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Radio Resource Allocation in C-V2X: From LTE-V2X to 5G -V2X

Sehla Khabaz

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Sehla KHABAZ

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Radio Resource Allocation in C-V2X: From LTE-V2X to 5G-V2X

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devant le jury composé de :

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Abstract

Vehicular networks have attracted a lot of research attention in the last decades. The main goal of vehicular communication is to ensure road safety by enabling the periodic communications between vehicles and between vehicles and other participants, such as roadside units.

Cellular-Vehicle-to-Everything (C-V2X) is a leading technology for vehicular networks. LTE-V2X is the first C-V2X technology, followed by 5G-V2X, and in both, resource allocation mechanisms play an important role in their performance. The resource allocation algorithms proposed in C-V2X must meet the requirements of V2X applications.

Certainly, the safety-related applications are the most critical and time-constrained V2X applications. For this reason, in the first part of this thesis, we propose a clustering-based resource allocation algorithm for safety V2V communications, the Maximum Inter-Centroids Reuse Distance (MIRD), which aims to improve the reliability of safety V2V communications.

In the second part of this thesis, we address resource allocation in 5G-V2X technology. Before performing resource allocation in 5G-V2X, we first consider the flexibility of the NR frame structure of 5G by focusing our interest on the 5G numerology concept. Therefore, we first investigate the impact of 5G numerologies on V2X application performance. Through simulations, we showed that choosing the appropriate numerology is a trade-off between V2X applications requirements, Inter-Carrier Interference (ICI) and Inter-Symbol Interference (ISI).

Next, we propose a new resource allocation algorithm, namely the Priority and Satisfaction-based Resource Allocation in Mixed Numerology (PSRA-MN). In the PSRA-MN algorithm, we first select the appropriate numerology considering the channel conditions and the vehicle speed. Then, we apply a prioritization policy in favor of the safety-related traffic to ensure the required resources for the safety-related traffic, and the remaining resources after the safety allocation are optimally allocated to the non-safety vehicles so that the average satisfaction rate is maximized. The proposed PSRA-MN algorithm is validated by simulations. The obtained results show that PSRA-MN outperforms the traditional resource allocation algorithms in terms of average allocation rate, average satisfaction rate and average delay.

Keywords— C-V2X, Resource Allocation, Vehicular Applications

Résumé

Les réseaux véhiculaires ont connu un vrai progrès technologique dans le domaine de la recherche scientifique au cours des dernières décennies. L'intégration des technologies de communications sans fil dans le domaine du transport a abouti à l'émergence d'un nouveau paradigme, à savoir les communications Vehicle-to-Everything (V2X). Ce dernier signifie les communications entre véhicules et tout autre objet. L'objectif primordial des communications véhiculaires, est d'assurer la sécurité routière à travers l'échange des messages périodiques entre les véhicules et entre les véhicules et d'autres participants, tels que les unités de bord de route ou les piétons.

La technologie C-V2X (Cellular-Vehicle-to-Everything) est une technologie émergente pour les réseaux véhiculaires standardisée par la 3GPP, dans laquelle les communications véhiculaires se basent sur les réseaux cellulaires. Le LTE-V2X est la première technologie C-V2X, suivie par la 5G-V2X. Les mécanismes d'allocation des ressources jouent un rôle important dans les performances des communications V2X. Pour cette raison, les algorithmes d'allocation des ressources proposés pour la technologie C-V2X doivent fortement répondre aux exigences des applications véhiculaires. Cependant, les applications liées à la sécurité routière sont les applications véhiculaires les plus critiques en termes de fiabilité et en termes de temps de latence. Pour cette raison, dans la première partie de cette thèse, nous proposons un algorithme d'allocation des ressources en LTE-V2X qui se base sur la technique du "clustering". Cet algorithme, nommé MIRD (Maximum Inter-Centroid Reuse Distance), vise à améliorer la fiabilité des communications véhiculaires de type sécurité routière.

Dans la deuxième partie de cette thèse, nous abordons l'allocation des ressources radio dans la technologie 5G-V2X. Avant d'entamer le processus d'allocation des ressources radio en 5G-V2X, nous nous intéressons d'abord en premier lieu à la flexibilité de la trame radio de la 5G en concentrant notre intérêt sur le concept de numérogie. À cette fin, nous étudions d'abord l'impact du choix de la numérogie sur les performances des applications véhiculaires. Par le biais de simulations, nous avons abouti à prouver que le choix de la numérogie appropriée est un compromis entre les exigences des applications véhiculaires, les interférences inter-porteuses et les interférences inter-symboles. En deuxième lieu, nous proposons un algorithme d'allocation des ressources en considérant à la fois le trafic de sécurité routière et celui non lié à la sécurité routière. Dans cet algorithme, nommé PSRA-MN (Priority and Satisfaction-based Resource Allocation with Mixed Numerology), nous procédons d'abord au choix de la numérogie appropriée en tenant en compte les conditions du canal radio et la vitesse du véhicule. Ensuite, nous appliquons une politique de priorisation en faveur du trafic lié à la sécurité routière afin de garantir les ressources demandées par ce type de trafic. Puis, les ressources restantes sont allouées de manière optimale aux véhicules dont le trafic est non lié à la sécurité routière afin de maximiser le taux de satisfaction moyen de ces véhicules. L'algorithme PSRA-MN est validé par des simulations. Les résultats obtenus montrent que cet algorithme permet d'atteindre de meilleures performances en comparaison avec les algorithmes traditionnels, tel que le MAX-C/I, en termes de taux d'allocation moyen, de taux de satisfaction moyen, et de temps de latence moyen.

Mots-Clefs: C-V2X, Allocation des Ressources, Applications Véhiculaires

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Acronyms

- 5GAA** 5G Automotive Association. 38
- BCC** Binary Convolutional Code. 36
- BER** Bit Error Rate. 91
- BLER** BLock Error Rate. 88
- BSM** Basic Safety Messages. 33
- BWP** BandWidth Part. 86
- CAM** Cooperative Awareness Messages. 33
- CBR** Channel Busy Ratio. 47
- CH** Cluster-Head. 58
- CR** Channel occupancy Ratio. 47
- CSI** Channel State Information. 62
- CSMA/CA** Carrier Sense Multiple Access with Collision Avoidance. 35
- D2D** Device-to-Device. 36
- DAM** Detect and Mitigate. 40
- DAV** Detect and Vacate. 40
- DCC** Decentralized Congestion Control. 35
- DCI** Downlink Control Information. 48
- DCM** Dual Carrier Modulation. 35

DENM Decentralised Notification Notification Messages. 33

DMRS Demodulation Reference Symbol. 36

DSRC Dedicated Short Range Communication. 23

EDCA Enhanced Distributed Channel Access. 34

eMBB enhanced Mobile Broadband. 25

FDM Frequency Division Multiplexing. 86

GNSS Global Navigation Satellite System. 53

HD Half Duplex. 66

ICI Inter-Carrier Interference. 64

ISI Inter-Symbol Interference. 64

ITS Intelligent Transportation Systems. 33

ITU International Telecommunication Union. 24

KPI Key Performance Indicators. 77

LDPC Low Density Parity Check. 36

LOS Line-Of-Sight. 39

LTE-V2X Long Term Evolution-V2X. 23

MAC Medium Access Control. 34

MANETs Mobile Adhoc NETworks. 33

MCS Modulation and Coding Schemes. 34

MIMO Multiple Input Multiple Output. 35

MIRD Maximum Inter-Centroids Reuse Distance. 25

NR New Radio. 26

NR-V2X New Radio-V2X. 24

OFDM Orthogonal Frequency-Division Multiplexing. 34

PCF Policy Control Function. 38

PDCCH Physical Downlink Control CHannel. 48

PF Proportional Fair. 101

PRB Physical Resource Block. 47

PSCCH Physical Sidelink Control CHannel. 38

PSFCH Physical Sidelink Feedback CHannel. 38

PSRA-MN Priority and Satisfaction-based Resource Allocation in Mixed Numerology. 26

PSSCH Physical Sidelink Shared CHannel. 38

PUCCH Physical Uplink Control CHannel. 48

QAM Quadrature Amplitude Modulation. 35

QoS Quality-of-Service. 26

QPSK Quadrature Phase Shift Keying. 44

RAT Radio Access Technology. 36

RB Resource Block. 103

RBP Resource Block Pairs. 44

RSRP Reference Signal Received Power. 47

RSU Road Side Unit. 32, 34, 63

SC-FDMA Single-Carrier Frequency Division Multiple Access. 44

SCS Sub-Carrier Spacing. 63

SINR Signal-to-Interference plus Noise Ratio. 52

SPS Semi-Persistent Scheduling. 25

TB Transport Block. 44

TCH Transport CHannel. 44

TDM Time Division Multiplexing. 86

UE User Equipment. 36

URLLC Ultra Reliable Low Latency Communications. 25

UTDOA Up-link Time Difference of Arrival. 52

V2I Vehicle-to-Infrastructure. 24

V2N Vehicle-to-Network. 24

V2V Vehicle-to-Vehicle. 24

V2X Vehicle-to-Everything. 7

VANET Vehicular Ad-hoc NETWORKs. 34

Wi-Fi Wireless-Fidelity. 27

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1.1 Thesis Context

Nowadays, vehicular networks form a large and important research field, attracting automotive and telecommunication industries. In the near future, connected vehicles will revolutionize the transport sector and the automotive industry. Road safety remains the main objective of the automotive industry. In this context, the integration of wireless communication technologies in this sector has led to the emergence of a new concept known as Vehicle-to-Everything (V2X) communication. V2X communications aim to ensure road safety and traffic management services. Furthermore, they are also able to provide other types of service, such as entertainment applications.

Vehicular communication is a prominent component of the Internet of Things (IoT) [1], contributing to the emergence of a new paradigm, which is the Internet of Vehicles (IoV) [2]. The IoV is an advanced application of the IoT in the intelligent transportation systems. The IoT is the key technology enabler of the smart cities [3], in which, smart objects can communicate with each other. The main goal of the IoV is to enable vehicles to communicate in real time with other vehicles, roadside infrastructure and pedestrians.

The first standardized technology for V2X (Vehicle-to-Everything) communications is Wi-Fi technology, known as Dedicated Short Range Communication (DSRC) or ITS G5 based on the 802.11p standard [4], followed by the cellular technology Long Term

Evolution-V2X (LTE-V2X). Today, applications in vehicular networks are evolving with high reliability and low latency requirements. The IEEE 802.11p and the LTE-V2X cannot really meet the requirements of future applications. To do so, standardization bodies have recognized the need to develop new technologies. 3GPP has standardized New Radio-V2X (NR-V2X) in its Release 16 to support advanced V2X applications [5], such as vehicle platooning, extended sensors, advanced and remote driving applications. The IEEE 802.11p performance results indicate its limited performance guarantees, specially for time-constrained IoV applications. However, C-V2X can provide better performances than 802.11p in terms of coverage range, latency and throughput.

C-V2X provides integration of both Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications, based on the sidelink PC5 interface, and the Vehicle-to-Network (V2N) communications based on the Uu interface as illustrated in Figure 1.1. The direct V2V communication via the sidelink PC5 interface is the basic mode of V2X communications. The International Telecommunication Union (ITU) has dedicated the 5.9 GHz band for V2X sidelink communications [6].

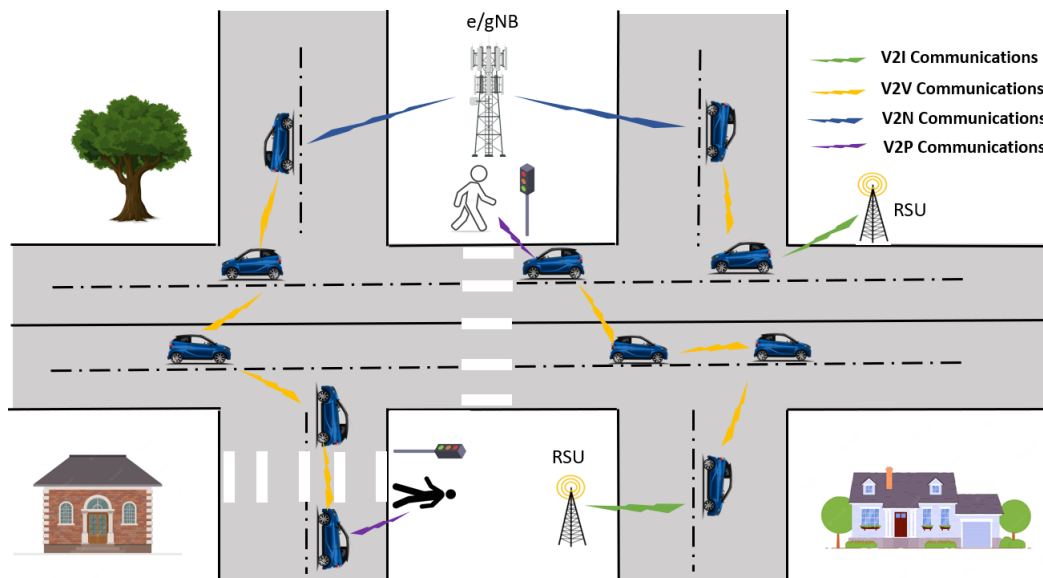


Figure 1.1: Vehicular Network Architecture

Even though C-V2X is a prominent technology for vehicular networks, solutions based on this technology must deal with resource allocation problems. In this regard, the resource allocation in C-V2X has drawn the attention of the research community in the last few years. In fact, radio frequencies, which are scarce and precious resources, must be efficiently managed to avoid interference and collisions. Besides, vehicular communications impose more challenges to the resource allocation problem due to constant changes in the network topology caused by the high mobility. Therefore, resource allocation in C-V2X is a key aspect to improve its performance.

As there exist always areas which cannot be served by a base station, C-V2X presents two modes of resource allocation: a centralized under-coverage mode and a distributed out-of-coverage mode. In LTE-V2X, they are respectively known as modes 3 and 4. In NR-V2X they are named modes 1 and 2 respectively. In the under-coverage mode, the

eNB/gNB schedules and allocates resources to vehicles. However, in the out-of-coverage mode, the vehicles autonomously select their radio resources using the Semi-Persistent Scheduling (SPS) algorithm. Contrary to the out-of-coverage mode, the 3GPP has not standardized a specific resource allocation algorithm for the under-coverage mode.

Several solutions have already been proposed for the C-V2X resource allocation modes and in particular for the out-of-coverage mode. This is due to the fact that the under-coverage mode is less challenging thanks to the control of the eNB/gNB. The out-of-coverage mode poses several problems related to collisions, interference and congestion control problems caused by its decentralized nature. However, even though the under-coverage mode has to cope with a significant reduced set of problems, it remains very important to propose new resource allocation algorithms aiming to optimize the network capacity, the data rate of vehicles or the reuse of resources between vehicles.

Moreover, as mentioned earlier, V2X applications include other types of applications such as entertainment and comfort-related applications, in addition to safety-related applications [7]. Consequently, the resource allocation algorithms need to deal with the categorization and requirements of different V2X applications. The present thesis is situated in this context. The contributions proposed in this thesis deal with resource allocation algorithms for the under-coverage mode considering the different requirements of V2X applications.

1.2 Motivations and Contributions

One of the challenges of resource allocation in C-V2X is to efficiently allocate resources to vehicles to meet the requirements of different V2X applications. Indeed, there is a lack of research works investigating the impact of resource allocation algorithms on the requirements of various V2X applications. Among those applications, we cite the advanced cooperative driving as an example of a 5G-V2X time-critical application, which is part of the Ultra Reliable Low Latency Communications (URLLC) and requires a very low latency. In addition, we cite also the 5G-V2X infotainment applications such as the video streaming for passengers, which is part of the enhanced Mobile Broadband (eMBB), and requires high data rates. However, the resource allocation algorithms proposed in the literature do not consider the requirements of V2X applications. The work carried out in this thesis addresses this challenge.

Even though the main goal of V2X communications is to provide traffic safety services, V2X applications also include other types of applications such as entertainment and comfort-related applications [7]. These applications have different requirements. The resource allocation algorithms proposed in this thesis aim to meet the requirements of various V2X applications.

Since the first goal of vehicular networks is to ensure road safety service, we are interested in the initial contribution to safety-related applications. For this reason, we propose a new efficient resource allocation algorithm in mode 3 of LTE-V2X for safety traffic, the Maximum Inter-Centroids Reuse Distance (MIRD) algorithm, which is presented in Chapter 5. The main goal of MIRD algorithm is to improve the reliability of safety V2V communications by efficiently allocating radio resources to vehicles using a clustering approach.

The second part of our thesis deals with resource allocation considering the 5G-V2X technology. One of the main differences between LTE-V2X and 5G-V2X is the flexibility of the New Radio (NR) frame structure of 5G thanks to the introduction of the numerology concept, which was not previously considered in LTE-V2X. Therefore, before starting the allocation of radio resources, it is necessary to choose the appropriate numerology for each V2X scenario. To do so, we first studied the impact of 5G numerologies on the performance of V2X applications. Indeed, the new 5G numerologies are one of the most important 5G key features, but choosing the appropriate numerology for a particular V2X scenario is still an open issue. As far as the literature is concerned, there are only a few research works dealing with the concept of numerology [8, 9, 10, 11]. However, there is a lack of research investigating their impact on V2X use cases. This study considers both the application and physical layers and aims to select the appropriate numerology considering the application requirements, vehicle speed, and channel conditions.

Still in the 5G-V2X resource allocation context, we then propose a new resource allocation algorithm for mode 1 of 5G-V2X that considers simultaneously the safety and non-safety applications, the Priority and Satisfaction-based Resource Allocation in Mixed Numerology (PSRA-MN) algorithm. As explained earlier, the resource allocation algorithm proposed in the first part of this thesis only deals with safety V2V communication. However, since the sidelink V2V communications can support both the safety traffic and the non-safety traffic, efficient resource allocation mechanisms are imperative to guarantee the Quality-of-Service (QoS) requirements of the different traffic types. For generalization, in the second part of our thesis, we have seen the need to propose a new resource allocation algorithm that takes into account different traffic types, including both safety and non-safety traffic in the 5G-V2X context. As already mentioned, the safety-related applications are the most critical applications in vehicular networks. Consequently, the application of a priority policy in favour of the safety applications is a necessary step. As for traditional resource allocation algorithms, we note that they are not always suitable for V2X applications [12]. For example, regarding the Max-C/I algorithm [12], which aims to maximize the system throughput by scheduling the vehicle with the best radio-link conditions first, we find that this algorithm can schedule a non-safety vehicle before another safety vehicle if that non-safety vehicle has good radio-link conditions, which is very dangerous for the safety service. Therefore, the main idea of the PSRA-MN algorithm is to ensure the necessary resources for safety vehicles by applying a priority mechanism in favour of safety traffic. Next, the remaining resources after safety allocation are then allocated to the non-safety vehicles by solving an integer linear optimization problem that aims to maximize the average satisfaction rate of non-safety vehicles. The main research contributions of this thesis are shown in Figure 1.2 and can be summarized as follows:

- An overview of the state-of-the art in resource allocation for C-V2X: from LTE-V2X to 5G-V2X.
- The proposition of a new resource allocation algorithm for safety V2V communications in mode 3 of LTE-V2X: the MIRD algorithm.
- A comprehensive study of the impact of 5G numerologies on the performance of V2X communications.
- The proposition of a new resource allocation algorithm for both safety and non-safety communications in mode 1 of 5G-V2X: the PSRA-MN algorithm.

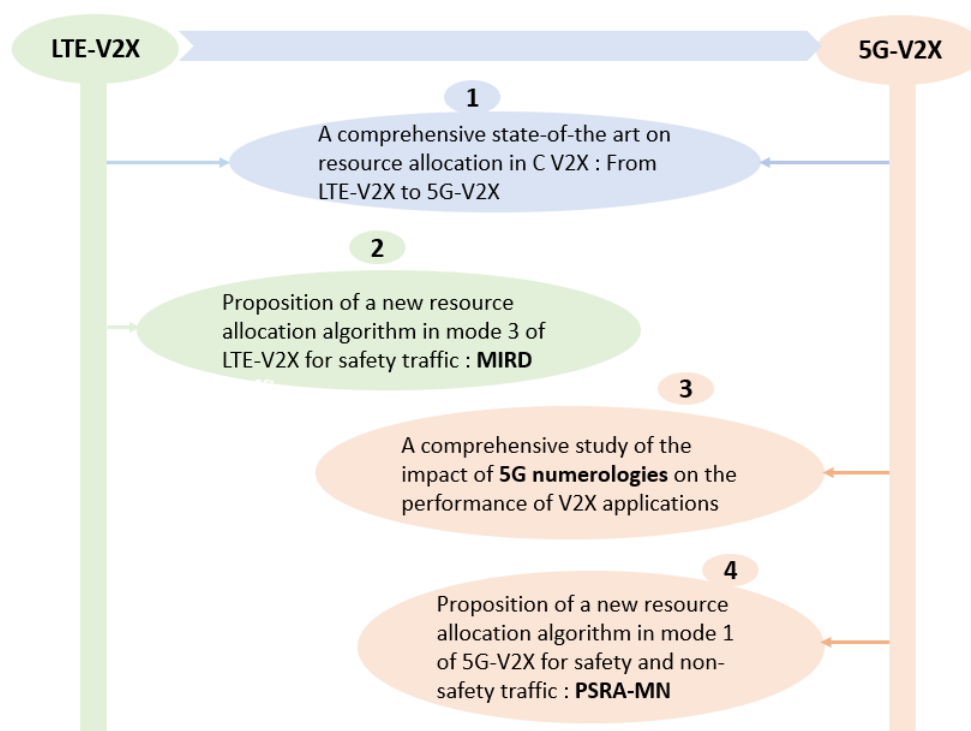


Figure 1.2: Summary of Thesis Contributions

1.3 Thesis Organisation

The thesis is organized in seven chapters. Figure 1.3 illustrates the organization of the thesis and the contribution of each chapter considering the type of the used C-V2X technology, i.e., LTE-V2X or 5G-V2X, and the category of V2X traffic, i.e. the safety traffic only or both safety and non-safety traffic. The thesis manuscript is organized as follows:

- Chapter 1, the current chapter, introduces the global view, context, and organization of the thesis. This chapter also presents the motivations for the work carried out in this thesis and the main contributions.
- Chapter 2, "General Background on Vehicular Networks", provides a better understanding of vehicular networks. This chapter presents a general background on vehicular networks, including their main characteristics, applications, and services, so that the differences between vehicular networks and other traditional networks become clear. In addition, this chapter introduces the communication technologies used in vehicular networks, namely Wireless-Fidelity (Wi-Fi) and C-V2X technologies. A comparison between C-V2X and Wi-Fi is also made and the possible solutions for the coexistence of these two technologies are also presented.
- Chapter 3, "Resource Allocation in C-V2X: Technical Background & State-of-the-art", presents a detailed technical background on resource allocation in C-V2X, since we are particularly interested, in this thesis, in resource allocation in C-V2X.

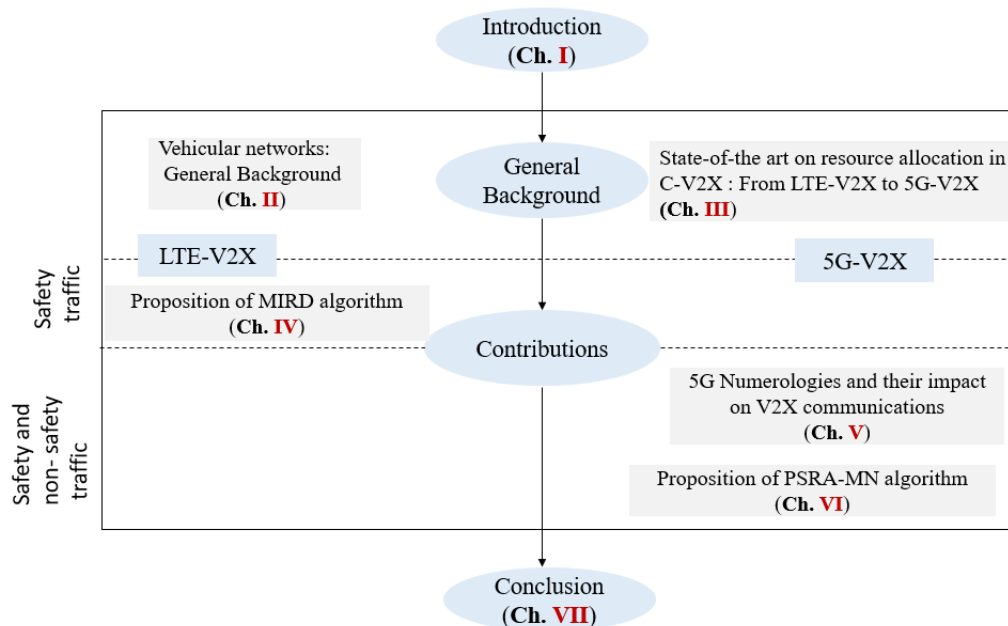


Figure 1.3: Thesis Organization

In this chapter, we start with the technical concepts for resource allocation in LTE-V2X and 5G-V2X. Then, we introduce the resource allocation modes in C-V2X, including the under-coverage modes, i.e., mode 3 and mode 1 for LTE-V2X and 5G-V2X, respectively, and the out-of-coverage modes, i.e., mode 4 and mode 2 for LTE-V2X and 5G-V2X, respectively. We then provide a comprehensive overview of the current state-of-the-art in resource allocation for C-V2X. The work done in this chapter enables us to better understand the resource allocation for C-V2X, its main challenges, and the possible research directions in this area.

- Chapter 4, "Resource allocation in LTE-V2X: Clustering-based resource allocation scheme for safety V2V communications", presents a new clustering-based resource allocation algorithm for safety LTE-V2V communications, the MIRD algorithm. In this chapter, we explain the clustering technique used in this algorithm. This clustering technique includes two main steps, which are the clustering of vehicles according to their geographical positions and the clustering of radio resources. In addition, the newly proposed resource reuse mechanism is also presented in this chapter. A detailed description of the MIRD algorithm and its performance evaluation are given in this chapter.
- Chapter 5, "Resource Allocation in 5G-V2X: 5G numerologies and their impact on V2X communications", addresses one of the most interesting 5G key features, namely the 5G numerologies. This chapter first presents a general technical background explaining the numerology concept, its main parameters, the multiplexing of different numerologies and the bandwidth part technique. Next, the impact of 5G numerologies on V2X communication performance is investigated in this chapter by considering both the application level and physical level performance evaluation.
- Chapter 6, "Resource Allocation in 5G-V2X: Priority and Satisfaction-based Re-

source allocation for safety and non-safety communications”, presents a new resource allocation algorithm for mode 1 of 5G-V2X that considers both safety and non-safety applications, the PSRA-MN algorithm. This chapter provides a detailed description of this algorithm and a performance evaluation against another traditional resource allocation algorithm.

- Chapter 7, ”Conclusion & Perspectives”, presents the conclusion of our thesis and gives an outlook on the future of our work.

1.4 List of Publications

1.4.1 Journals

- Sehla Khabaz, Thi-Mai-Trang Nguyen, Guy Pujolle, and Pedro Velloso, "Resource Allocation Modes in C-V2X: From LTE-V2X to 5G-V2X," in *IEEE Internet of Things Journal*, vol. 9, no. 11, pp. 8291-8314, 1 June1, 2022, doi: 10.1109/JIOT.2022.3159591.

