]. Another point favoring the use of HetVNET is that the ETSI ITS Station (ETSI ITS-S) architecture already includes the possibility of using more than one Radio Access Technology, leaving this election free to developers [88]. The ITS-S protocol stack is presented in Fig. 2.10.

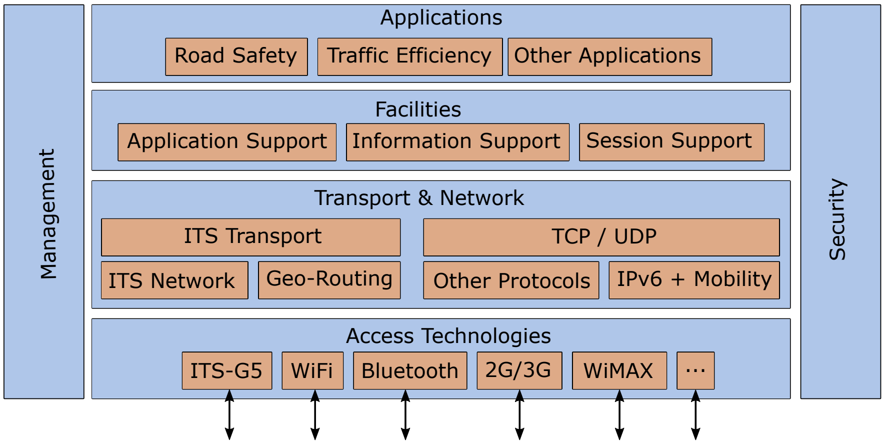


Figure 2.10: Protocol stack of ETSI ITS-S

In addition, C-V2X appears to be able to cope with difficult network conditions [89]. However, this technology is not as mature and heavily deployed as DSRC. According to [84], independently of C-V2X's ability to cope with the problems of DSRC, during its deployment, both C-V2X and DSRC should coexist on a heterogeneous network.

2.5.2. Basic Network Architecture

In the framework of this thesis, we consider the architecture of HetVNETs proposed in [79]. Fig. 2.11 presents the general architecture of the network and its relation with the Open Systems Interconnection (OSI) protocol stack. As seen in Fig. 2.11, the architecture of HetVNETs has three main macro components, which are a Service Center (SC), a Core Network (CN), and a Radio Access Network (RAN). The SC allows service providers to offer various services to vehicular nodes. The CN provides essential functions such as linking the nodes with the services provided by SC, switching between different RANs, authentication, aggregation, and connection to the Internet infrastructure. The RANs side of the heterogeneous networks is the topic of interest in this thesis. RANs allow the link between the endpoints (VRUs or cars, in this case) and the core network. They are the first link that enables the communication nodes to enter the network. Several access technologies compose the RAN macro-layer; taking the example of Fig. 2.11, we may consider the use of DSRC, C-V2X in its mode 3 or 4, or the traditional cellular communication. Also, the links may be differentiated between a communication V2V or V2I.

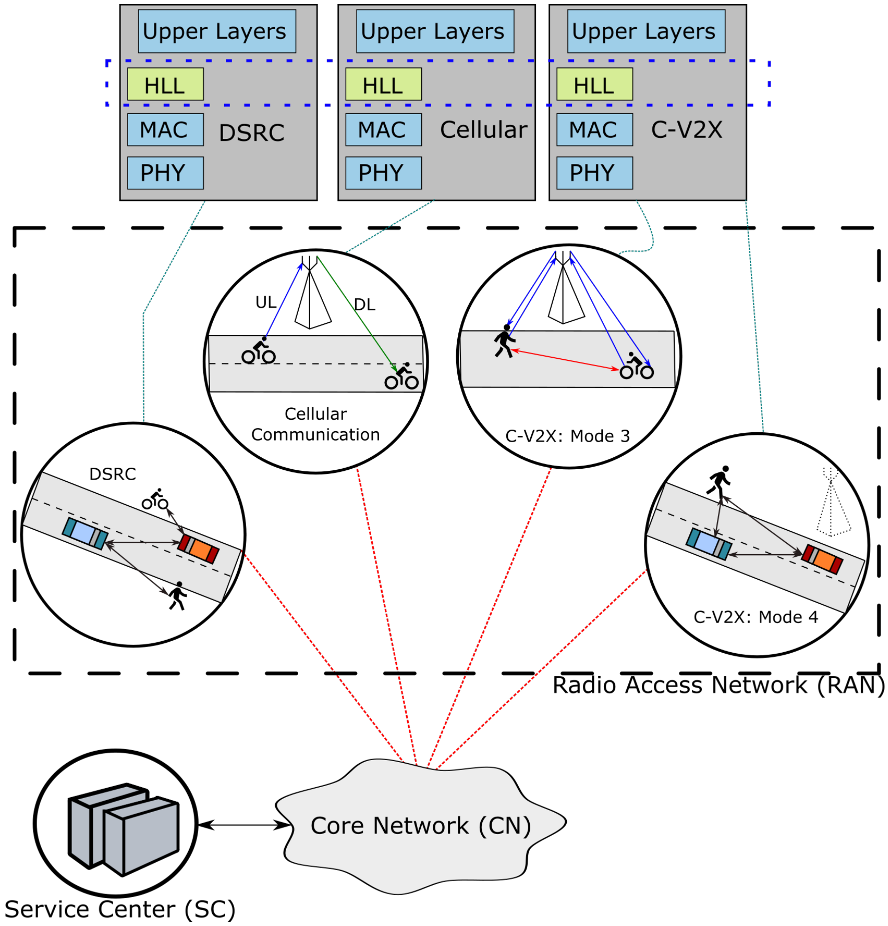


Figure 2.11: Architecture of a HetVNET. Figure based on [79]

Authors in [79] state that one of the challenges of the HetVNETs is their ability to support dynamic compositions of networks while using the available radio resource efficiently and flexibly. Considering these challenges, the authors propose incorporating a new layer into the commonly used protocol stack. The proposed layer is called the Heterogeneous Link Layer (HLL). It is located between the MAC layer and the upper layers of the protocol stack (from network to application). The formulation of HLL attends to the existing differences in physical and network layers presented by diverse network access technologies. The objective of HLL is to enable global management of network resources to meet the QoS characteristics of different applications. The idea of using this new layer is to introduce virtualization functions into HLL to abstract, slice, isolate and share resources by developing functions that manage the multi-radio resources and reach this goal. However, The development of management functions is not trivial, and it corresponds to a challenge itself.

Despite the improvements that HLL may bring to the HetVNETs, there are many open challenges related to its design and operation. In the first place, the characteristics of the transmission medium (high mobility, varying requirements, and others) add complications to the treatment of the radio medium resources [79]. In terms of management, HetVNETs complexifies the network fragmentation and routing [35]. The development of HetVNETs also comes with the challenges of non-vehicular heterogeneous networks, such as the need for vertical handover algorithms for seamless traffic exchange and the lack of coordinated management in decentralized scenarios [81]. Despite these challenges, several publications show the benefits of using a heterogeneous approach to bring to the vehicular communications context in terms of channel congestion reduction, throughput increase, among others [81, 82, 90]. These benefits motivate the development of HLL administration mechanisms that allow network nodes to select their Radio Access Technology more efficiently to offer the best QoS to the C-ITS applications.

2.6. Machine Learning Tools

The present section offers an overview of the essential concepts related to AI and ML. This thesis introduces these concepts as elements of ML are used by the proposed decision system (see Chapter 4). The term Artificial Intelligence, also called Computational Intelligence, describes the design of intelligent agents. These agents can be through as an element that intelligently interacts with its environment. Under this context, intelligent behavior means taking actions or decisions according to a certain context or environment, following a specific objective. The agent must also be flexible to changes in the environment or objectives, learning from its experience. In general, we called this ability the *generalization* capacity of an agent [91]. A way to address this behavior is by giving specific instructions to the machine to obtain a result from an input (the traditional programming paradigm). However, this approach has proven not to be suitable for some activities. Especially in terms of flexibility, these approaches have shown bad performances in activities considered intuitive for humans. For this reason, the AI problem is faced from a perspective of knowledge obtained from experience. In this way, the machines look to understand their context from their representation of the environment or reality [92].

Since the early stages of its study in 1956 until the present day, AI has been widely used in different tasks of a very diverse nature. Some examples are autonomous driving, image analysis, voice processing, gaming, and many others [93]. Despite the previous description and examples may show AI as a tool to solve all problems in all contexts, this is not a reality at the moment of writing this thesis. Although there are many tasks that machines can solve in a much more efficient way than humans, many other tasks, carried out almost unconsciously by humans, are of high complexity — or even impossible yet — for machines [92]. As seen from Fig. 2.12, AI encapsulates a wide diversity of techniques. Some of them are fuzzy logic, swarm intelligence, expert systems, evolutionary algorithms, and ML. In this thesis, the proposed beaconing control mechanism uses ML tools to estimate the neighbors' awareness.

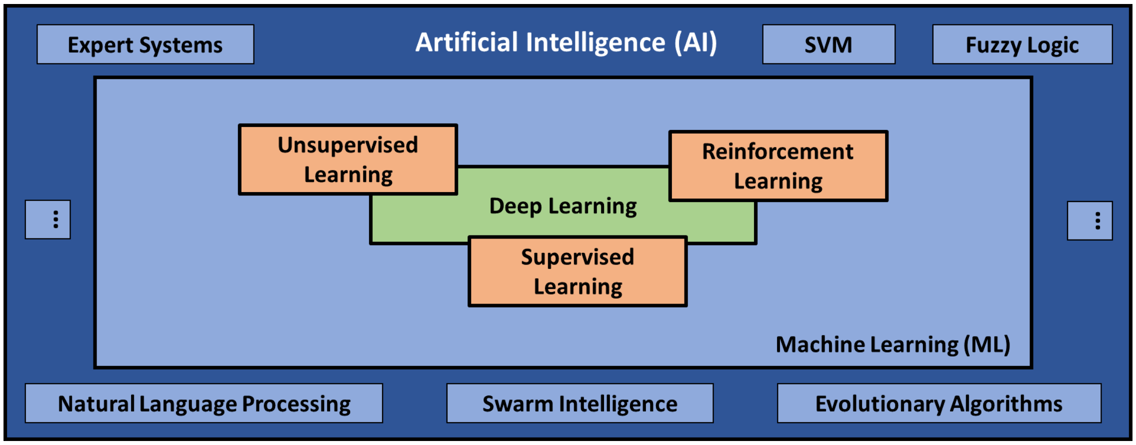


Figure 2.12: Scheme of AI techniques

Machine Learning is a subset of AI composed of various tools. These tools allow an agent to obtain knowledge from feature vectors that represent raw data (or an environment) or more general information, as in the case of Deep Learning (DL). Two steps compose a Machine Learning workflow. First, in the training stage, a model is taught based on the task objective and samples of the environment or dataset. Second, there is a test step, where the model is tested using new samples. This process allows computers or machines to deal with real-world problems. ML includes different techniques. These techniques can be categorized into non-supervised learning (which uses only features), supervised learning (which uses features and labels), or Reinforcement Learning (RL, which uses interactions and rewards). VARIATE, the algorithm proposed by this thesis, uses a supervised learning approach for the decentralized awareness metric estimation.

The present Chapter described the general theoretical framework needed for the correct contextualization and understanding of the VARIATE proposal. In this sense, we first reviewed the general framework of vehicular communication networks, followed by two of the most promising RATs for these networks' deployment — DSRC and C-V2X. Next, a review of the concept and conceptualization of heterogeneous vehicular networks is provided. Finally, we described the general concepts related to ML. Our proposal takes the topics described in this Chapter to assess the control of the congestion and VRU awareness in heterogeneous networks. The following Chapter revises the topics presented in this Chapter to contextualize the reader regarding the current state of VRU inclusion, HetVNETs, and ML in vehicular networks.

Chapter 3

Related Work

The present section surveys different works related to the integration of VRUs in VANETs and the development of decision systems for heterogeneous networks. First, Section 3.1 address VRU inclusion, directly. The section presents the motivation for VRU inclusion, the requirements and standardization elements, and different approaches for VRU integration. Second, Section 3.2 surveys different approaches that integrate different RATs into heterogeneous networks. Finally, Section 3.3 briefly presents applications of ML in the CV context. We can also consider the publications derived during the context of this thesis as related documents. Annex indicates the two published contributions.

3.1. Towards VRU inclusion

The present section surveys a series of works related to VRUs, emphasizing the ones considered relevant for this thesis. The section treats three main topics. First, we review works addressing the VRU applications requirements. This subsection considers both studies that analyze these requirements and standardization documents concerning VRUs. Second, the section surveys proposals for the integration of VRUs in the vehicular communications environment. We classify the efforts under different criteria, giving particular importance to contextual variables in the beaconing control context. Finally, an analysis of a specific set of works considered an inspiration for this thesis is included. These works have been important both for the previous work developed in [32] and the complete system proposed in this thesis.

At present, the development of C-ITS focuses the attention of both industry and academia. Part of this interest is based on the potential benefits these systems would bring when dealing with the increasing number of vehicles. It is expected that the deployment of C-ITS brings advantages not only in the reduction of traffic-associated deaths but also in the monetary and environmental costs brought by the increase of the vehicle number [8].

The threat of severe consequences for VRUs in traffic accidents is one of the primary motivations for developing technologies and schemes to support C-ITS. WHO and different publications have highlighted the ability of C-ITS in the prevention of traffic accidents citepworld2018global. These publications include a wide range of topics that goes from architecture proposals for VRU communication [1, 11] to the design of alert systems (e.g., [94]).

The following sections deeply analyze some of the works addressing VRU integration in the communication environment.

Another aspect that significantly encourages C-ITS development is their advantages when dealing with NLoS conditions compared to the exclusive use of sensors. As previously stated, a considerable percentage of traffic accidents (29.7 %) are associated with NLoS. Because of this, many authors state that communication-based information gathering should act as a complement of on-board sensors [11, 18]. Another advantage that has been remarked when comparing C-ITS and sensors-only approaches is the increase in the detection range, which directly determines the time before a collision that a car can detect a VRU [19]. Some works, as [22], discuss the advantages of communications technologies over sensors when considering the computational and economic costs.

3.1.1. Works on VRU requirements and current standardization

The vehicular networking community has developed an extensive range of studies on the requirements associated with VRU inclusion in vehicular networks. Some of the most mentioned aspects are the requirements in terms of latency and reliability. This section reviews the requirements suggested by different authors and those indicated by standardization organisms. This thesis mainly considers ETSI documents as the guidelines for VRU requirements and use cases.

The work in [95] studies vehicular communications using C-V2X in the context of Connected and Autonomous Vehicles (CAV). Related to VRU, the intent and situation awareness applications could improve the safety of VRU, especially in intersection scenarios. This case is one of the most complex traffic accidents scenarios, particularly for bicycles and scooters [96, 97]. For this purpose, the authors encourage V2V and V2P communications. URLLC is a requirement demanded by these applications.

Boban et al. [98] presents the requirements and design considerations for fifth-generation V2X communications networks. Based on the TS 22.186 specification by 3GPP [70], specifically the category of *Sensor information sharing between UEs supporting V2X application*, the authors established a set of requirements associated with VRUs.The authors set the need for an end-to-end latency between 100 ms and 1 s. For communication reliability, a value above 95% is required. In terms of data rate, the work establishes a requirement of 5 to 10 kb/s. The communication range is expected to cover ranges no longer than 200 m. In terms of range, for VRU safety, the works of [11] and [99] propose a certain time before a collision that allows the drivers to react and improve the safety of VRUs. Considering both works, a safety range of around 100 m is considered suitable for VRU safety.

Past years, ETSI defined the use cases and requirements associated with VRU in vehicular communication networks. The Technical Report (TR) ETSI TR 103.300-1 [13] includes the definitions of different VRU communications actors and elements along with a large variety of use cases expected for these users. Subsequently, ETSI set the associated requirements for the considered use cases in the Technical Specification (TS) ETSI TS 103.300-2 [37]. In the following, the most relevant aspects of both documents are described.

ETSI TR 103.300-1

The first important aspect described by this TR is the definition of the VRU category. The VRU set includes pedestrians of all kinds; the document differentiates particular cases as toddlers, elders, and joggers because of their different mobility characteristics. Emergency and road workers are included as VRUs at risk because of their proximity to the roads. Pets are also considered as VRUs while carried. Another distinction is made for people using wheelchairs or prams. Bicycles, segways, scooters, e-bikes, PTWs, and motorcycles are considered VRUs while operated by a driver. A point to emphasize is that the document defines that when pedestrians enter a vehicle (car, bus, emergency vehicle), they lose the status of VRU. Three VRU profiles are associated with different VRU groups. Pedestrians and sidewalk walkers are considered in one profile. Another profile includes light vehicles such as bicycles and PTWs. The third profile includes heavy vehicles such as motorcycles.

