Radio Resource Allocation in Cellular V2X: From Rule Based to Reinforcement Learning Based Approaches

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Funkressourcenzuweisung im Cellular V2X: Vom regelbasierten Ansatz zum Reinforcement Learning

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Abstract

The wireless communication technology has gained significant attention in the transportation industry over the recent years. Cellular Vehicle-to-Everything (V2X) communication facilitates the information exchange among road users (such as vehicles, pedestrians etc.) and the infrastructure with an intention to improve the overall road safety, driving comfort, traffic efficiency and save energy. Advanced use-cases aim towards enhancing key functionalities of vehicle automation by means of sensor data sharing and cooperative maneuver & trajectory planning. The introduction of the PC5 interface for sidelink (SL) communication within the mobile communication systems, supports direct exchange of messages between users, independent of the cellular network infrastructure.

Two types of radio resource allocation modes are supported in Cellular V2X: managed mode and the unmanaged mode. In the managed mode, a User Equipment (UE) remains connected to the cellular network and the process of resource allocation is coordinated by the base station. In the unmanaged mode, a UE selects its radio resources from a pre-configured resource pool without any assistance from the base station. Originally both these modes were developed by considering that the vehicles exchange periodic messages which are safety-critical in nature. The existing rule based radio resource allocation algorithms in both the modes are unable to adapt their selection parameters in the events of aperiodic data traffic patterns resulting from the diverse generation rules of different V2X messaging protocols.

We begin this PhD thesis by carrying out system level network simulations within the developed framework `Artery-C`, where we study the metrics and parameters that influence the performance of the rule-based radio resource allocation in the sidelink modes. In the first step, we derive the baseline conditions where each mode performs to its best efficiency. By varying the generation rules of the messaging protocols, we further analyze the behavior of the modes when V2X data traffic does not follow a specific pattern. Our studies have shown that both the modes suffer from frequent re-allocations because the messages are no longer periodic and the data sizes do not fit into the previously allocated radio resources. This results in poor utilization of the allocated resources. The unmanaged mode is particularly susceptible to radio resource

collisions because the vehicles only have partial awareness about the resource selection decisions of other road traffic participants.

As a second contribution, we examine the criteria for sidelink mode selection and the possibilities for a mode switching operation within the sidelink modes and also between the sidelink and the cellular (Uu) modes. We have formulated the strategies for mode switching and calculate the latency in each phase of the mode switch procedure. Although the managed mode has shown advantages with regard to allocation and management of radio resources, it is to be noted that a vehicle cannot remain connected to a base station at all instants of time. Also, switching between different modes is not seamless considering the associated latencies in each phase. This leads us towards the goal of improving the efficiency of the allocation & scheduling of radio resources in the unmanaged mode.

After a careful review of the enhancements that can be implemented within the rule based algorithm in the unmanaged mode, it was found that there needs to be a mechanism where vehicles can continuously share their resource selection decisions, adapt their selection parameters and even re-evaluate them (if needed) within a grant period. Therefore, we investigated the Reinforcement Learning (RL) based Artificial Intelligence (AI) approaches that facilitate independent learning, adapting and decision making among spatially distributed vehicular agents. We have developed a fully decentralized multi agent networked Markovian Decision Process (MDP) model of the Cellular V2X communication network where each agent executes an AI based radio resource scheduler. By extending the actor-critic methodology of the RL, we have derived two variants - Independent Actor Critic (IAC) and Shared Experience Actor Critic (SEAC). The results of our evaluations have indicated that both these schedulers have a potential to achieve better radio resource utilization with a reduced risk of radio resource collisions among the agents. Subsequently, it brings about $15-20\%$ improvement in the reliability of the communication link which we regard as a valuable contribution. To summarize, this PhD thesis investigates the performance of the rule based radio resource allocation algorithms in Cellular V2X and proposes the qualitative improvements that can be achieved by means of reinforcement learning.