1.4.2 Conferences

- Sehla Khabaz, Thi-Mai-Trang Nguyen, Guy Pujolle, and Pedro Velloso, "A New Clustering-based Radio Resource Allocation Scheme for C-V2X" 2021 Wireless Days (WD), 2021, pp. 1-8, doi: 10.1109/WD52248.2021.9508289.
- Sehla Khabaz, Kaouthar Ouali Boulila, Thi-Mai-Trang Nguyen, Guy Pujolle, Moustapha El-Aoun, and Pedro Velloso, "A Comprehensive Study of the Impact of 5G Numerologies on V2X Communications", 2022 13th International Conference on Network of the Future (NoF), October 05 - 07, Ghent (Belgium).
- Sehla Khabaz, Kaouthar Ouali Boulila, Thi-Mai-Trang Nguyen, Guy Pujolle, Moustapha El-Aoun, and Pedro Velloso, " A New Priority and Satisfaction-based Resource Allocation Algorithm with Mixed Numerology for 5G-V2X communications ", 2022 14th IFIP Wireless and Mobile Networking Conference (IFIP WMNC), October 17 - 19, Sousse (Tunisia).

General Background on Vehicular Networks

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Before we get to the heart of the matter, namely resource allocation in C-V2X, we begin in this chapter with a general background on vehicular networks. This chapter is divided into two main parts. In the first part, we present the main characteristics and applications of vehicular networks in Sections 2.1.1, and 2.1.2, respectively. The second part of this chapter introduces the main communication technologies in vehicular networks, starting from the Wi-Fi technologies, i.e., 802.11p and 802.11bd, and going through the C-V2X technologies, i.e., LTE-V2X and NR -V2X in Sections 2.2.1 and 2.2.2, respectively. Next, we discuss the main interesting ideas on the comparison and the coexistence of these two competing technologies in Sections 2.2.3, and 2.2.4, respectively. Finally, we conclude this chapter in Section 5.3.

2.1 Vehicular Networks

Vehicular networks are a category of wireless networks in which the communicating nodes are vehicles equipped with wireless interfaces. Today, vehicular networks form a large and important research area that attracts the automotive and telecommunications industries.

Road safety remains the main objective of the automotive industry. In this context, the integration of wireless communication technologies in this sector has led to the emergence of a new concept known as Vehicle-to-Everything (V2X) communication. V2X communications, which rely on the communication between vehicles and other objects, can be divided into four main types: Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Vehicle-to-Network (V2N), as shown in Figure 2.1. In addition to the traffic safety service, V2X communications are also expected to provide other types of service such as the traffic management services and the comfort-related services.

There are two main competing technologies to support vehicular communications, namely the Wi-Fi technology known as DSRC/ 802.11p and the cellular technology known as C-V2X. The communication technologies in vehicular networks are presented in more detail in Section 2.1.2 of this chapter.

In the following subsections, we present the main characteristics of vehicular networks, their own applications and services.

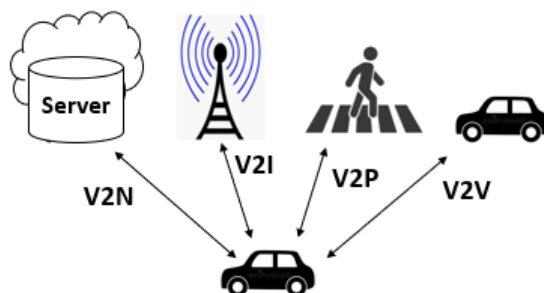


Figure 2.1: V2X Communication types

2.1.1 General Characteristics

The vehicular networks have come with some special characteristics compared to the other traditional networks. Those characteristics, which are mainly related to the mobility of vehicles, include some advantages and some other challenges. The main advantageous characteristics of vehicular networks can be summarized as follows:

- **Predictable Mobility:** in vehicular networks, predicting the mobility of vehicles is indeed not a difficult task. Vehicle mobility can be predicted based on the average speed of the vehicle, its current position, and the road topology, which is not the case in the traditional mobile networks.
- **Lower energy constraint:** vehicles and Road Side Unit (RSU), which serve as base nodes in vehicular networks, suffer less from the energy consumption problem compared to other mobile devices. This is due to the fact that the vehicles and RSUs have the necessary energy to run the required vehicular applications.
- **Higher computational capability:** thanks to the emergence of new technologies such as radar, camera and lidar on the vehicle, the latter benefit from a high computational and sensing capability.

Nevertheless, there are some challenging characteristics in vehicular networks, which are cited below:

- **Dynamic Network:** unlike the other Mobile Adhoc NETWORKS (MANETs), the vehicular network is an extremely dynamic network, which is of course due to the high mobility of the vehicles. Indeed, the high speed of the vehicles, especially in highway scenarios, leads to a rapid change of the network topology. In this context, it is important to emphasise that this rapid change of the network topology can have a negative impact on the communication performance.
- **Large-scale and partitioned network:** unlike the classical mobile networks where the topology of the network is limited, the vehicular network is a large-scale network, especially in dense urban areas where the network topology is very large. However, the very high mobility of vehicles in this case may lead to network partitioning if the vehicles are far from each other.
- **Frequent exchange of information:** in vehicular networks, the most critical and important service is the traffic safety service. The traffic safety service is based on the frequent and periodical exchange of safety messages between vehicles and between vehicles and RSUs, namely the Cooperative Awareness Messages (CAM). However, this frequent exchange of information can increase the communication load of the network, especially in dense urban areas.

2.1.2 Applications and Services

The main objective of the Intelligent Transportation Systems (ITS) is to ensure the road safety service in order to reduce the number of road accidents. To this end, among the applications designed for vehicular communication, the most important are the safety-related applications aimed at providing road safety to passengers and also to pedestrians. Besides, the traffic management services are also provided to manage the road traffic easily. In addition, there are also other types of services in vehicular networks, such as entertainment applications. In summary, applications in vehicular networks can be divided into three main categories: traffic safety applications, traffic management applications, and entertainment applications, which are discussed in more detail below:

- **Traffic Safety applications:** the road safety applications are based on the broadcasting of periodic messages between vehicles, known as cooperative awareness messages or Basic Safety Messages (BSM). These messages indicate critical informations such as the position, speed and direction of a vehicle. The size of CAM messages can vary between 50 and 300 bytes. The size of Decentralised Notification Notification Messages (DENM) messages is also variable and can be up to 1200 bytes [13]. Among the safety applications, we cite the emergency vehicle warning, the collision risk warning from RSU, hazardous location notification, vulnerable road user warning, motorcycle warning, intersection collision warning and many others.
- **Traffic management applications:** the second category of vehicular applications, namely traffic management applications, is less time-critical than the safety ap-

plications. Traffic management applications aim at managing road traffic by exchanging informations between RSU and vehicles. As examples of traffic management applications, we cite: regulatory/contextual speed limits, traffic information and recommended itinerary, enhanced route guidance and navigation, intersection management applications and more others.

- **Entertainment applications:** the third category of vehicular applications are entertainment applications. As the name suggests, the main objective of entertainment applications is to provide comfort to the drivers and also to the travelers. Examples of such applications include: automatic access control/parking access, local electronic commerce, media downloading, map download...

2.2 Communication Technologies in Vehicular Networks

To support vehicular communications and address the challenges associated with them, two major technologies compete with each other, namely the Wi-Fi and cellular networks. The Wi-Fi technology, known as 802.11p, operates in the 5.9 GHz band [4]. The cellular technology, known as C-V2X [6], operates not only in the 5.9 GHz band but also in the licensed bands of the cellular networks. The Long Term Evolution-V2X (LTE-V2X) is the first C-V2X technology standardized by the Third Generation Partnership Project (3GPP) in Release 14. More recently the 3GPP has also standardized the New Radio-V2X (NR-V2X) in Release 16. The IEEE 802.11p performance results indicate its limited performance guarantees, specially for time-constrained IoV applications. However, C-V2X can provide better performances than 802.11p in terms of coverage range, latency and throughput.

In the following subsections, we begin by a brief presentation of each technology, separately, i.e., Wi-Fi technology, including 802.11p and 802.11bd, and C-V2X technology, including LTE-V2X and NR -V2X. Then, we present the research works interested in the comparison between these technologies and the potential solutions for the coexistence of these technologies in the 5.9 GHz band.

2.2.1 Wi-Fi technologies

The first standardized technology for Vehicular Ad-hoc NETWORKS (VANET), which is now a mature technology, is the ITS-G5 in Europe or Dedicated Short Range Communication (DSRC) in the USA. This standard is based on the 802.11p protocol [4], a variant of the 802.11a adapted to the dynamic nature of vehicular environment. It allows two communication types, as presented in Figure 2.2: Vehicle-to-Vehicle (V2V) communication and Vehicle-to-Infrastructure (V2I) communication. The infrastructure of a vehicular network refers to the RSU deployed along the streets and highways.

The 802.11p protocol uses Orthogonal Frequency-Division Multiplexing (OFDM) with a 10 MHz channel bandwidth and 8 Modulation and Coding Schemes (MCS) at the physical layer. The maximum bit rate offered by 802.11p is 27 Mbps. At the Medium Access Control (MAC) layer, the 802.11p adopts the Enhanced Distributed Channel Access

(EDCA) protocol which adds the QoS to the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) standard. However, if the data load on the wireless channels exceeds the total available capacity, it is necessary here to introduce the Decentralized Congestion Control (DCC) mechanisms in the ITS -G5 stations, as described in [14], to control the channel load. These mechanisms have been designed to meet the requirements of ITS applications on high reliability and low latency, especially for road safety applications.

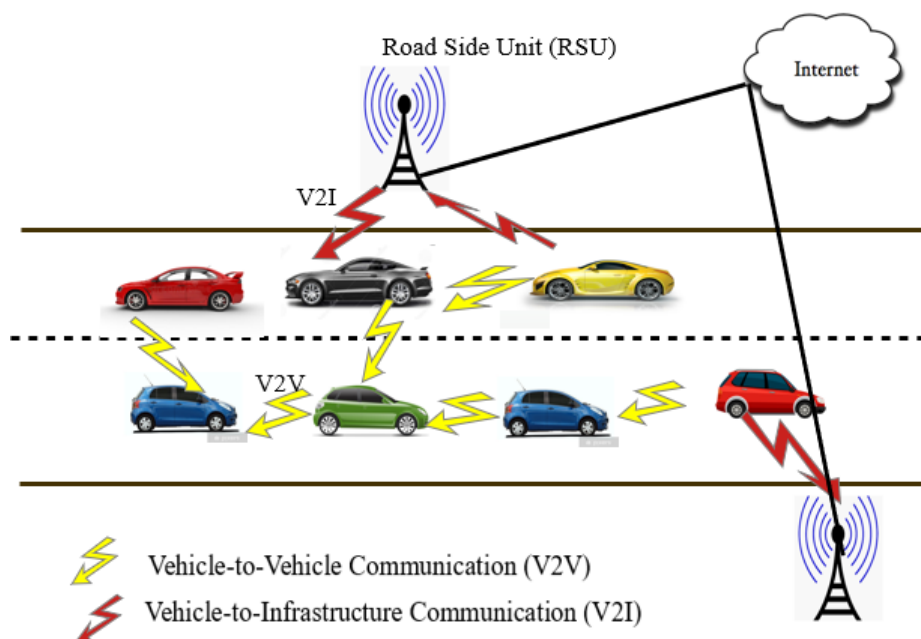


Figure 2.2: IEEE 802.11p Architecture

Recently, the IEEE have seen the need to standardize a new protocol dedicated for V2X communications to meet the requirements of future vehicular applications. This is possible thanks to the evolution of Wi-Fi standards from 802.11a to 802.11ax [15]. This new protocol, named 802.11bd, adds enhancements to the MAC and physical layers of its predecessor, 802.11p. These new mechanisms allow 802.11bd to achieve a data rate and a communication range two times better than those achieved by the 802.11p protocol in high mobility scenario with vehicle's speed reaching 500 km/h. The 802.11bd protocol is also interoperable and backward compatible with 802.11p. It deploys, at the physical layer [16], the following technologies:

- high MCS level up to 256 Quadrature Amplitude Modulation (QAM);
- Multiple Input Multiple Output (MIMO) technology;
- channel bandwidth up to 20 MHz;
- Dual Carrier Modulation (DCM) introduced at Wi-Fi 6, which consists in transmitting the same symbol on two different sub-carriers;

- Low Density Parity Check (LDPC) instead of the Binary Convolutional Code (BCC);
- using midambles instead of preambles for a better channel estimation because midambles are scattered throughout the frame between OFDM symbols.

Table 2.1 shows a comparison between the 802.11p and the 802.11bd standards.

Table 2.1: Comparison between 802.11p and 802.11bd

FEATURES	802.11p	802.11bd
Supported relative speed	252 kmph	500 kmph
Sub-carrier spacing	156.25 kHz	78.125, 156.25, 312.5 kHz
Channel coding	BCC	LDPC
Midambles	No	Yes
Radio bands	5.9 GHz	5.9 GHz, 60 GHz

2.2.2 Cellular Technologies (C-V2X)

The 3GPP has recently standardized in its Release 14 the LTE-V2X as a new technology competing with the IEEE 802.11p standard [17]. The first benefit of C-V2X is the availability of the cellular infrastructure, unlike DSRC which requires the deployment of a new infrastructure, i.e. Road-Side Units (RSU). LTE-V2X is based on the Device-to-Device (D2D) communications technology [18]. The side-link interface, known as PC5 interface, has been standardized for D2D communications. Enhancements are added to this interface in order to support the high mobility of vehicular environment, especially to support high speeds of vehicles. Thus, new Demodulation Reference Symbol (DMRS) are added to the frame structure to handle the Doppler effect.

In order to support V2X communications, two main elements are added to the LTE core network architecture, the V2X control function and the V2X application server [19], as illustrated in Figure 2.3. The V2X control function provides the User Equipment (UE) with the necessary parameters for V2X communications, and the V2X application server is responsible for the V2X communication data treatment. In LTE-V2X, two communication modes are possible: mode 3 and mode 4. The evolved Node B (eNB) schedules the radio resources and allocates them to vehicles in mode 3. However, in mode 4, vehicles reserve their radio resources autonomously using the sensing-based Semi-Persistent Scheduling (SPS) algorithm [20]. It is worth noticing that mode 3 depends on the cellular network to work properly, while mode 4 can operate without any cellular network.

The 3GPP has also standardized the NR-V2X to support advanced V2X applications [5]. Vehicle platooning, extended sensors, advanced and remote driving are among these applications. Such applications require low latency and high reliability. NR-V2X supports these new applications as well as those related to the basic safety service already supported by LTE-V2X. In case a vehicle is equipped with the two Radio Access Technology (RAT)

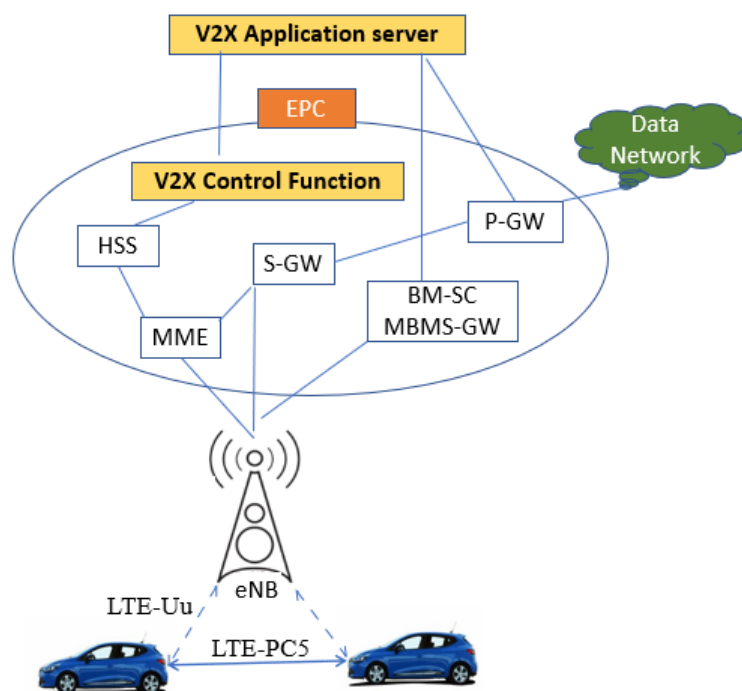


Figure 2.3: LTE-V2X Architecture

of C-V2X technologies, i.e. LTE-V2X and NR-V2X RATs, it can use the LTE-V2X RAT for basic safety applications and NR-V2X RAT for these new applications. Depending on the application, the exchanged messages can be of periodic or non-periodic nature. Furthermore, some messages are broadcasted for all vehicles while others are targeted to a specific group of vehicles, such as in the platooning scenario, where the platoon leader communicates with the platoon members. For this purpose, the NR-V2X supports the unicast and groupcast modes besides the broadcast mode, already supported in LTE-V2X [21]. These new modes can operate under and outside the cellular coverage. Note that the vehicle can use both groupcast and broadcast modes at the same time, i.e. the vehicle can communicate with a group of vehicles in groupcast mode, and simultaneously send its messages to other vehicles in broadcast mode. The platooning is the best example for this case, where the platoon leader communicates with platoon members in groupcast mode to maintain the platoon, and also broadcasts the periodic message to other vehicles outside the platoon for the cooperative awareness service. The NR-V2X has the following key features:

- **Support for new numerologies:** Indeed, in 3GPP Release 15 new numerologies have been standardized for NR of 5G [22]. These numerologies are also supported by NR-V2X standardized in Release 16. Unlike LTE-V2X, where the spacing between sub-carriers is fixed on 15 kHz, in NR-V2X it can take other values multiple of 15 kHz, i.e. 30, 60 and 120 kHz. As the sub-carrier spacing is variable, the time slot, i.e. the time to transmit 14 OFDM symbols, is also variable and decreases with the increase of the sub-carrier spacing, which reduces the latency and therefore favors critical applications in terms of latency. A more detailed comparison between LTE-V2X and NR-V2X, is presented in Table 2.2.

- **Multiplexing of PSCCH and PSSCH in time domain:** another key feature of NR-V2X, which also favors the reduction of latency time is the multiplexing of Physical Sidelink Control CHannel (PSCCH) and Physical Sidelink Shared CHannel (PSSCH) (PSSCH) in time domain, i.e., the PSCCH will be transmitted first, followed by the transmission of PSSCH, whereas in LTE-V2X these channels are multiplexed in frequency domain.
- **Use of the Physical Sidelink Feedback CHannel (PSFCH):** This new channel has been defined in NR-V2X in order to ensure the reliability for unicast and groupcast modes.

Table 2.2: Comparison between LTE-V2X and NR-V2X

FEATURES	LTE-V2X	NR-V2X
sub-carrier spacing	15kHz	15, 30, 60, 120 kHz
Communications modes	Broadcast	Unicast, Groupcast, Broadcast
MCS	QPSK, 16QAM	QPSK, 16QAM, 64QAM
Waveform	SC-FDMA	OFDM
PSCCH and PSSCH	FDM	TDM
Feedback Channel	No	PSFCH
DMRS /sub-frame	4	Flexible
Sidelink modes	3, 4	1, 2

NR-V2X also provides other enhancements on its physical layer such as the high MCS level up to 64QAM, the LDPC coding and a flexible number of DMRS symbols in the slot.

As in LTE-V2X, the 5G system architecture includes the V2X applications server, which is responsible for the V2X communication data treatment. However, the necessary parameters for the establishment of V2X communication are provided by the Policy Control Function (PCF) unit to the UE while those parameters are provided by the V2X control function in LTE-V2X.

2.2.3 C-V2X vs Wi-Fi

As there are two competing technologies for vehicular networks, the automobile industry, organizations and companies are supporting different technologies. Indeed, in the USA, Japan and South Korea, projects for the deployment of the 802.11p are already in place. In China, an open road test for LTE-V2X was carried out in September 2018. In Europe, the C-Roads Platform [23], deploying the cooperative ITS, is aiming for 6.000 km of ITS-G5 coverage and 200,000 km of cellular coverage. On the global scale, the 5G Automotive Association (5GAA), which is the first supporter for the C-V2X, is preparing for the integration of 5G in the automotive sector. For the telecommunication operators, they are asking for the abandonment of the ITS-G5 and the support of the C-V2X as the best technology for vehicular communications.

Given this technological competition and diversity of choice, much research work have focused on the comparison between the performance of these two technologies [24, 25, 26, 27, 28, 29, 30, 31, 32]. Research in this subject has proved that both technologies present some advantages and some other drawbacks, which depend on many factors, such as the Line-Of-Sight (LOS) conditions, the vehicular density, the size of transmitted packets, and also the distance between transmitter and receiver.

While most of the research community supports the use of only one technology, other research works have proposed a hybrid solution by exploiting the benefits of both technologies in order to support an efficient and reliable V2X communications. In this context, Abboud *et al.* investigate the potential mechanisms for the coexistence of DSRC and C-V2X. [33]. As proposed in this work, when both technologies are used, the cellular network can have two functions. The first one consists of using it as a backup for vehicular data in case the V2V connections are interrupted. In the second one, the cellular network can serve, for example, as an access network to the Internet. In the same context, King *et al.* address the interoperability issue between these two technologies [34]. The authors propose a converter protocol for the translation between these two technologies. In the first step of this protocol, each vehicle broadcasts a message in order to identify the used technology by all its neighbors, and then saves this information in a knowledge table. The authors are based on a cyclo-stationary analysis for the technology identification. In fact, generally, each type of wireless signal has unique cyclic frequencies with the frequency selective property, which distinguishes itself from other types of signals, and the cyclostationary analysis can be used to identify the type of the signal. Thus, whenever a vehicle wants to transmit a message it must access its knowledge table to know whether the destination vehicle uses the same technology or not. When both source and destination uses the same technology, the message is generated and transmitted as usual. However, if it is not the case, the proposed converter protocol is used to convert the signal into the necessary format of the other technology.

2.2.4 C-V2X and 802.11p Coexistence in the 5.9 GHz band

The coexistence between cellular and wi-fi technologies is a very relevant research subject. We can categorize two types of coexistence. The first one is the inter-technology coexistence that we refer to the coexistence between cellular and Wi-Fi technologies, i.e. between LTE-V2X/NR-V2X and 802.11p/802.11bd. The second type is the intra-technology coexistence that we refer to the coexistence between LTE-V2X and NR-V2X. The coexistence between cellular technologies, i.e. LTE-V2X or NR-V2X and the Wi-Fi technologies, i.e. 802.11p or 802.11bd in the 5.9 GHz band, is another topic of interest as discussed in [35]. As a proposal for the coexistence in the same band, the 5GAA has proposed a solution based on the division of the spectrum between these technologies in order to avoid the co-channel interference problem. In [36], it is proposed to dedicate to each technology a 10 MHz channel in the ITS band, and then each technology can also operate in the rest of the ITS spectrum by using a specific detect-and-vacate mechanism, as presented in Figure 2.4.

On the other hand, the NR-V2X is not backward compatible with LTE-V2X, because NR-V2X uses different numerologies. An LTE-V2X vehicle with a carrier spacing of 15 kHz is not able to decode the message of a NR-V2X vehicle using a carrier spacing of

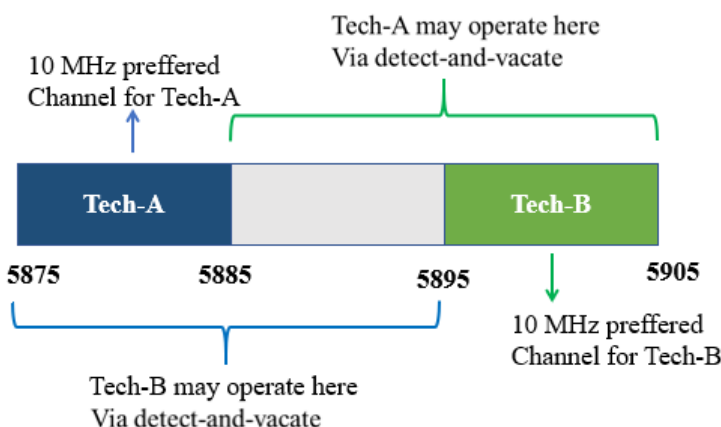


Figure 2.4: The 5GAA model for the Coexistence between IEEE 802.11p and C-V2X in the 5.9 GHz Band

30 kHz. Future vehicles can probably be equipped with both RATs, i.e. LTE-V2X and NR-V2X. These two technologies can operate in the same band, i.e. 5.9 GHz band, but in two different channels. Two main approaches of coexistence are proposed in [37]:

- **Coexistence with FDM:** in the FDM approach, LTE-V2X and NR-V2X simultaneously operate on two different channels. The drawback of this approach is that if the two RATs are using the same band, the total permitted transmission power must be therefore divided between them. The authors of [38] propose that the division can take into account the priority of packets by increasing the transmission power of the RAT with the higher priority packet at the expense of the transmission power of the second RAT.
- **Coexistence with TDM:** this second approach considers that both technologies must operate in orthogonal channels in time and frequency domains. In contrast to the first one, it allows both RATs to use the maximum permitted transmission power because they will not transmit simultaneously. However, this approach is not practical for the transmission of packets of latency-critical applications, because the packet has to wait during the transmission time of the second RAT, which can increase the latency time.

Regarding the intra-technology coexistence within Wi-Fi standards, Khan et al. propose in [39] two protocols: Detect and Mitigate (DAM) and Detect and Vacate (DAV), as solutions for the co-channel coexistence.

2.3 Conclusion

In this chapter, we present a general background on vehicular networks. In the first part of this chapter, we present the main characteristics of vehicular networks, their main applications and services. In the second part, we present the two main communication

technologies in vehicular networks, namely Wi-Fi and C-V2X technologies. We also present the interesting ideas related to the comparison and the coexistence of these two competing technologies. In our thesis, we are interested in the C-V2X technology and, in particular, the resource allocation in C-V2X considering both LTE-V2X and NR-V2X. To this end, a general background on resource allocation in C-V2X is presented in the following chapter.

Resource Allocation in C-V2X: Technical Background & State-of-the-art

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This chapter gives a general overview of resource allocation in C-V2X. In the first part, we explain in details the concepts of radio resources and resource allocation for LTE-V2X and 5G-V2X in Sections 3.1 and 3.2, respectively. In the second part, we present a detailed state-of-the-art of the resource allocation modes of LTE-V2X and 5G-V2X in Sections 3.3 and 3.4, respectively. Then, we discuss the main challenges of resource allocation in C-V2X in Section 3.5. Finally, we conclude this chapter in Section 3.6.