Regarding the applications focused on VRU safety, the document indicates that these can run in any ITS-S. According to their purposes, there are three main domains of applications defined by the standard. In the first place, some applications look to increase the awareness of VRU (studied in this thesis). Second, there are applications focused on providing collision alerts to VRUs, vehicles, and infrastructure elements. Finally, applications intended to trigger an action (mainly focused on the CAVs' operation).

The TR defines three different types of VRUs regarding their communication capabilities. The VRU-Tx set includes the VRUs that only can send messages but not receive them. The VRU-Rx group consists of the VRUs that only can receive information but not transmit messages. The VRU-St are the ones that combined both abilities, being able to both send and receive packets.

ETSI TS 103.300-2

This TS provides a set of requirements for VRUs. The document divides these requirements into two categories: functional and operational. Functional requirements directly influence the system architecture, while operational requirements are expected to be tested and satisfied when the VRU communication systems are under development and deployment. To describe the requirements considered relevant or referential for this thesis, we indicate the reference as in the original specification, as Functional Communication (FCOM), Operational System (OSYS), Operational Communication (OCOM), and Operational Security (OSEC) requirements, for each case. The highlighted requirements are described in the following:

- *FCOM01:* A VRU system should be able to operate up to 5000 users within the same communication radius (300 m according to [100]). Clustering should be considered for this purpose.

- *FCOM02:* VRU systems should count with a congestion control mechanism. The mechanism should consider the maximum number of VRUs and the available bandwidth.

- *FCOM03:* VRU devices shall consider the reduction of the channel congestion in their operation. This requirement also indicates the use of contextual variables and Collective Perception Messages (CPMs) for congestion reduction.

- *FCOM04:* VRU systems shall support flexible and dynamic message triggering policies. Support from message generation rates until 10 Hz. The use of dynamic variables and risk metrics is suggested concerning VRU Awareness Messages (VAMs).

- *FCOM06:* Regarding VAM, when a VRU ITS-S can transmit messages (VRU-Tx or VRU-St), it should modify the periodicity of its transmissions to its profile, velocity, context, and risk estimation.

- *OSYS05:* The exchanged data shall be recent enough to be useful for safety applications. This condition leads to maximum latency values and minimum transmission periods. Given examples are a latency of 300 ms [100] and 10 Hz.

- *OSYS10:* Interoperability as a key characteristic of ITS-S

- *OSEC01:* Security processes shall support generation rates up to 10 Hz and reception rates of 2 kHz. Latency of 300 ms end-to-end shall be considered as a maximum value.

3.1.2. VRU communication systems

This section presents a survey of works related to VRUs and practical applications that look to improve VRU safety. The analyzed efforts are those that exhibit an active communication approach. Active communication means that the VRUs transmit packets without requiring a previous message from a vehicle or infrastructure element. These transmissions may be periodic or not.

Table 3.1 presents the set of analyzed works. Table 3.1 uses five criteria to classify the studied approaches. The following list presents these criteria. Works that include some beaconing context-based beaconing control will be described in more detail after the classification is shown.

1. **Direct Communication:** This criterion indicates if VRUs have direct communication with other nodes (✓) or the communication occurs through infrastructure elements (×).

2. **Beaconing control mechanisms:** This criterion indicates if the system presents some kind of beaconing control mechanism or channel congestion reduction technique, considering beaconing control as a dynamic beacon rate. This criterion must not be thought of as an alert filter. Most beaconing systems present alert filters to avoid the users' fatigue caused by a large number of alert notifications. We use an affirmative sign (✓) to indicate the systems that include a beaconing control mechanism and a negative sign (×) for those that do not.

3. **Used RAT:** Indicates the RATs used for the communication.

4. **VRU type:** Since most of the VRU systems tend to focus on a specific kind of VRU, this criterion describes the VRU types integrated by the different summarized approaches.

5. **Notification side:** Indicates the member of the communication system that receives the alert of a possible collision.

Table 3.1: Related Work Clasification

Reference	Direct Communication	Beaconing Control Mechanism	Used RAT	VRU Type	Notification side
[94]	✓	✓	DSRC	General VRU	Car
[30]	✓	✓	DSRC	Pedestrian	Not studied [a]
[17]	✓	✓	DSRC	Pedestrian	Not studied [a]
[101]	×	×	LTE	Pedestrian	Car/VRU
[20]	✓	×	WiFi	Pedestrian	Car/VRU
[22]	✓	×	LTE	Pedestrian	Car/VRU
[23]	✓	✓	WiFi	Pedestrian	Car
[24]	×	×	LTE	Pedestrian	Car/VRU
[25]	✓	×	BLE and DSRC	Motorcyclist/Cyclist	Car
[31]	✓	✓	DSRC	Pedestrian	Car/VRU
[102]	×	✓	Open (Cloud connection)	Pedestrian	Car/VRU
[103]	✓	✓	WiFi Direct and DSRC	Pedestrian	Not specified
[96]	×	×	WiFi and ITS-G5	Cyclist	Car
[97]	✓	×	WiFi	Scooters	Car/VRU
[104]	✓	×	LTE/DSRC/WiFi	Pedestrian	Car/VRU
[105]	✓	×	700 MHz ITS	Pedestrian	Not specified
[106]	×	×	LTE [b]	Pedestrian	Car/VRU
[107]	✓	×	WiFi/LTE	Pedestrian	Car/VRU
[108]	✓	×	3G and WiFi	Pedestrian	Car/VRU
[109]	✓	×	DSRC	Motorcyclist	Car
[110]	×	×	3G/LTE, WiFi and DSRC	Cyclist	Car/VRU
[111]	×	×	Open	General VRU	Car/VRU
[112]	✓	✓	DSRC	Pedestrian	Not specified

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[a] V2P-P2V communication

[b] Suggested by trials

The work developed by Tahmasbi-Sarvestani et al. [94] incorporates VRUs in a more general definition. The type of VRU determines some communication features, e.g., faster VRUs — as bicycles — and emergency workers should transmit using a higher rate. The application can set the VRU type; otherwise, the system must infer it from the motion characteristics of the VRUs, as in the case of smartphone devices. Then, the VRU type is informed using Personal Safety Messages (PSMs) as defined in [113]. This information, along with sensors and GPS data, is used to detect possible collision scenarios. Then, depending on the collision probability, a danger alert is sent to the driver to take evasive maneuvers. For channel congestion management, the system proposes a set of features useful to reduce channel congestion and battery consumption. If one of the following conditions is satisfied, a VRU must turn off the GPS and DSRC modules: 1) Static VRU. 2) VRU inside a building. 3) VRU inside a vehicle. 4) VRU in parks, hiking, or regions far from vehicles. If these conditions are not satisfied, the radio module transitions into a *listening* mode until a vehicle detection. After a vehicle detection, the module emits messages periodically. The authors also consider reducing the transmission range to form clusters in high pedestrian and low car density scenarios.

WiSafe system, developed in [23] is a Pedestrian Collision Avoidance (PCA) system based on active pedestrian transmissions. In the proposed scheme, pedestrians periodically send beacons using regular WiFi (authors discuss compatibility with IEEE 802.11a/b/g/n). Pedestrians are considered APs that regularly transmit their SSID, including GPS, type of pedestrian tag, heading, and speed information as beacons. Vehicles periodically scan the medium to read the pedestrians' SSIDs and information. Based on cinematic-based filters, the vehicle side is warned in collision danger detection. The beaconing control of this system is straightforward, where only pedestrians outside buildings and set as APs are allowed to send messages.

In [102], Bagheri et al. propose a situation-adaptive beaconing for the communication between pedestrians and the cloud. The system works by defining three modes for VRUs. Risk-free mode is considered when pedestrians are indoors or far enough from the street. In risk-free mode, the smartphone device is in a sleep state (i.e., not sending beacons). A low-risk state is considered when pedestrians are outdoors, but no vehicles are within a defined range or they are moving away from the pedestrian. In this mode, pedestrians transmit messages at a rate lower than 10 Hz. The high-risk scenario is considered when vehicles are inside a range and moving towards the pedestrian. In a high-risk state, pedestrians transmit messages with a 10 Hz frequency by instruction of the Cloud server. Cars are considered to be sending messages with a 10 Hz beacon rate. Here we briefly explain the operation of the proposed algorithm. When a pedestrian is in a risk-free state and moves, it transitions to a low-risk state. Based on the beacons received from Pedestrian-to-Cloud (P2C) and Vehicle-to-Cloud (V2C) communications, the server in the cloud determines the probability of collision. If the server detects a high probability of collision, it will alert both the pedestrian and the car.

The work developed in [103] focuses on the battery consumption reduction in pedestrians. The authors address the problem of energy consumption in smartphones stating that it is one of the main problems of V2P communications. The work does not manipulate the beacon rate directly but proposes a method that modifies it indirectly. The system is based on the use of WiFi Direct and DSRC. WiFi direct allows the system to create Peer-to-Peer Groups (P2P Groups) clusters. In the P2P Group, a P2P Group Owner (P2P GO) relays the messages from the other nodes inside the P2P group. In the proposed system, only the P2P GO communicates with the vehicles using DSRC and distributes the information among its peers. Here, the first element of channel load control appears, as the work proposed a cluster creation using WiFi Direct, reducing the number of messages exchanged through DSRC technology. Clustering mechanisms have been presented as a channel load reduction mechanism by organisms such as ETSI [37]. The contextual mechanism proposed for the system is related to vehicles' velocity. When vehicles move at a low speed (determined by P2P GO), the P2P GO allows its peers to set a longer sleep time. Contrarily, if the vehicle speed is considered fast, the P2P GO requests more information (higher transmission rate) from the peers. The approach developed by [110] also presents a clustering system. The cluster is composed of bicycles connected by WiFi, while the cluster leader exchanges the group's information with an external server.

The work by [112] consider a mechanism for QoS control based on priority modifications. The proposed system is based on the active direct communication between pedestrians and cars. The QoS manipulation aims to increase the QoS of pedestrian-vehicle pairs at risk of collision. As the safety messages in DSRC are already sent with the highest priority allowed by EDCA, the authors propose a mechanism to reduce the priority of non-risked nodes. By doing this, the pedestrian-vehicle pairs at risk of collision can improve their QoS.

3.1.3. VRU Context-Based Transmissions

The term *Context-Based Transmission* is related to the design and development of transmission decision systems. The particularity of this kind of system is that the transmission decision is made based on contextual variables. The decision criteria may include many contextual variables, including motion variables (e.g., position and velocity of the VRU), global position (e.g., distance from the street), or neighbor awareness. Decision systems for VRU may have many purposes. Of particular relevance for this thesis is channel congestion control; however, there are also proposals for energy saving. This last point, not commonly considered in the vehicular case [3], is mentioned widely in the literature as critical for the acceptance of VRU communications, especially when considering smartphone usage [31].

Although contextual-based transmission mechanisms are a well-investigated field in vehicular communications, similar techniques that focus on VRUs do not present the same depth of exploration. Elements of vehicular context-based triggering systems were an essential inspiration for this work. One example is the development of the context-based rules for CPMs and its posterior evaluation, based on the detection effectiveness (closely related to awareness). CPMs, standardized by ETSI [114], allow the exchange of sensor information among vehicles, increasing each vehicle's environmental knowledge of the road [115]. For the CPMs generation, the context-based rules include environmental variables of the detected objects, such as their movement, novelty, and speed changes, to determine if a message should be transmitted. Previous works have studied the channel load variations derived from the transmissions triggered by these rules compared with a baseline case — a fixed message transmission rate. They also introduced metrics related to object awareness. In [115], the authors used two relevant evaluation metrics: the Object Awareness Ratio (OWR) and the time between object updates. OWR measures object-related awareness as the probability of node detection through CPMs exchange. In contrast, the time between object updates measures the time between two object detections. Along this line of study, the authors in [116] measure object awareness using the number of different objects recognized via CPMs.

In the VRU context, three works stand out because of their channel congestion management based on message generation rules. The authors in [31] designed a DSRC-based system for V2P communications using smartphones. For the deployment of the proposal, the authors implemented the DSRC stack utilizing the smartphone's hardware. The system incorporates a context-awareness module to enable and disable the DSRC operation on the VRU side and alert vehicles if pedestrians are distracted by their phones. The operation of the system consists of a set of steps synthesized here. First, the smartphone determines the pedestrian's motion state (i.e., stationary, walking, or running). The smartphones use the state information to turn off the message transmission and GPS signal reception in motionless pedestrians. The message transmission and GPS connection are only allowed when the VRUs move. Although the latter was not analyzed, the authors stated that the system's control mechanism reduces power consumption and channel congestion. They also discussed several challenges related to VRU inclusion in C-ITS, such as the spectrum and channel congestion. They proposed a mitigation alternative, termed *receive-only mode*, where mobiles (carried by pedestrians) are only allowed to receive messages. However, such a mode resembles a passive approach, which can reduce pedestrian detection compared to an active communication approach [26].

Sewalkar et al. [17] studied VRU transmissions using simulations. In the simulated scenarios, the authors studied two metrics, namely the Channel Busy Percentage (CBP) and the Beacon Packet Error Ratio (B_pER), to evaluate the impact of the inclusion of pedestrians in the existing V2V communications. In light of the simulation results, the authors concluded that implementing critical safety applications in V2P communications is not possible using a fixed beaconing rate. To cope with this problem, the authors proposed a variable beaconing rate based on a context-aware system. The system proposed by the authors uses a context-sensitive clustering mechanism. This mechanism groups pedestrians and allows just one to send group information to vehicles, thereby reducing the number of exchanged messages.

Rostami et al. [30] studied the problem of channel congestion in IEEE 802.11p. To reduce congestion, the authors proposed a context-based transmission system using three possible rules based on the motion and position of pedestrians. The first rule allows transmission only from pedestrians on the street (PedOnStreet rule). The second rules filter the transmission of stationary pedestrians, allowing the transmission of only moving ones (MovPed rule). The third rule allows the transmission of all pedestrians at different rates depending on their movement (MultiTx rule). To test these rules, they performed simulations and compared the decision system performance to a fixed-rate mechanism based on CBP, Packet Error Rate (PER), and a near-the-worst-case Inter Packet Gap (95 % IPG). The results show an improvement in these metrics when applying the triggering rules. However, there was no evaluation of VRU detection capabilities.

Based on the previously present context-based mechanisms, we developed a work that motivates the design of the decision system proposed in this thesis. The two main motivations for studying these rules were the lack of inclusion of a diversity of VRU (most studies only consider pedestrians) and the analysis of the neighbor awareness capabilities when using message generation rules. Our work in [32] showed that while the rules proposed by Rostami et al. [30] effectively reduced the overall channel load, they can heavily affect the general knowledge about the neighbors. To quantify the awareness, we proposed the metric VRU Awareness Probability (VAP) that quantifies the detection probability of VRUs in the transmission range. Based on VAP, the results showed that this metric worsens while the CBR is reduced by filtering the VRU transmissions. The situation is particularly critical when considering the PedOnStreet rule, where every pedestrian out of the street cannot transmit messages. Based on the study results, we concluded that while the use of fixed transmission rules may help in channel load reduction, they can be harmful when considering the general awareness of the network. These results motivate the development of the dynamic decision system proposed by this thesis. The contribution of this approach is to simultaneously consider the channel load and awareness capabilities when managing VRU transmissions.

3.2. HetVNETs Approaches

This section describes some recent developments in vehicular communications using more than one RAT. These works detail heterogeneous and hybrid networks in terms of architecture or operation proposals. The analysis focuses on the used access networks and considered variables. Table 3.2 presents the most relevant analyzed efforts in the context of HetVNETs classified under several criteria. The table presents four features used to summarize the approaches, along with a brief description of the objective of each publication. The four criteria are presented here in the following list.

1. **RAT:** This criterion indicates the set of RATs used by the proposed heterogeneous approach.
2. **VRU:** This criterion indicates if the studied approach includes VRUs in its formulation or simulation (✓) or does not (×).
3. **Control criteria:** This criterion indicates the set of criteria used by the approach for the operation of the heterogeneous network.
4. **Evaluation criteria:** This criterion indicates the set of metrics used for the evaluation of the system.

We observe common points among the works presented in Table 3.2. Some points of high interest for this thesis are: (i) None of the studied approaches consider the integration and simulation of VRUs in the HetVNET context. (ii) The most commonly used RAT is DSRC, usually combined with infrastructure-based LTE. (iii) The evaluation used for the systems' evaluation omits awareness metrics; also, only a few approaches study channel load through CBR. (iv) The study of latency is relevant in HetVNETs as seen from the Evaluation Criteria column of Table 3.2. The rest of this section details each of the presented works in more depth.