Kurzfassung

Drahtlose Kommunikationstechnologien haben in der Verkehrsbranche in den letzten Jahren stark an Bedeutung gewonnen. Die Cellular Vehicle-to-Everything (V2X) -Kommunikation ermöglicht den Informationsaustausch zwischen Verkehrsteilnehmern (wie Fahrzeugen, Fußgängern usw.) sowie der Infrastruktur mit dem Ziel die allgemeine Verkehrssicherheit, den Fahrkomfort und die Verkehrseffizienz zu verbessern und Energie einzusparen. Fortschrittliche Anwendungsfälle nutzen diese Technologie um Kernfunktionen der Fahrzeugautomatisierung durch den Austausch von Sensordaten und kooperative Manöver- und Trajektorienplanung zu verbessern. Die Einführung der PC5-Schnittstelle für die Sidelink (SL)-Kommunikation in die zellularen Mobilfunksysteme, wird die direkte Kommunikation zwischen Nutzern unabhängig von etwaiger Mobilfunkinfrastruktur ermöglicht.

Cellular V2X unterstützt mit dem vewalteten (managed mode) und unverwaltetem Modus (unmanaged mode) zwei Arten der Zuweisung von Funkressourcen. Im verwalteten Modus bleibt ein Endgerät (UE) mit dem Mobilfunknetz verbunden und die Ressourcenzuweisung wird von der Basisstation koordiniert. Im unverwalteten Modus wählt ein UE seine Funkressourcen selbst aus einem vorkonfigurierten Ressourcenpool aus, ohne dass eine Basisstation dabei mitwirkt. Ursprünglich wurden beide Modi unter der Prämisse entwickelt, dass Fahrzeuge vorrangig periodische, sicherheitskritische Nachrichten austauschen. Die bestehenden regelbasierten Algorithmen zur Zuweisung von Funkressourcen beider Modi sind nicht in der Lage ihre Parameter bei aperiodischem V2X-Datenverkehr anzupassen, die sich aus den Generierungsregeln der verschiedenen V2X-Nachrichtenprotokolle ergeben.

Wir beginnen diese Doktorarbeit mit Netzwerksimulationen auf Basis unseres eigens entwickelten `Artery-C` Frameworks. In diesen Simulationen untersuchen wir die Metriken und Parameter, welche die Leistung der regelbasierten Funkressourcenzuweisung beider Sidelink Modi beeinflussen. Im ersten Schritt leiten wir die Ausgangsbedingungen ab, unter denen jeder Modus seine beste Leistung erbringt. Indem wir die Generierungsregeln der Nachrichtenprotokolle variieren, analysieren wir weiter das Verhalten der Modi bei unregelmäßigem V2X-Datenverkehr. Unsere Studien haben gezeigt, dass beide Modi aufgrund häufiger Neuzuweisungen negativ beeinflusst werden,

sobald Nachrichten nicht mehr periodisch sind und die Datengrößen nicht zu den vorab allokierten Ressourcen passen. Dies führt einerseits zu einer schlechten Auslastung der zugewiesenen Ressourcen. Andererseits ist besonders der unverwaltete Modus anfällig für Kollisionen der Funkübertragungen, da die Fahrzeuge nur teilweise über die Entscheidungen anderer Verkehrsteilnehmer bezüglich der Ressourcenauswahl informiert sind.

Als zweiten Beitrag untersuchen wir die Kriterien für die Auswahl des Sidelink-Modus und die Möglichkeiten für eine Umschaltung innerhalb eines Modus sowie auch zwischen den Sidelink- und zellularen (Uu) Modi. Wir haben hierfür Strategien zur Umschaltung formuliert und berechnen die Latenzen jeder Phase beim Wechselvorgang. Obwohl der verwaltete Modus in Bezug auf die Zuweisung und Verwaltung von Funkressourcen Vorteile bietet, ist zu beachten, dass ein Fahrzeug nicht zu jedem Zeitpunkt mit einer Basisstation verbunden bleiben kann. Insbesondere ist der Wechsel zwischen den verschiedenen Modi nicht nahtlos möglich, da die dabei auftretenden Latenzen berücksichtigt werden müssen. Dies motiviert uns schließlich die Effizienz der Zuweisung und Planung von Funkressourcen im unverwaltetem Modus zu verbessern.