3.1 Resource Allocation in LTE-V2X

As in LTE up-link, LTE-V2X adopts OFDM in its physical layer and the Single-Carrier Frequency Division Multiple Access (SC-FDMA) at the MAC layer. The available bandwidth, i.e. a 10 or 20 MHz channel, is subdivided in time and frequency domains into several orthogonal resources, as illustrated in Figure 3.1. In time domain, the signal is organized into frames of 10 ms. Thus, each frame is formed by 10 sub-frames of 1 ms and each sub-frame is formed by 2 Time-Slots. In the frequency domain, the signal is formed by Resource Block Pairs (RBP), which is defined by 12 sub-carriers, spaced by 15 kHz and carrying 14 OFDM symbols. In LTE-V2X, a sub-channel is defined by a group of RBPs in the same sub-frame. The subchannel size can be configured from 4 to 50 RBPs as defined in [40] but all subchannels in an eNB must have the same size. Each vehicle can use one or multiple subchannels to transmit its data. A sub-channel is defined as the smallest unit of resource that can be assigned to a vehicle to transmit its CAM packet. In C-V2X, Quadrature Phase Shift Keying (QPSK) and 16QAM modulations are used to transmit the Transport Block (TB), whereas the Sidelink Control Information (SCI) is always transmitted using QPSK. LTE-V2X uses the Turbo coding and the normal cyclic prefix. The Transport CHannel (TCH) transporting data is carried by the PSSCH while the PSCCH carries the SCI. The SCI provides the critical informations in order to successfully decode the message at the receiver, such as the MCS information, the RBs occupied by the associated TB, the priority of the message and the resource reservation interval. The resource reservation interval enables us to determine when the vehicle will use the reserved resources for its next transmission. PSCCH and PSSCH are multiplexed in frequency domain, i.e. they are transmitted in the same sub-frame but using different frequency resources. There are two configuration schemes for the PSSCH and PSCCH. The first one is the adjacent configuration, where the PSCCH occupies the two first RBs of the allocated sub-channel, and it is directly followed by the PSSCH. The second configuration is a non-adjacent configuration, where the PSSCH and the PSCCH do not occupy successive RBs in the same sub-frame. The number of RBs in a sub-channel is variable [41]. Together with this information, are also sent 4 DMRS symbols inserted in the OFDM sub-frame, which are used for channel estimation in high mobility environments.

LTE-V2X defines two modes of resource allocation as illustrated in Figure 3.2. These modes are related to the availability of the cellular infrastructure. The first mode is applied under the cellular coverage and known as mode 3. In this mode, the eNB schedules and allocates resources to vehicles. However, in order to ensure the basic safety services even though the vehicles are out-of-the-cellular coverage, the 3GPP has standardized a second mode known as mode 4. In mode 4, vehicles autonomously select their radio resources using the SPS algorithm. The SPS is based on the sensing of the channel before choosing a resource from a list of candidate resources, as we will detail later.

3.1.1 Mode 3

In contrast to mode 4, 3GPP has not standardised a specific algorithm for resource allocation for mode 3. Therefore, each operator can propose its own algorithm. However, there are two choices for resource allocation in this mode :

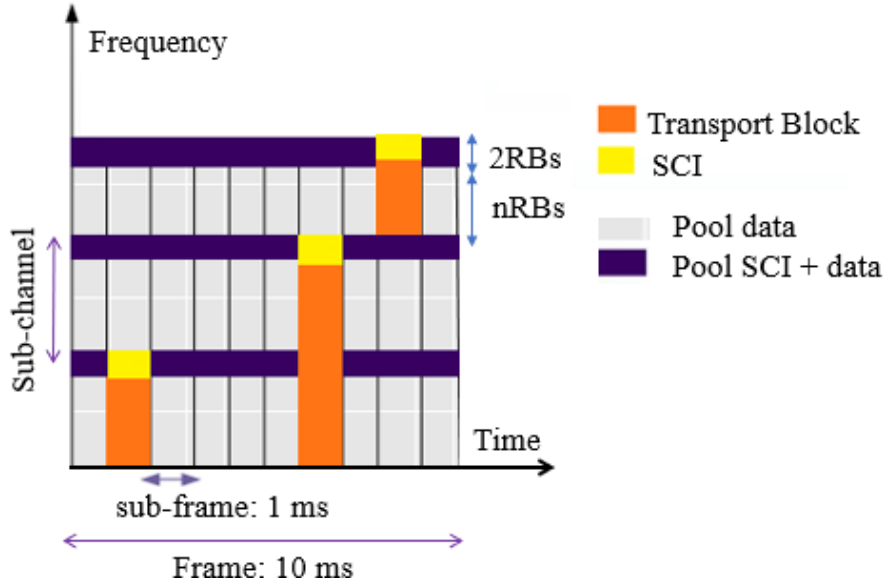


Figure 3.1: LTE-V2X Frame Structure

- The dynamic allocation: In the dynamic allocation, each vehicle requests sub-channels to the eNB for each CAM packet transmission. The drawback of the dynamic allocation is the increase of the signaling overhead and the latency.
- The Semi-Persistent Scheduling (SPS): in the SPS, the eNB reserves sub-channels for the periodic transmissions of vehicles. Each vehicle sends to the eNB the necessary information such as packet size, transmission frequency, and priority of packets. This information is referred to as the assistance information, which is used by the eNB to semi-persistently reserve the appropriate resources for each vehicle. The main advantage of the SPS approach is the reduction of the signaling overhead and the delay of the resource allocation mechanism. It is important here to note that the periodic nature of the basic safety messages, on which are based the primary use cases in LTE-V2X, makes the semi-persistent-scheduling approach the more suitable for the V2V services.

3.1.2 Mode 4

Mode 4 is the mode standardized by 3GPP for the autonomous radio resource selection. In this mode, vehicles autonomously select their radio resources using the SPS algorithm, which is more detailed in [42, 43, 44]. The SPS is based on the sensing before choosing a resource from a list of candidate resources. The basic principles are:

- When a vehicle reserves one resource, this resource is used to transmit a random number of consecutive messages. This random number, also called the re-selection counter, depends on the periodicity of the CAM messages. The re-selection counter is chosen between [5 - 15] for a periodicity of 10 Hz, [10 - 30] for a periodicity of 20 Hz, and [25-75] for a periodicity of 50 Hz;

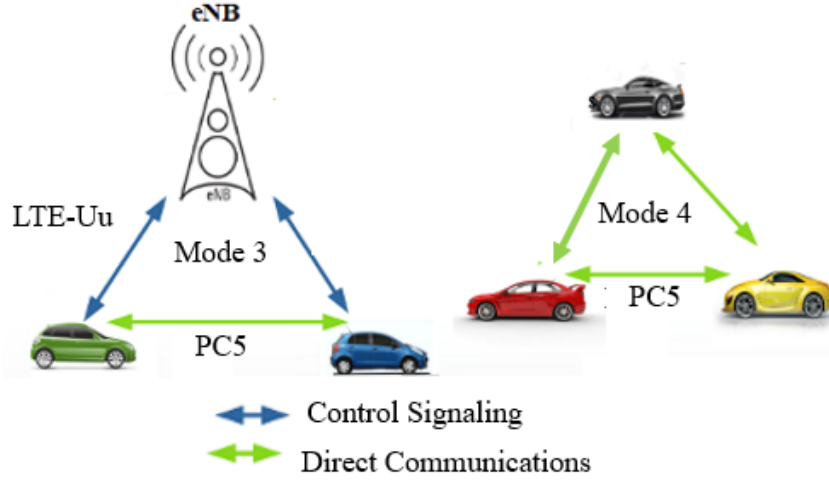


Figure 3.2: Resource Allocation Modes in LTE-V2X

- The periodicity of the CAM messages and the value of the re-selection counter are included in the SCI field. Thus, based on this information, the vehicle can know which resources are free and which ones are occupied by other vehicles;
- After each transmission of a CAM message, the value of the re-selection counter is decremented by 1. When the re-selection counter reaches zero, a new resource must be selected with a probability of $(1 - P)$, where P is the probability of keeping the same resource for the next transmissions.

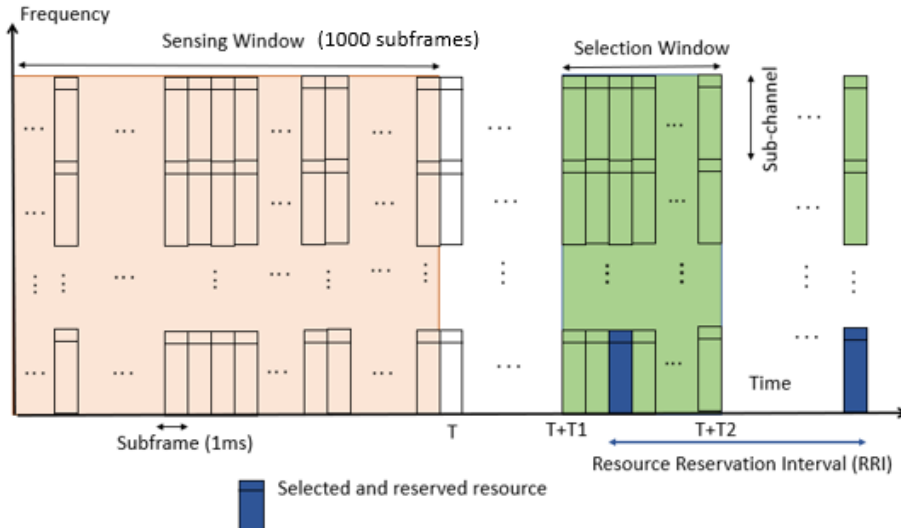


Figure 3.3: Sensing and Selection Windows in LTE-V2X

We can divide the operation of the SPS algorithm in three main steps, as illustrated in Figure 3.4.

In the first step, the vehicle reserves candidate resources within a Selection Window (SW). The SW is a time window defined by $[T + T_1, T + T_2]$, where T is the subframe at

which the vehicle wants to select a new candidate resource. T_1 is the processing time (in subframes) required by a vehicle to identify and select candidate resources for transmission with $1 \leq T_1 \leq 4$. T_2 is also selected by the vehicle and must be included within the range $20 \leq T_2 \leq 100$. Then, the vehicle listens to the channel during the ‘‘Sensing Window’’ for a period of 1 s. The Sensing Window corresponds to the last 1.000 sub-frames. In Figure 3.3, we illustrate the sensing and selection windows for the SPS algorithm.

In the second step, the vehicle creates a first list ‘‘ L_1 ’’ containing the resources previously selected during the selection window, except those presenting a level of Reference Signal Received Power (RSRP) higher than a fixed power threshold Th . Also, ‘‘ L_1 ’’ excludes the resources occupied by other vehicles for their next transmissions according to the SCI information. This list must contain at least 20% of the total resources selected in the first step. Otherwise, this step is iteratively repeated by increasing the power threshold h each time by 3 dB.

In the third step, the vehicle creates a list of resources L_2 presenting the minimum RSSI values. The number of these resources must be equal to 20% of the total resources selected in the first step. Thus, the vehicle chooses randomly a final resource from the L_2 list and reserves this resource according to its re-selection counter for its next transmissions. Random selection avoids collision problems in case two vehicles select the same resource presenting the lowest RSSI value.

In LTE V2X mode 4, performance degradation may occur due to packet collision problems with higher channel load. In this context, the 3GPP has not standardized a specific congestion control mechanism, but it has specified two metrics for determining the channel congestion, which are the Channel occupancy Ratio (CR) and the Channel Busy Ratio (CBR). The CR provides an indication on the channel occupancy generated by the transmitting vehicle and the CBR provides an estimation on the total state of the channel. The LTE-V2X standard defines up to sixteen CBR ranges and it defines for each one a fixed CR_{Limit} that cannot be surpassed by a vehicle. Thus, before the vehicle sends a message, it first measures the CBR and gets the associated CR_{Limit} . Then, the vehicle estimates its appropriate CR. When the measured CR exceeds the CR_{Limit} , the vehicle must adjust its transmission parameters. To this aim, the vehicle can, for example, discard certain packets or augment the MCS to use less sub-channels and hence reduce its CR.

3.2 Resource allocation in 5G V2X

In NR-V2X, we still find the same radio frame of 10 ms and the sub-frame of 1 ms as in LTE-V2X [22] whatever the used numerology, as shown in Figure 3.5. A Physical Resource Block (PRB) is defined by 12 consecutive sub-carriers in frequency domain and a time-slot is defined by 14 OFDM symbols. The Resource Element (RE) is the smallest resource unit. It is defined in the frequency domain as well as in the time domain. A Resource Element is defined by 1 sub-carrier in frequency domain for 1 OFDM symbol duration in time domain. The duration of a time-slot depends on the used numerology. The time-slot follows the rule: $\text{time-slot} = 1/2^n$, where n indicates the order of the numerology. For example, in case of the numerology 0, the time-slot value is 1 ms and it is of 0.5 ms for the numerology 1.

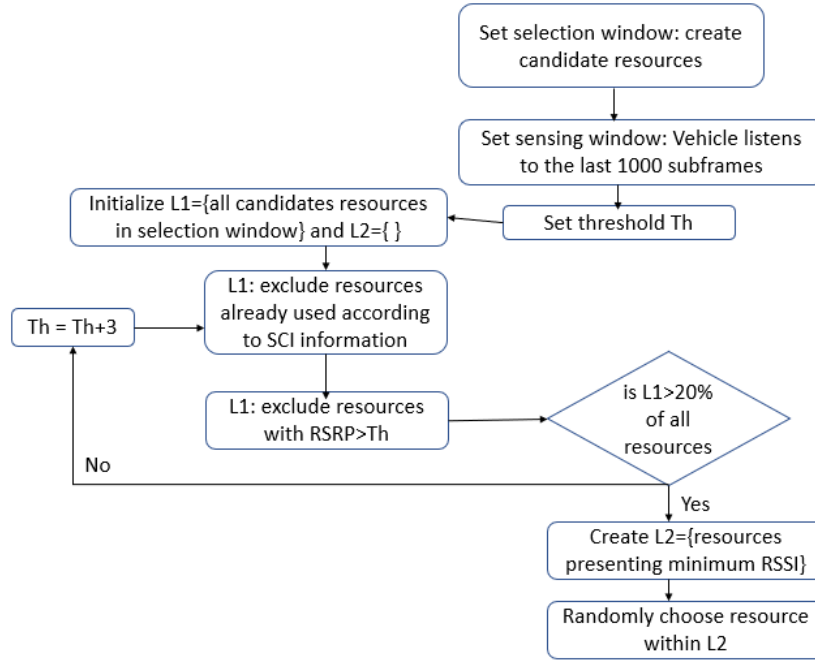


Figure 3.4: Sensing-based Semi-Persistent Scheduling (SPS) algorithm for Mode 4 in LTE-V2X

As in LTE-V2X, 5G-V2X supports two resource allocation modes. The first mode is the under-coverage mode known as mode 1 [45] and the second mode is the out-of-coverage mode known as mode 2 [46]. The 3GPP has discussed the resource pool sharing between NR-V2X mode 1 and mode 2. It is stated that these two modes can use separate resource pools, or they can share the same resource pool. The main advantage of the resource pool sharing is the more efficient use of resources, but it is prone to potential collisions between vehicles operating in mode 1 and those operating in mode 2. In order to solve this problem, vehicles operating in mode 1 notify vehicles operating in mode 2 of the resources allocated for their future transmissions by using the SCI field.

3.2.1 Mode 1

In mode 1, the Next Generation Node B (gNB) schedules and allocates resources to vehicles. Like the LTE-V2X mode 3, the NR-V2X mode 1 uses the DG scheduling, but it uses the CG Scheduling instead of the SPS used in LTE-V2X mode 3 [47]. In the DG, the vehicle must request resources to the gNB for the transmission of every message using the Physical Uplink Control CHannel (PUCCH). Then, the gNB responds with the Downlink Control Information (DCI) over the Physical Downlink Control CHannel (PDCCH). The DCI indicates the sub-channels and slot allocated to the vehicle for the transmission of its message. Then, the vehicle informs other vehicles about the scheduled resources using the SCI. As a result, the nearby vehicles operating under mode 2 can then know which resources vehicles in mode 1 will utilize.

The main drawback of the DG is the increase of the delay and the signaling overhead. For that, mode 1 includes the Configured Grant Scheduling as a second option. In the

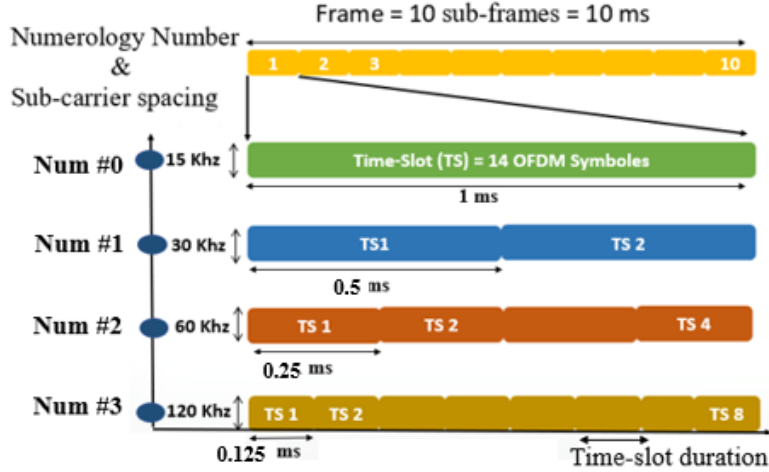


Figure 3.5: NR-V2X Frame Structure

Configured Grant scheduling, the gNB can assign a set of resources, referred to as a Configured Grant (CG), to a vehicle in order to transmit several messages. To this aim, the vehicle sends a message to the gNB indicating information about periodicity of the message and its maximum size. Also, it indicates the QoS information such as the latency and reliability required by the transmitted message. Thus, based on this information, the gNB creates, configures and allocates a CG to the vehicle that satisfies the requirements of the sidelink traffic.

3.2.2 Mode 2

In mode 2 vehicles choose autonomously their appropriate resources. The resources in mode 2 are chosen from the sidelink resources configured by the gNB or pre-configured in the vehicles. However, in order to accommodate new use cases of the NR-V2X, 3GPP members have discussed some solutions for the improvement of the SPS algorithm used in mode 4 of LTE-V2X [48]. For advanced safety service, NR-V2X supports the transmission of periodic and non-periodic traffic with variable packet sizes, unlike LTE-V2X, which considers only the periodic traffic with fixed packet sizes. The 3GPP offers, in NR-V2X, a new channel sensing method, called short-term sensing, similar to the Listen Before Talk (LBT) mechanism, as discussed in [49]. For mode 2, the proposed resource allocation algorithm is the sensing-based Semi-Persistent Scheduling (SPS) algorithm, already standardized for LTE-V2X mode 4, but the 3GPP proposals suggest to modify the sensing and the resource selection procedures in order to adapt to the periodic and the non-periodic traffic. one of the most discussed open issue in mode 2 is the sensing and the resource selection procedures. There are two proposed channel sensing mechanisms:

- *Long-term-sensing*: the sensing used in LTE-V2X mode 4 is an example of the long-term sensing procedure. The main advantage of the long-term sensing consists of avoiding interference problems caused by the transmission with resources used by other UEs;

- *Short-term-sensing*: the short-term-sensing is based on listening the medium before the transmission. The short-term-sensing is more beneficial in case of non-periodic traffic and it can be used as a complementary solution for the long-term-sensing in order to avoid collision problems.

Many discussions have suggested that the long-term-sensing is suitable for the periodic traffic and the short-term-sensing is more adequate for the non-periodic traffic. In fact, in case of non-periodic traffic, the transmission behavior of a vehicle is not predictable, so the resource selection in LTE V2X mode 4 based on the long-term sensing is not applicable any more. The long-term sensing procedure used in LTE-V2X mode 4 can be reused in NR-V2X mode 2 for periodic traffic, where the short-term sensing based on LBT should be used for non-periodic traffic.

The combination of the long-term sensing and the short-term sensing is also another solution. In this case, the long-term sensing can be used to determine and exclude occupied resources and form the list of candidate resources for transmission within sidelink resource selection window. Then, the short-term sensing operates within resource selection window taking into account information from long-term sensing procedure, i.e. list of candidate resources, in order to select a particular resource for transmission within resource selection window.

The 3GPP plans to adopt a new version of mode 2 in Release 17 that can reduce the power consumption of UE devices [50]. Indeed, the power consumption is not a major problem when considering UEs such as vehicles or RSUs. However, this is the case when it comes to other types of UEs, such as UE devices used by pedestrians and cyclists for V2X sidelink communication. The autonomous sidelink mode 2, which is standardized in Release 16, is based on the sensing of the channel during a sensing window, which consumes a non-negligible amount of the energy from the transmitting devices. To address this issue, 3GPP plans in Release 17 to replace the first channel sensing method with partial sensing and random resource selection schemes, which can significantly reduce the overall power consumption of UE devices. However, we note that it is interesting to study the performance of the new proposed methods compared to the traditional autonomous mode 2, which can be considered as an interesting future research direction.

In addition to resource allocation modes 1 and 2 of 5G-V2X, we note that there are other potential sub-modes of mode 2 that were analyzed during Rel.16 but were not standardized. Those sub-modes are still considered as particular use cases of NR-V2X mode 2 and could be of interest in future 3GPP releases. The first one is known as sub-mode 2(b), in which an UE can assist the resource selection of another UE with the assistance information [51]. The assistance of one UE in resource selection by other UEs [50] is already known as mode 2(b) in Release 16 but was not standardized. This assistance information can include several parameters such as the geographical position or the velocity of vehicle, the priority of traffic, the channel occupancy ratio or the Reference Signal Received Power (RSRP). The inter-UE coordination includes two types: type A or type B, where one UE restricts or suggests the resources that can be selected by another UE, respectively. One of the advantages of inter-UE coordination is that it avoids the hidden terminal problem, which may occur when a transmitting vehicle is not in the range of another vehicle and therefore does not know which resources are already being used by that vehicle. In this case, the transmitting vehicle can choose the same resource

that is already used by another vehicle, which can lead to packet collisions. For this purpose, an intermediate vehicle can recommend or restrict the resources to be used by the transmitting vehicle. The second mode of resource allocation, which is discussed in Release 16, but is not adopted in neither Release 16 nor Release 17, is the sub-mode 2(d), in which, a vehicle known as Scheduling UE (S-UE) is responsible for the scheduling of radio resources for a group of vehicles [52], as illustrated in Figure 3.6. For this sub-mode, one of the most important issues is how to choose the S-UE. The choice of the S-UE can be done considering, for example, the geographical position or the hardware capacity of vehicles. Here, we note several open issues about the operation of this sub-mode. Firstly, which resource the S-UE should use when allocating resources to its members? Secondly, is there a probability of interference between vehicles allocated by different S-UEs? Thirdly, how can the S-UE indicate the allocated resources to its members and what is the procedure for members when the S-UE disappears? Finally, what is the adequate scenario for the operation of this sub-mode? In this context, we point out that the platooning scenario, obviously, seems to be the easiest scenario for the operation of the sub-mode 2(d). The stability of the group of vehicles facilitates the resource allocation task for the platoon leader. However, this assumption doesn't preclude the possibility to apply this sub-mode for the other scenarios. We suggest to consider, for example, the position, speed, and direction of vehicles, as decisive parameters, in order to choose the stable scenarios, in which, the operation of the sub-mode 2(d) is easier.

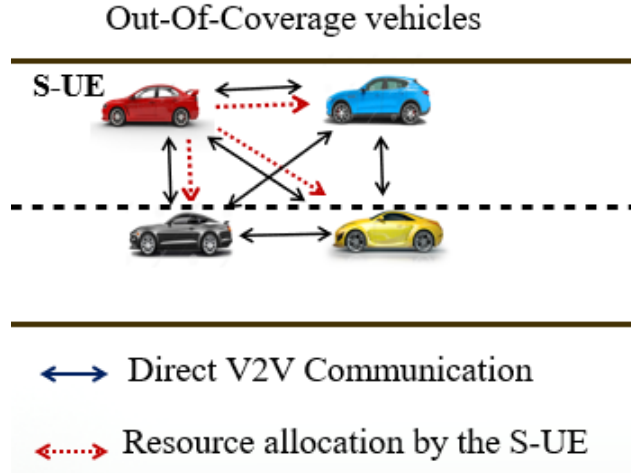


Figure 3.6: Sub-mode 2(d) of NR-V2X

Finally, it is important to note other drawbacks of this sub-mode. In fact this sub-mode may not offer reasonable performance advantages because it may increase the latency and it generates extra signaling overhead. Additionally, this sub-mode may cause interference problems among UEs belonging to different groups. In this context, we conclude that the sub-mode 2(d) needs more research works and experimental results in the future in order to have a more in-depth vision of its advantages and its drawbacks.

3.3 State-of-the-art on LTE-V2X

Regarding the literature review, we note that mode 4 has a huge volume of research works in literature compared to mode 3. This is explained by the fact that mode 3 is less challenging thanks to the control of the eNB, while mode 4 presents different issues related to collision, interference and congestion control problems caused by its decentralized nature. However, even though mode 3 has to cope with a significant reduced set of problems, it remains very important to propose new resource allocation algorithms aiming to optimize the network capacity, the data rate of vehicles or the reuse of resources between vehicles. In the following, we present the state-of-the-art of resource allocation in mode 3 and mode 4, respectively.

3.3.1 State-of-the-art on Mode 3

Authors of [53, 54, 55] have represented the centralized resource allocation in mode 3 by a weighted bipartite graph. In these proposed solutions, vehicles and spectral resources are represented by the vertices of a graph and the edges represent the achievable data rate in each resource based on the Signal-to-Interference plus Noise Ratio (SINR) that the vehicles perceive. In [53], the resource allocation solution aims to efficiently manage resources and to enable the reuse of resources between vehicles with an interference avoidance mechanism. Authors show mathematically and through simulations that this approach improves the performance in terms of the achieved data rate requested by vehicles. Then, in [55], the proposed resource allocation algorithm is based on two approaches, namely bipartite graph matching-based successive allocation (BGM-SA) and bipartite graph matching-based parallel allocation (BGM-PA). The main objective of this algorithm is to find the optimal one-to-one vertex assignment in order to maximize the capacity of the system defined as the achieved data rate. However, in [54], it is assumed that vehicles monitor the sidelink sub-channels with the sensing mechanism and send to the eNB the perceived SINR on these sub-channels. The eNB efficiently allocates resources to vehicles based on this information. However, the perceived SINRs are sent by vehicles to eNB via the up-link interface, using a part of the bandwidth. Next, the authors try to quantify the SINR granularity and evaluate the impact of this quantization on the performance of the system. The same authors propose in [56] two resource allocation schemes. The first scheme aims to minimize the perceived power of sub-channels. In this approach, it is assumed that vehicles send via up-link interface the channel conditions to the eNB. Then eNB schedules resources based on this information with a minimization of perceived power of allocated sub-channels in order to allocate suitable sub-channels. The suitable sub-channels are the not occupied sub-channels or those sub-channels experiencing a negligible interference. However, the second approach aims to maximize the distance for the reuse of sub-channels between vehicles in order to avoid the co-channel interference. The authors demonstrate through simulations that these two approaches outperform the decentralized approach, i.e mode 4, in terms of the Packet Reception Ratio (PRR), as the sub-channels are assigned in a more efficient manner with mitigated interference.

Authors of [57], [58] and [59], focus on the geographical positions-based resource allocation schemes and the distance-based resource reuse approaches. In [57], the resource allocation solution is based on the knowledge of the position of vehicles through the Up-link

Time Difference of Arrival (UTDOA) or the Global Navigation Satellite System (GNSS) positioning. Besides, authors propose that a resource can be allocated for two vehicles if the distance between those vehicles is longer than a fixed resource reuse distance. Next, the same authors propose a new algorithm that aims to maximize the resource reuse distance between vehicles in order to control the probability of interference [58]. The authors prove that this last algorithm allows to improve the PRR when compared to its predecessor, presented in [57].

However, the study in [59] does not propose a specific resource allocation scheduling in mode 3. It demonstrates analytically the existence of an optimal resource reuse distance that maximizes the throughput. This work is also validated by the authors through Monte-Carlo simulations.