Table 3.2: HetVNETs approaches classification

Reference	**RAT**	**VRU**	**Control criteria**	**Evaluation criteria**	**Objective**
[85]	DSRC LTE	×	Data type, PRR[a] in each RAT	PRR, delay	RAT selection based on PRR and application characterization
[82]	DSRC LTE	×	Application requirements, communication type (V2V or V2I), network density, payload size	Delay, PDR	Parallel use of network diversity for traffic flow separation
[84]	DSRC C-V2X	×	Vehicle's position, SNIR, DSRC WT[b]	PDR	RAT relay in heterogeneous networks
[90]	Agnostic	×	CBR, PDR and PSR[c].	Throughput, CBR	Agnostic RAT selection based in CBR and throughput constrains fulfillment
[117]	DSRC LTE	×	Available bandwidth, DSRC neighbors, CQI[d]	PDR, delay, hops number, communication distance	LTE micro-cell communication range extension using DSRC retransmissions
[118]	DSRC LTE	×	DSRC's channel occupancy, LTE's channel load	VHO[e] number, throughput, latency	Se QoS improvement using RRM[f] and RAT selection
[119]	DSRC LTE-V	×	Vehicle's position	NLoS PDR	DSRC-based scheduling mechanism for LTE-V in NLoS scenarios

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[a] Packet Reception Ratio (PRR)
[b] Waiting Time (WT)
[c] Packet Sensing Ratio (PSR)
[d] Channel Quality Indicator (CQI)
[e] Vertical Handover (VHO)
[f] Resource Radio Management (RRM)

The work by [85] proposes a hybrid network architecture including DSRC and LTE. The authors emphasize the features of each RAT to select when to use a direct transmission through DSRC or an infrastructure-based message exchange using LTE. The proposal addresses the QoS requirements fulfillment for three different types of applications. First, the safety applications, with stringent latency requirements, include the exchange of Cooperative Awareness Messages (CAMs) and Distributed Environmental Notification Messages (DENMs). Second, the streaming of video for *see-through* is considered an application requiring high bandwidth. As a middle point regarding requirements, the study includes Voice over IP (VoIP) traffic. The authors propose a set of rules for the RAT selection. In the case of the safety and video stream traffics, these are sent through DSRC and LTE, respectively. In the case of VoIP, the selection between DSRC and LTE is made based on PRR conditions defined by the authors.

[82] also proposed a heterogeneous network approach considering DSRC and the LTE infrastructure. First, the work remarks on the disadvantages of each technology in terms of scalability (DSRC) and latency (LTE). The authors propose the parallel use of different RATs to transmit the different traffic flows — control, data, and signalization — from a unique application. A set of rules is proposed based on the application requirements for the information forwarding. The rules are designed manually and automated based on a Random

Forest mechanism.

[84] states that the simultaneous use of DSRC and C-V2X in the same vehicular communication networks is unavoidable. Considering this assumption, the authors remark on the problems arising from the coexistence between cars with heterogeneous capacities, named Dual Interface Vehicles (DV), and vehicles with only one RAT (DSRC or C-V2X). The authors propose a mechanism where DVs act as relays for the transmission from one-RAT-equipped vehicles. The idea of this mechanism is to allow the correct connection between DSRC-only and C-V2X-only cars using the heterogeneous capacities of DVs. The paper proposes a series of rules and criteria to perform the relay selection and transmission based on the waiting time, the Signal to Interference plus Noise Ratio (SINR), and distance to select the most appropriate resources for the retransmission.

The decision system designed by this thesis uses the work developed by [90] as an essential inspiration. The designed proposal uses this work's general structure and the elements proposed for congestion control. We give more details about this approach because of its importance for this thesis. The algorithm proposed by [90] coordinates the use of different RATs in a multi-link, multi-RAT configuration. The system is presented in an agnostic manner and tested considering a set of RATs composed of DSRC operating at 5.9 GHz, DSRC operating at 700 MHz, WiFi operating at 5.6 GHz, WiFi operating at 2.4 GHz, and 'an OFDM-like technology operating in TV White Space (TVWS) band at 460 MHz'. The algorithm assumes that the vehicles broadcast their position and the CBR measurements for each RAT. Also, the proposal considers that each vehicle shares its neighbors' table, composed of the information of its direct neighbors. Periodically, each vehicle evaluates its conditions to determine if it should change its current RAT. This evaluation starts by estimating the PDR expected for each RAT at a certain distance (D, design parameter) based on the CBR measurements. To calculate this PDR, the authors use previously obtained curves for PDR as a function of distance and CBR. Based on the PDR estimation, the algorithm selects a subset of pre-selected RATs in which PDR at a distance D surpasses a 90%. In a second step, a car estimates the CBR perceived by each neighbor in a RAT, considering that the vehicle selects that RAT. With this estimation, the cost of each pre-selected RAT is the maximum CBR perceived by the cars' neighbors. Finally, the node only changes its current RAT if the new cost differs from the current cost more significantly than a design threshold. Another consideration is that each time a node changes its RAT, it indicates this update to its surrounding nodes to postpone their updates for a certain period.

The heterogeneous approach proposed in [117] uses DSRC and LTE together to improve the connectivity conditions to a server. The proposal assumes that vehicles intend to exchange messages with an LTE-connected server. The proposal uses DSRC to improve the effective communication range of LTE, rebroadcasting a vehicle's information until it reaches a node closer enough (in the terms defined by the approach) to the server. The idea of the proposed system is also to reduce the probability of packet loss in the connection vehicle-server by using different hops to reach an area considered to have good transmission characteristics. For this purpose, the algorithm uses different metrics to represent the channel conditions and the information stored on a neighbors' table.

In [118], the authors state that it is not feasible to offer the QoS requirements of vehicular applications using a unique RAT. Considering this limitation, they propose a complete protocol stack and RAT control algorithm for the interoperation of DSRC and LTE. The general idea of the work is to improve the performance in terms of latency and loss of data throughput while also reducing the number of VHOs between the studied technologies. The algorithm uses three stages of RAT selection, VHO, and a Dynamic Communication Management (DCM). Using channel occupation criteria for DSRC evaluation and channel load for LTE, the algorithm selects the RAT and controls the beaconing rate to improve the QoS.

The proposal by [119] uses DSRC and LTE-V2X for the improvement of the PDR in an urban intersection context. Based on the position of cars at an intersection, the authors divided the LTE-V2X sub-frames into pools associated with the number of incoming streets. The division is made to avoid packet collisions between nodes in different streets of the intersection (NLOS conditions) when using LTE-V2X. DSRC is used here as a redundancy, primarily focused on exchanging information between cars in the same street. The authors show that DSRC has a better performance in LOS conditions, hence, improving the communication in the same street, an aspect not considered by C-V2X in the proposed system formulation. The authors extensively studied the packet collisions and PDR in LOS and NLOS conditions.

The work developed in [34] endorses the idea of using a set of RAT for tackling the different limitations of three of the most popular technologies for vehicular communications, DSRC, mmWave, and LTE. The paper proposes a heterogeneous architecture based on an in-vehicle intelligent module, with cross-layer functionalities under the application layer. The authors establish the importance of designing a suitable MAC mechanism. For this purpose, they design a Q-learning-based MAC system for DSRC. The authors propose to continue this development in future work, including the two other mentioned technologies.

Other works, as [36], are focused on the development of a framework of concepts, architectures, and requirements of heterogeneous communication systems. In the case of [36], the authors first encourage the use of hybrid communications in vehicles as a way to satisfy the more stringent QoS requirements of completely autonomous vehicles. The authors state that it is necessary to develop a set of application profiles to map different groups of applications to the available RATs. For this purpose, a set of channel conditions, RAT load, and RAT characteristics must be considered. The proposed architecture is similar to the one presented in [79] (Fig. 2.11), used as a reference for the design of this thesis approach. [120] proposes a similar approach for the interaction between cars equipped with different RATs. In this case, the authors suggest using Mobile Edge Computing (MEC) equipped node, equipped with dual-technology capabilities to relay the communication between C-V2X and DSRC enabled vehicles. The work of [35] encourages the use of multiple RATs in the 5G architecture. This work explores the possibilities given by Software Defined Networks for the multiple RAT vehicular networks. [83] also encourages a hybrid approach using DSRC and LTE, based on the limitations of each technology.

3.3. Machine Learning in Connected Vehicles

This section describes several works using ML techniques in the vehicular communications context. The studied works address various current challenges present in vehicular communication networks. Despite this variety, this section mostly emphasizes congestion control mechanisms and resource management proposals. 3.3 presents the analyzed efforts. The table uses four criteria to summarize the approaches and a brief description of the objective of the used ML techniques. In the following, we go deep into more details about each presented work. The next four criteria were used to classify the different approaches.

1. **RAT:** This criterion indicates the RAT or set of RATs used by the approach.
2. **ML Approach:** This criterion indicates the used ML tool or tools
3. **Decentralized training:** This criterion indicates if the training of the ML mechanism is made in a decentralized (✓) or centralized (×) manner.
4. **Decentralized execution:** This criterion indicates if the execution of the ML mechanism is decentralized (✓) or centralized (×) manner.

We can observe common points among the works presented in Table 3.3. Some points of high interest for this thesis are: (i) Most of the works using ML are focused on non-heterogeneous networks. (ii) A considerable percentage of the studied approaches use a centralized training phase followed by a distributed execution. This methodology is adopted by the system proposed in this thesis. (iii) The uses of ML in vehicular communication networks are diverse in nature.

Table 3.3: ML approaches classification

Reference	**RAT**	**ML Approach**	**Decentralized training**	**Decentralized execution**	**ML Objective**
[82]	DSRC, LTE	RF[a]	×	✓	Information flows assignation for in HetVNETs
[121]	DSRC	SVM[b], Naive Bayes	×	✓	NLoS detection
[122]	Sub-6 GHz, mmWave	KNN[c]	×	×	Assistance to mmWave blindspots in handover situations
[123]	LTE, DSRC	Feed forward neural network	×	×	Mobility prediction for routing improvement
[124]	DSRC	Fuzzy logic, RL, game theory	✓	✓	Vehicle cluster formation, cluster behavior encouragement
[125]	C-V2X	RL	×	✓	Distributed resource selection in out-of-coverage situations
[126]	DSRC	RL	✓	✓	Congestion management using beaconing rate an transmission power control
[127]	DSRC	RL	✓	✓	Decentralized dynamic channel assigment
[128]	DSRC	RL	✓/×[d]	✓/×[d]	Broadcast management mechanism
[129]	C-V2X	RL	×	✓	Reusage of V2I resources for V2V communications

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[a] Random Forest (RF)
[b] Support Vector Machine (SVM)
[c] K-Nearest Neighbors (KNN)
[d] Two algorithms

In the V2X context, different authors show that recent developments in artificial intelligence and ML open a wide variety of applications related to ITS [93]. Moreover, it is expected that these types of tools and techniques have an essential role in the mobile wireless communications from 5G and on [130]. Nowadays, a large variety of works propose ML-based solutions in the vehicular environment context. However, most of these applications focus on the sensors' management, environment awareness, and information fusion [93, 130]. For example, to this author's knowledge, there are no works that address the inclusion of VRUs in vehicular networks in terms of communications. However, VRUs have been considered in terms of movement predictions [131] or the efficient management of traffic signalization [132], mainly using in-vehicle sensors.

Different works have shown the benefits and diverse applications of ML in the vehicular context. [133] surveys ML applications related to resource allocation. In this context, the authors emphasize the diverse nature of current ML-oriented works. According to the authors' studies, ML has been applied for resource allocation (e.g., channel allocation), user association, handoff management, and virtual resource management. From this work, we can also notice the relevance of RL in current ML applications in the vehicular context. The authors highlight the advantages of these approaches in their ability to solve optimization problems. The works in [121] and [130] emphasize the potential of ML when considering the large amount of data generated from using vehicular sensors and also vehicular communication stored information. [130] mentions the possible application of ML for efficient resource management in heterogeneous scenarios of high dynamism and many devices with stringent latency requirements. In the case of [121], the survey also developed an NLoS detector based on ML and the information exchanged by vehicular nodes. The authors state that these applications could help design routing and MAC protocols. [93] states that the fusion of AI and V2X communications allows the management of different types of applications. The most relevant for this thesis include location-based applications and congestion control in VANETs.

The use of ML for mobility estimation in a C-ITS context is broadly studied. Although the estimation of vehicle mobility is not a direct application of ML in the C-ITS, many authors use it for different purposes. In the case of [122], the authors propose the use of ML for the mobility estimation of vehicles using the Channel State Information (CSI) of sub-6 GHz bands. Then, the authors use this estimation to coordinate the directionality of mmWave antennas in a heterogeneous network composed of sub-6 GHz and mmWave technologies. Another ML mechanism is used for handover position predictions used for fast handover improvement. Another case, presented in [123], also uses the mobility estimation. In this work, the authors present a routing mechanism based on estimating the vehicles' position using ML.

The literature also includes works employing other techniques inside the AI spectrum. In the case of [124], the authors propose to use fuzzy logic for the creation of vehicle clusters based on mobility and networking features. The authors also use game theory and RL for the multi-hop routing on the proposed network. Another technique that has gained momentum is Federated Learning. Because of its distributed nature and the possibility of privacy management, this tool has arisen as a potentially efficient way to improve the performance of vehicular networks [134].

The work by [125] proposes a Distributed Resource Allocation (DRA) system based on the use of Multi-Agent Deep Reinforcement Learning (MADRL). The authors mention LTE-V2X as RAT, using slotted time. The proposed system's objective is to maximize the overall PRR. For this purpose, the authors formulate an optimization problem where the aggregated PRR is maximized subject to each node's action (resource selection). The authors use a MADRL approach to solve the optimization problem, where the nodes use local information and neighbor maps to select the frequency resources. The proposal uses centralized training and distributed execution of the RL algorithm. In general terms, the approach uses a Double Deep Q-Learning approach (DDQL) to generate the policy with a Long-Short Term Memory (LSTM) layer to predict the mobility patterns. The system's reward encourages resource reuse between nodes farther than a design distance and avoids collisions in the immediate neighbor.

The work of [126] proposes a mechanism of congestion control using an IEEE 802.11p-based technology. The system controls the beaconing rate and transmission power to manage the channel congestion conditions. The authors' objective is to maintain the system in CBR values around 0.6, described as the Maximum Beaconing Load (MBL). This value is chosen based on cited studies indicating that a channel load above this value could harm packet delivery abilities. The complete communication system is formulated as a Markov Decision Process (MDP). For the MDP, each vehicle represents an agent that can select the beacon rate and transmission power setting. The authors define the state using a vector composed of the beacon rate, the transmission power, and the number of neighbors. For the reward, the authors used three components. The first component, related to CBR, is designed to increase the reward while the CBR is increased until reaching the MBL, after which the returns are negative. As a second component, the authors include a term to reduce the number of power changes. Finally, the third component intends to maintain the power over a certain threshold. Considering location and propagation conditions assumptions, the authors estimate the transition probabilities and use them for the system's training.

[127] proposes a Dynamic Channel Assignment (DCA) mechanism for DSRC. The authors propose a fully distributed approach based on Multi-Agent RL-based Cooperative DCA (RL-CDCA). The system considers each car as a mobile agent in the RL context. Each car uses two different RL models to manage the channel congestion in a complete VANET, one for the channel selection management (service channels) and the other for the backoff window management. The complete state for each node is represented by the number of Communication Node Pairs (CNPs) in each channel, the requirements of each application, and the backoff window in the previous timestep. As actions, each agent selects indexes for the channel and backoff window size to be used. A point to highlight in this work is the formulation of the reward. The authors propose using a collaborative reward to avoid greedy competition among vehicular nodes. In this approach, each node computes an independent reward based on the number of sent packets, correctly received packets (known from Acknowledgements packets), and the number of packets in the queue. This independent reward is exchanged among nodes to compute a collaborative reward as a weighted mean. Each node trains a DDQL system based on its interactions in the VANET and the use of this collaborative reward.

The work developed in [128] proposes an RL-based Exponential Backoff (RLEB) algorithm for safety broadcast management. The algorithm uses DCF parameters, such as the size of the congestion window, to adapt the beaconing procedure when using DSRC. The authors use Q-learning for policy learning in two setups, distributed and centralized. The distributed version of the algorithm uses DCF parameters, e.g., the size of the congestion window and the number of backoff times to define the node's state. In the centralized version, the same data is considered, but it is assumed that an RSU in the scenario possesses knowledge of every surrounding vehicle. This information makes it possible to include fairness criteria in the algorithm's formulation. The system's reward is related to the correct and incorrect transmissions and the communication delay.