Aus der sorgfältigen Überprüfung möglicher Verbesserungen an den bisherigen regelbasierten Algorithm leitet sich der Bedarf nach einem Mechanismus ab, welcher es Fahrzeugen erlaubt ihre jeweiligen Entscheidungen zur Ressourcenauswahl kontinuierlich auszutauschen, ihre Auswahlparameter anzupassen und bei Bedarf diese auch innerhalb einer Zuweisungsperiode neu zu bewerten. Daher untersuchen wir auf Reinforcement Learning (RL) basierende Ansätze der Künstlichen Intelligenz (KI), welche unabhängige Lern-, Anpassungs- und Entscheidungsprozesse zwischen räumlich verteilten Fahrzeugagenten ermöglichen. Wir haben ein vollständig dezentrales, vernetztes, Multi Agenten Markow-Entscheidungsproblem (MDP) für das Cellular V2X-Kommunikationsnetzwerk formuliert, in welchem jeder Agent einen KI-basierten Funkressourcenplaner ausführt. Durch die Erweiterung der Actor-Critic Methodik des RL haben wir zwei Varianten abgeleitet: Independent Actor Critic (IAC) und Shared Experience Actor Critic (SEAC). Die Ergebnisse unserer Untersuchungen haben gezeigt, dass beide Ansätze das Potenzial die Funkressourcen bei einem verringerten Risiko von Kollisionen zwischen den Agenten auszulasten. Weiterhin verbessert sich die Zuverlässigkeit der Kommunikationsverbindung um 15 – 20%. Zusammenfassend lässt sich sagen, dass diese Dissertation die Leistung der regelbasierten Algorithmen zur Zuweisung von Funkressourcen bei Cellular V2X quantitativ analysiert und qualitative Verbesserungen darlegt, die mit Hilfe von Reinforcement Learning erreicht werden können.

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Chapter 1

Introduction

The core vision of Cooperative Intelligent Transport Systems (C-ITS) revolves around an integrated communication and transportation network that targets towards achieving better road traffic safety, efficiency and enhanced awareness of the surroundings. Following the technological advancements made by the passive and active safety systems in automobiles, the next level of vehicle automation addresses the need to enable information sharing mechanisms among vehicles, infrastructure and other road traffic participants. Although several measures are undertaken by the department of Mobility and Transport in the European Commission in order to improve the road traffic safety and efficiency over the last decade, studies published in the European Commission's C-ITS report have indicated that the objective of achieving close to 50% reduction in the fatalities (caused by road traffic accidents) were unfortunately not achieved by the year 2020 [28]. Since the year 2016, the average number of fatalities per year is reported to be around $25,620$ and the number of serious injuries on EU roads is around $246,000$. Congested roads with poorly managed traffic not only affects the quality of transportation but also the environment, climate and eventually the economy of the countries.

1.1 Role of communication technology in C-ITS

The past decade has witnessed several remarkable new developments in technologies that support C-ITS; however, these are far from being used at their full potential despite their potential benefits. To enable communication between different road traffic users, standardized communication techniques for use cases including cooperative awareness and sensing already exist. The first standards were based on WLAN (IEEE 802.11p); more recently cellular communication systems have been extended to incorporate direct communication between any two User Equipments (UEs) using the sidelink (PC5) interface [40, 48]. In May 2018, the EU Commission [28] rolled out the strategy that

calls for an acceleration in the large-scale deployment of Vehicle-to-Everything (V2X) technology which continuously evolves with the emerging standards of the subsequent generations. The flexibility of the Cellular V2X technology to simultaneously support different V2X application scenarios such as Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P) and Vehicle-to-Network (V2N) in a scalable manner makes it suitable for deployment in the C-ITS.