The limitation of the aforementioned algorithms is that they do not take into account traffic density and channel conditions simultaneously, which is in contrast to the work presented in [60]. Authors in [60] propose to use the geographical location of the vehicles and the environmental conditions, such as the channel load and the traffic density, to allocate resources to vehicles. This proposal is called adaptive Spatial Reuse of Radio Resources (DIRAC). DIRAC defines 2 distances: the reuse distance and the HD distance. The reuse distance is the distance between 2 vehicles reusing the same resource and the HD distance is the distance between two vehicles transmitting in the same sub-frame but using different sub-channels. This proposal adapts the computed distances to the context conditions, such as the traffic density and the channel load. DIRAC aims to minimize the probability that two interfering vehicles are close to each other in order to minimize the QoS degradation. The simulation results show that DIRAC outperforms existing LTE-V2X mode 3 and mode 4 scheduling schemes in terms of the Packet Delivery Ratio (PDR) in both LOS and NLOS conditions.

Based on the aforementioned research works, we note that many resource allocation proposals in Mode 3 are based on the geographical positions of vehicles. However, despite the performance shown by these algorithms, there may be performance degradation due to inaccurate positioning of vehicles. Moreover, we point out another limitation of the proposed resource allocation algorithms, namely the failure to take into account the QoS requirements of the various V2X traffic types. There is an attempt in this direction in [61], where Allouch *et al.* propose a new algorithm for mode 3, named Priority and guaranteed-based Resource Allocation (PEARL) algorithm. In the PEARL algorithm, authors classify the V2X traffic in two types: safety traffic and non-safety traffic. In this work, the authors aim to guarantee the minimum of resources to the basic safety traffic. For that, the algorithm reserves a guaranteed group of resources for the safety traffic, which is used in case of high traffic density. The guarantee of those resources aims to ensure that the vehicles have always the needed resources to transmit their basic safety messages. Then, the remaining resources are divided between the safety traffic and the non safety traffic. However, in dense traffic scenario and when the reserved resources for the safety traffic are all consumed, the PEARL uses a priority-based resource allocation scheme. In this scheme, a high priority is attributed to the safety messages and a low priority is attributed to the non-safety messages. The simulations demonstrate that the PEARL algorithm can achieve the high reliability and low latency required by the safety traffic without impacting the transmission of the non-safety messages. Recently, the same authors have extended the PEARL algorithm to a new version called PEARL-RM [62].

In PEARL-RM, a new resource Reuse Mechanism (RM) is proposed in order to reuse resources between vehicles of both safety and non-safety traffic.

As previously pointed out, there are not many research works investigating mode 3 in the literature, so this mode remains until now an immature research subject and needs more investigative research works. We summarize the state-of-the-art of the main proposals for resource allocation solutions in mode 3 in Table 3.1.

Reference	Objectif	Scenario	Main results
[53]	Efficiently managing resources and enabling the reuse of resources between vehicles.	High vehicle density	High performance level in terms of the achieved data rate requested by vehicles.
[55]	Find the optimal one-to-one vertex assignment between vehicles and sub-channels	Not defined	Maximization of the capacity of the system defined as the achieved data rate.
[56]	Minimization of the overall power perceived by vehicles and the maximization of the resource reuse distance	Freeway scenario with 600 vehicles	Better performance in terms of the Packet Reception Ratio (PRR).
[57]	New resource allocation algorithm based on the geographical positions of vehicles.	A realistic and congested highway scenario, 2000 vehicles with 50 km/h [63]	Low appreciated error rate when using the GNSS positioning system compared to the UTDOA technique.
[58]	Maximization of the resource reuse distance between vehicles in order to control the probability of interferences	<ul style="list-style-type: none"> • Highway scenario (3 lanes per direction and linear density of 119 vehicles/km) • Urban scenario (667 vehicles) [64] [63] 	High performance level in terms of packet reception ratio and latency compared to [57].

[60]	New resource allocation solution based on the use of the geographical position of vehicles, the channel load and the traffic density	Urban and highway scenarios with 120 vehicles/km and 70 km/h [65].	Better performance than the existing LTE-V2X mode 3 and mode 4 scheduling schemes
[61]	Proposition of PEARL algorithm that aims to guarantee the QoS requirements of the V2X safety and non-safety applications	Highway scenario	High reliability and low latency
[62]	Extension of PEARL algorithm to PEARL-RM algorithm by adding new resource reuse mechanism	Highway scenario	Better performance in terms of reliability, latency and capacity utilisation.

Table 3.1: State-of-the-art of Main Resource Allocation Proposals in Mode 3

3.3.2 State-of-the-art on mode 4

We can categorize the research works related to mode 4 in three main categories. The first category is interested in the evaluation of the impact of the SPS parameters on the performance of mode 4. The second category demonstrates the need to modify the SPS algorithm by adding new procedures in order to enhance the performance of mode 4. The third category proposes new alternatives to the SPS algorithm and demonstrates that those proposed algorithms outperform this last one.

As previously pointed out, the first category of research works, which group the largest number of research works, is interested in the improvement and the evaluation of the performance of the SPS algorithm. In the literature, the first work presenting an evaluation of the performance of the SPS algorithm is presented in [44]. In this work, the evaluation of the SPS algorithm is done under realistic traffic conditions in urban scenarios. The authors demonstrate through simulations that the SPS algorithm can experience significant packet collisions, and its benefits decrease with the increase of the distance between transmitter and receiver, and the channel load. In addition, Nabil *et al.* demonstrate that the resource reservation interval, which refers to the periodicity used by vehicles to transmit their packets, significantly influences the packet data rate performance [66]. The authors conclude through simulations that the PDR increases with the increase of the resource reservation interval. This is explained by the fact that if this interval increases, the probability that another vehicle uses the same resource decreases, thus the PDR increases.

However, authors in [67] demonstrate that the increase of the probability of re-selection P can improve the performance of the SPS algorithm when the vehicles transmit at 10 packets per second. This is explained by the fact that augmenting P reduces the number of resource reservations, and then provides a more stable sensing environment. However, simulations demonstrate that when the channel load increases, the increase of P can reduce

the PDR. In fact, the increase of the channel load reduces the communication range, and due to the high mobility of vehicles, if a vehicle selects a resource and maintains it for a long time, it is highly probable that it will get in range with vehicles that were previously not under its sensing range, and were not taken into account for the resource selection by the sensing-based SPS scheme. As a result, this vehicle will experience packet collisions, which decreases the performance of the SPS algorithm. Also, this study demonstrates the benefits obtained using a low RSRP threshold in step 2 of the SPS algorithm and a high transmit power.

The above-mentioned research works are based on simulations to evaluate the performance of the SPS algorithm. However authors in [42] use analytical models for this purpose. Authors have chosen the PDR as the performance metric. The study models four main types of errors that can affect the quality of transmission in mode 4. Those errors are mainly related to the half-duplex nature of the sidelink interface PC5, to propagation conditions and collision problems. The study also aims to compare the results obtained with the analytical models to those obtained with the simulator implemented over the Veins platform [68]. This work demonstrates that analytical models are capable to accurately model the performance of the LTE-V2X mode 4 communication.

Recently, Stefania *et al.* study the impact of the generation of the CAM packet on the overall performance of autonomous mode 4 [69]. In this work, the authors study the case where the generation of the CAM packet is not exactly periodical even though CAMs are continuously exchanged. For that, they consider the case where the CAM packet generation interval T_g is larger or shorter than the allocation period T_b . The authors study the impact of those parameters on the overall performance considering the PRR parameter. The simulation results show that the optimal value of T_b depends on the conditions but a value of 0.1 s is the optimal one. Furthermore, they demonstrate that the overall performance of mode 4 reduces as soon as the CAM packet generation interval is not equal to the allocation period.

The limitation of the first category of research works is that the authors do not investigate the impact of the SPS algorithm of the autonomous mode 4 on the stringent requirements of V2X applications such as latency and reliability of safety messages under different channel conditions. This aspect needs to be studied more seriously since the autonomous mode 4 is considered as a basic mode due to its independence from the cellular coverage.

After the indication that the SPS algorithm might experience significant performance issues, the need for further enhancements in the mode 4 operation was clear. Therefore, the second category of research works is related to modifying SPS algorithm to improve the mode 4 performance.

The collision problem is among the main performance issues detected by previous works since it significantly affects the overall performance. In fact, in the resource selection phase of the SPS algorithm, a packet collision can happen if two or more vehicles select the same radio resource. Even if the random selection in the final step of the SPS algorithm helps to reduce the collisions between vehicles, it can't totally cope with this problem and then the probability of packet collisions remains therefore not negligible.

Hence, Bonjourn *et al.*, propose a new mechanism for the SPS algorithm that can avoid the collision problems [70]. This solution aims to decrease the transmission collision

probability and to improve the reliability in mode 4 communication. In fact, in the SPS algorithm, the overlapping re-selection window can cause the collision between vehicles. To avoid this problem, the authors propose a Counter Learning and Re-selection (CLR) mechanism. In this mechanism, vehicles transmit the counter values in each packet transmission. The vehicles are then informed about future concurrent re-selections. In this way, the system will not allow the vehicles to perform resource re-selection that can cause a collision within the re-selection window.

In addition, Jeon *et al.* propose a new solution for resource reservation in order to avoid packet collisions [71]. This proposal aims to enhance the SPS algorithm with an additional reservation mechanism. In this reservation mechanism, each vehicle announces the resource reservation information by using a time-frequency coordinate of the reserved resource. This resource reservation is also made much earlier than the actual use of this resource and so it requires a lot of announcements in order to enhance the reliability of this reservation information. Authors demonstrate through simulations that this proposal achieves better performance than the standard SPS in terms of reliability and latency. However, the proposed solution can lead to the overload problem that can be caused by the required announcements of the reserved resource. Another Short-Term Sensing-based Resource Selection (STS-RS) scheme is proposed by authors in [72]. In this proposal, a short-term sensing is used and configured before the resource selection phase. In this scheme, each transmitting vehicle can start the short term sensing based resource selection from the beginning of the resource Selection Window (SW) defined in the standard SPS algorithm. Then, the vehicle performs the short-term sensing measurements during a configured back-off timer. As a result, the selection of the appropriate resource depends then on the result of this short-term sensing procedure. The simulation results demonstrate that this proposed scheme achieves better performance in terms of reliability by reducing the packet collisions probability.

On the other hand, the resource selection phase in the SPS algorithm is based on the linear average of the power intensities perceived on each sub-channel during the sensing window. However, Luis *et al.* propose a new non-linear power averaging method [73], in which the most recent measurements are given a higher priority via exponential weighting. This approach is applied on both step 2 and step 3 of the SPS algorithm. Authors prove, through simulations, that their solution has shown a positive impact in terms of PRR performance, which enhances the reliability in V2V communication in mode 4.

Here, it is worth noting that a wrong resource selection can cause the packets loss problem for a successive packet transmissions during the resource reservation period. For that, Bazzi *et al.* define this event as wireless Blind Spot (WBS) and try to study the probability that it occurs [74]. In order to avoid this problem, authors propose an enhancement to the legacy SPS operation by limiting the maximum duration of any wrong reserved resource. In their proposal, each vehicle keeps an additional parameter that is used to define the maximum duration for the resource reservation period. The authors demonstrate through analytical results, validated by simulations, that this enhancement outperforms the legacy SPS algorithm.

Another important aspect related to the variation of the packet size has taken the attention of Rafael *et al.* in [75]. In fact, in V2V communication, the transmitted messages are formed by a first packet of 300 bytes followed by four packets of 190 bytes. So, let us assume for example that the packets of 300 bytes need 2 sub-channels and those of

190 bytes need only one sub-channel for transmission. In this case, just one of the two sub-channels selected for the transmission of the packets of 300 bytes, which is reserved during the re-selection counter, will be used for the transmission of the packet of 190 bytes. To overcome this problem, the authors propose that the resources are reserved using the re-selection counter only for packets of 190 bytes, which are the more frequent ones. Whereas, for packet of 300 bytes, the SPS is only used to select the adequate resource but this selected resource is not reserved during the re-selection counter. The new proposed SPS achieves a better performance than the standard SPS algorithm in terms of PDR. Here we note that the authors do not consider the case of aperiodic traffic such as the DENM messages.

Finally, the third category aims to propose new alternative solutions to mode 4 that are not based on incremental improvements to the SPS algorithm. In this context, Sabeeh *et al.* propose a new algorithm named Estimation and Reservation Resource Allocation (ERRA) as a new alternative to the SPS algorithm [76]. The ERRA algorithm tries to enhance the reliability of mode 4 by solving the collision problem and enhancing the Packet Reception Ratio. The main idea of the ERRA algorithm is that each vehicle lists all resource locations of the received packets that have the same random counter. With this solution, each vehicle can then predict the resources that will be free in the next resource selection. As a result, the vehicle does not need to depend on the sensing process. The ERRA algorithm is validated through simulations and the authors demonstrate that it presents a significant improvement compared to the standardized SPS algorithm. Then, the same authors have extended the ERRA algorithm to a new version, named Extended-Estimation and Reservation Resource Allocation (E-ERRA) [77]. The main goal of the E-ERRA algorithm is to solve the problem of the lost reserved resources. This problem appears when a vehicle with pre-allocated resource has just left or appeared in the broadcast range before the re-selection process. To solve this problem, E-ERRA specifies alternative resources that will be used by the vehicle if this problem appears. Authors prove through simulations that the E-ERRA reduces the collision ratio and increases the PRR. In the same context, Yang *et al.* propose a new algorithm for mode 4 named PRESS (PREdictive assessment of resource usage) [78]. In this algorithm, the transmitting vehicle should firstly predict the status of the channel for its future transmissions using the aggregate reselection counter information. By exploiting the periodicity of CAM messages, PRESS algorithm can estimate the status of future resource usage at the time of resource use. With this solution, a vehicle can choose the least used resources. The authors demonstrate through simulations that PRESS algorithm outperforms the standard SPS algorithm in terms of packet reception ratio.

In addition, Zhao *et al.* propose a new autonomous cluster-based resource selection scheme, which divides resource pool into orthogonal resource sets in order to reduce the probability of collisions [79]. In their approach, the vehicles are grouped into clusters. Then, each Cluster-Head (CH) selects a resource set that suffers less interference based on sensing. The authors prove that this approach, compared to the SPS algorithm, provides better performance in terms of PRR. However, the limitation of this work is that the selection of resource sets by the CH method may cause a collision problem. The collision problem may occur when a CH selects a resource set that has already been selected by other CH outside its sensing range, which may affect the performance of the autonomous mode 4. Another interesting resource allocation approach is presented in [80] that aims to mitigate the hidden node problem. The authors propose a new resource allocation scheme

aiming to reduce packet collisions. In this solution, vehicles select their resources based on the location and ordering of neighboring vehicles on the road, where the ordering is estimated using the location and speed information received in the beacons messages. The proposed solution is evaluated analytically and through simulations and it is demonstrated that this new scheme outperforms the standard SPS algorithm. Despite the performance achieved by the proposed resource allocation scheme, performance may be degraded if the positioning of vehicles, on which the proposed scheme is based, is inaccurate

The above-mentioned proposed algorithms are globally focusing on the out-of-coverage areas in general. However, Sahin and Boban, focus on the resource allocation in the Delimited Out-of-Coverage Area (DOCA) [81]. DOCA can be considered as a tunnel where no reception from the BSs is possible but the BSs deployed at each end of DOCA are able to serve the vehicles just before their entry or after their exit. Their resource allocation algorithm aims to improve reliability for V2V communication. Therefore, the authors propose that the resource allocation for the out-of-coverage vehicles entering the tunnel is still managed by the eNB based on the predictions of vehicle locations and the propagation conditions. The eNBs deployed at each end of tunnel are able to serve vehicles just before they enter.

Despite the fact that mode 4 has been of interest of many researchers in recent years, there is still a need to further investigate other aspects related to collision avoidance, interference management and congestion control mechanisms. So, new proposals are needed because this mode is considered as the baseline mode of C-V2X technology due to its independence of the cellular infrastructure. We summarize the state-of-the-art of the main proposals for resource allocation solutions in mode 4 in Table 3.2.

Reference	Objective	Simulation scenario	Main results
[44]	Evaluation of the SPS algorithm	Urban scenario [65], 85 vehicles/km and 15 km/h	The SPS algorithm experiences significant packet collisions.
[66]	Study of the impact of the Resource Reservation Interval (RRI) on the performance of the SPS algorithm	Highway scenario [65], 70 km/h and 140 km/h	The Packet Delivery Ratio (PDR) increases with the increase of the RRI.
[67]	Study of the impact of the probability of resource reservation P and the RSRI threshold on the performance of SPS algorithm	Highway slow [65], 120 vehicles/km and 70 km/h	<ul style="list-style-type: none"> • The influence of P on the performance of the SPS algorithm depends on the channel load conditions. • Low values of RSRP threshold in step 2 of the SPS algorithm improve the performance of C-V2X Mode 4.
[42]	Evaluation of the performance of the SPS algorithm with analytical models	Highway scenario: 5 km with 4 lanes (2 lanes per direction) and speed of 70 km/h.	The performances of mode 4 are accurately represented by the analytical models.
[69]	Study of the impact of the non-periodical generation of the CAM packet on the overall performance of mode 4.	Highway scenario	The overall performance reduces as soon as the CAM packet generation interval is not equal to the allocation period.
[70]	Proposition of a new Counter Learning and Re-selection (CLR) mechanism.	Several scenarios: not detailed	Decrease of the probability of collision problems .
[71]	Proposition of a new reservation scheme in order to decrease the probability of collisions.	Urban scenario	High performance in terms of reliability and latency

[72]	Proposition of a new short-term sensing scheme before the resource selection phase	Highway scenario [82]	Reduction of the packet collisions.
[73]	New non-linear power averaging method applied in the SPS algorithm	Urban and Highway scenarios	Better system performance in terms of Packet Reception Ratio (PRR) for both scenarios
[74]	New solution that aims to enhance the SPS algorithm by avoiding the Wireless Blind Spot (WBS) problem	Highway Scenario	The proposed solution outperforms the legacy SPS algorithm
[75]	New resource reservation procedure taking into account the different packets size of transmitted messages	Highway scenarios [65]	Better performance than the standard SPS in terms of PDR.
[76]	Proposition of ERRA algorithm that aims to enhance the reliability of mode 4	Different traffic scenarios	The ERRA presents a significant improvement compared to the standardized SPS algorithm.
[77]	Extension of ERRA to E-ERRA algorithm that aims to solve the problem of the lost reserved resources.	Highway scenario	E-ERRA reduces the collision ratio and increases the PRR
[78]	Proposition of PRESS algorithm that aims to enhance the sensing and the resource selection for mode 4	Highway scenario	PRESS algorithm outperforms the legacy SPS algorithm
[79]	New autonomous resource selection scheme based on the division of resource pool into orthogonal resource sets.	Urban and Highway scenarios [83]	Better performance in terms of PRR
[80]	New autonomous resource selection scheme based on the geographical positions of vehicles and the order of neighboring vehicles on the road	Highway scenario [65]	Enhancement of the performance of C-V2X communications.

[81]	Proposition of a resource allocation algorithm dedicated for the Delimited Out-of-Coverage Area (DOCA)	Highway scenario	Enhanced reliability for V2V communication in DOCA
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Table 3.2: State-of-the-art of Main Resource Allocation Proposals in Mode 4

3.4 State-of-the-art on NR-V2X

As the NR-V2X is recently standardized by the 3GPP, there exist few research works, in the literature, investigating the resource allocation in NR-V2X technology. In this section, we present the most recent research works interested in this subject. We first begin with the research works interested in mode 1, then we present those interested in mode 2.

3.4.1 State-of-the-art on Mode 1

In [\[84\]](#), Song *et al.* propose a new resource allocation algorithm for mode 1. In this work, authors suppose that the gNB allocates resources to vehicles based on the reported Channel State Information (CSI). However, the reporting of the channel state information can lead to the overhead problem. For that, in order to cope with this problem, authors propose in a first stage a new power allocation scheme of CSI transmission, that aims to reduce the energy consumption in transmitting the CSI from the vehicles to the gNB. Then, in the second stage, authors try to maximize the system throughput by modeling the sidelink radio resource allocation problem as a Mixed Binary Integer Non-linear Programming (MBINP).

In [\[85\]](#), Abbas *et al.* propose a two-level resource allocation scheme that aims to reduce the latency, increase the throughput and guarantee the reliability for V2V and V2N communications. In this work, authors consider the scenario where the direct link between the gNB and a transmitting vehicle is blocked by a bypassing trailer. So, in this case, another vehicle can act as a relay between the gNB and the transmitting vehicle. In this scenario, the vehicle considered as a relay should obviously have a good connection with both the transmitting vehicle and the gNB. This vehicle can forward an uplink signal with the V2N link or a downlink one with the V2V link. For that, authors consider two types of traffic, which are the V2V and the V2N communications, sharing the same radio resources. In this context, authors propose an efficient resource allocation algorithm that aims to avoid the interferences between the V2V and V2N vehicles and guarantee the different QoS requirements of both V2N and V2V communications. The simulation results demonstrate that the proposed scheme achieves better performance in terms of high throughput and low latency. Another Deep Neural Network (DNN)-based resource allocation algorithm for mode 1 is proposed by Gao *et al.* in order to maximize the overall system throughput of the V2X links by allocating to vehicles the optimal transmit power [\[86\]](#).

3.4.2 State-of-the-art on Mode 2

In the literature, there exist recent research works interested in the SPS algorithm standardized for the autonomous mode 2 of NR-V2X. Among those research works, we cite the work in [87], where Ali *et al.* evaluate the impact of the main parameters of the SPS algorithm on the overall system performance. In this work, authors take into account different parameters such as the NR flexible numerologies, the maximum number of resources per reservation, the MCS level and the resource selection window. However, Romeo *et al.* focus on the reliability of transmission of the DENM in this autonomous mode [88]. In fact, the DENM, which are of aperiodic nature, are transmitted by a vehicle in order to prevent other vehicles of road hazard events. In this context, authors are interested in the case where both the periodic and the aperiodic messages are transmitted in the same scenario and they share the same radio resources. They analyze the impact of the main parameters of the SPS algorithm of mode 2 on the DENM delivery ratio. They also study the impact of the generation of the aperiodic DENM messages on the reliability of transmission of the periodic CAM messages. Furthermore, authors study the effectiveness of using a short-term sensing with a duration of 100 ms for the transmission of DENM messages. They demonstrate that the use of a short-term sensing with multiple repetitions of DENM messages has an effective advantage on the DENM delivery ratio. However, the reliability of the CAM messages is affected when the load of the DENM messages increases in the scenario. In addition, Yoon *et al.* [89] try to enhance the standard SPS algorithm by proposing a stochastic reservation scheme for the aperiodic traffic. The main idea of their proposal is to predict the next transmission time of the next packet in order to reserve resources for this transmission. This prediction is done by analyzing the last packets intervals. The authors demonstrate through simulations that the proposed scheme achieves high PRR values. Most of the above-mentioned proposals don't consider congested scenarios, where the resource allocation is more challenging due to the possibility of packet collisions and interference problems. However, authors of [90] are interested in the congested intersection areas. For that they propose a novel sensing-based semi-persistent scheduling method in order to efficiently allocate resources to vehicles using the sensing information generated by the RSU. In this work, the authors propose that the RSU acts as a central controller and periodically receives the channel state information from each vehicle. Then, based on these informations, the RSU generates RSRP and S-RSSI maps that will be broadcasted to vehicles in order to better autonomously choose their radio resources. This proposed scheme enables to avoid the collision problems and so outperforms the Standard SPS algorithm proposed for mode 2.

Another important aspect is also recently investigated in the literature, which is the study of the impact of the NR flexible numerologies on the performance of the autonomous mode [91, 92]. In [91], Ali *et al.* focus on the study of the impact of the NR numerologies on the sensing and the selection windows of the SPS algorithm. Authors demonstrate that when the resource selection window size is the same for all numerologies, a higher Sub-Carrier Spacing (SCS) brings better performance and it is beneficial for the reliability of the basic safety service. In addition, Campolo *et al.* evaluate the impact of the SCS on the reliability of transmission of CAM messages in the autonomous mode [92]. This work takes into account different conditions with different CAM periodicity values, channel density values and MCS levels. Authors demonstrate that increasing the SCS significantly improves the reliability of CAM transmission by increasing the PRR. Furthermore, it

also reduces the Update Delay, which refers to the time difference between two successive receptions of two decoded CAM messages. However, the limitation of this work is that authors do not consider the delay spread of the channel and the vehicle speeds as important parameters. In fact, these two parameters have a direct impact on the overall system performance, due to the Inter-Carrier Interference (ICI) and the Inter-Symbol Interference (ISI) problems caused by the Doppler shift and the multipath fading problem, respectively, as demonstrated in [93].

Here, we note that new techniques such as the machine learning technology are recently used to propose new resource allocation algorithms. In this context, authors in [94] propose a decentralized resource allocation algorithm based on deep reinforcement learning technique for V2V communications. In this proposal, the agent, which is considered the V2V connection, can make its own decision to choose the optimal radio resource based on the channel state information. The goal of this proposal is to minimize the interferences between vehicles and meet the reliability and latency required by the V2V communication.

In Table 3.3, we summarize the state-of-the-art of the main proposed resource allocation algorithms for modes 1 and 2 of NR-V2X.

Reference	Mode	Objective	Simulation scenario	Main results
[84]	Mode 1	A new resource allocation algorithm that aims to: <ul style="list-style-type: none"> • Reduce the overhead caused by the reporting of the SCI by the vehicles to the gNB • Maximize the overall throughput for NR-V2X communications 	Urban scenario	Low energy consumption in transmitting the CSI information and high system throughput

[85]	Mode 1	New resource allocation algorithm that aims to guarantee the QoS requirements for both V2V and V2N vehicles	Highway scenario [95]	Minimization of the probability of interferences between V2V and V2N vehicles with high throughput and low latency
[88]	Mode 2	Study of the impact of the autonomous mode 2 on the transmission of the aperiodic DENM messages	Not defined	the application of a short-term sensing increases the DENM delivery ratio
[89]	Mode 2	A new stochastic reservation scheme for the aperiodic traffic	Highway scenario of length 3 km	High performance in terms of Packet Reception Ratio
[90]	Mode 2	Proposition of a novel sensing-based semi-persistent scheduling scheme in the congested intersection areas	Urban scenario with 2 lanes in each direction	Reduction of the probability of collision
[91]	Mode 2	Study of the impact of the NR numerologies on the performance of mode 2	Highway scenario	Higher Sub-Carrier Spacing (SCS) is beneficial for the basic safety service in autonomous mode 2
[96]	Mode 2	Study of the impact of the SPS algorithm on the platooning application	Highway Scenario	the impairments of the SPS algorithm reduce the performance required by the platooning application
[97]	Mode 2	Proposition of a new resource management scheme in the multi-cell scenario	Freeway scenario [98]	Increase of the system performance
[94, 99]	Mode 2	Proposition of a new deep reinforcement learning-based resource allocation scheme for platooning scenario	Manhattans Scenario defined in 3GPP TR 36:885 [100]	Minimization of the interferences with guarantee of the reliability and latency required by the platooning
[86]	Mode 1	New Deep Neural Network-based transmit power allocation	Not defined	Maximization of the overall system throughput of the V2X links

[101]	Mode 2	New Multi-Agent Reinforcement Learning-based resource allocation algorithm for platooning scenario	Urban scenario	Reduction of the Age-of-Information parameter and increase of the probability of transmission of the CAM messages.
[102]	Mode 2	New deep reinforcement learning-based resource allocation algorithm in the platooning scenario	Highway scenario	Decrease of the collision probability between platoon members

Table 3.3: State-of-the-art of resource allocation modes in NR-V2X

3.5 Challenges of resource allocation in C-V2X

Resource allocation in C-V2X has some challenging aspects that remain to be explored. Among the challenging aspects is the collision problem, which is one of the more stringent problem in the autonomous mode identified by the literature review. In fact, the autonomous mode is based on the sensing of the channel for the resource selection procedure. However, a wrong sensing can lead to the choice of a radio resource already used by another vehicle, which can lead to packet collisions. The wrong sensing occurs when two vehicles are unable to detect each other. As a result, one vehicle may choose a radio resource that is already in use by the other vehicle. Furthermore, packet collisions can increase in the congested scenario with high vehicle speeds. This is explained by the fact that when a vehicle selects a resource and moving at a high speed, this vehicle can quickly come within the range of another vehicle using the same resource that was not originally in its sensing range and was obviously not considered during the resource selection phase of the SPS algorithm. For that, we highlight that, even if many proposals existing in the literature try to solve the collision problem with their proposals, there is still a need to more investigate this challenging aspect in the future research works.