[129] deals with the spectrum assignation problem in a vehicular scenario with the coexistence of V2V and V2I links. The considered scenario consists of a vehicular communication network based on a cellular setup. The authors assume that V2I links (through the Uu interface) are orthogonally preassigned. In the case of V2V, the nodes use the PC5 interface with the Mode 4 communication of C-V2X. The scenario setup considers that the V2V links can reuse the resources of the V2I links. The authors present a system based on Q-learning with fingerprint-based methods. The proposed scheme considers the interference between links and intends to maximize the V2I links' capacity while reducing the delivery time of V2V packets. The proposed approach also deals with these two objectives to improve spectrum efficiency.

This Chapter presented a revision of state of the art concerning VRU inclusion, heterogeneous approaches, and ML applications on vehicular networks. Based on this revision, we can identify different research gaps and common elements that can be used to develop new solutions to a diversity of challenges. Section 3.1 showed that there are research possibilities on beaconing mechanism design for VRUs. Also, there is a lack of study on different types of VRUs, since most works are focused on VRUs. Section 3.2 shows a need for VRU inclusion in heterogeneous networks. Also, the use of C-V2X as one of the used RATs appears as an interesting possibility. In terms of evaluating the systems, the awareness analysis remains incomplete. Section 3.3 showed the diversity of potential uses of ML and the potential of this technology to be used in HetVNETs. Considering these elements, we can identify this thesis's proposal's contribution to the current state of the art. The following section presents the details of this thesis contribution

Chapter 4

Proposed System

The present section introduces the design and development of the proposed decision system, named VRU Awareness-based Intelligent Beaconing System for Heterogeneous Networks (VARIATE). Section 4.1 details the system model of the proposal along with the assumptions made for its design. Section 4.2 introduces the complete description of the proposal, including the metrics used for its operation, those used for the evaluation of the proposed system, and the full explanation of the algorithm. Section 4.3 presents the details of the tested scenarios, the simulation setup, and the analyzed experiments.

4.1. System Model

The scenario used for the design and simulation of VARIATE considers three general categories of nodes. The first category encompasses cars that have communication capabilities to exchange messages with other vehicles and VRUs, as commonly considered in C-ITS. The designed scenario assumes the existence only of ordinary cars, neglecting the presence of cars with special requirements such as emergency vehicles (e.g., ambulances), school buses, and similar. Special vehicles may require different beaconing generation mechanisms, given their critical characteristics. In the second category, the scenario incorporates VRUs into its traffic network. The VRU safety improvement is the main subject of study in this thesis. In the case of the performed simulations, the scenario considers three types of VRUs: pedestrians, bicycles, and motorcycles. In the third category, the scenario includes an RSU. The purpose of this RSU is to gather information sent by other nodes and use it for the training of the system. The purpose of the RSU will be explained more in detail in the following sections.

In terms of communications, the proposed system model assumes that all groups of nodes have the same communications capabilities. In the proposed HetVNET, nodes have the necessary equipment to support DSRC and C-V2X radio access technologies. More specifically, nodes have both Multi-Link and Multi-RAT features, the same assumptions made in [84, 90, 119]. Multi-RAT nodes can communicate using different access technologies, in this specific case, DSRC and C-V2X. Multi-link nodes can communicate using multiple wireless links simultaneously. Considering both characteristics, nodes in the simulated scenario can communicate simultaneously using more than one RAT to transmit and receive messages. The purpose of the proposed system is to choose the RAT and beaconing rate to be used by each VRU.

In terms of using the proposed heterogeneous scheme, we differentiate between cars and VRUs. As the interest of this thesis is the study of the VRU newly-generated communication traffic, the vehicular transmissions are considered to be background traffic. For this purpose, the proposed system model assumes that cars send beacons through both RATs when studying the heterogeneous approaches (as assumed in [84]). In the case of VRUs, they operate by choosing between DSRC and C-V2X using VARIATE and the heterogeneous modes used as the baselines for the algorithm. The VARIATE decision system for VRUs will be described in the following section.

4.2. VARIATE

4.2.1. General Aspects

This section presents the algorithm employed by the VARIATE system. The algorithm takes inspiration from the set of rules proposed in [90]. In [90], the authors propose a set of Multi-RAT and Multi-Link load balance rules based on Packet Delivery Ratio (PDR) and CBR criteria. The technologies considered in [90] are DSRC operating at 5.9 GHz, DSRC operating at 700 MHz, WiFi operating at 5.6 GHz, WiFi operating at 2.4 GHz, and 'an OFDM-like technology operating in a TVWS band at 460 MHz.'

VARIATE controls two different parameters in the beaconing process. The first, as in [90], is the RAT employed, considering as options DSRC and C-V2X. The second parameter is the beaconing rate used by VRUs, which is critical for the awareness metric. VARIATE selects one of four beaconing rates, 1, 2, 5, and 10 Hz. Another aspect to consider is that only a variation of 'one step' is allowed in frequencies to avoid abrupt beaconing frequency variations. For example, if a VRU uses a transmission frequency of 1 Hz, the transition to 10 Hz is not allowed. In this case, only maintaining a frequency of 1 Hz or increasing it to 2 Hz are valid actions. In the execution stage, the algorithm uses only locally obtained information to select a RAT and beaconing rate. The use of only locally obtained information implies that the system is entirely decentralized and, hence, independent of the network coverage. The independency of network coverage is consistent with the use of C-V2X Mode 4 since we consider that the safety of VRU should not rely solely on a connection to network infrastructure. It has to be noted that only VRUs use the proposed algorithm, while cars are allowed to transmit using a fixed beaconing rate and one or two RAT, depending on the tested scenario.

4.2.2. Metrics

This section presents the metrics used to operate and evaluate the decision system. In terms of awareness, this thesis defines three metrics named Node Detection Probability (NDP), Risked VRU Detection Probability (RVDP), and Knowledge About Me (KAM). NDP and RVDP are only used for evaluation since their actual values are unknown in a decentralized system. We can separate the metrics that each VRU can compute in a decentralized fashion and those used exclusively for the decision system's evaluation. The following metrics are calculated in each VRU in a decentralized manner:

- **Latency:** This metric is measured as the time difference between the time of creating a beacon and its reception time in the receiver. According to the requirements OSEC01 and OSYS05 of the ETSI TS 103.300-2 [37], the document that defines the functional architecture and requirements, this value must be under 300 ms for VRU-related components and applications (e.g., collision avoidance).

- **Knowledge About Me (KAM):** This metric, computed locally by each VRU, is meant to estimate the level of awareness in the communication network independently. The real value of this metric is used only in the training phase of the algorithm, hence, considering that the 1-hop neighbors' tables are shared. To compute KAM, the VRU observes the information shared by its directly connected neighbors. Then, the VRU divides the number of beacons with tables containing its own ID over the total number of received beacons in a time window. An example of this computation is presented in Fig. 4.1. In the top sequence, VRUs 1 and 3 correctly receive the beacon from VRU 2, including it in their neighbors' table. In the interval between KAM computations, both VRUs send beacons to 2, containing the information of VRU 2 itself. In this case, the awareness is perfect, and KAM is 1. In the bottom case, node 3 does not receive the information from 2, so when node 2 receives the data from 3, its ID is not in the table. In this case, only one of the two received messages contains node 2's information; hence, KAM has a value of 0.5.

- **CBR of DSRC (CBR_{CV2X}):** The CBR in the DSRC RAT is measured as the percentage of time that the channel is sensed busy over the time between measurements of the CBR.

- **CBR of C-V2X (CBR_{DSRC}):** The case of the CBR for C-V2X is analogous to the DSRC one. In this case, the node measures the proportion of used resource blocks between measurements. The CBR for C-V2X is measured every 100 ms [40]. The CBR of DSRC is measured in the same window for consistency purposes.

- **Proportion of DSRC use:** The nodes compute the DSRC use proportion using the neighbors' table. It is computed as the number of nodes using DSRC over the total number of nodes in the table.

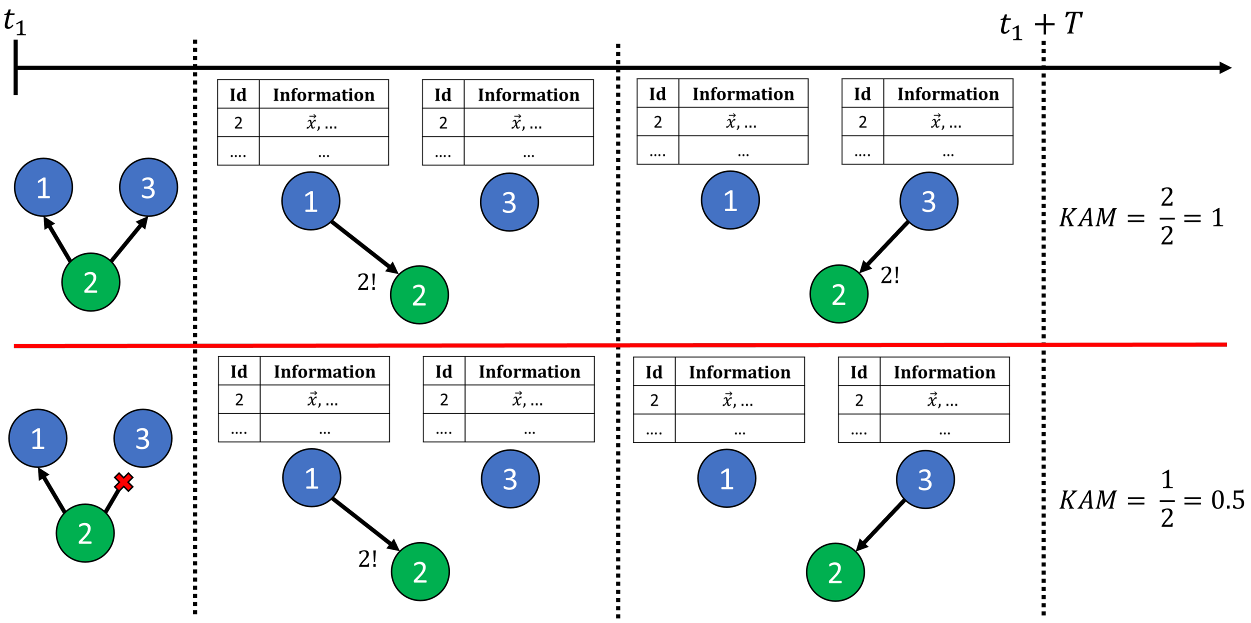


Figure 4.1: KAM computation example

This thesis defines two metrics to evaluate the actual values of awareness, named NDP and RVDP. The former studies the general node detection, while the latest computes specifically the VRU awareness. It has to be emphasized that both of these metrics are used only to evaluate the system since the actual number of neighbors may not be available in a realistic scenario. For evaluation purposes, this value is known from the setup of the tests. Both metrics are defined in the following:

- **Node Detection Probability (NDP):** The NDP is computed using the information of the neighbors' table and the knowledge of the node's absolute position. A circumference of 100 m around the node is considered to calculate this value. The circumference's radius is chosen based on previous studies on the safety of VRU, as [11] and [99]. Therefore, each node computes the NDP as the number of nodes (cars and VRUs) in its neighbors' table over the actual number of nodes in the circumference.
- **Risked VRU Detection Probability (RVDP):** The RVDP is similar to NDP with the difference that it considers the VRU awareness solely. The computation procedure is the same that the one used for NDP computation, but RVPD considers only the nodes of VRU type.

4.2.3. Algorithm

The algorithm is described in a modular way, where each module executes one or more of the tasks required to run the algorithm. We can also divide the algorithm into training and execution phases. In general terms, VRUs first run a centralized training, where the information exchanged by VRUs is gathered and processed by an RSU. Then, it operates in a decentralized or distributed manner, where each VRU makes a decision considering only its own information and information received from its neighbors. Note that each node (i.e., cars and VRUs) maintains information about its directly connected neighbors. We also assumed that nodes share the neighbors' table during the training stage.

Module A explains the general process of the algorithm execution, delivering a context for the execution of modules B, C, and D. In terms of the algorithm execution, modules B, C, and D are executed sequentially to select the RAT and beaconing rate. Module B describes the information sharing between the nodes in the simulation. Module C explains the sequence of steps performed by each VRU to compute the value associated with the selection of a pair of RAT j and beaconing rate k. Module D shows the selection of the combination based on the calculated value of a decision and the value of the current configuration used by the VRU. Module E explains the training of the KAM predictor and its most relevant features. A detailed explanation of each process is presented in the rest of this section.

A. Execution process

To decide when to run the VARIATE algorithm, we use a similar methodology to the one in [90]. The execution of the algorithm occurs every T seconds. T, in this case, is a uniformly distributed random variable. The range of T is the interval $[T_{update}, (n_{changes} + 1)T_{update}]$. In this interval, T_{update} is a design parameter, and $n_{changes}$ is the number of consecutive changes performed by a VRU. This formulation looks to avoid a high number of changes in beaconing rate or RAT.

Another aspect to mention is that VRUs include an *update flag* in their packets. Every time a VRU changes its RAT, it sets the flag to true. When a VRU receives a packet with this flag activated, it defers its updates for $T_{postpone}$, which is a design parameter.

Fig.4.2 illustrates the VARIATE operation. As seen from the diagram, a VRU uses a counter t that acts as a timer in order to manage the different time variables defined by the algorithm (e.g., T and $T_{postpone}$). If this timer surpasses the value of T, the VRU must execute the process of RAT and beaconing rate selection (modules C and D). After this selection, the VRU picks the variable T according to the algorithm and reinitializes the timer t. Also, according to the change in the previous configuration, the variable $n_{changes}$ is set. Based also on the configuration change, the VRU sets the update flag in the beacon. The diagram also shows the case of receiving a beacon with an update flag. In this case, the algorithm postpones the selection process by $T_{postpone}$ adding this amount to time T.

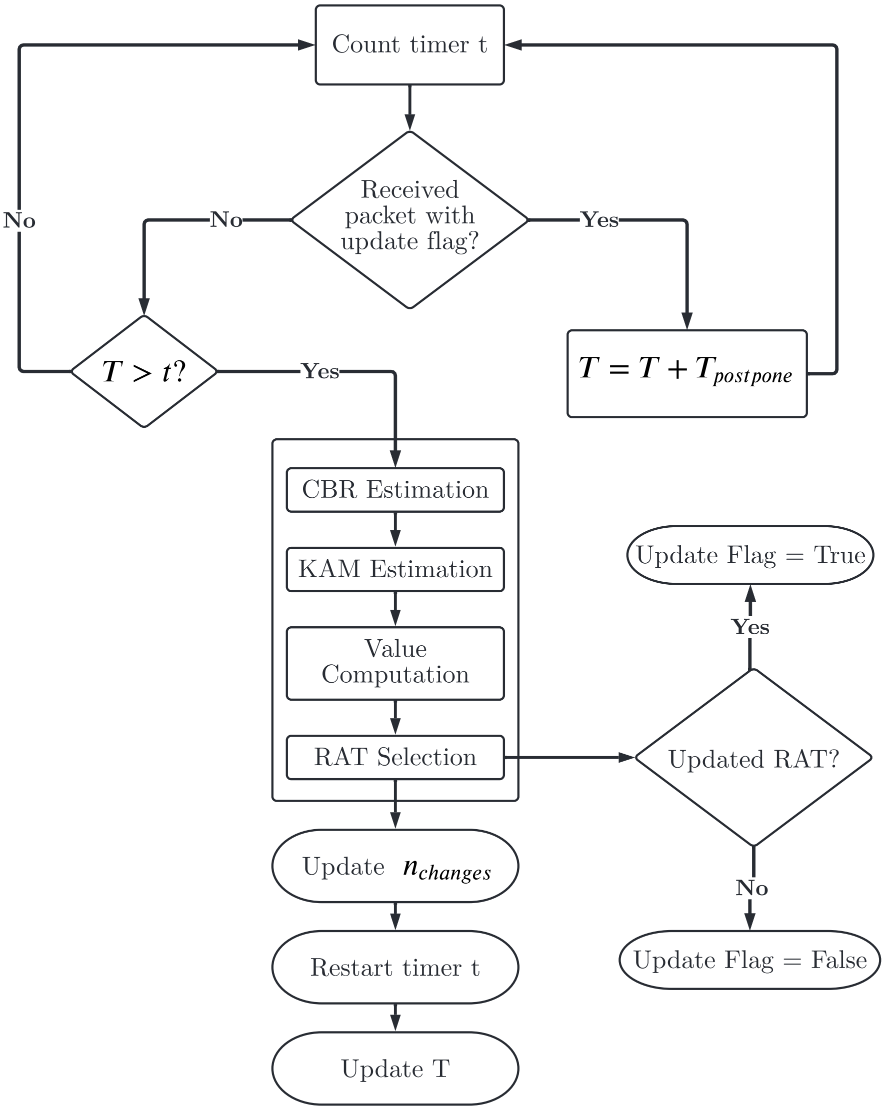


Figure 4.2: VARIATE state diagram

B. Information sharing and neighbors' table

Each node keeps a 1-hop neighbors' table to learn about the environment. This table contains information about directly connected neighbors. The table has the structure and includes the data presented in Table 4.1. Each node sends the following information to create and maintain the neighbors' table:

- Node Id
- Beacon creation time
- Node position coordinates.
- CBR_{CV2X}: Value of CBR measured in the C-V2X technology
- CBR_{DSRC}: Value of CBR measured in the DSRC technology
- Transmission period.