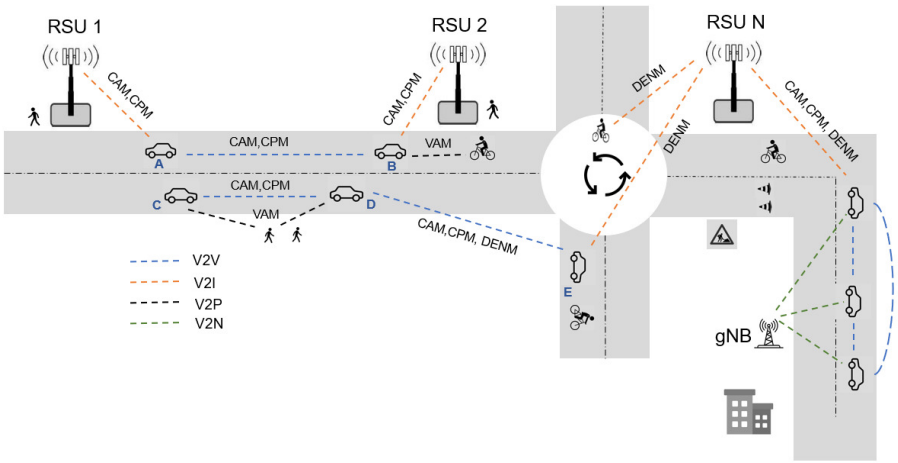

Figure 1.1 – Different types of V2X message exchanges between the road traffic participants on one of the public roads in the city of Ingolstadt, Germany[1] [67].

The European Telecommunications Standards Institute (ETSI)[2] [31] considers separate V2X messaging services depending on the use-case, type of information to be transmitted, their frequency and the corresponding latency & reliability requirements. The messaging protocols considered within the scope of this thesis are listed in Table 1.1. However, it is to be noted that there can be different categorizations for use-cases and combination of messaging protocols other than those illustrated in the example Figure 1.1.

Initial Cellular V2X use cases primarily target at driver information and warning, such as warning in case of hazards, roadworks (for example, in Figure 1.1, the Road Side Unit (RSU) N sends out warning messages to the nearby cars and bicycle riders about the road closure) and green light optimal speed advisory. In these use-cases, the V2X communication came as an enhancement to the existing Advanced Driver Assistance Systems (ADAS) by providing a means for explicit cooperation - some examples include hazard warning, Cooperative Adaptive Cruise Control (CACC) etc.

[1] Ingolstadt Innovation Lab (IN²Lab) project website: `https://in2lab.thi.de`

[2] European Telecommunications Standards Institute; ETSI standards are available at `https://etsi.org/standards`.

In the context of better traffic management at intersections, the Cellular V2X technology plays a key role - for example, when traffic lights are equipped with sensors and communication devices, it can help the vehicles to detect other vehicles in the neighbourhood and give warnings to stop and wait for oncoming traffic. Additionally, the vehicles can also be informed about the waiting times, road conditions and potential hazards.

An advanced use case such as sensor data sharing provides the potential to improve the perception capabilities of vehicles and to provide better situational awareness. As we can observe in Figure 1.1, the RSUs $1, 2, \cdots$N continuously monitor the road traffic movement and the underlying objects on the road. When an object is detected in the form of a car, pedestrian, cyclist or any other stationary/moving object, the RSUs send out Collective Perception Messages (CPMs) which contain the object list information (such as object distance, ID, velocity and many more) to the cars. This way, the cars A, B, C and D in Figure 1.1 are informed in advance about the road traffic conditions, movement of pedestrians etc. The sensor data sharing use case also helps to enhance the key functions of vehicle automation such as providing local and extended perception, prediction of driving situations & intentions and further extending to cooperative maneuver and trajectory planning. In addition to realizing V2V and V2I communication, the C-ITS also considers the safety of VRUs such as pedestrians, motorists and other users with reduced mobility. A warning system, where VRUs can actively send and receive messages instead of being passively monitored as road traffic objects, can play an important role in detecting risky situations and warn the vehicle drivers in advance.

Table 1.1 – Cellular V2X messaging protocols and their corresponding use-case.

Use-case	**Messaging protocol**	**ITS-Station**
Awareness	Cooperative Awareness Message (CAM)	Vehicle, RSU
Perception	Collective Perception Message (CPM)	Vehicle, RSU
VRU safety	VRU Awareness Message (VAM)	VRU
Hazard warnings	Decentralized Environmental Notification Message (DENM)	All

The messages listed in Table 1.1 can be transmitted either on the sidelink PC5 interface (referred to as direct mode) or through the conventional uplink and downlink Uu interface (referred to as cellular/networked mode). The advantage of the sidelink interface is that it can operate independent of the cellular network infrastructure and thereby guarantees lower latencies. The support of the V2N mode in Cellular V2X makes it possible for the stations (vehicles, RSUs etc.) to communicate with the network infrastructure about the current traffic situation(s). This way, a central entity at the infrastructure can have an overall perspective of the whole road traffic situation which can be useful for different types of threat analysis and prediction of hazardous situations.