In addition, a lot of proposals in the literature highlight the limitations of the Half Duplex (HD) nature of the sidelink PC5 interface. In fact, the C-V2X equipment operate under the HD mode. As a result, a vehicle cannot transmit and receive simultaneously. For this reason, when a vehicle is under transmission, it is not able to receive other messages from its neighbors, which is very dangerous for the road safety when the received messages are belonging to the safety applications. The problems caused by the HD limitation of C-V2X equipment can be easily mitigated by the e/gNB in the network-controlled mode by allocating time-orthogonal resources to neighboring vehicles. However, in the autonomous mode, the vehicle does not have a holistic perception of the network topology, so the impact of the HD is stronger in this mode.

Furthermore, regarding the literature review, we note that the majority of the research works found in the literature are interested in the performance evaluation of the proposed resource allocation algorithms for C-V2X, while others have proposed new alternative solutions. However, there is a lack of research that addresses resource allocation considering

the requirements of different vehicular applications. Indeed, there are different traffic types and services with different requirements in vehicular applications, as presented in the previous chapter. For this reason, categorization should be considered in the proposed resource allocation algorithms to significantly improve the scheduling process for V2X communications.

3.6 Conclusion

Resource allocation in C-V2X has a major impact on the performance of V2X communications. For a better understanding of the up-coming chapters, we reviewed in the first part of this chapter the main technical concepts related to resources and resource allocation modes in both LTE-V2X and NR-V2X technologies. In the second part, we provide a comprehensive overview of the state-of-the-art in resource allocation in C-V2X technology. We present the existing research work on modes 3 and 4 of LTE-V2X. We also present the most recent published research addressing mode 1 and mode 2 of NR-V2X. In addition, we identify a number of challenging aspects of resource allocation in C-V2X.

Reviewing the literature, we find that only a few research works address the resource allocation in mode 3 of LTE-V2X, while several research works investigate the performance of mode 4. Furthermore, we find a lack of research that addresses resource allocation considering the requirements of vehicular applications. For this reason, in the next chapter, we present the first contribution of our thesis that addresses resource allocation in mode 3 of LTE-V2X considering the safety-related applications.

Resource allocation in LTE-V2X: Clustering-based Resource Allocation Algorithm for Safety V2V Communications

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4.1 Introduction

With respect to the state-of-the-art already presented in Chapter 3, we note that the resource allocation algorithms proposed in the literature do not take into account the requirements and categorization of different V2X applications. However, the safety related applications are the most critical and time-constrained V2X applications. Since the resource allocation strategies have a great impact on the overall performance of V2X communications, we emphasise here that the safety traffic requires an efficient radio resource

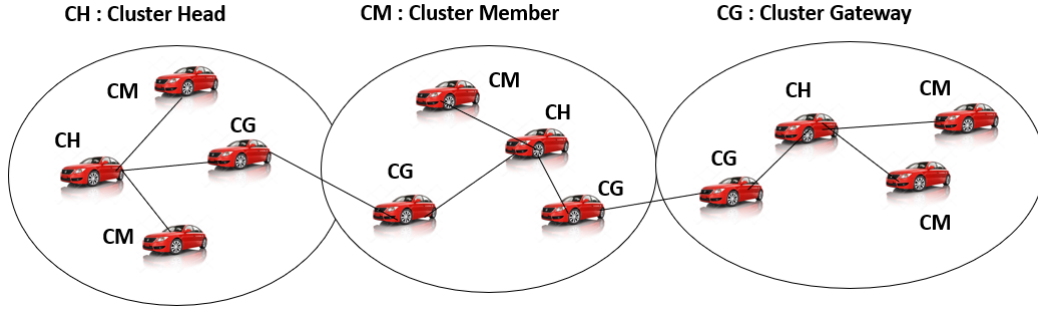


Figure 4.1: Clustering Architecture in VANETs

management. Therefore, in this chapter, we propose a new algorithm for resource allocation in LTE V2X mode 3, where we are only interested in the safety-related traffic. The proposed resource allocation algorithm, which we call the Maximum Inter-Centroids Reuse Distance (MIRD) algorithm, is based on the clustering technique, and includes three main steps. In the first step, the vehicles are clustered according to their geographical position and direction. The second step consists of allocating radio resources to clusters so that the radio resources are divided into multiple resource sets. Finally, the third step is for the case when the number of available resources is not sufficient for all transmitting vehicles. In this case, the MIRD algorithm uses clustering by proposing a new approach for reusing resources between clusters. The remainder of this chapter is organized as follows. In Section 4.2, we first introduce the clustering in vehicular networks. Section 4.3 provides a detailed description of the resource allocation strategy in MIRD algorithm. Then, we discuss the performance evaluation of the proposed algorithm in Section 4.4. Finally, we conclude this chapter in section 4.5.

4.2 Clustering in vehicular networks

Clustering is considered as one of the most important widely used machine learning techniques that facilitate many processes [103]. Clustering is applied in a large number of domains and has many practical applications [104]. Vehicular network is one of the most widely used application areas of clustering technique [105], in which vehicles are grouped into clusters, as shown in Figure 4.1. In our proposed resource allocation algorithm, we have applied a new specific clustering technique in order to facilitate the resource management task. However, before presenting the clustering approach applied in the MIRD algorithm, we first give a brief overview of the state-of-the-art of the application of the clustering in vehicular networks.

4.2.1 State-of-the-Art

In our literature search, we found many clustering approaches for vehicular networks as described in [106, 107]. Each proposed clustering algorithm has an appropriate mechanism for selecting the cluster head based on a particular metric. The vast majority of the proposed clustering approaches consider the relative mobility of the vehicle as an appropriate

metric for cluster head (CH) selection. The first algorithm proposed in the literature is the MOBility-based Clustering (MOBIC) algorithm [108]. MOBIC was originally proposed for Mobile Adhoc NETWORKS (MANETs), but is also suitable for VANETs. The basic idea of the MOBIC algorithm is to calculate the relative mobility of the vehicle based on the Received Signal Strength (RSS). In MOBIC, the vehicle with the lowest relative mobility is selected as CH. Another algorithm, known as Aggregate Local Mobility (ALM), is also proposed in [109]. The relative mobility in the ALM algorithm is defined as the relative distance of the vehicle from all its neighbors. The vehicle with the smallest relative distance from its neighbors is selected as CH. The author in [110] proposes the Adaptable Mobility-Aware Clustering Algorithm, which is based on the Destination positions (AMACAD). In AMACAD, the used metric depends on several parameters, such as relative destinations, final destinations, relative speed, and current position of vehicles. In [111], the relative mobility is calculated from the difference between the position, velocity, and acceleration of the vehicle and all other vehicle members of the cluster. Thus, the cluster head is the vehicle with the lowest relative mobility. However, in [112], the author proposes a new clustering approach where the selected CH is the vehicle whose geographical position is closest to the central position of the cluster. The cluster members are the vehicles that are located within a hop of CH.

4.2.2 MIRD clustering approach

All of these previously mentioned clustering algorithms are based on a distributed approach. However, in the MIRD algorithm, a centralized approach is used for clustering. We assume that the eNB can group vehicles according to their geographical position and direction. Here, we define a cluster by its centroid, which refers to the central position of the cluster, and its radius, denoted by R , as shown in Figure 4.2. The eNB retrieves the geographic positions of the vehicles using either the UTDOA technique or the GNSS. UTDOA is a technique based on the difference between the arrival times of two consecutive up-link packets. We mention here that our clustering approach is based only on grouping vehicles according to their geographic position, and therefore the cluster head selection step is not required in our clustering approach.

Considering $\mathbb{V} = \{v_1, v_2, \dots, v_M\}$ the set of M vehicles present in the cell at a given time, when the cell starts the resource allocation procedure. Based on the positions of the vehicles, the eNB runs the clustering algorithm to divide M vehicles into K clusters $\mathbb{C} = \{C_1, C_2, C_3, \dots, C_K\}$ so that:

$$\sum_{i=1}^K |C_i| = M \quad (4.1)$$

and

$$\bigcap C_i = \emptyset \quad (4.2)$$

If we denote the number of vehicles in cluster C_i by M_i , we also have:

$$\sum_{i=1}^K M_i = M \quad (4.3)$$

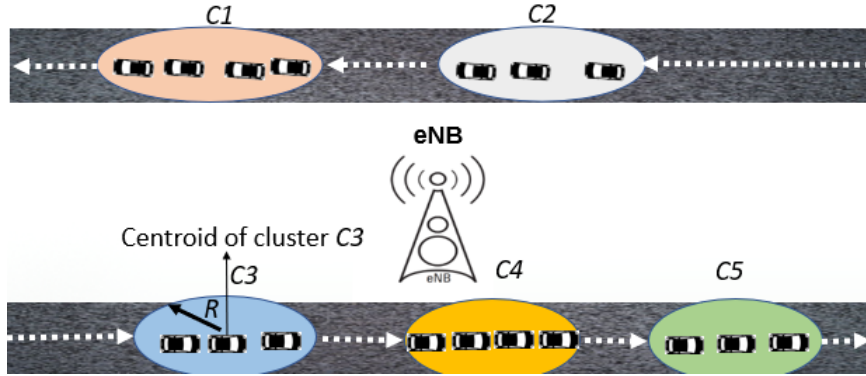


Figure 4.2: MIRD clustering architecture

In the MIRD algorithm, we have chosen the clustering algorithm presented in [113]. However, any clustering algorithm based on the geographical positions and direction of vehicles can be chosen. Next, after the clustering of vehicles, the eNB executes the second task which is the resource allocation as described in Section 4.3.

4.3 Resource allocation

The resource allocation mechanism applied in the MIRD algorithm is divided into two main steps. The first step is the resource sets formation and the second step is the resource reuse as explained in detail in Sections 4.3.1 and 4.3.2, respectively. The MIRD resource allocation process takes into account the HD limitation of sidelink PC5 interfaces. In fact, the PC5 interface is of HD nature and so a vehicle cannot transmit and receive at the same time, i.e. using the same time-slot. For this reason, when a vehicle is under transmission, it is not able to receive other messages from its neighbors, which is very dangerous for the road safety when the received messages are belonging to the safety applications. In order to avoid the problems caused by the HD aspect, we propose to allocate sub-channels within different sub-frames to vehicles of the same cluster.

In addition, the resource allocation in mode 3 of LTE-V2X supports both the dynamic allocation and the semi-persistent scheduling as already explained in the previous chapter. However, since the MIRD algorithm is interested in the basic safety messages, which are of periodic nature, the SPS approach still the best choice. In this approach, a reselection time (T_{resel}), which is a multiple of the beacon period, is used in order to transmit with the same resource for a successive number of transmissions. The work in [58] has already demonstrated that a reselection time (T_{resel}) of 2 seconds is the best compromise between control signaling and performance. For this reason, the MIRD algorithm is executed every 2 seconds.

4.3.1 Resource sets formation

In the MIRD algorithm, the resources are allocated to vehicles so that the overall resources are divided into multiple resource sets. Figure 4.4 illustrates an option when resources are

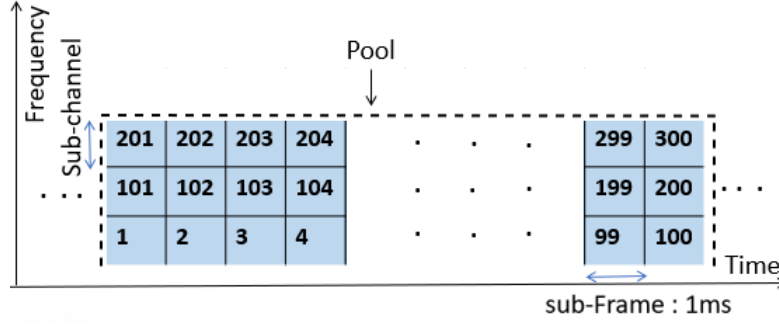


Figure 4.3: Resource Pool with $N_{sf} = 100$ sub-frames and $N_{sc} = 3$ sub-channels

divided into 3 time-orthogonal resource sets, denoted by $subset_1$, $subset_2$ and $subset_3$. In this context, we mean by resources the Beacon Resources (BR). The BR is defined by one or more sub-channels required to transmit the CAM packet. A set of sub-channels within a certain number of sub-frames forms a resource pool in LTE-V2X. The number of sub-frames in the resource pool depends on the transmission interval of the beacon messages, and it is computed as 1,000 divided by the beacon transmission rate λ . For example, if the beacon transmission rate is $\lambda = 10$ pps, the number of sub-frames in the pool is then equal to $N_{sf} = 1,000/10 = 100$ sub-frames. Thus, if the number of sub-channels is set to $N_{sch} = 3$ sub-channels, then the total number of available resources is $N_{res} = 300$ resources as illustrated in Figure 4.3.

For a better understanding of the resource set formation mechanism, let us denote by $\mathbb{R} = \{r_1, r_2, r_3, \dots, r_N\}$ the set of resources in the cell. Each resource corresponds to a BR which is a fixed number of sub-channels necessary to transmit a CAM message. We also suppose that each vehicle only needs one resource allocated by the eNB. Depending on the number of vehicles present in the cell, the number of resources can be greater than, equal to or smaller than the number of vehicles. When $M < N$, the eNB doesn't run out of resources and there are still unused resources in the cell. When $M = N$, each vehicle is allocated a distinct resource in the cell and there is no free resource available in the cell any more. When $M > N$, it is necessary to reuse resources in different clusters. The present work focus on the last case where the resource reuse approach is more detailed in Section 4.3.2.

We denote the set of resources allocated to cluster C_i by $\mathbb{R}_{C_i} = \{r_{C_i}^1, r_{C_i}^2, r_{C_i}^3, \dots, r_{C_i}^{M_i}\}$. As each vehicle only needs one resource, we can consider $r_{C_i}^j$ as the resource that the eNB allocates to vehicle j in cluster C_i . For each cluster C_i , $i = 1, 2, \dots, K$, the eNodeB executes Algorithm 1 and allocates a set of M_i resources. Algorithm 1 presents the first phase of resource allocation. In the case that $M > N$, the first phase of resource allocation in which each resource is allocated once ends with some cluster C_j so that the number of remaining resources is smaller than the number of vehicles of this cluster. That means:

$$N - \sum_{i=1}^{j-1} M_i < M_j \quad (4.4)$$

In this case there still other vehicles belonging to other clusters not yet allocated, which needs the reuse of resources between clusters as more detailed in Section 4.3.2

Algorithm 1: Resource allocation in phase 1

```

Result:  $\mathbb{R}_{C_i}, \forall C_i \in \mathbb{P}_1$ 
 $\mathbb{P}_1 = \text{Null};$ 
/*  $\mathbb{P}_1$  is the set of clusters having resources allocated in phase 1
   */
 $S = N;$ 
/*  $S$  is the remaining resources */
 $i = 1;$ 
while ( $S \geq M_i$ )  $\&\&$  ( $i \leq K$ ) do
    Add_cluster_into_ $\mathbb{P}_1$  ( $C_i$ );
    for  $x = 1$  to  $M_i$  do
        |  $r_{C_i}^x = r_x;$ 
    end
     $S = S - M_i;$ 
     $i++;$ 
end

```

4.3.2 Resource Reuse Approach

Resource reuse is a well-known technique that is widely used in all wireless networks [114, 115, 116, 117]. In particular, the vehicular network is characterized by being a large-scale network, especially in dense urban areas. As a result, the network capacity in terms of the available resources may not be sufficient to meet the needs of all vehicles. In this case, a special resource reuse mechanism is needed. In fact, the safety traffic is a very critical traffic that always requires the availability of radio resources. If a vehicle wants to transmit a critical safety message and no resources are available, the message will not be transmitted, which may lead to a dangerous traffic accident. For this reason, the reuse of resources between vehicles is necessary, especially when vehicle density is high.

Regarding the resource allocation algorithms proposed in the literature for vehicular network [57, 58]), where the distance-based resource reuse mechanism is used, it should be noted that this mechanism requires the calculation of the distance between all pairs of vehicles to make resource reuse decisions. However, the resource reuse in MIRD algorithm is based on the already deployed clustering architecture, which facilitates the resource reuse task. Indeed, the resource reuse task is applied between clusters instead of applying it between vehicles, as it is the case in the traditional algorithms. In MIRD algorithm, it is sufficient to compute the inter-centroid distance between two clusters in order to enable the reuse of resources between all vehicles of both clusters. In fact, in our proposal, two clusters C_i and C_j can reuse the same resource set, if the ICD_{ij} of clusters C_i and C_j is greater than a fixed threshold, known as RC_{reuse} . We denote by Inter-Centroid Distance (ICD) the distance between the centroids of two clusters. For that, MIRD has the advantage of reducing the number of calculation operations required, the power consumption of computation resources and the time needed to make decisions for the resource reuse. The RC_{reuse} parameter, illustrated in Figure 4.4, is calculated in Equation (4.5) as follows.

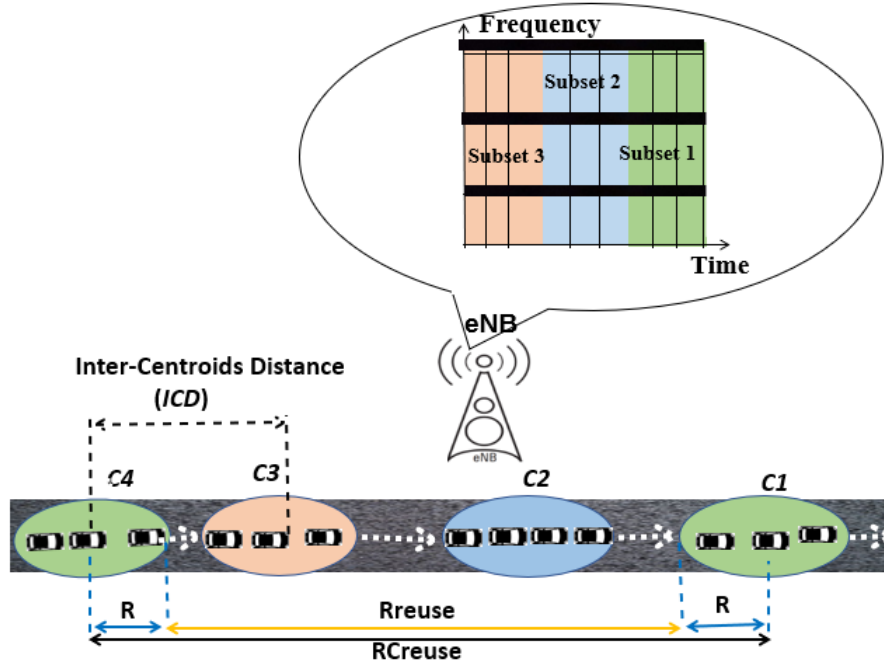


Figure 4.4: Clustering-based resource allocation scheme under-cellular coverage

Definition 4.3.1. The RC_{reuse} is defined as:

$$RC_{reuse} = R_{reuse} + 2 * R \quad (4.5)$$

Here, the R_{reuse} parameter specifies the minimum distance between two vehicles that can reuse the same resource. For the calculation of the R_{reuse} parameter, we refer to the work presented in [118], where the formula and equations are more detailed.

Let's now consider the resources reuse between clusters in detail. After the first phase of resource allocation, i.e., the resource set formation as already described in Section 4.3.1, there are $j - 1$ clusters having resources allocated and $K - j + 1$ clusters waiting for resource allocation. In phase two, we adopt a cluster-based resource allocation approach to reduce the complexity of the resource allocation algorithm. The whole number of resources allocated to a cluster in the first phase will be given to another cluster in the second phase. Algorithm 2 presents the second phase of resource allocation in which different clusters can use the same resources when they are sufficiently far from each other.

Let's call a cluster which has not received allocated resources and must reuse resources of another cluster a *requesting cluster*. The cluster which has already resource allocated in phase one and its resources can be given to a requesting cluster is called an *offering cluster*. To minimize the interference between two clusters using the same resources, the distance between them should be maximized. In order to allocate resources to a requesting cluster C_j , the eNB establishes a list of candidate clusters. The candidate clusters are the clusters which have been already allocated with resources in phase 1 and have the inter-centroid distance with cluster C_j greater than RC_{reuse} . This list is sorted by the inter-centroid distance with C_j in a decreasing order. The eNB traverses the list from one cluster to

Algorithm 2: Resource allocation for a requesting cluster C_j in phase 2

```

Result:  $\mathbb{R}_{C_j}$ 
 $\mathbb{L} = \text{Distances\_from\_}C_j\text{\_greater\_than\_}RC_{reuse}(\mathbb{P}_1)$ ;
Sort_by DECREASING Distance_from  $C_j$  ( $\mathbb{L}$ );
 $\mathbb{R}_{C_j} = \text{Null}$ ;
 $\mathbb{X} = \text{Null}$  ;
/*  $\mathbb{X}$  is the set of resources already reused by requesting clusters
   */
resource_found = false;
p = 0;
while (!resource_found) &&& ( $\mathbb{L} \neq \emptyset$ ) do
     $C_k = \mathbb{L}[0]$ ;
     $p = p + M_k$  ;
     $\mathbb{R}_{C_j} = \mathbb{R}_{C_j} \cup \mathbb{R}_{C_k}$  ;
    if  $p \geq M_j$  then
        if ( $\mathbb{R}_{C_k} \notin \mathbb{X}$ ) OR ( $\mathbb{R}_{C_k} \in \mathbb{X}$  AND  $ICD_{jx} \geq RC_{reuse}$ ) then
            resource_found = true;
             $\mathbb{X} = \mathbb{X} \cup \mathbb{R}_{C_k}$  ;
            /*  $ICD_{jx}$  is the inter-centroid distance between the
               cluster  $C_j$  and any cluster  $C_x$  which already reuses the
               resource set  $\mathbb{R}_{C_k}$  */
        else
            |  $\mathbb{L} = \mathbb{L} \setminus C_k$  ;
        end
    else
        |  $\mathbb{L} = \mathbb{L} \setminus C_k$  ;
    end
end
if resource_found == false then
    |  $\mathbb{R}_{C_j} = \text{Null}$ ;
end

```

Table 4.1: Main parameters of MIRD algorithm

Parameter	Description
ICD	Inter-centroids distance: distance between the centroids of two clusters
R	Cluster radius
R_{reuse}	Minimum distance between two vehicles reusing the same resource as computed in [118].
RC_{reuse}	Minimum distance between two clusters reusing the same resource set as computed in equation (4.5)

another and selects one or more clusters so that the number of total resources is greater than or equal to M_j . The selected resources may be already reused by another requesting cluster C_x but the inter-centroids distance ICD_{jx} between clusters C_j and C_x must be greater than the RC_{reuse} threshold. We present the main parameters of MIRD algorithm in Table 4.1.

4.4 Performance Evaluation

In order to demonstrate the performance of the MIRD algorithm, we rely on simulations performed with the LTEV2VSim simulator [119][120]. LTEV2VSim is a Matlab-based open-source simulator dedicated for resource allocation in LTEV2V communications. The vehicle mobility is based on realistic traffic traces generated by the PTVVISim simulator [64] of an urban scenario of Bologna. The simulated scenario consists of $M=60$ vehicles that periodically exchange safety CAM messages every 0.1 ms. The size of a CAM message is 300 bytes. The radius of the cluster in our scenario is 200 m and the number of clusters in the scenario is $K=9$ clusters. We chose the total number of available resources $N=40$ resources so that we can model the case where the total number of required resources in the scenario is higher than the total number of available resources. The propagation and NLOS modeling implemented by the LTEV2V simulator is the WINNER + B1 channel model as presented in [121]. The simulation parameters are presented in Table 4.2.

The performance evaluation of MIRD algorithm is done by comparing it with a reference algorithm, denoted as $Algo_{ref}$, where the eNB sorts the resources and assigns to each vehicle the first free BR. In our simulations, we evaluate the performance of the proposed algorithm considering the reliability, the resource reuse, and the complexity as more detailed below.

4.4.1 Reliability

The reliability is one of the most important requirements of the V2X applications, and in particular the safety V2V communications, in order to ensure the basic safety service. In our simulations, we chose the Packet Reception Ratio (PRR) and the Average Error Rate (AER) as Key Performance Indicators (KPI) for the evaluation of the reliability, which are defined as follows.

Definition 4.4.1. The PRR is defined as the ratio between the number of successfully received beacons and the total number of neighbors.

$$PRR = \frac{\text{Number of successfully received beacons}}{\text{Sum of the number of neighbors}}$$

Definition 4.4.2. The AER parameter is defined as the ratio between the number of not correctly decoded beacons and the total number of beacons expected to be received.

$$AER = \frac{\text{Number of not correctly decoded beacons}}{\text{total number of beacons expected to be received}}$$

Figures 4.5(a) and 4.5(b) show the variation of the PRR and the AER, respectively, in function of the distance between transmitter T_x and receiver R_x for MIRD algorithm compared to the reference algorithm $Algo_{ref}$. The PRR decreases when the distance between transmitter and receiver increases. On the contrary, the AER increases when the distance between transmitter and receiver increases. The difference between MIRD and $Algo_{ref}$ is very clear in the figures for the distances higher than 100 m. For example, for the same distance of 150 m, the PRR of MIRD is about 92%, while the PRRs of $Algo_{ref}$ is about 81%. Also, for the same distance, the AER of MIRD is about 0.09 while the AER of $Algo_{ref}$ is about 0.19. Based on the obtained results, we demonstrate that MIRD algorithm achieves better performance by increasing the reliability of safety V2V communications.