Table 4.1: Structure of the neighbors' table

Node Id	Beacon creation time	Position	CBR_{CV2X}	CBR_{DSRC}	Transmission Period	Used RAT
A						

C. Value estimation: Awareness and channel load

One of the primary purposes of VARIATE is to reduce the channel load without excessively compromising the awareness capabilities. With this purpose, we define a value function with channel load and awareness components. The estimation of the channel load uses the values of CBR measured for DSRC and C-V2X. In the case of the awareness capabilities, we take the value of KAM to estimate the proportion of nodes that know a given node's information.

C.1. CBR estimation

In the same manner that [90], each VRU computes the cost in terms of channel load as the maximum estimated CBR experienced among its neighbors. The estimated CBR is the value that a VRU estimates for its neighbors when it chooses the RAT j and beaconing rate k considering the current congestion information that the VRU stores in its table for each neighbor. To estimate the CBR perceived by each neighbor, we modify the approximation used in [90]. Along with considering the RAT change, the proposed estimation also accounts for modifying the transmission rate. The VRU estimation of the CBR for the neighbor (i) in the RAT j when the VRU picks the RAT j and beaconing rate k is given by (4.1)

$$L_{i,j,k} = LE_{i,j} + LG_{i,j,k}, \tag{4.1}$$

where $L_{i,j,k}$ is the estimation of the new CBR measured by the neighbor i when the combination *(j,k)* is selected by the VRU who is computing the estimation. $LE_{i,j}$ is the value of CBR registered in table for the neighbor i in the RAT j. $LG_{i,j,k}$ is the estimation for the increment in CBR measured by the neighbor i when the VRU picks the RAT j and the beaconing rate k. This estimation is given by (4.2) as follows

$$LG_{i,j,k} = k * t_j * PSR_j(d_i), \tag{4.2}$$

where t_j is the packet transmission time considering the RAT j, and $PSR_j(d_i)$ is the Packet Sensing Ratio for RAT j measured at a distance d_i, which is the distance between the VRU and the neighbor i. To compute the PSR, the pathloss and fading model Winner+ case B1 [135] is used, which is a common model in literature [90, 115, 136], simulation frameworks [40], and 3GPP specifications [137]. Then, CBR-related cost of picking the RAT j and transmission rate k is the maximum CBR estimated value among all the neighbors, given by (4.3)

$$c_{j,k} = max_i\{L_{i,j,k}\} \tag{4.3}$$

C.2. KAM estimation

To estimate KAM, each VRU uses a pre-trained regression neural network. After a process of feature selection and training, each VRU uses the following inputs to estimate the KAM value given a combination of RAT (j) and beaconing rate (k):

- Selected beaconing rate (k).
- Selected RAT (j).
- Mean estimated CBR measured in C-V2X when using RAT j and beacon rate k ($\bar{L}_{j,k}(CV2X)$).
- Mean estimated CBR measured in DSRC when using RAT j and beacon rate k ($\bar{L}_{j,k}(DSRC)$).
- Number of neighbors using DSRC (N_{DSRC}) and CV2X (N_{CV2X}).
- Estimated new proportion of DSRC when choosing RAT j ($prop_j(DSRC)$).

In the estimation of KAM, the number of neighbors is assumed to be the same since the selection of RAT and transmission period made by the VRU does not modify this variable. For the calculation of the new proportion of use of DSRC, the approximation is presented in (4.4) as follows

$$prop_j(DSRC) = \frac{N_{DSRC} + j}{N_{DSRC} + N_{CV2X} + 1} \tag{4.4}$$

in (4.4), j is zero for a C-V2X selection and one for a DSRC selection. N_{DSRC} and N_{DSRC} are obtained from the neighbors' table.

C.3. Value of a decision

Finally, we compute the total value associated with the choice of RAT j and the transmission rate k considering the components associated with channel load (CBR) and awareness (KAM). The expression of the value function for the pair (j, k) to maximize is presented in (4.5) as $\mathcal{V}_{j,k}$

$$\mathcal{V}_{j,k} = w_1 \widehat{KAM}_{j,k} - w_2 c_{j,k} \tag{4.5}$$

where $\widehat{KAM}_{j,k}$ is the estimated value of KAM when the tuple (j, k) is selected. In (4.5) weights w_1 and w_2 associated with the KAM and channel load component are normalized in the interval [0,1].The purpose of the proposed algorithm is to select the pair of RAT and beaconing rate that allows the VRU to maximize the value function.

D. RAT and frequency selection

To select the technology and transmission rate to be used, VRUs execute two computations. First, a VRU calculates the current value of the RAT-beaconing rate combination. The value ($\mathcal{V}^*$) is the value of maintaining the current RAT and beaconing rate during the next execution period. Considering the value previously calculated in step C.3, VRUs get the best value, $max_{j,k}\{\mathcal{V}_{j,k}\}$, computed as the maximum value of $\mathcal{V}_{j,k}$ among all the valid combinations of RAT and beaconing rate. Then, a VRU only changes its current configuration to the combination of RAT and transmission period given by $argmax_{j,k}\{\mathcal{V}_{j,k}\}$ if the difference between these two values is higher than a threshold α as shown in (4.6)

$$(max_{j,k}\{\mathcal{V}_{j,k}\} - \mathcal{V}^*) > \alpha \tag{4.6}$$

E. Training of the regression model

For the training of KAM regression, each VRU shares additional information. Specifically, the nodes share their 1-hop table, which their neighbors use to compute KAM. Nodes also share their KAM values to allow the RSU to train the regression. The sharing of the directly connected nodes is reasonable since already published works consider it an assumption. For example, in [138], the authors consider the sharing of maps for the construction of heat maps in pedestrians. The authors of [90] assume the sharing of the 1-hop neighboring table among cars.

Sharing the 1-hop neighbors' table is expected to improve the knowledge about the number of neighbors around a node. As studied in [139], the sharing of information of more than one hop can improve the estimation of the absolute number of nodes. However, the inclusion of the table and its constant distribution causes a significant amount of overhead in the network. This overhead is particularly substantial when a situation of high congestion is studied. For this reason, we consider the sharing of the neighbors' table only in the training stage of this algorithm.

Using the node's own information and the one received from its neighbors, each node can compute different indicators used to train the KAM regressor. Using extensive simulations, we created a dataset with 38,180 samples obtained by the RSU. Each sample contains different variables which, to improve the performance of the prediction, pass through a process of feature selection based on the mutual correlation between variables. Table 4.2 indicates the variables that compose the dataset, indicating the variables used for the regressor training and testing.

Table 4.2: Features of the created dataset

Variable	**Selected**
CBR value for the C-V2X RAT	×
CBR value for the DSRC RAT	×
Mean transmission period measured among neighbors	×
Mean CBR for the C-V2X RAT measured among neighbors	✓
Mean CBR for the DSRC RAT measured among neighbors	✓
Proportion of use of DSRC among neighbors	✓
Transmission period	✓
RAT selection (categorical variable)	✓
Number of neighbors	✓
Number of VRU neighbors	×

We consider using multiple sets of features for the regression and various machine learning tools. After evaluating Linear Regression, SVM, Naive Bayes, and different topologies of Neural Networks, the selected regressor was a neural network. The network topology consists of one hidden layer with Rectified Linear Unit (ReLU) activation function and an output layer with a linear activation function. The hidden layer includes one hundred neurons. The dataset is split into three subsets for the regression training: a training set containing 70 % of the samples, a validation set containing the 10% of the samples (used for early stopping), and a test set comprising 20 % of the samples. Table 4.3. presents the values of Mean Square Error (MSE), Root Mean Square Error (RMSE), and KAM.

Table 4.3: Training metrics summary

Test values	Mean KAM	0.9122
	Standard deviation	0.1647
Test predictions	Mean KAM	0.9139
	Standard deviation	0.1327
MSE		0.0092
RMSE		0.0522

Even though the KAM regressor may not need to be updated a priori, some factors could damage its accuracy. Considering the regressor training, a fact that could negatively affect its performance is a considerable change in the VRU and vehicles flow (e.g., due to substantial infrastructure changes). However, we also have to notice that the training stage considered different congestion scenarios since the beaconing rate of vehicles - a critical factor of the channel load - was modified to collect a more diverse dataset. If a system retraining is needed, the procedure would be the same as the initial training. Revisiting the procedure, it would be necessary that the network nodes resend their neighbor's table for a period of time. The use of the standard training of the system could lead to some safety issues since the nodes are required to send beacons to different transmission rates for the variance of the dataset. Accordingly, two alternatives are thought. The first includes the neighbor information using an additional channel to avoid experimentation in the safety messages channel. The second alternative would be using a simulation environment (as the one used in this thesis) for the regressor training. The modification of the street's topology and the node flow in the simulation makes it worthwhile to represent the nodes. As studied by [130], the use of simulation environments is seen as a promising tool for the training of ML models in the communications context.

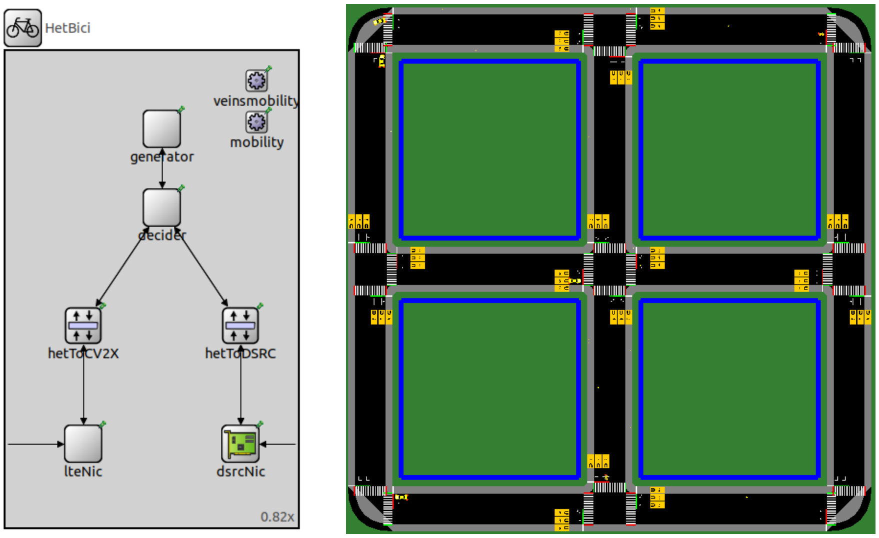
4.3. Simulation Setup and Experiments

This section gives a detailed explanation of the performed simulations. First, we describe the simulation setups, giving details about the physical scenario, the type of nodes, and the node density. Next, the different operation modes and experiments are described.

4.3.1. Description of the Scenario

The tested scenario (A) has the composition presented in Table 4.4. We assume that nodes have multi-RAT and multi-link characteristics. The simulated VRU structure is presented in Fig. 4.3 (a). The generator is the module in charge of the beacon generation. The decision block includes the intelligence of the system. This block can choose between only-DSRC mode, only-C-V2X mode, random RAT selection, CBR greedy RAT selection, or the VARIATE system, depending on the operation mode. In the case of cars, this can only be set only-DSRC mode, only-C-V2X, and both RAT modes with a fixed beaconing rate. Nodes (cars and VRUs) also have two adaptation layers that connect the generation of messages with their access technologies.

The physical scenario is a 200 m by 200 m typical Manhattan grid topology (Fig. 4.3 (b). The scenario's streets have two lanes per direction and share these lanes with cyclists and motorcyclists. Pedestrians have dedicated sidewalks. The traffic of pedestrians and vehicles is regulated by traffic lights as defined by the SUMO default intersections. The RSU is located at the intersection of the shown scenario.



(a) Heterogeneous node (b) Manhattan scenario

Figure 4.3: Heterogeneous node and environment

Table 4.4: Number of nodes in the scenario

	Node type				
Scenario	**Car**	**Pedestrian**	**Bicycles**	**Motorcycles**	**Total**
A	178	151	49	26	405

4.3.2. Experiments

Five operations modes are defined to be tested and compared. The differences among them are the type of technology or technologies they use. We defined the operation modes in the following manner:

- **CV2X:** The CV2X mode is a non-heterogeneous mode. In the simulations that use this mode, both cars and VRUs only use the C-V2X technology. The transmission frequency is fixed in this mode and does not change dynamically.
- **DSRC:** The DSRC mode is a non-heterogeneous mode. In the simulations that use this mode, both cars and VRUs only use the DSRC technology. The transmission frequency is fixed in this mode and does not change dynamically.
- **RANDOM:** The RANDOM mode is a baseline in the case of a heterogeneous operation. When operating in this mode, the VRUs select every T_{update} seconds, a random combination of RAT and transmission period. When the simulation operates in this mode, cars send beacons with a fixed frequency using both technologies.
- **GREEDY:** The GREEDY mode is another baseline of a heterogeneous operation. When operating in this mode, the VRUs select every T_{update} seconds the RAT that presents the lowest value of CBR. When the simulation operates in this mode, cars and VRU send beacons with a fixed frequency using both technologies.
- **VARIATE:** When the simulation is configured in the VARIATE mode, VRUs are effectively running the VARIATE algorithm presented in Section 4.2. When the simulation operates in this mode, cars send beacons with a fixed frequency using both technologies.

Table 4.5 described the parameters that are common for all the performed tests. The table is divided, giving details about the physical layer, the parameters configured in the generator-decider blocks, and the simulation itself.

Table 4.5: Simulation Parameters

Physical Layer	
Carrier frequency C-V2X	5.91 [GHz]
Carrier frequency DSRC	5.89 [GHz]
Fading type	Nakagami Fading
Pathloss model	WINNER+ B1 LoS (urban micro-cell)
Transmission power C-V2X	≈200 [mW]
Transmission power DSRC	20 [mW]
Obstacles	No
Generation Layer & Decision System	
Beacon size	200 [bytes]
Safety Range	100 [m]
T_{update}	1 [s]
$T_{postpone}$	0.2 [s]
Simulation	
Simulation time limit	320 [s]
Simulation start time	300 [s]
Warmup Time	10 [s]
Number of runs	5

We define three experiments to study the performance of the proposed system. In each experiment, we explore different congestion scenarios related to a specific beaconing rate used by cars and VRUs using a fixed transmission rate (CV2X, DSRC, and GREEDY modes). As previously described, VRUs operating in the C-V2X, DSRC, or GREEDY mode use a fixed beaconing rate. Considering this, we design four congestion scenarios named C_1, C_2, C_5, and C_{10}, where the sub-index represents the beaconing rate of the nodes using a fixed beaconing rate (e.g., when in C_5, cars and VRU in GREEDY mode use a beaconing rate of 5Hz).

The specific parameters used for each of the tests are presented in Table 4.6. Experiment **A** intends to analyze the use of only one technology in the tested conditions. Experiment **B** shows the comparison when using a heterogeneous network composed of C-V2X and DSRC. Three modes are compared. These modes are the GREEDY and RANDOM modes, previously defined, and the best VARIATE system, obtained from the testing of different parameters configurations. Experiment **C** shows a sensitivity analysis, testing various parameters of the VARIATE systems. These tests were used to get the best combination of parameters (among the tested configurations). The results obtained for each test will be presented and discussed in the next section.

Table 4.6: Description of the experiments

Experiment	**Expiration Time**	**Congestion Scenario**	**Tested Modes**
A	1 s	$\{C_1, C_2, C_5, C_{10}\}$	CV2X
			DSRC
B	1 s	$\{C_1, C_5, C_{10}\}$	RANDOM
			GREEDY
			VARIATE: $w = 8; \alpha = 0.1$
C	1 s	$\{C_1, C_5, C_{10}\}$	VARIATE: $w = \{0.5, 2, 8\}; \alpha = \{0.05, 0.1, 0.2\}$

Chapter 5

Results and Discussion

This chapter presents the results obtained from simulating the evaluation scenarios presented in Table 4.6. The tests proposed in the table allow us to evaluate the performance of the systems against different baselines and using a variety of configurations. Each test also allows us to analyze different evaluation metrics to evaluate the awareness, channel load, and latency. The purpose of each of the experiments described in Table 4.6 is described in Table 5.1.