The synergies between the operational interfaces of Cellular V2X provides it an ability to deploy both short-range and wide-range applications. The opportunity for integration with smart city and other connected transportation services is definitely expected to deliver additional qualitative benefits from this technology.

1.2 Radio resource allocation in Cellular V2X

Two types of radio resource allocation modes are defined for the sidelink interface in the Long Term Evolution (LTE) V2X within the 3GPP Release 14 specifications [31] - managed mode and the unmanaged mode. The managed mode of LTE V2X supported two types of radio resource scheduling algorithms - *(i)* Dynamic and *(ii)* Semi Persistent Scheduling (SPS). In the dynamic scheduling, the base station allocates radio resources for every V2X message a UE intends to transmit. In the SPS, a certain number of radio resources are pre-allocated for future transmissions. The SPS is more efficient in the sense that signalling overheads are much lower.

The managed mode in the Fifth Generation New Radio (5G-NR) V2X [48] (3GPP Release 16 [45]) underwent further changes where two new types of scheduling are introduced - *(i)* Configured Grant (CG) type I and *(ii)* Configured Grant (CG) type II. In both mechanisms, the base station (gNB) reserves resources for future use by the UE but the difference is that in CG type II algorithm, it activates only a portion of the resources based on the size of the data to be transmitted. In this way, the CG type II scheduling is more efficient in terms of radio resource utilization.

In the unmanaged mode of LTE V2X, a UE selects its resources autonomously from a pre-configured pool of radio resources without any assistance from the base station. It monitors the resource usage when it receives messages from other UEs in the previous time window of $1,000$ ms. This process is referred to as sensing. Based on the patterns in which it receives the messages, it makes future reservations which is governed by a re-selection counter (*cResel*) value. Moving to 5G-NR V2X, this is enhanced with two new features - prioritization mechanisms for aperiodic traffic and the possibility for re-evaluation of selected resources. It is to be noted that in the intermediate 3GPP Release 15, the sidelink does not undergo any specific changes in comparison to Release 14 specifications. Further technical details of the scheduling algorithms in both the sidelink resource allocation modes are explained in Chapter 2.

Investigation of radio resource allocation modes in sidelink

The highly dynamic nature of the Cellular V2X communication network consisting of several fast moving vehicles, unpredictable behavior of VRUs and frequently changing network and road topology conditions directly affect the triggering conditions and the generation rules of V2X messaging protocols listed in Table 1.1. The radio resource

scheduling algorithms should be robust enough to adapt their parameters to facilitate the distribution of radio resources among different road traffic participants in the events of changing V2X data traffic patterns. Although in the initial stages, these algorithms were designed by considering the periodic nature of the V2X messages, over a period of time it was realized that messages such as CAMs and CPMs can no longer be periodic and also their data sizes vary based on the containers needed to be transmitted.

As outlined in Section 1.2, the standards do not specify any protocols or strategies for selection of the appropriate sidelink mode of operation. The first question that arises is, which mode is more suitable for operation: the managed or the unmanaged and in which situation? Taking into account the time varying parameters such as geographic location of the vehicle, generation frequency of V2X messages & their data sizes, vehicle driving dynamics and many more, it becomes necessary to develop appropriate strategies for mode selection and mode switching.

Thinking one step forward, when vehicles are only operating in the unmanaged mode of the sidelink, currently even in the 5G-NR V2X standards [45], there exists no structured mechanism where vehicles can be notified of the radio resources utilized by the other vehicles. Due to lack of this knowledge, it leads to potentials risks of two or more vehicles selecting the same radio resource which we refer to as radio resource collision. Under high vehicular density conditions and unpredictable V2X data traffic patterns, it leads to misinformed resource selection decisions for neighboring vehicles causing poor resource utilization and unnecessary resource blocking. Although literature studies in [24] and subsequent standards releases [56] discuss this aspect, there are no clear solutions developed to address these issues. The possibility to use Artificial Intelligence (AI) based approaches seem interesting in the first glance but cannot be directly applied without detailed investigation of the boundary conditions and careful evaluations and experiments. Therefore, we argue that dedicated analytical and simulation based studies are needed to be carried out in order to make appropriate decisions for the selection of modes of operation, tuning of relevant parameters to optimize the radio resource scheduling and also further investigate the possibility of using decentralized AI based approaches.