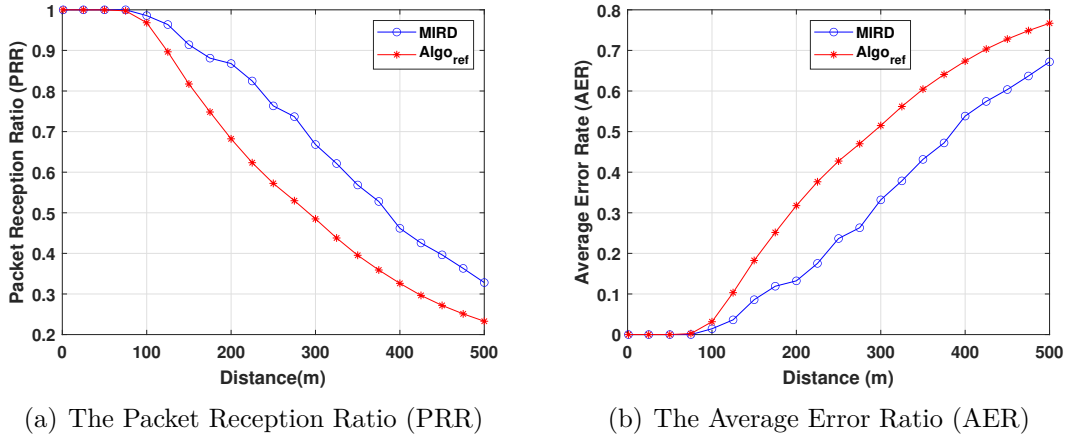


Figure 4.5: The Packet Reception Ratio and Average Error Ratio for MIRD and $Algo_{ref}$ in an urban scenario of Bologna

4.4.2 Resource Reuse

For the performance evaluation of the MIRD resource reuse approach, we chose the Average Blocking Rate (ABR) parameter, which is defined here by the following formula:

Definition 4.4.3. The ABR is defined as the ratio between the number of blocked vehicles due to the unavailability of resources and the total number of vehicles.

$$ABR = \frac{\text{Number of blocked transmitters}}{\text{total number of vehicles}}$$

In addition, we also consider the resource reuse rate (λ) parameter, which we define here as:

Table 4.2: Simulation Parameters

Parameter	Value
Beacon Period	0.1 s
Beacon size	300 bytes
Channel Bandwidth	10 MHz
Frequency	5.9 GHz
Modulation and Coding Scheme (MCS)	5
Duplexing	HD
Equivalent Radiated Power (dBm)	20 dBm
Tx/Rx antenna Gain	3 dB
Antenna height	1.5 m
Path Loss model	WINNER +(B1)
Reselection time (T_{resel})	2s

Definition 4.4.4. The resource reuse rate (λ) is defined as the ratio between the number of clusters reusing the resource sets and the total number of clusters in the scenario.

$$(\lambda) = \frac{\text{Number of clusters reusing resources}}{\text{total number of clusters}}$$

Figure 4.6 illustrates the ABR of MIRD compared to the reference algorithm. As shown in the figure, MIRD presents an ABR equal to 0% thanks to the resource reuse approach, while the ABR of $Algo_{ref}$ is not null. This is explained by the blocking of transmitters when there are no resource available. As already explained, the blocking of transmitters is very dangerous in the context of the basic safety messages because the blocked vehicle is not detected by its neighbors.

Figure 4.7 shows the values of the resource reuse rate for three traffic scenarios with a fixed number of resources $N = 40$ resources, as presented in Table 4.3. As shown in the figure, the resource reuse rate increases with the increase of the number of vehicles. For $M = 80$ vehicles, the resource reuse rate is $T = 50\%$ which increases also the resource allocation capacity. Here, we define the resource allocation capacity as the total number of resources that can be allocated to vehicles without collision. Assuming for example that we have 100 resources, so 100 vehicles can be allocated without collision. However, when we apply the resource reuse approach with a resource reuse rate of 50%, the resource allocation capacity will be of 150 resources which is more beneficial in case of high vehicle density areas.

4.4.3 Complexity Gain

We can also highlight another advantage of the MIRD algorithm, which is related to the algorithm complexity. For this purpose, we define another parameter, referred to the gain in the number of needed computation operations, denoted by $G_{N_{co}}$ and defined as follows.

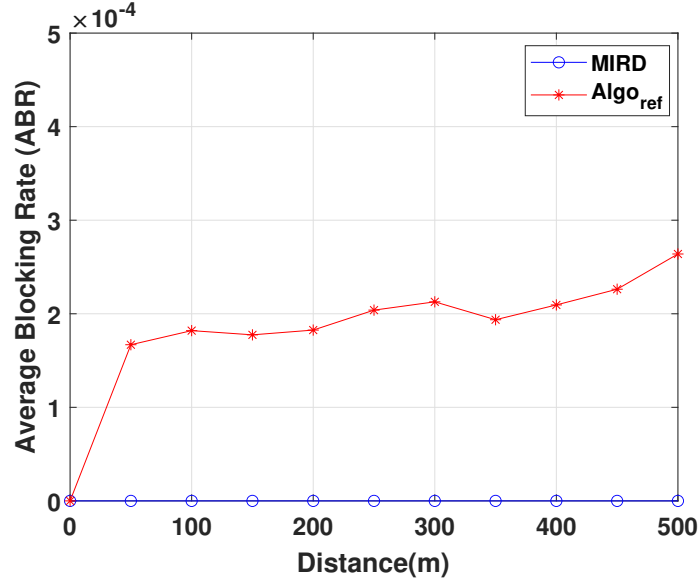


Figure 4.6: The Average Blocking Rate (ABR) for MIRD and $Algo_{ref}$ in an urban scenario of Bologna

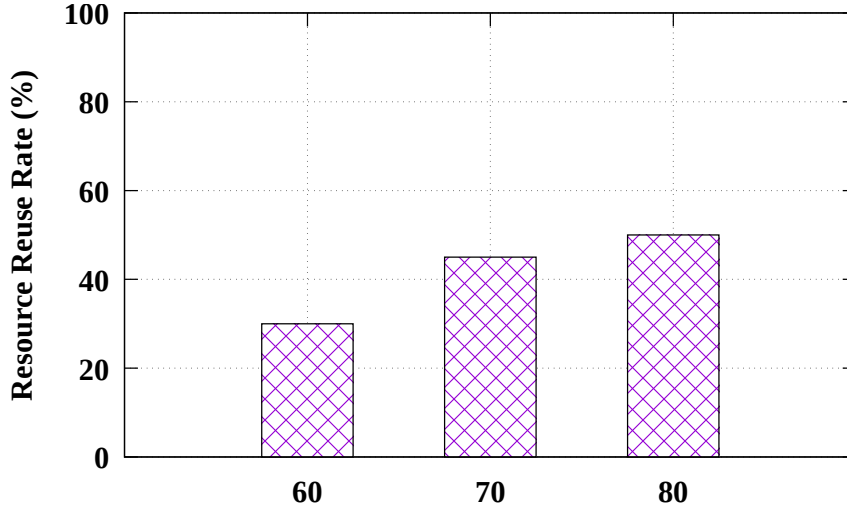


Figure 4.7: The Resource Reuse Rate (λ) for MIRD in 3 traffic scenarios

Definition 4.4.5. The complexity gain ($G_{N_{co}}$) is computed as the difference between the number of needed operations to make resource reuse decision in the standard Resource Reuse Distance (RRD)-based approach and the number of needed operations to make resource reuse decision in the MIRD algorithm.

$$G_{N_{co}} = \text{Needed operations}_{RRD} - \text{Needed operations}_{MIRD}$$

We remind that in the standard RRD-based approach, the resource reuse for a given vehicle v_i is applied after the computation of the distance between this vehicle and all other

Table 4.3: traffic scenarios

Number of vehicles	Number of resources	Total number of clusters	Number of offering clusters	Number of requesting clusters
Scenario (a): 60	40	9	6	3
Scenario (b): 70	40	11	6	5
Scenario (c): 80	40	12	6	6

vehicles in the scenario. Let us suppose that we have 60 vehicles grouped into 9 clusters and 40 resources. Among those clusters, there are 6 offering clusters and 3 requesting clusters. The total number of vehicles in the offering clusters is 40 vehicles and the total number of vehicles in the requesting clusters is 20 vehicles. Here, we compare the resource reuse mechanism for both approaches. In the standard approach, for each requesting vehicle v_i , we need the computation of the distance between v_i and all other offering vehicles. In our scenario, each vehicle needs 40 operations and thus we need $40 \times 20 = 800$ operations for all requesting vehicles. However, when we apply the MIRD approach, we need for each requesting cluster 6 operations and thus we only need $6 \times 3 = 18$ operations for all requesting clusters. So, the gain in the number of computation operations is very high and it is of $G_{N_{co}} = 800 - 18 = 782$ operations, which reduces the complexity of the MIRD algorithm. We illustrate the complexity gain in Figure 4.8 for three traffic scenarios as presented in Table 4.3. As shown in the figure, the number of computation operations increases with the increase of the total number of vehicles in the scenario. So, the gain achieved by the MIRD algorithm is very important in the congested traffic scenarios.

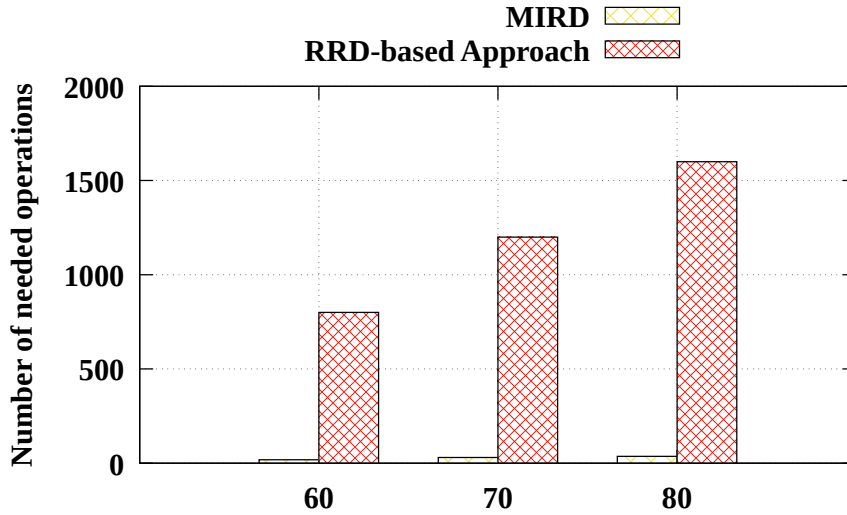


Figure 4.8: The complexity gain for MIRD in 3 traffic scenarios

4.5 Conclusion

In this chapter, we focus on resource allocation for safety V2V communications. For that, we propose a clustering-based resource allocation algorithm for mode 3 of LTE-V2X, named Maximum Inter-Centroids Reuse Distance (MIRD). The MIRD algorithm aims to enhance the reliability of safety V2V communications and avoid the blocking of transmitters caused by the unavailability of radio resources, which is very dangerous for safety traffic. Moreover, MIRD algorithm achieves a very high complexity gain compared to the standard RRD-based approach.

In the second part of this thesis, we address the resource allocation in the 5G-V2X context. In doing so, we are interested in different traffic types, which we categorize into safety-related traffic and non-safety-related traffic.

Resource Allocation in 5G-V2X: 5G numerologies and their impact on V2X communications

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The flexibility of the New Radio (NR) frame structure is one of the most interesting 5G key features enabled by the use of the new 5G numerologies. The 5G numerologies are an enabler to meet the requirements of a wide range of 5G services. Indeed, V2X communication encompasses a variety of applications with different requirements. Therefore, choosing an appropriate numerology for each V2X scenario is of particular importance. To this end, in this chapter we present a comprehensive study of the impact of 5G numerologies on the performance of V2X applications.

Regarding the literature review, there are few research works that address the choice of numerology for vehicular communication. However, the vehicular environment, which is a dynamic network due to the high mobility of vehicles, is strongly influenced by the Doppler effect [122]. Since this later has a great impact on the choice of numerology, it is interesting to consider realistic vehicle environments and study the impact of numerologies on the communication performance.

This chapter is organized as follows. Firstly we present a technical background on the 5G numerologies in Section 5.1. Secondly, we study the impact of 5G numerologies on V2X communications in Section 5.2. Finally we conclude this chapter in section 5.3.

5.1 Technical Background of 5G NR Numerologies

5.1.1 Numerology Concept

The concept of numerology standardized in Release 15 of 3GPP relates to 5G waveform parameterization, including OFDM subcarrier spacing, time-slot duration, symbol duration, and CP duration [22]. Unlike LTE-V2X, where the subcarrier spacing is fixed at 15 kHz, corresponding to numerology index $\mu=0$, in NR-V2X it can take other values that are multiples of 15 kHz, i.e. 30, 60 and 120 kHz, corresponding to numerologies $\mu=1$, $\mu=2$ and $\mu=3$, respectively, as shown in Figure 5.1. The parameters for the individual numerologies are presented in the Table 5.1 and are defined as follows.

Definition 5.1.1. The subcarrier spacing Δ_μ corresponding to the numerology with index μ is defined as:

$$\Delta_\mu = 2 * \Delta_{\mu-1}$$

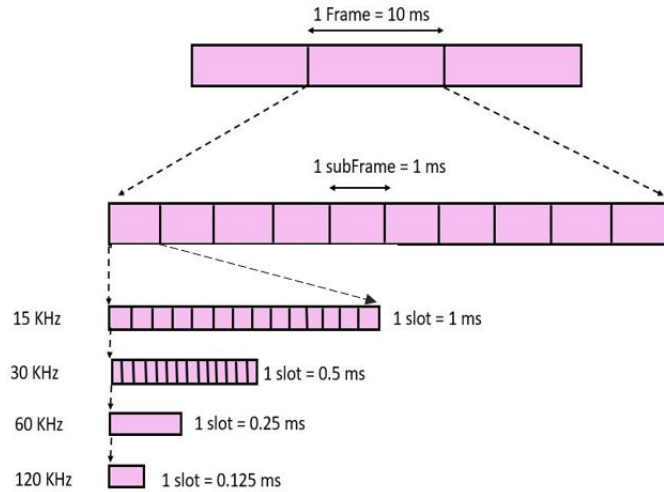


Figure 5.1: New Radio Frame Structure

Definition 5.1.2. For a fixed numerology μ , the symbol duration T_S^μ is the inverse of the subcarrier spacing Δ_μ for that numerology:

$$T_S^\mu = 1/\Delta_\mu$$

Definition 5.1.3. For a fixed numerology μ , the time-slot duration T_{slot}^μ is computed as:

$$T_{slot}^\mu = 1/2^\mu$$

where μ indicates the numerology index.

Since the symbol duration is variable with the numerology index, the time slot, i.e., the time to transmit 14 OFDM symbols, is also variable and decreases as the numerology index increases, which reduces the latency and therefore favors time-critical applications. For example, in the case of numerology 0, the time slot value is 1 ms and for numerology 1 it is 0.5 ms.

Numerology	Slots per sub-frame	Symbol length (μ s)	Slot length (ms)	Sub-carrier spacing (kHz)	Symbols per slot
0	1	71.42	1	15	14
1	2	35.71	0.5	30	14
2	4	17.85	0.25	60	14
3	8	8.92	0.125	120	14
4	16	4.46	0.0625	240	14

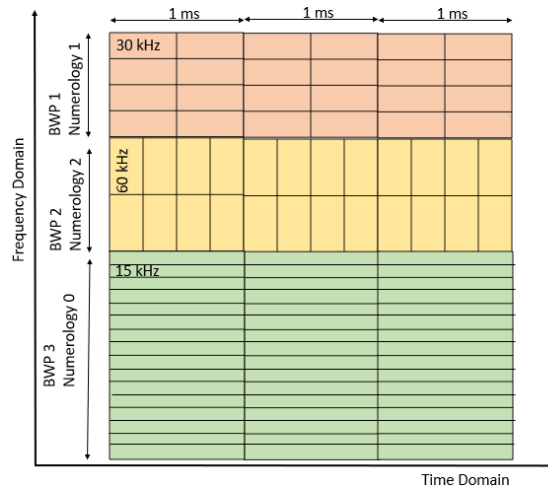
Table 5.1: Main Parameters of NR-V2X Numerologies

5.1.2 Multiplexing of different numerologies

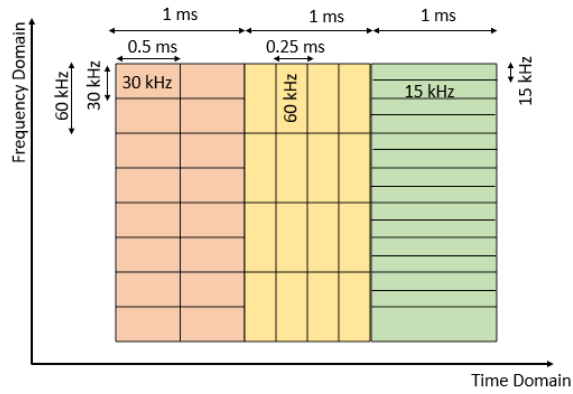
Different numerologies can be used in the same scenario depending on the requirements of the applications and the channel conditions thanks to the multiplexing of different numerologies technique. This latter presents another level of flexibility of the NR frame structure, and allows to meet the requirements of different applications. The NR-V2X numerology multiplexing can be done either by the Frequency Division Multiplexing (FDM) technique as shown in Figure 5.2(a), the Time Division Multiplexing (TDM) technique as illustrated in Figure 5.2(b) or by mixing both FDM and TDM techniques as presented in Figure 5.2(c) [123]. The FDM-based numerology multiplexing is enabled by the Band-Width Part (BWP) technique [22]. The BWP is defined as a contiguous set of Physical Resource Blocks (PRBs) on a given carrier. The BWP technique is introduced in 3GPP Release 15 in order to support UEs that cannot handle large bandwidths due to processing limitations or high power consumption. The BWP has also been adopted for the NR-V2X sidelink and allows the multiplexing of different numerologies in the frequency domain as illustrated in Figure 5.3. Each BWP, defined for a specific numerology, can have the three different parameters, which are the sub-carrier spacing, the symbol duration and the cyclic prefix.

5.2 Impact of 5G numerologies on the performances of V2X communications

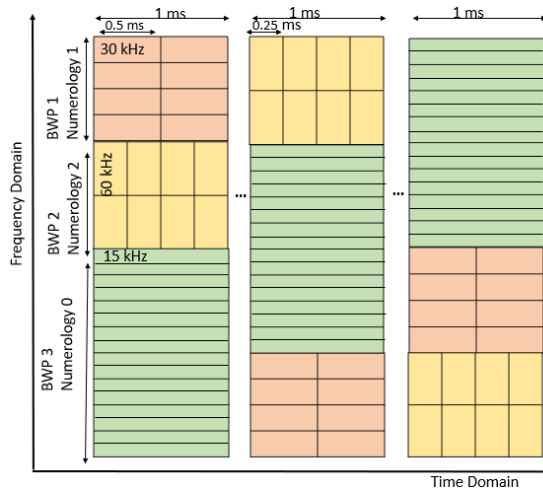
As mentioned earlier, the new 5G numerologies are one of the most important features of 5G, but choosing the appropriate numerology for a particular V2X scenario is still an



(a) FDM Numerology Multiplexing



(b) TDM Numerology Multiplexing



(c) Mix of TDM and FDM Numerology Multiplexing

Figure 5.2: TDM, FDM and Mix TDM and FDM Numerology Multiplexing

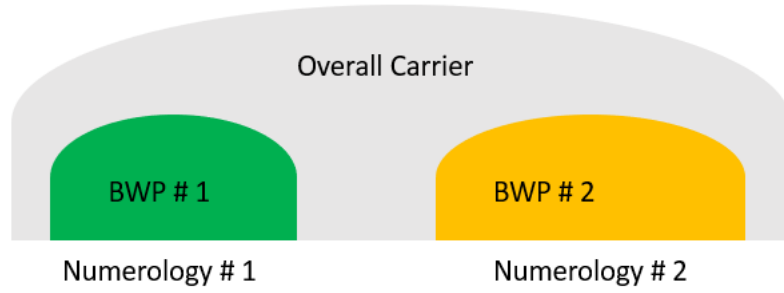


Figure 5.3: Bandwidth Part

open issue. As far as the literature is concerned, there are only a few research works dealing with the concept of numerology. In [8, 9, 10, 11], authors investigate the impact of numerologies on 5G system performance. However, only few research works focus on their impact on V2X communications. The authors of [92, 91] are interested in the impact of numerologies on the sidelink autonomous mode 2 of NR-V2X, in which the resources are autonomously selected by vehicles using the SPS algorithm. Indeed, the authors show that the used numerology affects the size of the sensing and resource selection windows used in the SPS algorithm for mode 2. In this context, the authors show that increasing the numerology improves the overall performance of the system. Moreover, the authors of [124] propose an adaptive numerology selection algorithm that aims to choose the appropriate numerology to satisfy the QoS (Quality of Service) of V2X applications such as reliability and throughput. However, the authors do not clearly present the direct impact of these numerologies on the requirements of V2X applications. To the best of our knowledge, the only research work that makes an attempt in this direction is the one presented in [93], where the authors study the impact of 5G numerologies on V2X communication performance considering the Block Error Rate (BLER) parameter. The authors conclude that the choice of the appropriate numerology depends on the ICI and ISI problems. However, the limitation of this work is that the authors have only focused on the physical level performance evaluation and neglected the impact of these numerologies on the application level system performance. In addition, the authors do not consider a wide range of use cases for the channel conditions, which makes this study incomplete.

For this reason, the main objective of this work is to present a more comprehensive study on the impact of 5G numerologies on V2X communications. Our study is based on simulations and it includes two complementary parts. In the first part, we are interested in studying the impact of numerologies on application layer performance, while in the second part we focus on physical layer performance. In the following subsections, we present the application-layer performance evaluation and the physical-layer performance evaluation, respectively.

5.2.1 Application layer performance evaluation

In the first part of this study, we simulated two different V2X applications using the network simulator Simu5G [125], an OMNeT++ based simulator. For each application, we chose a rigorous KPI. Since the safety V2V application is a time-critical application, the

main KPI parameter we evaluate for this application is the latency. However, we are interested in the average throughput of the video stream application. The latency is defined as the average time of sending packets from source to destination. The throughput is defined as the average number of received packets per second. The simulation scenario consists of 20 vehicles, among them 12 vehicles are running safety applications and 8 vehicles are running infotainment applications. In the safety V2V application, the transmitting vehicles periodically send a CAM message of 190 bytes to their neighbors every 10 ms. The second application, an infotainment application, is the video streaming application where infotainment vehicles receive video stream packets from other transmitting vehicles. The video streaming application parameters consists of a video size of 100 MB, a video packets length of 3000 bytes and a transmission time interval of 1 ms. For vehicle mobility, we used the traffic simulator SUMO (Simulation of Urban MObility) [126]. The vehicles move at an average speed of 40 km/h on a lane of 300 m length. The relevant parameters of our simulations can be found in the Table 5.2.

Table 5.2: Simulation Parameters using Simu5G

Parameter	Value
Frequency	5.9 GHz
Scenario	Urban Macro (UMa)
Number of RBs	50 RB
UeTxPower (dBm)	23 dBm
gNBTxPower (dBm)	46 dBm
Fading channel model	Rayleigh
Number of vehicles	20 vehicles
Simulation time	60 s

Figures 5.5 and 5.4 show the average latency and average throughput for safety and video streaming applications, respectively. When we vary the numerology index from 0 to 3, we find that the average throughput increases with the increase of the numerology index, unlike the latency, which decreases as the numerology index increases. We can explain the obtained results by the following hypothesis:

Hypothesis 5.2.1. When the numerology index increases, the number of transmitted symbols per 1 ms time slot increases. As a result, the number of packets transmitted during a given time period also increases, increasing the average throughput.

Hypothesis 5.2.2. when the numerology index increases, the transmission rate increases and the transmission delay decreases, reducing the overall latency.

At this level of our study, we can quickly confirm that the higher numerologies are always the best choice for all V2X scenarios. However the Simu5G simulator does not take into account the ICI and ISI problems. Therefore, the results obtained at the application layer do not provide any information about the reliability of the transmissions with respect to ICI and ISI. For this purpose, a comprehensive study is performed at the physical layer regarding the reliability, which is very interesting in V2X communications and especially in the case of the safety V2V communications.

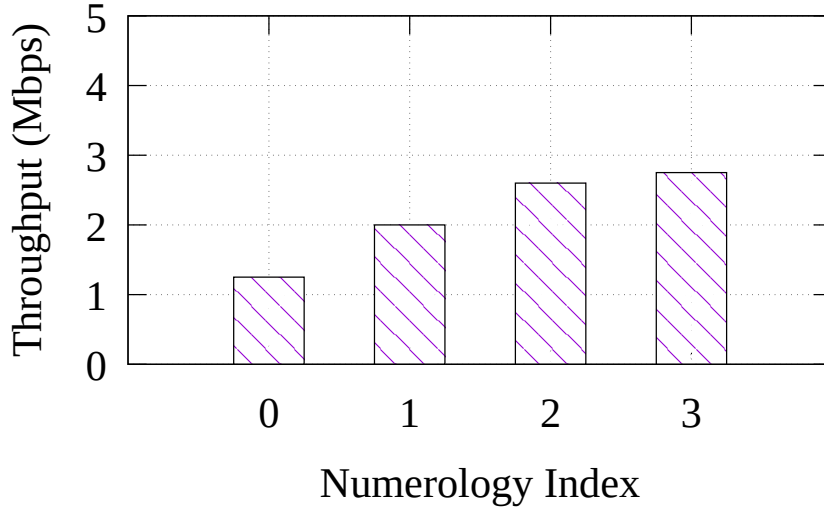


Figure 5.4: Average Throughput as a function of numerology for Video Streaming application

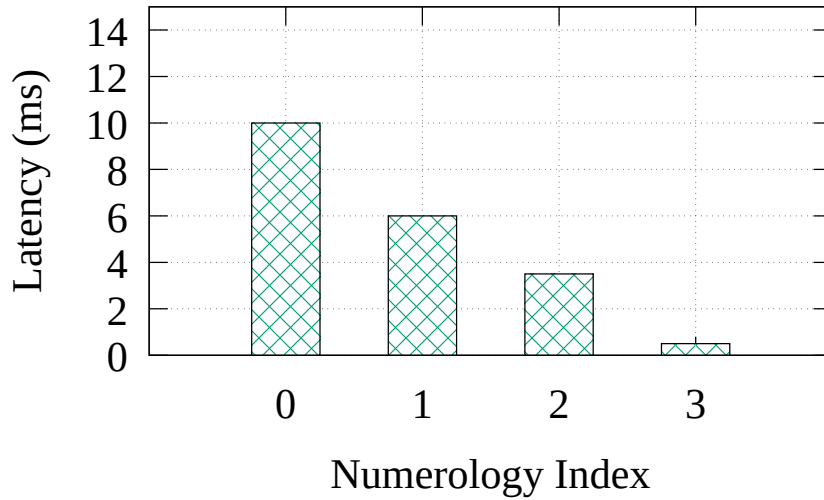


Figure 5.5: Average Latency as a function of numerology for Safety V2V application

5.2.2 Physical layer Performance Evaluation

The second part of our study provides an in-depth analysis of the impact of 5G numerologies on physical layer performance. For this purpose, we used the 5G Vienna Link Level (5GVLL) simulator. The Vienna 5G Link Level Simulator is a Matlab-based link level simulator and part of the Vienna Cellular Communications Simulators (VCCS) software suite, which is described in detail in [127]. The simulation parameters for the 5GVLL simulator are given in Table 5.3. Before presenting the scenarios of the conducted simulations and the obtained results, we start in this section by presenting some physical phenomenon used to explain and analyse the obtained results.

- **Inter-Carrier Interference (ICI):** The ICI is one of the well known impairments that degrade the performance of OFDM systems when subcarriers lose their orthogonality [128]. The ICI is caused by the Doppler effect. The Doppler effect is defined as the change in the carrier frequency of the signal as the distance between the transmitter and the receiver varies. In vehicular networks, the Doppler effect is more pronounced because of the high mobility of vehicles.
- **Inter-Symbol Interference (ISI):** Intersymbol interference is one of the well-known signal distortions caused by the multipath propagation effect. In a multipath propagation environment, the intermediate objects between the transmitter and the receiver, i.e., buildings, trees, etc., may cause additional paths. In this environment, there is only one Line of Sight (LoS) path and all other paths are additional paths, as shown in Figure 5.6. Multiple copies of the signal propagate until they reach the receiver. Since each path has its own delay and attenuation, different versions of the signal arrive at the receiver at different times. The resulting signal at the receiver is the sum of all copies of the signal. However, the signals can add destructively, causing the problem of intersymbol interference, as shown in the Figure 5.6. To avoid the occurrence of the ISI problem, the used cyclic prefix must be sufficiently longer than the delay spread of the channel. As explained in section 5.1.1, each numerology has its own cyclic prefix. However, depending on the delay spread of the channel, the cyclic prefix of the numerology may or may not overcome the ISI problem.