Table 5.1: Description of the experiments

Experiment	Tested Modes	Variables	Expected Insights
A	CV2X, DSRC	Base beaconing rate	Comparison of non-heterogeneous approaches
B	CV2X, DSRC, VARIATE	Base beaconing rate	Comparison of the best configuration of VARIATE against heterogeneous baselines
C	VARIATE	Base beaconing rate, w, α	Sensitivity analysis of VARIATE. Variation of the weights relation (w) and transition threshold (α)

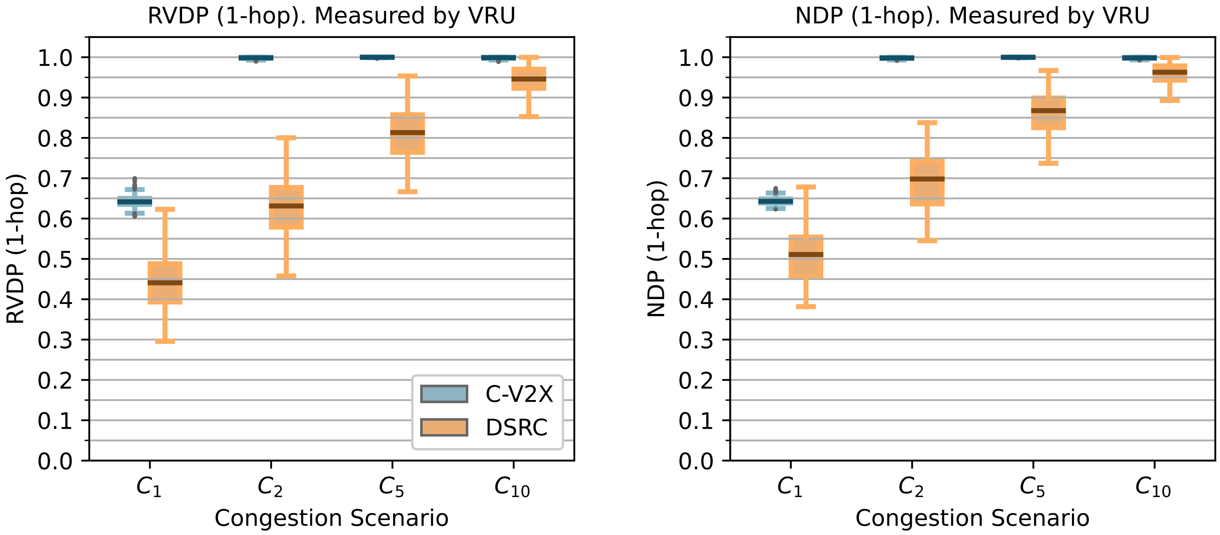
5.1. Experiment A: Non-heterogeneous approaches

The first experiment studies the performance of a non-heterogeneous network using only C-V2X or DSRC. In the tests, all nodes transmit using four different fixed beaconing rates, as described in Table 4.6.

In terms of awareness, Figs. 5.1 and 5.2 present the RVDP and NDP values as measured by VRUs and cars, respectively. Several observations arise from these results. Regarding the beaconing rate, we observe that awareness, both in terms of VRU detection (RVDP) and general node detection (NDP), highly depends on the beaconing frequency. Analyzing the RVDP of C-V2X technology for VRUs (Fig. 5.1 a.), we observe an increase of 55.42%

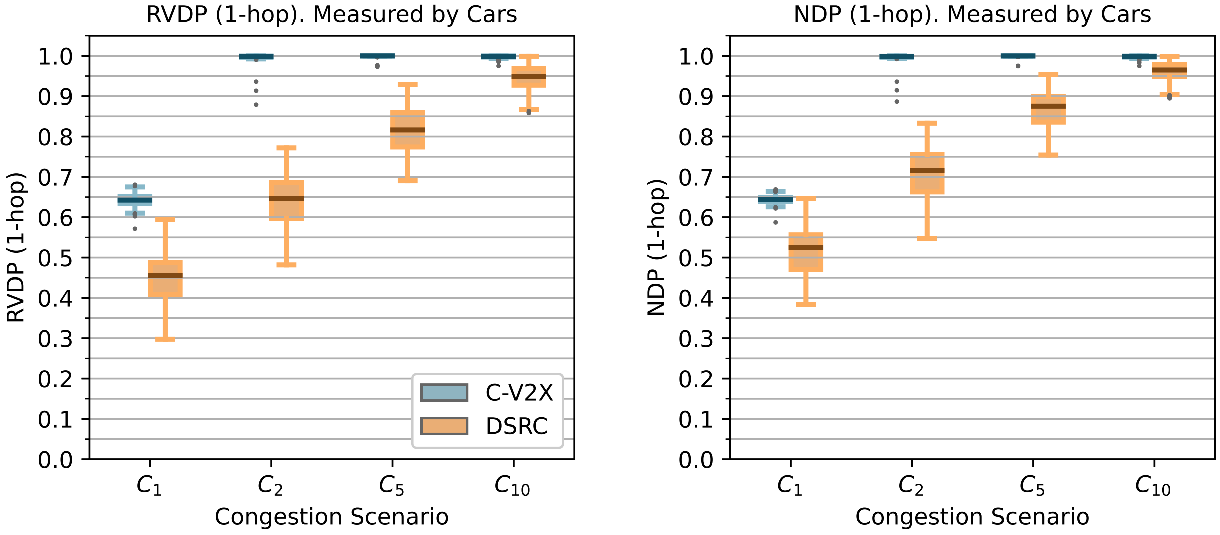
in the median when comparing the 1 Hz (C_1) and 10 Hz (C_{10}) beaconing rates. In the case of DSRC, the increase for the same cases is 114.56%. The expiration time of the neighbors' table explains this difference as nodes keep their neighbors in the table for 1 second. Increasing the beaconing frequency increases the probability of receiving at least one message per second. When the transmission frequency is comparable to the expiration time, the awareness capabilities are reduced drastically.

Concerning the used RAT, we observe that the awareness capabilities when using C-V2X are always better than those presented by DSRC. This difference is significantly higher when considering the 2 Hz transmission rate (C_2), with a difference of 58.18% in the median with respect to the DSRC technology (Fig. 5.1 a.). The variation is shorter when nodes use a beaconing rate of 10 Hz (C_{10}), with an increase of 5.59% in the median — always been better for the C-V2X technology (Fig. 5.1 a.). Another remarkable change when considering the technology difference is the variance presented in the metrics. For the case of DSRC, we observe that the variance is higher than in the case of C-V2X; this causes some of the simulation nodes to present a considerably worse awareness capability than others.



(a) RVDP (b) NDP

Figure 5.1: Awareness metrics measured by VRUs in a single-RAT scenario

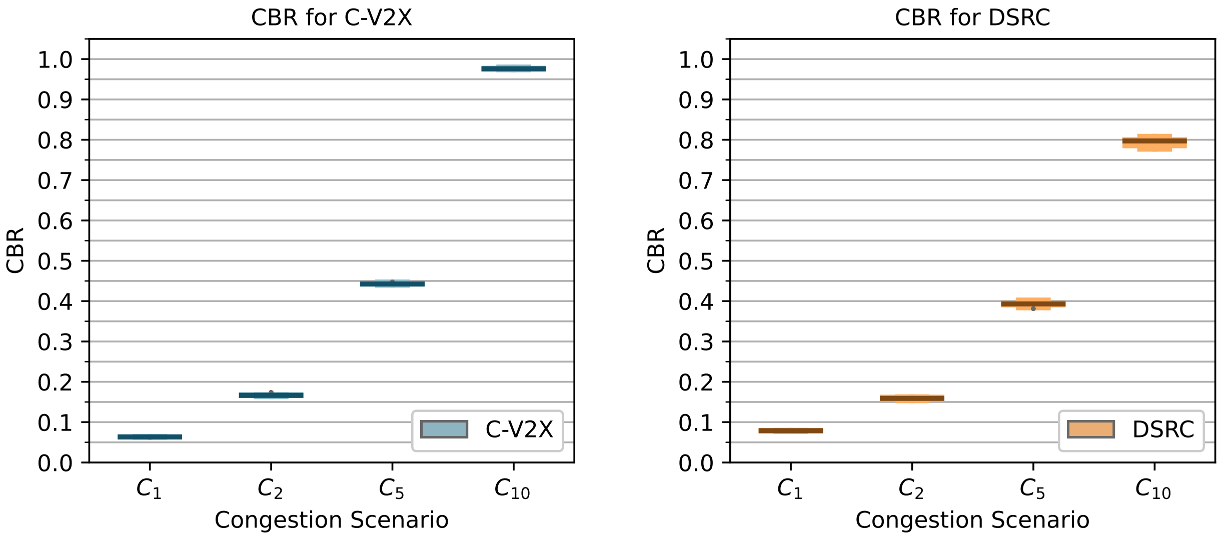


(a) RVDP

(b) NDP

Figure 5.2: Awareness metrics measured by cars in a single-RAT scenario

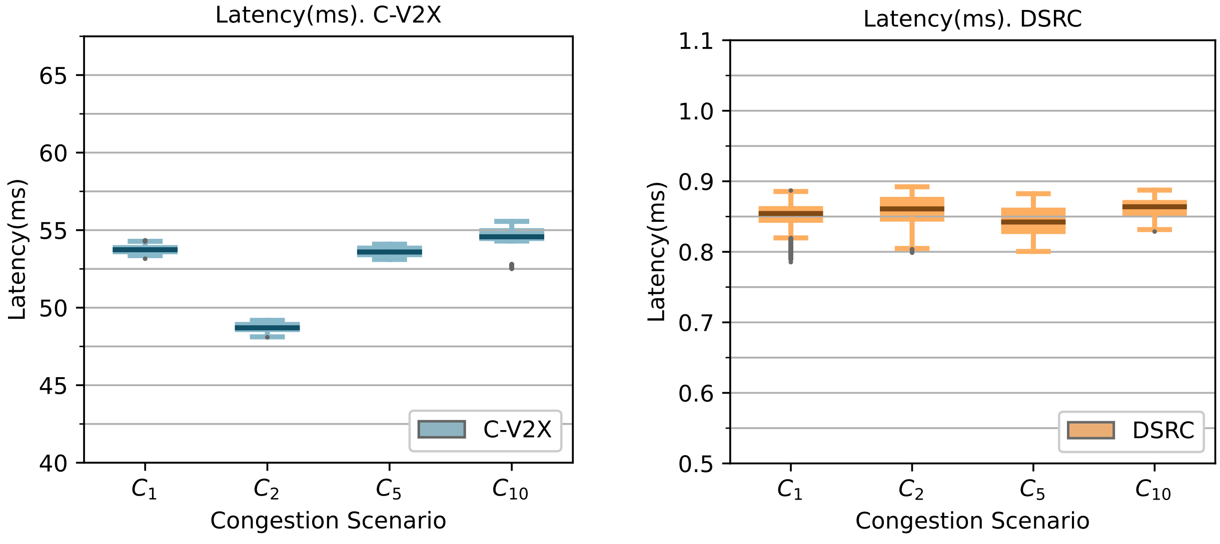
In terms of the CBR, the behavior can be analyzed from different perspectives. Regarding the beaconing frequency, the CBR increases closer to a quadratic fashion with respect to the congestion scenario. The values of CBR for the C-V2X technology are higher than those presented by the DSRC technology except in the 1 Hz frequency, where the difference is not significant. This difference is higher at higher frequencies with a difference of 22.44% with respect to the DSRC values in the 10 Hz beaconing frequency (C_{10}). The value of the CBR of C-V2X for the 10 Hz frequency (C_{10}) is approximately 0.98, which can be problematic in terms of channel load, considering that the recommended values for CBR are around 0.6 [126].



(a) C-V2X (b) DSRC

Figure 5.3: CBR measured by VRUs in a single-RAT scenario

In the case of the latency, we observe that the values presented by the DSRC technology are almost two orders of magnitude lower than the latency showed by C-V2X. Nevertheless, both technologies accomplish the requirements stated by the ETSI TS 103.300-2 [37] of 300 ms in the application layer level. The flexibility of the DSRC access mechanism compared to the most structured mechanism used in C-V2X could explain the latency reduction [72].



(a) C-V2X (b) DSRC

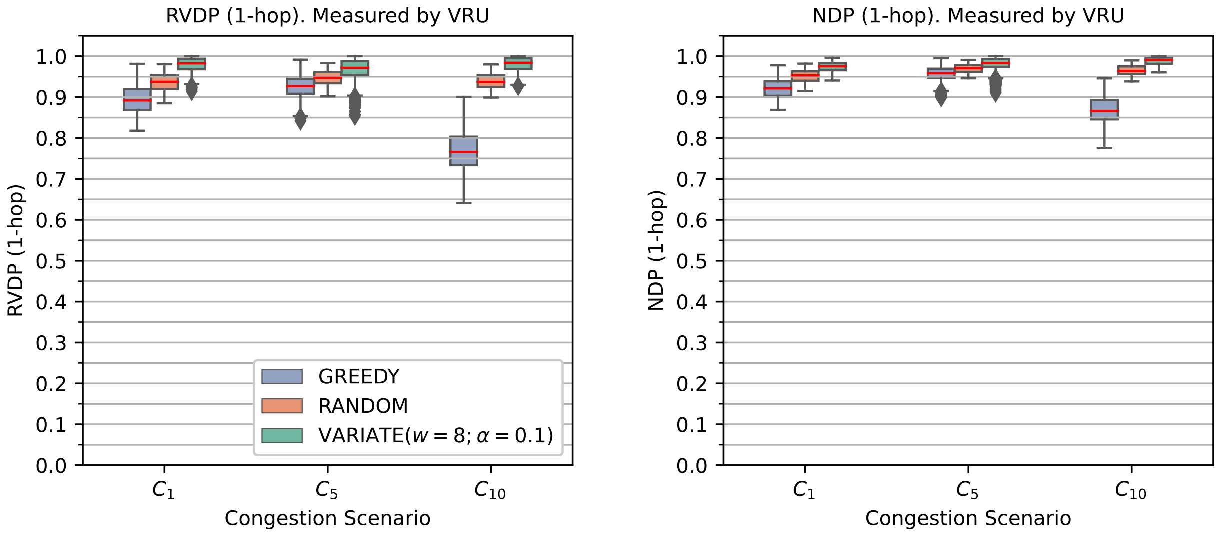
Figure 5.4: Latency (ms) measured by VRUs in a single-RAT scenario

In general terms, the only-C-V2X and only-DSRC modes present a high CBR level in the scenarios of high beaconing rate. Nevertheless, the awareness values are increased when using shorter transmission periods. The CBR values can be problematic when using a high beaconing rate since they overpass the most commonly suggested values. The latency of each technology satisfies the ETSI requirements.

5.2. Experiment B: VARIATE comparison

The second experiment shows the comparison among different heterogeneous modes. We consider two baseline configurations named GREEDY and RANDOM. These modes differ in how they update the RAT and beaconing period every update period. The GREEDY mode uses a fixed beaconing rate and selects the RAT according to greedy CBR criteria, i.e., choosing the RAT that has the lower CBR. In the case of RANDOM, each vehicle picks a random beaconing rate and RAT to use during the update period. This section presents the comparison between these modes and the best-evaluated VARIATE system. The best VARIATE algorithm uses a reason of *8:1* (denoted by $w = 8$) for the KAM and CBR weights, respectively. The algorithm also uses a value of 0.2 for the threshold α. The choice of these values is justified in section 5.3.