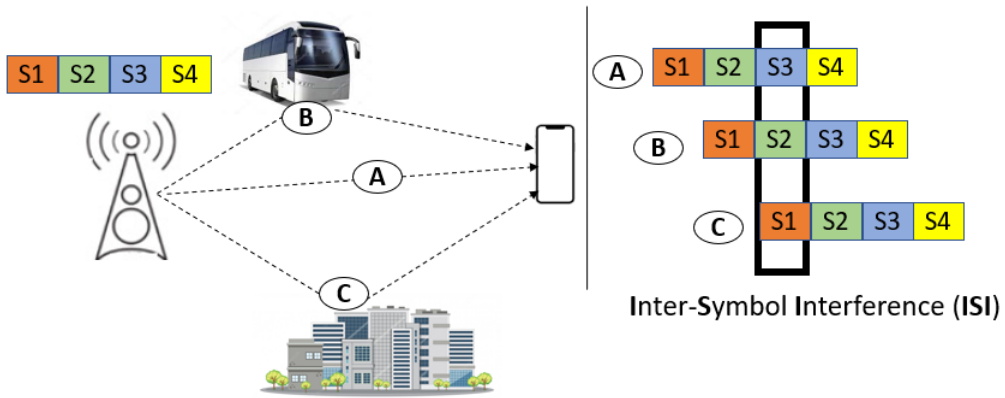


Figure 5.6: Inter-Symbol Interference (ISI)

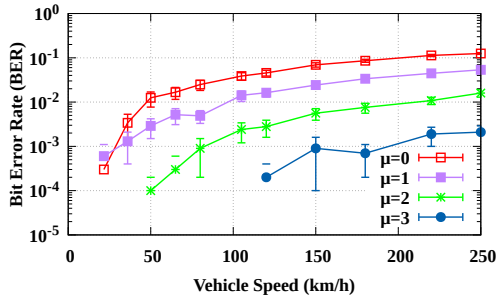
For the physical layer performance evaluation, we have chosen the Bit Error Rate (BER) indicator. For each vehicle speed value, we calculated the average BER after 50 simulations with 95% confidence interval. In order to vary the simulation scenarios, we have also considered both urban and rural scenarios with different delay spread values. The delay spread of the channel is defined as the difference between the arrival time of the last multipath component and the arrival time of the first multipath component in a multipath propagation environment. The delay spread values chosen for our simulations can be found in the Table 5.4. These values are chosen based on the standardized values considering different scenarios for urban and rural areas. The characterization of urban or rural scenarios is related to the values for the delay spread parameter, as described

in [129]. For the rural scenario, low delay spread values are considered, with the longest value being 153 ns, while for the urban scenario, higher delay spread values of over 800 ns are considered, as shown in Table 5.4.

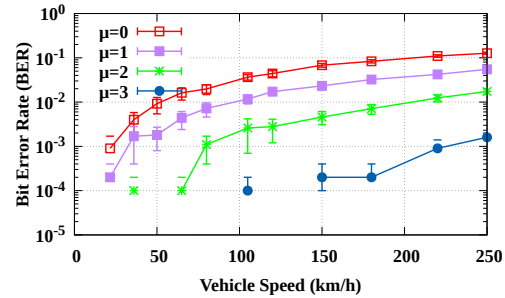
In order to obtain accurate results depicting the impact of 5G numerologies on physical layer performance, we simulate only one vehicle moving at speeds ranging from 20 km/h to 250 km/h. The choice of a single vehicle is intended to avoid inaccuracy in the results. In fact, many factors, such as the problem of interference between vehicles [130] can have an impact on the BER. However, the choice of the appropriate numerology is directly influenced by only two types of interference, namely the ICI and the ISI, as already shown in the work presented in [93]. For this reason, we have avoided the presence of other types of interference in order to obtain only the errors due to the choice of the numerology and not the errors due to other factors.

Table 5.3: Simulation Parameters using 5GVLL

Parameter	Value
Channel Bandwidth	5 MHz
Frequency	5.9 GHz
Subcarrier Spacing (Khz)	15, 30, 60, 120
Number of Subcarriers	384, 192, 96, 48
UeTxPower (dBm)	23
gNBTxPower (dBm)	46
Doppler channel model	Jakes
Number of Simulations	50

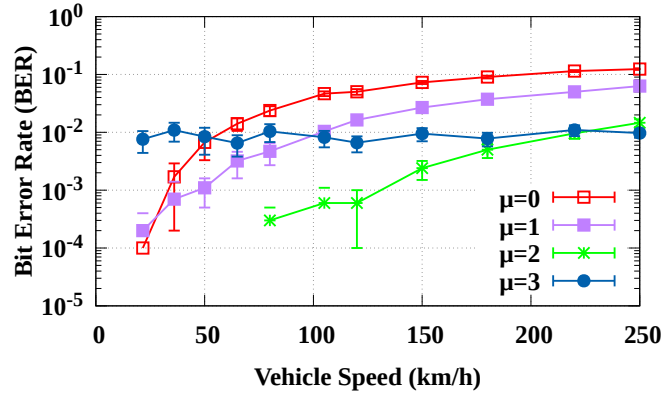


(a) BER with delay spread = 32 ns



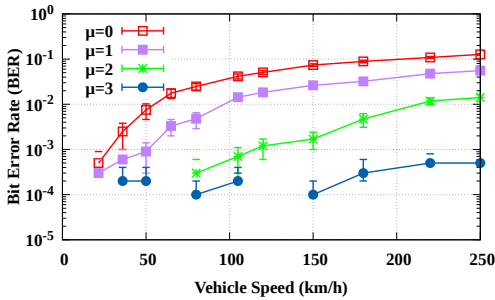
(b) BER with delay spread = 37 ns

Figures 5.7(a), 5.7(b) and 5.7(c) show the BER as a function of vehicle speed, considering delay spread values of 32 ns, 37 ns and 153 ns, respectively for the rural scenario. As can be seen in Figures 5.7(a) and 5.7(b), the BER increases with the increase in vehicle speed. This can be explained by the ICI caused by the Doppler effect due to vehicle mobility. However, we note that for the same vehicle speed, the BER decreases as the numerology increases. This behavior can be explained by the fact that as the numerology increases, the sub-carrier spacing is increased and the system is then less affected by the ICI phenomenon. For that, the lower numerologies are more affected by the ICI than the higher numerologies due to their lower sub-carrier spacing values as shown in [93]. In

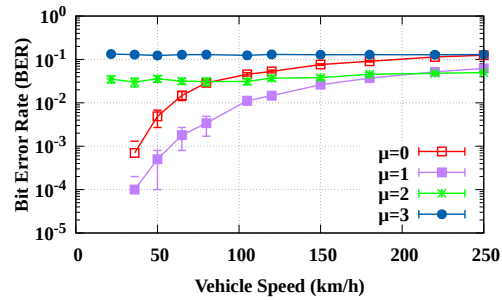


(c) BER with delay spread = 153 ns

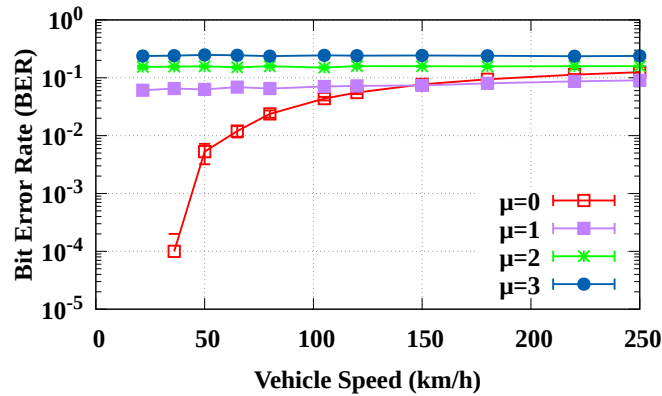
Figure 5.7: BER as a function of vehicle speed varying numerology index (μ) for Rural Macro (RMa) scenario



(a) BER with delay spread = 93 ns



(b) BER with delay spread = 363 ns



(c) BER with delay spread = 850 ns

Figure 5.8: BER as a function of vehicle speed varying numerology index (μ) for Urban Macro (UMa) scenario

this context, we also notice that the BER has a particular behavior for numerology 3. Regarding the curves of numerology 3 in Figures 5.7(a), 5.7(b) and 5.7(c), we note that

BER is almost independent of the velocity values of the vehicles. This behavior, which can be seen more clearly in Figure 5.7(c), can be explained by the fact that the system performance is not affected by the ICI when numerology 3 is used, since the subcarrier spacing is larger enough to overcome the ICI problem.

Looking at Figures 5.7(a), 5.7(b) and 5.7(c), we notice that the curves of the same numerology show the same behavior for numerology index 0, 1, and 2. However, for the curves of numerology 3, we notice that BER increases when the delay spread is increased from 32 ns to 153 ns. As a result, the system exhibits a performance degradation when numerology 3 is used in this case.

Figures 5.8(a), 5.8(b) and 5.8(c) show the variation of the BER as a function of vehicle speed considering three delay spread values of 93 ns, 363 ns and 850 ns, respectively for the urban scenario. If we compare the curves of the same numerology in Figures 5.8(a)

Table 5.4: Delay Spread Values

Scenario	Delay spread value		
	<i>Short</i>	<i>Normal</i>	<i>Long</i>
Urban Macro (UMa)	93 ns	363 ns	850 ns
Rural Macro (RMa)	32 ns	37 ns	153 ns

and 5.8(b) with delay spread values of 93 ns and 363 ns, respectively, we find that the curves of numerologies 0 and 1 show the same behavior, while the curves of numerologies 2 and 3 show a remarkable difference. Looking at the curves of numerologies 2 and 3, we notice that the BER values are higher for a delay spread of 363 ns than for a delay spread of 93 ns. Moreover, we find that the BER is higher with numerology 3 when compared to numerology 2. Furthermore, if we increase the delay spread value to 850 ns, we find that the BER also increases for numerology 3, 2, and even more for numerology 1, as shown in Figure 5.8(c). Thus, we conclude that the system performance decreases significantly when using higher numerologies as the delay spread of the channel increases. Indeed, the system performance is more susceptible to the ISI problem when using the higher numerologies due to their shorter cyclic prefix. For this reason, we note that in urban scenarios and with higher delay spread values, it is not recommended to use the higher numerologies. Since the numerology 3 exhibits a special behavior, we show in Figure 5.9 the BER as a function of vehicle speed for the numerology 3 only, considering four delay spread values: 32 ns, 153 ns, 363 ns, and 850 ns. The figure demonstrates the hypothesis already explained above.

Another observation is that for lower values of the delay spread, i.e. 32 ns, and for lower vehicle speeds, i.e. speed ≤ 120 km/h, the BER of numerology 3 is practically zero for most values of the vehicle speed, as can be clearly seen in Figure 5.9 (if there is no BER value for a given vehicle speed in the curve, it means that the BER is close to zero). This behavior can be explained by the fact that using numerology 3 with low delay spread value can overcome the ICI and ISI problems.

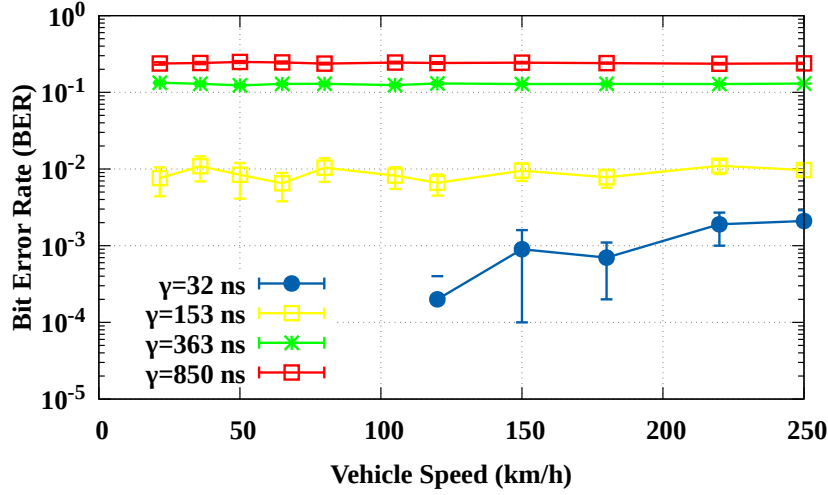


Figure 5.9: BER as a function of vehicle speed varying delay spread (γ) for numerology index 3

5.2.3 Summary of the Study

After analyzing the results obtained from the two parts of this study, we demonstrate a theoretical hypothesis, which is that increasing numerology leads to an increase in throughput and a decrease in latency. These results seem to lead to the conclusion that higher numerologies are almost the best choice for all V2X scenarios. However, this is not always the case, since problems at physical layer such as Doppler shift and multipath variation have to be taken into account, which causes the ICI and ISI problem, respectively. The obtained results show that higher numerologies can mitigate the ICI problem due to their larger subcarrier spacing, but they are more susceptible to the ISI problem. In contrast, the lower numerologies can mitigate the ISI problem in a multipath propagation environment with their higher cyclic prefix, but they are more prone to the ICI problem. In conclusion, our study allows us to prove the following hypothesis:

Hypothesis 5.2.3. Throughput increases as the numerology index increases, as opposed to latency, which decreases as the numerology index increases

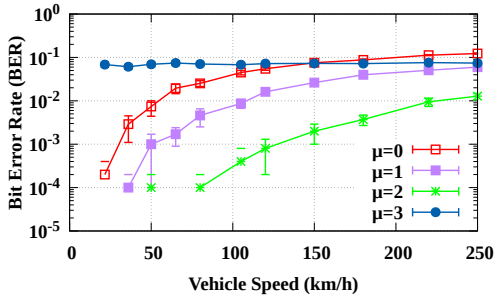
Hypothesis 5.2.4. The higher numerologies can overcome the ICI problem due to their higher sub-carrier spacing, but they are more susceptible to the ISI problem due to their lower cyclic prefix.

Hypothesis 5.2.5. The lower numerologies can overcome the ISI problem due to their higher cyclic prefix, but they are more susceptible to the ICI problem due to their lower sub-carrier spacing.

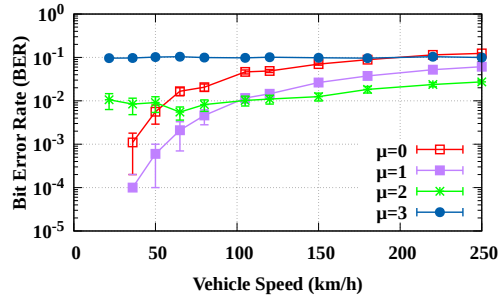
Thus, we conclude that the choice of the appropriate numerology depends not only on the V2X requirements such as latency or throughput but also on the vehicle speed and propagation channel conditions.

Table 5.5: Our Recommendations for the Selection of the appropriate Numerology Index based on the delay spread of the channel and vehicle speed

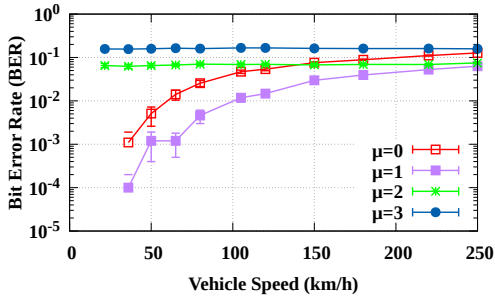
Delay Spread	Appropriate Numerology Index
[32 ns, 93 ns]	3
153 ns	2 for speed \leq 240 km/h & 3 for speed \geq 240 km/h
250 ns	2
300 ns	1 for speed \leq 100 km/h & 2 for speed \geq 100 km/h
363 ns	1 for speed \leq 225 km/h & 2 for speed \geq 225 km/h
450 ns	1
520 ns	0 for speed \leq 40 km/h & 1 for speed \geq 40 km/h
650 ns	0 for speed \leq 90 km/h & 1 for speed \geq 90 km/h
750 ns	0 for speed \leq 125 km/h & 1 for speed \geq 125 km/h
850 ns	0 for speed \leq 150 km/h & 1 for speed \geq 150 km/h



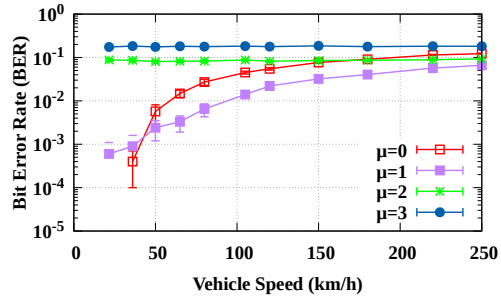
(a) BER with delay spread = 250 ns



(b) BER with delay spread = 300 ns



(c) BER with delay spread = 450 ns



(d) BER with delay spread = 520 ns

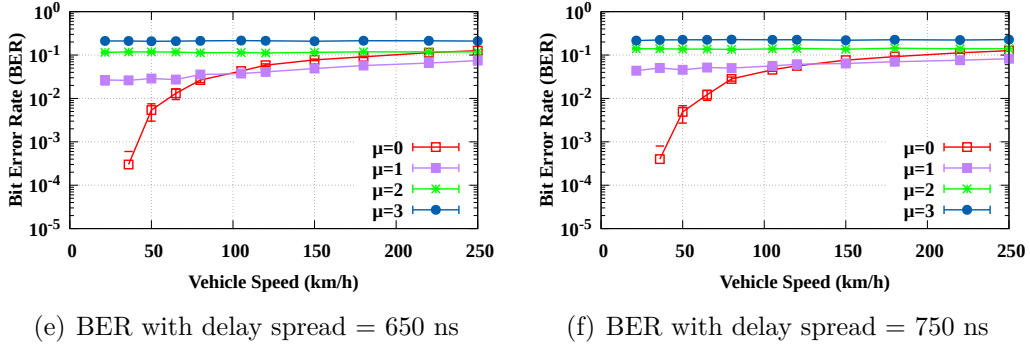


Figure 5.10: BER as a function of vehicle speed varying numerology index (μ) for different delay spread values

Here it is interesting to highlight that the before-demonstrated hypothesis do not bring an exact choice for the appropriate numerology for a given V2X scenario. For this reason we have extended our study by performing a series of simulations, in which we consider randomly a wide range of delay spread values and vehicle speeds, as shown in the Figure 5.10. The analysis of these figures follows the same strategy as that of the previously analyzed figures. After analyzing all those figure, we present our recommendations for choosing the appropriate numerology as a function of channel conditions and vehicle speeds in the table 5.5. In fact, in a real scenario, it is possible to determine the delay spread of the channel and the vehicle speed accurately enough to choose the appropriate numerology. If these parameters are known, this table can be used as a reference for choosing the appropriate numerology. As can be seen from the table, we can propose to use numerology 3 for the urban scenario with a delay spread of 93 ns and also for the rural scenario with a delay spread of 32 ns and 37 ns. However, numerology 1 seems to be the best choice for the rural scenario with a delay spread of 300 ns when the vehicle speed is less than 100 km/h, while numerology 2 can be selected for this delay spread when the vehicle speed is more than 100 km/h.

5.3 Conclusion

The 5G numerologies are considered as one of the most important 5G key features to meet the requirements of various 5G services. However, in V2X communication, choosing the appropriate numerology for a particular V2X scenario is still a challenging task. In this chapter, we have studied the impact of 5G numerologies on V2X communication performance, considering both safety and non-safety applications. Our study shows that higher numerologies are the best choice to achieve low latency and higher throughput, which is beneficial for both safety and non-safety applications, respectively. However, considering the problems at physical layer such as ICI and ISI, we find that the choice of the appropriate numerology depends on the propagation channel conditions and the vehicle speed, which affects the reliability of the V2X communications. Finally, we conclude that the choice of the appropriate numerology is a trade-off between the stringent requirements of V2X applications, the ICI problem, and the ISI problem. In the next chapter, we will

propose a new resource allocation algorithm for both safety and non-safety traffic, using the appropriate numerology considering the channel conditions and vehicle speed.

Resource Allocation in 5G-V2X: Priority and Satisfaction-based Resource Allocation in Mixed-Numerology for V2X communications

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6.1 Introduction

C-V2X provides integration of both V2V and V2I communications, based on the sidelink PC5 interface, and the V2N communications based on the Uu interface. The direct V2V communication via the sidelink PC5 interface is the basic mode of V2X communications. The ITU has dedicated the 5.9 GHz band for V2X sidelink communications [6]. Regarding the regulation of the 5.9 GHz band, it should be noted that the use of this frequency band varies from one area to another. On the one hand, the ECC (European Cooperation Centre) has allocated a part of the spectrum to safety traffic and another part to non-safety traffic [131]. However, it is not prohibited for safety applications to use the non-safety bands. In addition, other countries, do not decide on the possibility of sharing frequencies

for these applications. Since the sidelink communications can support both safety and non-safety traffic types, we address in this work the case where the safety and non-safety traffic share the same spectrum bands. For that, efficient resource allocation mechanism is imperative to guarantee the requirements of the different traffic types.

Regarding the requirements of vehicular applications, the safety-related traffic is considered as the most critical traffic type in vehicular networks. Thus, the application of a priority policy in the resource scheduling scheme to prioritize the safety-related traffic is a necessary step, which is the goal of the proposed PSRA-MN algorithm. As for traditional resource allocation algorithms such as Max-C/I and Proportional Fair (PF), we note that they are not always suitable for V2X applications [12]. For example, regarding the Max-C/I algorithm [12], which aims to maximize the system throughput by scheduling the vehicle with the best radio-link conditions first, this algorithm can schedule a non-safety vehicle before another safety vehicle if that non-safety vehicle has good radio-link conditions, which is very dangerous for the safety service. In the same context, we note that the PF algorithm is not the best choice for V2X communications because it is based on the fairness among users. However, if the number of safety vehicles in the scenario is higher than the number of non-safety vehicles, the application of fairness between users in this context is not ideal, because some safety vehicles may be ignored in the scheduling, while other non-safety vehicles are scheduled, which is very dangerous for the safety service.

The remainder of this chapter is organized as follows. First, we present the proposed resource allocation algorithm in Section 6.2. The performance evaluation of this algorithm is presented in Section 6.3. Finally, we conclude this chapter in Section 6.4.

6.2 Resource Allocation in PSRA-MN algorithm

The PSRA-MN algorithm aims to ensure the necessary resources for safety vehicles by applying a priority mechanism in favour of safety traffic. The remaining resources after safety allocation are then allocated to the non-safety vehicles by solving an integer linear optimization problem that aims to maximize the average satisfaction rate of non-safety traffic. The PSRA-MN algorithm includes two main steps: The first step consists of selecting the appropriate numerology according to the channel conditions and vehicle speed, as explained in Section 6.2.1. The second step is the allocation of radio resources for safety and non-safety traffic, as described in Sections 6.2.2 and 6.2.3.

6.2.1 Numerology Selection Phase

To benefit from the flexibility of the 5G NR frame structure, the proposed resource allocation algorithm, PSRA-MN, is executed in a mixed numerology scenario. We propose a TDM approach for multiplexing different numerologies as shown in Figure 6.1, where the choice of the numerology at each time-slot is based on the channel conditions and vehicle speed. The choice of the appropriate numerology for a particular V2X scenario has already been studied in Chapter 5, where we concluded that the choice of the appropriate numerology depends not only on the application requirements, but also on the channel conditions and the vehicle speed. With respect to the literature review addressing resource

allocation in mixed numerology scenarios, we note that there are few research works that address resource allocation with mixed numerology in 5G [132, 133, 134, 135, 136, 137]. However, the cited research is not interested in the vehicular scenario, which is very different from traditional networks. For this reason, in PSRA-MN, before starting the radio resource scheduling process, we select the appropriate numerology index as a first step. To be closer to reality, in our scenario, the delay spread of the channel is varied in a wide range from 32 ns to 850 ns, and then the appropriate numerology is selected based on the delay spread value and the vehicle speed according to the numerology selection recommendations presented in Chapter 5 [138].

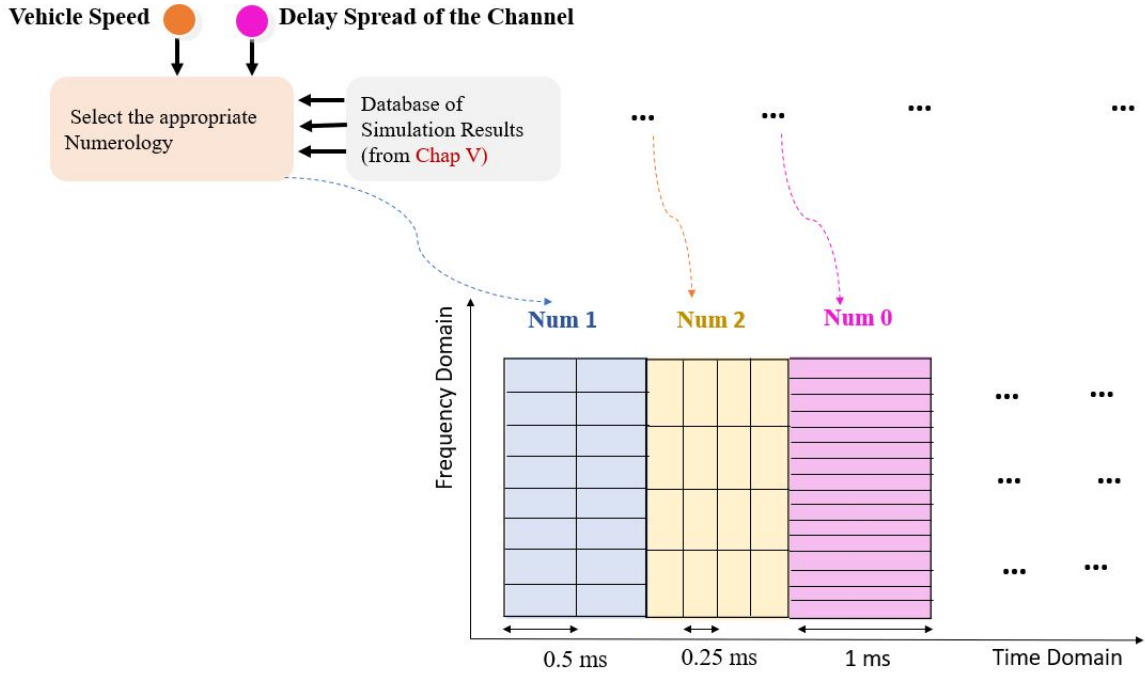


Figure 6.1: Numerology Selection Step

6.2.2 Priority-based Resource Allocation

After the numerology selection step, we perform the resource scheduling in the PSRA-MN algorithm. First, we apply a priority-based resource allocation strategy, where we prioritize the safety traffic by allocating the required number of RBs to the safety vehicles. Let $\mathbb{V} = \{v_1, v_2, \dots, v_M\}$ denote the set of M vehicles present in the cell at a given time and sending requests to the gNB in order to be allocated. We denote by C , the total system capacity, defined as the set of available Resource Blocks (RBs). The system capacity C , which depends on the used channel bandwidth, can be formulated as follows:

$$C = \{RB_j\}_{j \in \{1..N\}} \quad (6.1)$$

where N designates the total number of RBs.