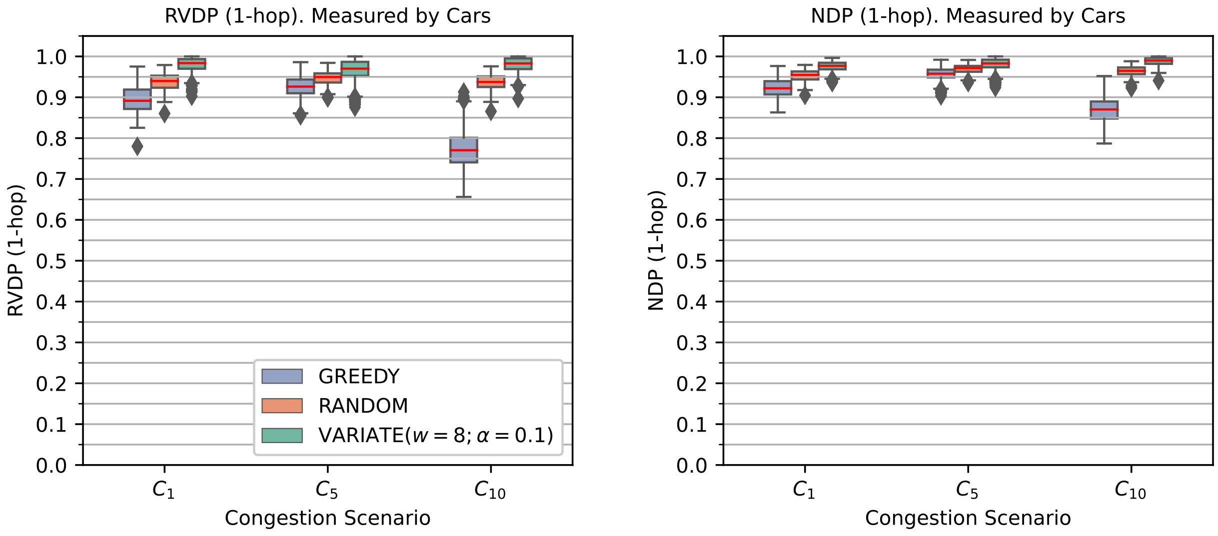
In terms of awareness, Figs. 5.5 and 5.6 present the results for the RVDP and NDP measured by VRUs and cars, respectively. We observe that the values of RVDP and NDP are higher for VARIATE than those presented by the baselines heterogeneous modes in all tested scenarios. Both for RVDP and NDP, the worst performance is presented by the GREEDY mode. The difference in the awareness metrics' values is higher for the most congested scenario C_{10}, where GREEDY VRUs and cars use a 10 Hz beaconing rate. Here, we present a brief synthesis of the differences when considering the car recorded RVDP (Fig. 5.6 a.). The decision to get more into the details of these results is the danger vehicles represent to VRUs compared to the accidents between members of the same group. Considering Fig. 5.6, in the case of the C_1 scenario, VARIATE improves the median RVDP by a 10.36% with respect to the GREEDY and 4.67% with respect to RANDOM. In the case of the C_{10} scenario, VARIATE improves the median RVDP by 27.58% with respect to the GREEDY and 4.85% with respect to the RANDOM. In terms of quartiles, we observe that the 25% of the lowest samples using VARIATE surpasses the 75% of the samples obtained from using the RANDOM mode for most of the cases presented in Fig. 5.5 and Fig. 5.6. This fact shows an improvement in terms of general awareness.



(a) RVDP

(b) NDP

Figure 5.5: Awareness metrics measured by VRUs when using heterogeneous modes



(a) RVDP

(b) NDP

Figure 5.6: Awareness metrics measured by cars when using heterogeneous modes

Regarding the GREEDY mode, we observe that, unlike the previous results for the non-heterogeneous mode (Fig. 5.1 and 5.2), the performance worsens with the frequency increment above 5 Hz. In the cases of RANDOM and VARIATE modes, we observe that the behavior for the scenario is the same presented in the non-heterogeneous modes. It is worth reminding that the GREEDY mode uses a fixed transmission rate, the same as the vehicles, while the RANDOM and VARIATE modes select this frequency dynamically. The tendency of picking DSRC over C-V2X for most of the cases can explain this behavioral difference, as shown in Fig. 5.8.

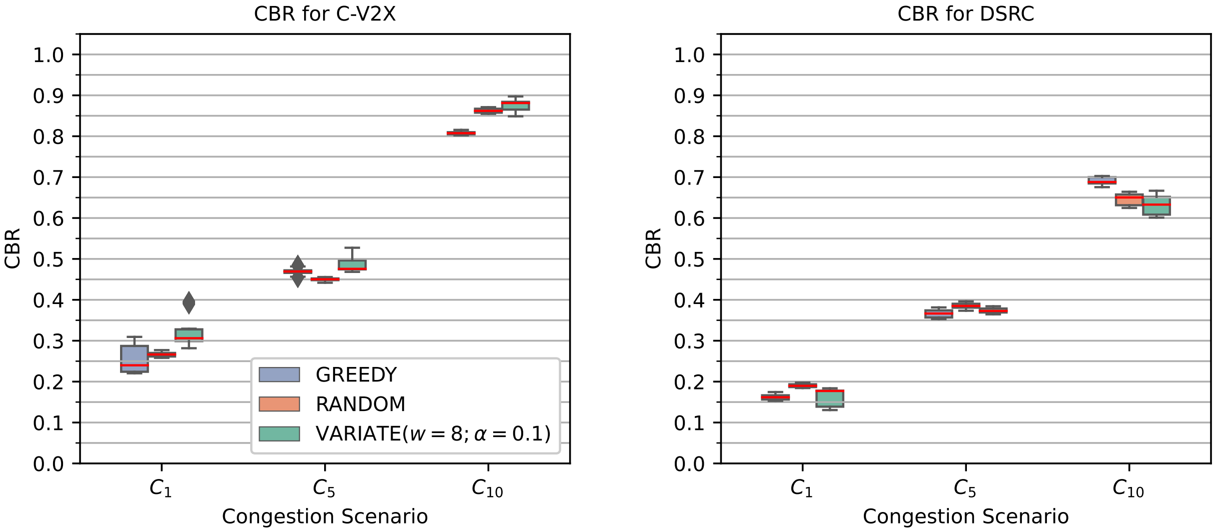
From the NDP results presented in Fig. 5.1 b) and 5.2 b), we can observe that the general knowledge about nodes is slightly higher than the one presented when we consider only the VRU awareness (Fig. 5.1 a) and 5.2 a)). This behavior can be explained considering that cars send messages through both technologies, increasing the probability of receiving messages from these nodes. Nevertheless, both the NDP and RVDP follow the same tendency.

The gains of RVDP are crucial for pedestrians' safety since they directly represent the ability to detect neighboring VRUs. In this regard, the proposed VARIATE algorithm improves the knowledge about VRUs compared to other heterogeneous techniques without a high complexity algorithm, as presented before. As a complement to the analysis made from Fig. 5.6 (a), Table 5.2 presents the variations in the RVDP values of VARIATE against both heterogeneous baselines.

Table 5.2: Percentual RVDP variation with respect to baselines

	C_1 (%)	C_5 (%)	C_{10} (%)
GREEDY	10.36	2.63	27.58
RANDOM	4.67	1.18	4.85

In terms of CBR, Fig. 5.7 shows the CBR values measured in both tested RATs. When comparing the results, we observe comparable values of CBR for RANDOM and VARIATE for the DSRC CBR (Fig. 5.7 b)) among all frequency scenarios. In the case of the C-V2X technology, there are more considerable differences in CBR, particularly for the scenarios C_1 and C_5. In the first one, VARIATE presents an increment of 14.85 % with respect to RANDOM, while the increment is 5.62% in the C_5 scenario. The C_10 scenario shows a reduction in the DSRC CBR when using VARIATE, a result that is consistent with the DSRC proportion observed in Fig. 5.8 (a). As a complement to the results observed in Fig. 5.7 Table 5.3 shows the percentual variation of the C-V2X and DSRC CBR values compared to each of the baselines.



(a) C-V2X

(b) DSRC

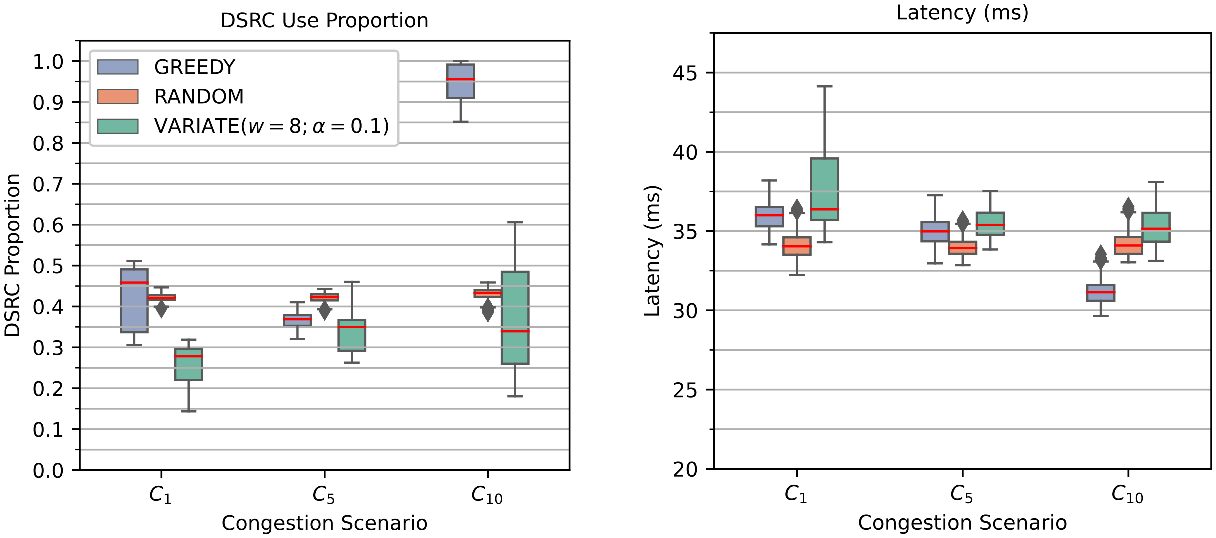
Figure 5.7: CBR measured by VRUs when using heterogeneous modes

Table 5.3: Percentual CBR variations with respect to baselines

	CV2X CBR			**DSRC CBR**		
	C_1 (%)	C_5 (%)	C_{10} (%)	C_1 (%)	C_5 (%)	C_{10} (%)
GREEDY	27.45	1.34	9.38	27.44	1.34	-8.02
RANDOM	14.84	5.64	2.29	14.84	5.64	-2.68

Fig. 5.8 presents the results obtained for the proportion of DSRC use and latency, respectively. In terms of DSRC use, RANDOM shows the expected behavior, with a median near 0.5 independently of the scenario. This is the expected behavior as the mode selects the technology in a uniform random way. GREEDY presents the highest variations compared to the other approaches. In lower congestion scenarios, such as C_1 and C_5, the technology selection is distributed between DSRC and C-V2X; however, when increasing the congestion to the C_{10} scenario, the majority of nodes tend to choose DSRC. Fig. 5.3 explains this behavior since we can observe that the CBR values of DSRC are lower than the ones presented by C-V2X, especially in the high traffic scenarios. In the case of VARIATE, Fig. 5.8 (a) shows that the proportion of DSRC usage is smaller compared to the other two heterogeneous modes.

In terms of latency, the results presented in Fig. 5.8 show the expected behavior. As observed, the higher the use of DSRC, the lower the latency, and vice-versa. These results are coherent with the previously observed behavior of the latency presented in Fig.5.4.



(a) Proportion of DSRC use (b) Latency (ms)

Figure 5.8: DSRC use and latency (ms)

Fig.5.9, shows the distribution of the selected beaconing period. As observed in the figure, the median data rate of the RANDOM mode is approximately the same for the different scenarios; this is because the mode does not consider environmental variables in its functioning. In the case of the VARIATE algorithm, we observe that the tendency is to choose the transmission period of 0.2 s (5 Hz) in the majority of the cases. As we observed from previous results, this beaconing period showed a high level of awareness without causing high levels of CBR, as in the case of the 0.1 s period.

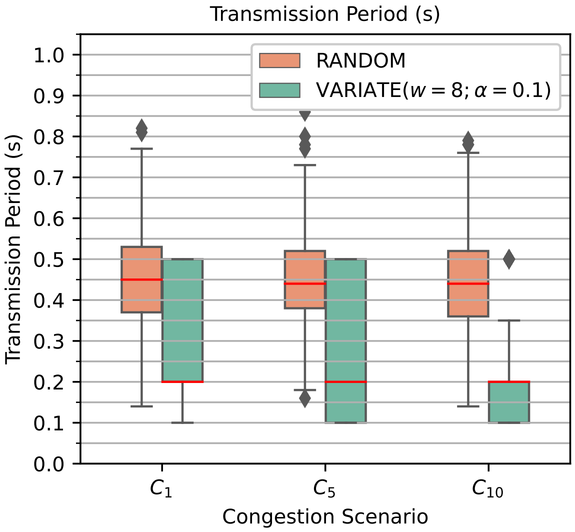
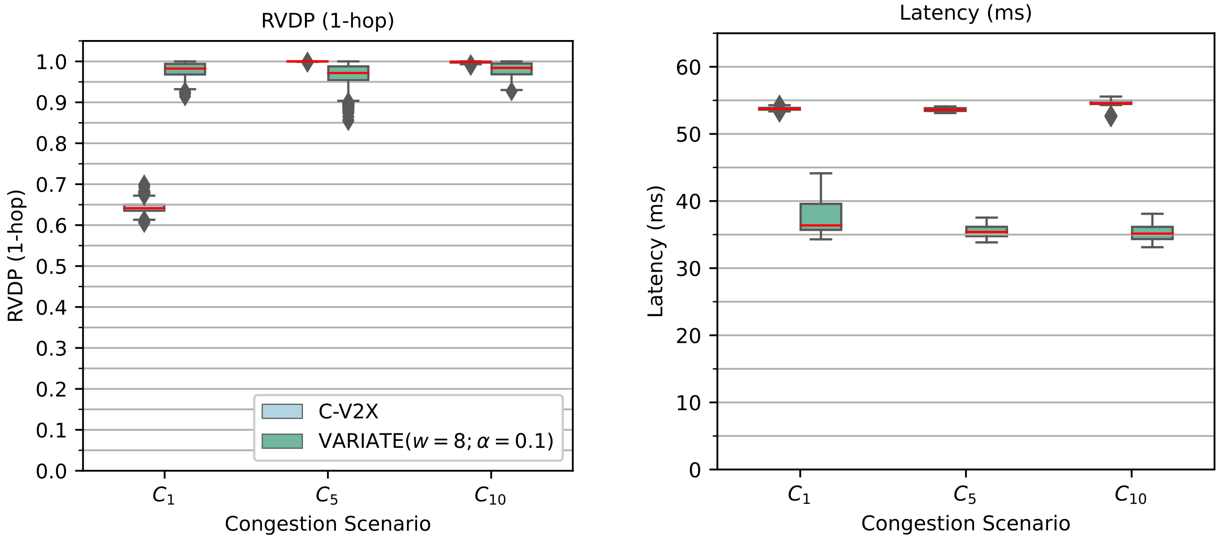


Figure 5.9: Instant beaconing period

To compare the performance of the proposed VARIATE algorithm against the best non-heterogeneous approach (i.e., C-V2X), we compare both the RVDP and latency. We consider these two metrics since they are independent of the subjacent RAT as they are directly measured on the reception side. In terms of RVDP, analyzing Fig. 5.10 (a), we observe that the awareness is comparable for the highest congestion scenario (C_{10}). In the C_5 scenario, VARIATE cannot outperform the use of only C-V2X; there is an RVDP reduction of 1.48 % with respect to the only C-V2X mode. In the scenario C_1, where both cars and VRUs use a beacon rate of 1 Hz in the C-V2X mode, the VARIATE algorithm can outperform the non-heterogeneous approach considerably by a 53.16%. This behavior can be explained because of the dynamic control of the transmission rate made by VARIATE. In this sense, the proposed algorithm can adapt the rate to the context in an autonomous manner, improving the performance for this low-rate scenario.

When comparing the performance in terms of latency, we observe a reduction between 32% and 35.5% compared to the C-V2X-only mode. This latency reduction while maintaining a comparable level of awareness could be particularly beneficial for safety purposes, improving the support of applications with more stringent requirements of information freshness. The detail of the latency reduction of VARIATE compared to C-V2X is shown in Table 5.4.



(a) RVDP

(b) Latency

Figure 5.10: RVDP and Latency for VARIATE and C-V2X

Table 5.4: Percentual Latency variations with respect to C-V2X

C_1 (%)	C_5 (%)	C_{10} (%)
-32.32	-33.96	-35.59

5.3. Experiment C: VARIATE sensitivity analysis.

Experiment C shows a sensitivity analysis of the VARIATE system, varying the hyper-parameters of the proposed algorithm. The input parameters of the VARIATE algorithm are the weights associated with CBR and KAM and the threshold for configuration changes

(α). This section explores the variation of both parameters and studies the metrics of interest. This study justifies the election of the combination of parameters tested as the best VARIATE configuration in Section 5.2.

Figs. 5.11, 5.12, 5.13, show the results obtained for the RVDP metric when testing the congestion scenarios C_1, C_5, and C_{10}, respectively. Studying the median value and the distribution of RVDP values, we observe that the combination of $\alpha = 0.1$ and a weight relation of 8:1 (i.e., $w = 8$) presents the best performance. Considering the results for the C_5 congestion scenario, we observe that the median value of the combination $w = 8, \alpha = 0.05$ is higher than the one presented by the combination $w = 8, \alpha = 0.1$; however, studing the values distribution we observe a smaller variance and a higher 25% percentile.

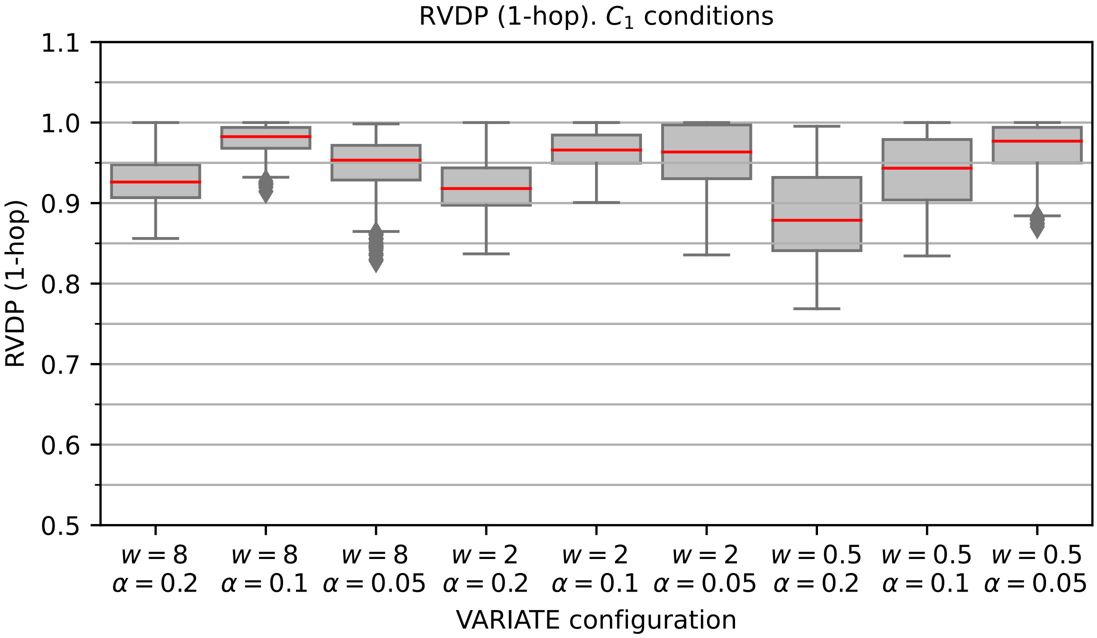


Figure 5.11: RVDP C_1 scenario

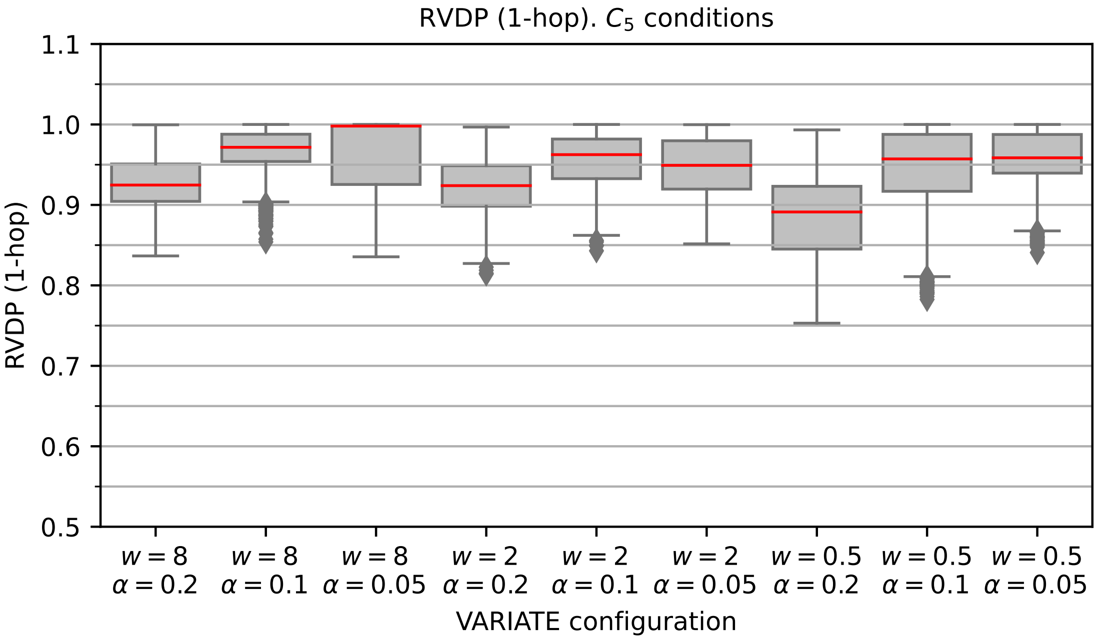


Figure 5.12: RVDP C_5 scenario

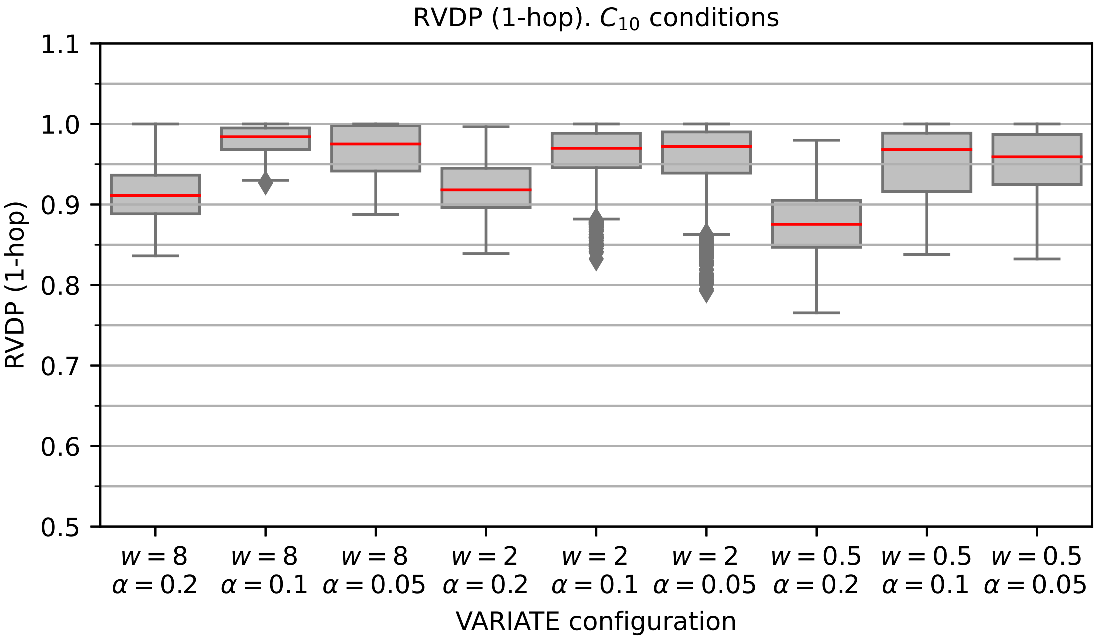


Figure 5.13: RVDP C_{10} scenario

In terms of channel load, Figs. 5.14 and 5.15 present the results for the CBR values of the C-V2X and DSRC RAT, respectively when studying the C_{10} congestion scenario. Both figures show the results for this scenario because it is the most critical scenario in terms of CBR, as shown in Sections 5.1 and 5.2. As we observe here, the performance in terms of channel load is comparable among the configurations.

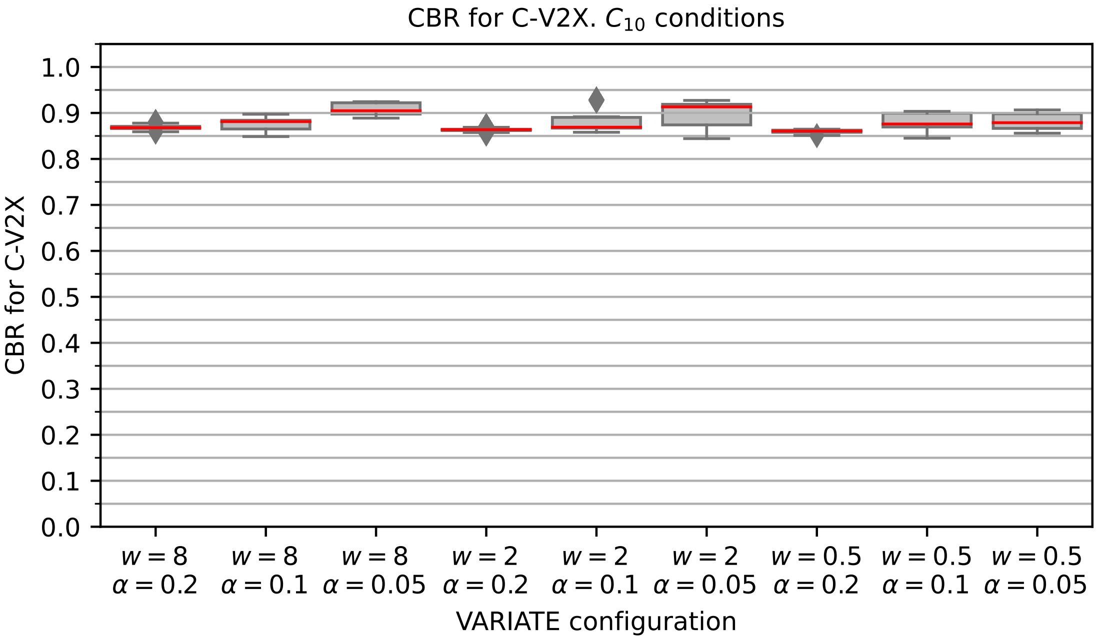


Figure 5.14: CBR for C-V2X RAT. C_{10} scenario

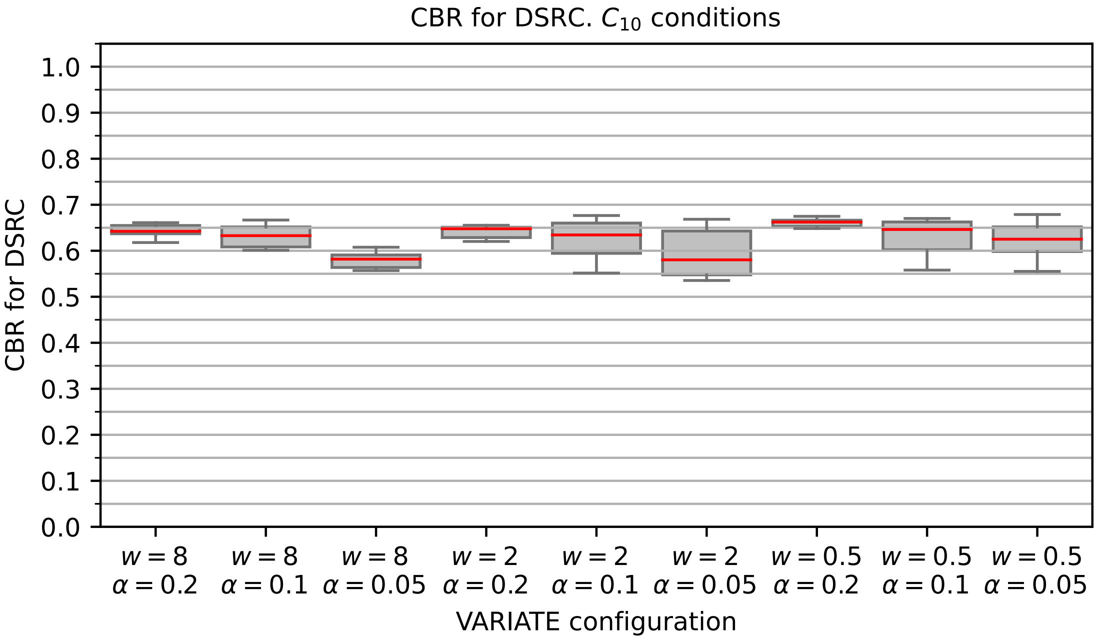


Figure 5.15: CBR for DSRC RAT. C_{10} scenario

For the latency performance, the combination $w = 8; \alpha = 0.1$ presents a median latency value higher that the mean among the configurations. Another configurations that exhibit larger values of latency are ($w = 2; \alpha = 0.1$) and ($w = 2; \alpha = 0.05$), showing also a higher variance. Despite this fact, all values are concetrated between 35 ms and 40 ms, following the ETSI requirement of 300 ms [37].

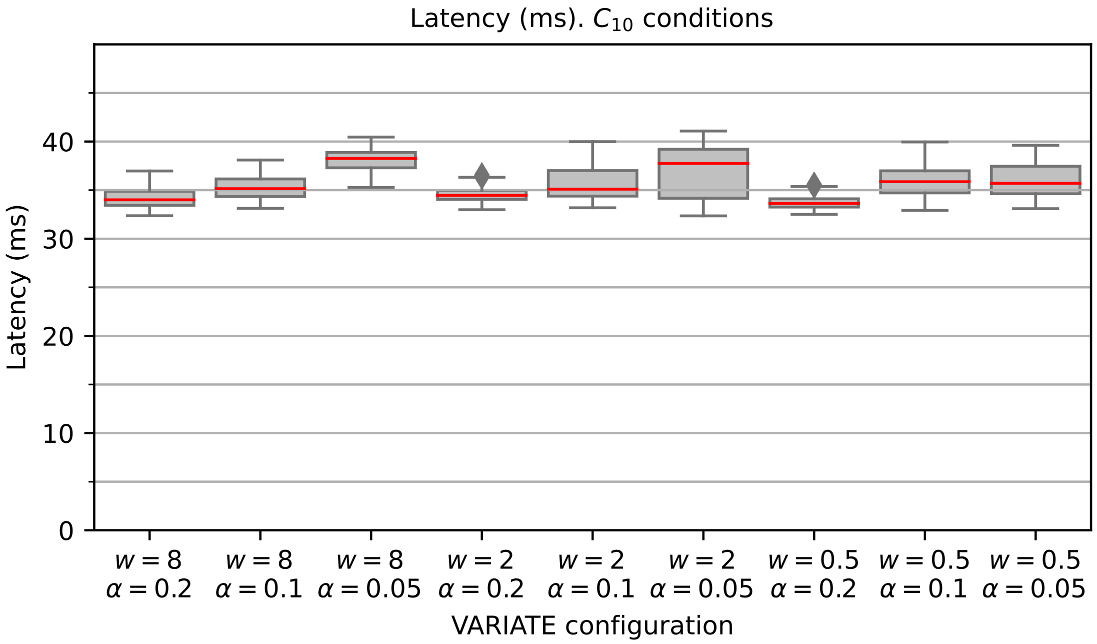


Figure 5.16: Instant beaconing period

Chapter 6

Conclusion

This thesis proposes a VRU beaconing system named VRU Awareness-based Intelligent Beaconing System for Heterogeneous Networks (VARIATE). The system integrates DSRC and C-V2X to deal with the channel congestion while using awareness prediction techniques to avoid severely sacrificing VRU awareness. VARIATE uses the awareness estimator, KAM, and the CBR to manage the beaconing frequency and RAT in a decentralized manner.

We performed extensive simulations to test the proposed system against different benchmarks. Compared to the heterogeneous baselines, the best configuration of VARIATE improves the VRU awareness for all beaconing rates. The DSRC channel is decompressed thanks to C-V2X transmissions in terms of CBR. The latency reduction is the most relevant difference with the C-V2X-only mode. The communication latency can be reduced to up to a 35% when using VARIATE compared to the C-V2X-only mode.

From the results, we observed the following relations to the hypotheses proposed in Section 1.3: VARIATE improves the performance in terms of awareness compared to the other heterogeneous modes and the DSRC-only mode; however, this improvement is around 4.85 % in the best case, less than the hypothesized 10%. In terms of latency, VARIATE outperforms the heterogeneous baselines and C-V2X-only mode, satisfying ETSI's latency requirements. In terms of awareness, the system maintains RVDP and NDP values over 70%.

Finally, we consider the following points as future work: (1) To prioritize VRU awareness according to contextual variables such as the position of VRUs on the street, their heading, or others. This line of research is based on the fact that some VRUs may be in a higher level of danger than others. This prioritization left out of the scope of this thesis could be a helpful variable in congestion reduction. (2) To study the information freshness, which may be relevant in VRU applications. Information freshness can be studied as an additional metric to the evaluation made in this thesis. Requirements of information freshness and its fulfillment should be studied. (3) To perform a deep study of beaconing control in a C-V2X-only mode. A more extensive simulation study and potential improvements to the access mechanism of C-V2X could be carried out. The study of C-V2X is even more relevant with the new developments associated with Releases 16 and 17 of 3GPP. (4) To apply additional techniques, such as clustering formation using ML, to improve the performance of heterogeneous or non-heterogeneous networks. The study should be performed based on awareness and channel load. ETSI guidelines on VRU clustering formation can be explored.

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Annexed

The following scientific works were published during the development of this thesis:

- T. Lara, A. Yáñez, S. Céspedes, and A. S. Hafid, “Impact of safety message generation rules on the awareness of vulnerable road users,” *Sensors*, vol. 21, no. 10, p. 3375, 2021.
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