We classify the vehicles into 2 groups according to their traffic type. The first group represents the safety vehicles, which we denote by $\mathbb{V}_S = \{v_1^s, v_2^s, \dots, v_K^s\}$, where K is the total number of safety vehicles in the scenario. By safety vehicles we mean here the vehicles that run safety applications. The second group represents the non-safety vehicles, which we denote by $\mathbb{V}_F = \{v_1^f, v_2^f, \dots, v_L^f\}$, where L represents the total number of non-safety vehicles in the scenario. This means that:

$$\mathbb{V} = \mathbb{V}_S \cup \mathbb{V}_F \quad (6.2)$$

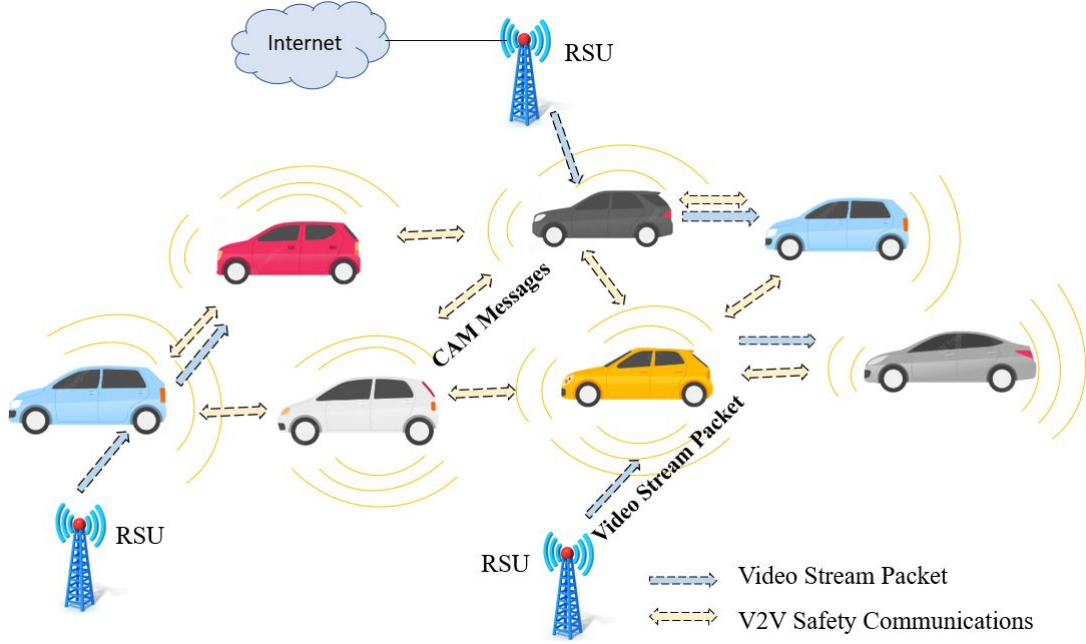


Figure 6.2: Simulation Scenario

The Figure 6.2 illustrates the considered scenario. We denote by D_S and D_F the vectors of the resource demands of safety vehicles and non-safety vehicles, respectively. These requirements are represented as the number of resource blocks requested by the vehicles. We denote by $d_p^s \in D_S$ and $d_q^f \in D_F$ the resource demands of the safety vehicle $v_p^s \in \mathbb{V}_S$ and the non-safety vehicle $v_q^f \in \mathbb{V}_F$, respectively:

$$D_S = (d_1^s, d_2^s, \dots, d_K^s) \quad (6.3)$$

and

$$D_F = (d_1^f, d_2^f, \dots, d_L^f) \quad (6.4)$$

Since the Resource Block (RB) is the smallest unit of resource that can be allocated to a vehicle, we define x as the number of RB allocated by the gNB to a vehicle. We use x_p^s and x_q^f to denote the number of resource blocks that the gNB assigns to the safety vehicle v_p^s and the non-safety vehicle v_q^f , respectively. For example, $x_2^s = 4$ and $x_5^f = 7$

mean that the gNB allocates 4 RBs to the safety vehicle v_2^s and 7 RBs to the non-safety vehicle v_5^f .

In the first step of resource allocation, the gNB allocates the required resources to all safety vehicles so that the total capacity allocated to safety traffic is $\sum_{p=1}^K x_p^s$. The pseudo code of the resource allocation in the first phase for safety traffic is presented in Algorithm 3.

Algorithm 3: Resource allocation in phase 1 for safety vehicles

```

Result:  $\mathbb{C}'$ 
Select the appropriate numerology index  $\mu$  corresponding to channel conditions
and vehicle speed ;
 $\mathbb{C} = \{\text{RB}\}$ ;
/*  $\mathbb{C}$  is the available capacity in terms of the set of RB */
for  $p = 1$  to  $K$  do
    /*  $K$  is the total number of safety vehicles requesting resources
    */
     $v_p^s \leftarrow d_p^s$  ;
    /* Assign to vehicle  $v_p^s$  the resource blocks requested in its
    demand  $d_p^s$ , where  $d_p^s$  is the number of RB requested by safety
    vehicle  $v_p^s$ ;
    */
     $\mathbb{C}' = \mathbb{C} \setminus d_p^s$  ;
end
/*  $\mathbb{C}'$  is the rest of the capacity in terms of number of RB after the
allocation of all safety vehicles. */

```

6.2.3 Satisfaction-based resource allocation:

After the application of a priority mechanism for the resource allocation of all safety vehicles, we optimally allocate the remaining resources to the non-safety vehicles so that the average satisfaction factor Γ is maximized. The average satisfaction rate is a fairness indicator as proposed earlier by Jain *et al.* in [139]. The average satisfaction factor indicates the average percentage of satisfaction of all non-safety vehicles present in the scenario. Here, the satisfaction is calculated as a function of whether a vehicle is allocated a number of resource blocks less than or equal to its demand. That is, a vehicle is satisfied at 100% if the gNB allocates to that vehicle the requested number of RBs specified in its demand.

Definition 6.2.1. The average satisfaction factor Γ is calculated as follows:

$$\Gamma = \frac{1}{L} \sum_{q=1}^L \gamma_q^f, \text{ where } \gamma_q^f = \frac{x_q^f}{d_q^f} \quad (6.5)$$

Here γ_q^f is the satisfaction factor of the non-safety vehicle v_q^f , which is the ratio between the number of resource blocks x_q^f allocated by the gNB to the vehicle v_q^f and its actual demand d_q^f . This means that:

In this proposal, the resource allocation for non-safety vehicles can be modeled mathematically by the following optimization problem:

$$\max \frac{1}{L} \sum_{q=1}^L \frac{x_q^f}{d_q^f} \quad (6.6)$$

s. t.

$$\sum_{q=1}^L x_q^f \leq N - \left(\sum_{p=1}^K x_p^s \right) \quad (6.7)$$

$$0 \leq x_q^f \leq d_q^f, q \in \{1..L\} \quad (6.8)$$

where, equation (6.6) models our goal for maximizing the average satisfaction factor Γ and equation (6.7) models the fact that resource blocks are allocated to non-safety vehicles after ensuring the requirements of all safety vehicles. Algorithm 4 represents the second phase of resource allocation for non-safety traffic. The diagram of the PSRA-MN algorithm is shown in Figure 6.3.

Algorithm 4: Resource allocation in phase 2 for non-safety vehicles

```

Result:  $\mathbb{X}$ 
if  $|\mathcal{C}'| \leq D_F$  then
     $\mathbb{X} = \text{optimize}$  ( equations 6.6 under the constraints of 6.7, and 6.8) ;
    /* call the optimization function which returns the matrix  $X$ 
       containing exactly the resources that should be allocated to
       each non-safety vehicle ;
    */
end
for  $q = 1$  to  $L$  do
     $v_q^f \leftarrow x_q^f$ ;
    /* Assign to vehicle  $v_q^f$  the optimal number of resource block  $x_q^f$ 
       with respect to the optimization problem.
    */
end

```

6.3 Performance Evaluation

The simulation is conducted through the Simu5G simulator. Simu5G is an OMNeT++-based open-source simulator. In our scenario, we have 50 vehicles running a V2V safety application. Among them, a subset of 20 vehicles runs a non-safety application in parallel. In the safety V2V application, the transmitting vehicles periodically send a CAM message

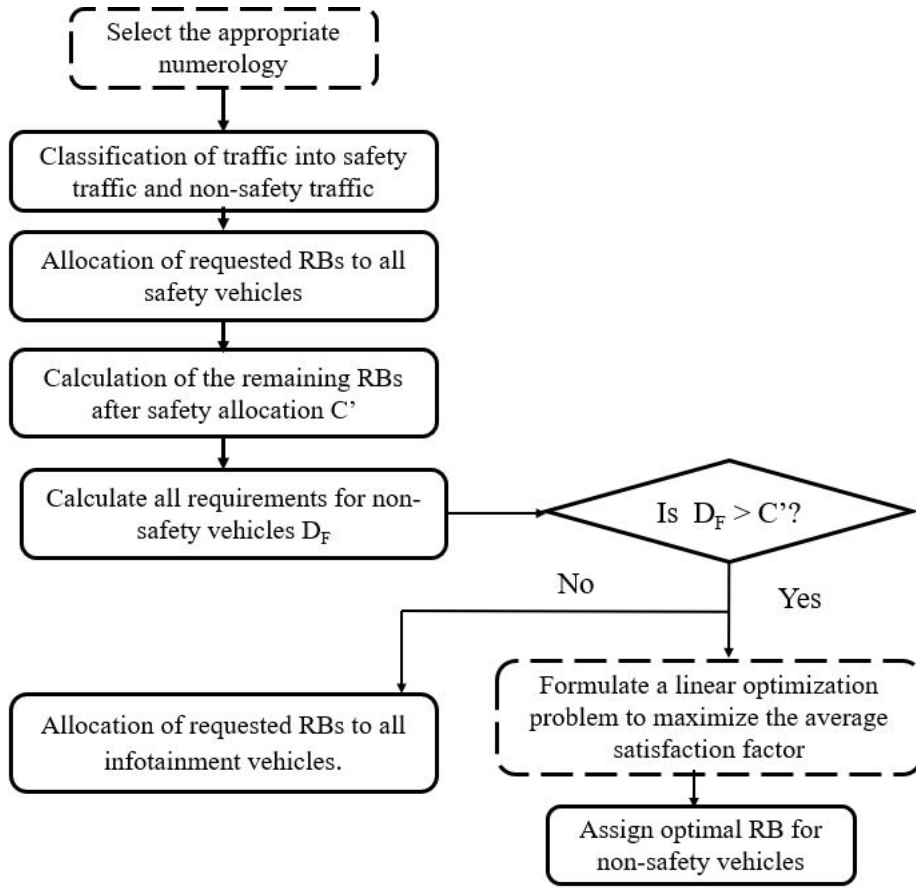


Figure 6.3: Diagramm of the PSRA-MN algorithm

of 190 bytes to their neighbors every 10 ms. The second application, an infotainment application, is a video streaming application, in which the non-safety vehicles receive video stream packets from other transmitting vehicles. For vehicle mobility, we used the traffic simulator SUMO [126]. The vehicles move at an average speed of 40 km/h on a lane of 300 m length. The relevant parameters of our simulations can be found in Table 6.1.

Table 6.1: Simulation Parameters using Simu5G

Parameter	Value
Frequency	5.9 GHz
Scenario	Urban Macro (UMa)
UeTxPower (dBm)	23 dBm
gNBTxPower (dBm)	46 dBm
Fading channel model	Rayleigh
Number of vehicles	50 vehicles
Simulation time	20 s

In our simulations, we evaluate the performance of the proposed algorithm with the

following Key Performance Indicators (KPI):

Definition 6.3.1. The Average Allocation Rate (AAR): is defined as the ratio between the number of allocated vehicles N_{alloc} and the total number of vehicles requesting RBs N_{req} .

$$AAR = \frac{N_{alloc}}{N_{req}} \quad (6.9)$$

Definition 6.3.2. The Average Satisfaction Rate (ASR): is already defined by the Equation 6.6.

Definition 6.3.3. The average delay: is defined as the average time it takes for a packet to travel from source to destination.

The AAR parameter indicates the priority level, while the ASR parameter indicates the fairness level. Moreover, the average delay is analyzed here as one of the most important requirements of safety applications. For this purpose, in our simulations, we analyze the AAR and the average delay for the safety traffic, while the Average Satisfaction Rate (λ) is analyzed for the non-safety traffic. We have used the Max-C/I algorithm as a reference algorithm for the comparison between the performances of this algorithm and the PSRA-MN algorithm. The comparison between these algorithms is made by analyzing the AAR, the ASR, and the average delay, as shown in Figures 6.4, 6.5, and 6.6, respectively.

6.3.1 Average Allocation Rate (AAR)

Figure 6.4 shows the average allocation rate for safety traffic in function of the number of RBs, for the PSRA-MN algorithm compared to the Max-C/I algorithm. The AAR increases when the number of RBs increases for both algorithms. The difference between PSRA-MN and Max-C/I is very clear in the figure for the lower number of RBs. As can be seen from Figure 6.4, for a fixed number of RBs, the AAR for safety traffic is higher for the PSRA-MN than for the Max-C/I algorithm. For example, with 50 RBs, the AAR for PSRA-MN exceeds 40%, whereas the AAR for Max-C/I in this case does not reach 30%. This is due to the fact that the PSRA-MN algorithm allocates more safety vehicles than the Max-C/I algorithm due to the priority policy applied by PSRA-MN in favour of the safety traffic. Unlike PSRA-MN, Max-C/I allows a non-safety vehicle to be scheduled before another safety vehicle if the non-safety vehicle has good channel conditions. For this reason, the Max-C/I presents a lower performance with respect to the AAR for safety traffic. We conclude that PSRA-MN performs better than the Max-C/I algorithm in terms of the AAR for safety traffic, especially when the number of RBs is smaller.

6.3.2 Average Satisfaction Rate (ASR)

Figure 6.5 shows the average satisfaction rate for non-safety traffic as a function of the number of RBs for the PSRA-MN algorithm compared to the Max-C/I algorithm. The

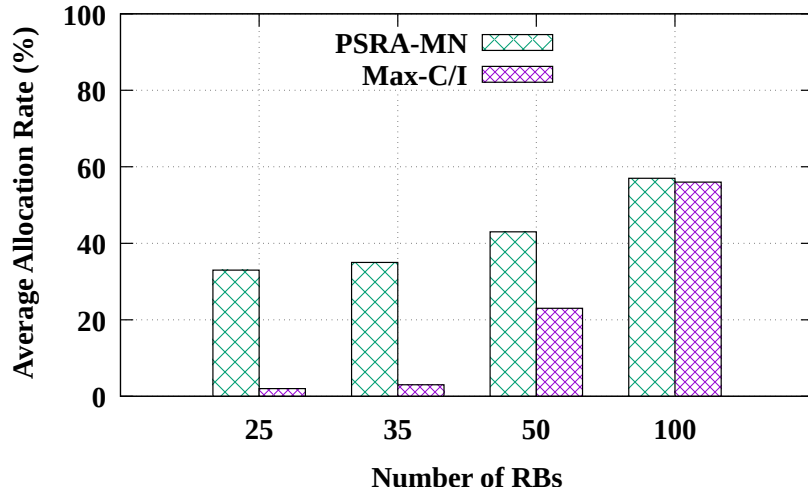


Figure 6.4: The Average Allocation Rate (AAR) for safety traffic

ASR increases as the number of RBs increases. As can be seen in this figure, for a fixed number of RBs, the ASR is higher for PSRA-MN than for Max-C/I. For example, with 100 RBs, the ASR of PSRA-MN exceeds 90%, while that of Max-C/I does not reach 30%. The Max-C/I algorithm does not consider a fairness strategy in its allocation process. Therefore, when Max-C/I is applied, there are some vehicles that are satisfied at 100%, while others are not scheduled, which means that the average satisfaction rate is not very high. In contrast, PSRA-MN tries to satisfy the large number of vehicles in the scenario by maximizing the average satisfaction rate. As a conclusion, we can state that PSRA-MN achieves better performance than Max-C/I in terms of ASR for non-safety related traffic, thus providing a high degree of fairness compared to the Max-C/I algorithm.

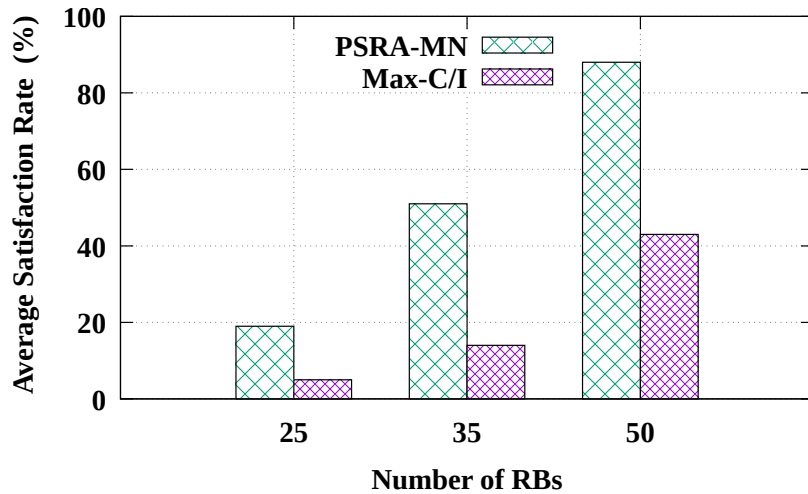


Figure 6.5: The Average Satisfaction Rate (ASR) for non-safety traffic

6.3.3 Average end-to-end delay

Figure 6.6 shows the average delay for safety traffic for our algorithm with fixed and flexible numerology, which corresponds in the figure to PSRA and PSRA-MN, respectively, compared to Max-C/I. As can be seen in this figure, the average delay of both PSRA and PSRA-MN is lower than that of the Max-C/I algorithm. The average delay of the PSRA algorithm is about 16 ms and that of PSRA-MN is about 6 ms, while the average delay of Max-C/I algorithm exceeds 20 ms. In fact, there are two reasons for this result. First, unlike the PSRA algorithm, in the Max-C/I algorithm a safety vehicle must sometimes wait until another non-safety vehicle is scheduled, which increases the overall safety message delay for Max C/I. Second, the use of the TDM multiplexing approach allows the use of different numerologies. However, when a high numerology index is used, the average delay decreases, as explained earlier in [138]. For this reason, when mixed numerology is used in our scheduling scheme, PSRA-MN has the lower average delay value compared to PSRA and Max-C/I. In this context, we emphasize that PSRA-MN outperforms Max-C/I in terms of latency, which is a very important KPI since the safety-related applications are time-sensitive.

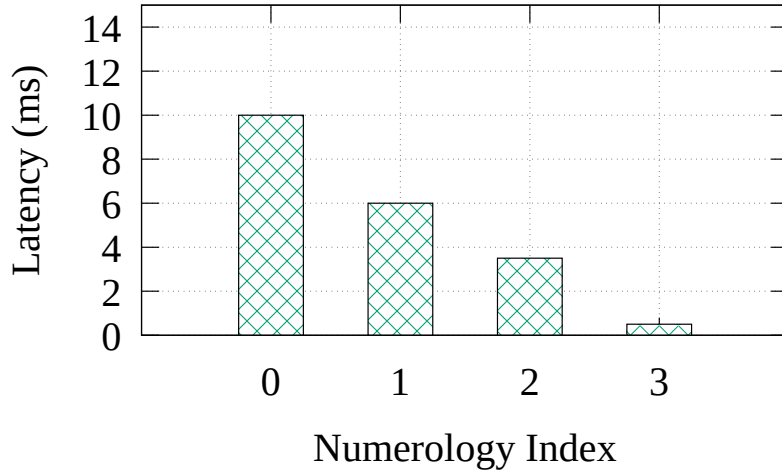


Figure 6.6: The Average end-to-end delay for safety traffic

6.4 Conclusion

In this chapter, we propose a new priority-based resource allocation algorithm for mode 1 of 5G-V2X, named PSRA-MN. First, in the PSRA-MN algorithm, we select the appropriate numerology corresponding to the channel conditions and vehicle speed. Second, we apply a prioritization policy in favor of the safety traffic in order to ensure the required resources for the safety-related service. Finally, the remaining resources after safety allocation are optimally allocated to non-safety vehicles so that the average satisfaction rate is maximized. The PSRA-MN algorithm is validated by simulations using the Simu5G simulator compared with the Max-C/I algorithm. The obtained results show that PSRA-

MN outperforms Max-C/I in terms of the average allocation rate, the average satisfaction rate, and the average delay.

Conclusions and Perspectives

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7.1 Conclusion

Nowadays vehicular networks represent a revolution in transportation sector and are receiving a great deal of attention in scientific research. Through communication between vehicles and between vehicles and other actors such as road infrastructure or pedestrians, vehicular networks aim to reduce the number of accidents by ensuring road safety and efficient traffic management. Among the research topics that feed into the research area is the radio resource allocation in C-V2X.

The Cellular Vehicle-to-Everything (C-V2X) is an emerging technology for vehicular networks in which resource allocation mechanisms play a crucial role in its overall performance. In C-V2X, there are two resource allocation modes: the under-coverage mode and the out-of-coverage mode. The work made under this thesis focuses on the under-coverage mode where the resources are scheduled and allocated by the e/gNB to vehicles. Contrary the out-of-coverage mode, the 3GPP has not standardized a specific resource allocation algorithm for the under-coverage mode.

Since the main goal of vehicular applications is to ensure the road safety service, the safety applications are then considered as very critical in terms of performance. For this reason, better management of resources in their favor is required. To this end, we address resource allocation in safety V2V communication in the first part of this thesis. We have proposed a clustering-based resource allocation algorithm to ensure the reliability of LTE-V2V communications and to find an efficient solution for radio spectrum reuse. This solution tries to facilitate the reuse of resources between vehicles belonging to different clusters to avoid the blocking of transmitters due to the unavailability of radio

resources, which is very dangerous in safety road traffic. The proposed solution improves the performance of safety V2V communication.

In the second part of this work, we focus on resource allocation for 5G V2X communication. In this part, we focus on both numerology and radio resource allocation. First, we answer the question: how can I choose the right numerology for my V2X scenario? To answer this question, we conducted a simulation-based study of the impact of the choice of the numerology on V2X communication performance, considering both the safety and non-safety applications. We have shown through simulations that increasing the numerology leads to an increase in throughput and a decrease in latency, which is beneficial for both safety and non-safety applications. However, physical phenomenon such as ICI and ISI should also be considered when choosing the numerology, taking into account the channel conditions and vehicle speeds.

Finally, we propose an algorithm for resource allocation in a mixed numerology scenario where safety and non-safety applications share the same spectrum ITS. Before allocating radio resources, we first perform numerology selection. After that, we apply a priority mechanism in favor of the safety traffic and then solve an optimization problem to satisfy the non-safety vehicles as much as possible. This proposed solution aims to maximize the satisfaction of the non-safety vehicles after the allocation of the non-safety vehicles. The proposed resource allocation algorithm achieves better performance in terms of AAR, ASR, and average delay.

7.2 Perspectives

The work carried out in this thesis can be extended in the future, taking into account other interesting research directions. On the one hand, we can extend the first part of this theses, in which we deal with resource allocation for safety traffic, by considering also the advanced safety applications in 5G-V2X such as the platooning, advanced sensors, advanced and remote driving applications. These types of applications are very critical in terms of latency and reliability. Therefore, in the future, it is interesting to improve the resource allocation to meet the requirements of these types of applications.

Regarding the second part of our thesis, we note that the study of the impact of numerologies on V2X communication performance can be complemented by a mathematical analysis based on analytical models to strengthen the obtained simulation analysis. Moreover, in the proposed PSRA-MN algorithm, we have considered the TDM-based approach for the multiplexing different numerologies. However, an FDM-based approach that can be based on the bandwidth part technique should also be considered as an interesting prospect and future research direction of this work.

On the other hand, we highlight as perspectives and future research directions of the work carried out in this thesis the integration of new emerging technologies in resource allocation in vehicular networks, which can be summarized in the following aspects:

- Machine Learning-based RA:

Nowadays, the machine learning (ML) or artificial intelligence (AI) is a new emerging technology that draws the attention of the scientific research community [140, 141].

This new emerging technology is widely applied in the wireless communication domain. However, the application of the machine learning in the resource allocation subject is considered as one of the most important future trends that needs to be more investigated by the research community in the future. In fact, in the vehicular network context, there already exist some recent research works [94, 99, 101, 102] investigating the resource allocation based on the machine learning technique. However, the V2X use cases are different from the cases in which machine learning is typically used. This is due to the fact that the vehicular networks have specific characteristics such as the high mobility of vehicles, the rapid change of the topology, the multitude V2X use cases with different requirements and more others. As a result, we highlight the interesting open issue in this context, which is how to efficiently allocate resources to vehicles based on historical data? For that, there is a need to more investigate the use of this new emerging technology in C-V2X communications.

- RA for vehicular Edge Computing:

The Mobile Edge Computing (MEC) is one of the new 5G emerging technologies, recently used in very large scale networks. MEC is beneficial for time-critical applications thanks to the storing and processing of contents and applications in the proximity of mobile users. In the vehicular context, in the near future, the connected vehicles are also expected to use the advanced on-board sensors such as the cameras, radar and lidar. Consequently, a large volume of data will be generated, processed and transmitted with a very low latency requirement. Therefore, MEC technology is considered a promising tool for analysing such huge amounts of data to enhance the performance of vehicular networks. The utilization of MEC in vehicular networks is known as Vehicular Edge Computing (VEC) and is considered an important research direction that has been widely investigated by the research community in recent years [142, 143]. However, the radio resource allocation in VEC is generally associated with computational resource allocation, as studied in [144, 145, 146, 147]. The reduction of the total latency, which includes the transmission time at the radio interface and the processing time at the edge server, is one of the main goals in joint resource allocation for vehicular edge computing. To achieve this goal, the allocation of radio resources, which affects the transmission time, must be managed efficiently. In addition, allocating high computational resources is the best choice to reduce the processing time at the edge server. Therefore, the question of how radio resources can be allocated to reduce the transmission time and how many computing resources should be allocated at the edge server to reduce the processing time is an important research direction that needs to be investigated in more detail in the future.

- Network Slicing-based RA:

The network slicing, enabled by the Network Function Virtualization (NFV) technology, is one of the new emerging technologies of 5G enabling the building of multiple virtual networks on a common shared physical infrastructure [148]. The network slicing is crucial in 5G network because of the different QoS requirements of the multitude services.

As the network slicing is a new emerging technology, there are few research works

investigating its application in the vehicular network context. In fact, the multitude use cases of vehicular applications does not enable the mapping of all V2X applications on only one slice of the three well-known slices, which are the enhanced Mobile Broadband (eMMB) slice, the massive Machine Type Communications (mMTC) slice and the Ultra Reliable Low Latency Communications (URLLC) slice. For this reason, it is expected that various V2X applications shall be mapped separately in different slices. As a result, there is a need to efficiently allocate resources to vehicles to meet the requirements of different V2X applications belonging to different slices. In this context, the assignment of different numerologies to different V2X applications is an example of the slicing of radio resources in the Radio Access Network (RAN). As an example of time-critical V2X use case, we cite the advanced and remote driving, which need a large sub-carrier spacing to ensure the ultra-low latency and high reliability required for this use case. Finally, we highlight that the slicing of radio resources forms a future research aspect, which needs to be more investigated as a very important attractive direction.

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