1.3 Problem description

The current design of the radio resource allocation modes in sidelink is not robust enough to support a diverse nature of V2X data traffic patterns under constantly changing road topology and network coverage conditions. In this section, we further elaborate on the specific problems identified as a part of this thesis and discuss the methodology for their further investigation.

1.3.1 Diverse V2X data traffic patterns

Originally, the radio resource scheduling algorithms in the sidelink modes were designed by considering that the V2X message Inter Arrival Times (IATs) are fairly constant with deterministic data sizes. Moving forward, it led to the development of advanced use-cases that require the vehicles and infrastructure to send larger data sizes [12] based on different levels of changes in the environment perception, vehicle dynamics, driving intentions (for example, in maneuver coordination) and many more. The existing algorithms for radio resource scheduling in the managed and the unmanaged modes cannot be easily adapted by simple tuning of related parameters [4, 31, 45].

1.3.2 Limited awareness of resource usage among road traffic participants

Operation in the unmanaged mode:
When vehicles are operating in the sidelink unmanaged mode, they have only partial or no knowledge of the radio resources selected and utilized by other vehicles. Owing to the dynamically changing nature of the road topology, sporadic availability of network coverage and constantly changing V2X data traffic patterns, it becomes very tricky for the vehicles to make resource reservation decisions for future time windows. To tackle this problem, some research works [24] consider sharing of certain resource allocation parameters between the vehicles but so far there are no structured approaches to solve this problem.

Operation in the managed mode:
When vehicles are operating in the sidelink managed mode, the base station is aware of the resources utilized by its connected users and their V2X data traffic patterns & requirements. However, it cannot be ignored that there can be some vehicles in the vicinity that operate in the unmanaged mode. The base station cannot pre-determine the V2X data traffic patterns of such vehicles while making the decisions for future reservations for its connected UEs. However, there exists a potential advantage that it can switch from SPS to dynamic scheduling during such events and manage the resource allocation process. The CG type II algorithm in the 5G-NR V2X standards [45, 48] further provides an advantage that a subset of the pre-allocated resources can be activated based on the data traffic requirements and remaining resources can be re-distributed.

1.3.2.1 Potential risks for radio resource collisions

Due to limited awareness about the radio resource utilization and unpredictable V2X data traffic patterns, the subsequent problem that arises is that more than one vehicle

selects the same radio resource for its transmission. We refer to this as radio resource collision.

When all vehicles are operating in the unmanaged mode, the SB-SPS algorithm (in both LTE V2X and 5G-NR V2X) checks for potential collisions at the time of resource allocation but cannot guarantee that allocations in the future time windows are free of collisions. Although the sensing process occurs continuously, the allocation of radio resources is performed only once for the entire length of the sidelink grant period. In the events of frequent re-allocations due to changing V2X data traffic patterns especially in high vehicular density conditions, the sidelink unmanaged mode is highly susceptible to radio resource collisions. On the other hand, the managed mode handles this situation in a better manner since the base station is aware about the radio resource allocation & utilization by its connected users.

1.3.3 Mode selection and switching decisions

The choice of the radio resource allocation mode for a given UE is not always a straightforward decision considering the effect of the following time varying factors.

- Geographical location of the ITS-station - whether a UE is located within the region of cellular coverage or not.
- Nature of the V2X application - safety-critical, environmental perception, infotainment etc.
- V2X data traffic characteristics - periodic or aperiodic traffic patterns with variable data sizes.
- Communication link quality requirements - maximum allowable latency and reliability.
- Operational costs - communication with the network infrastructure by means of a SIM card.
- Availability of hardware for each of the modes[3] - currently the V2X hardware in the market supports only the unmanaged mode.

In the managed mode, there exists a possibility to change between the dynamic scheduling and SPS mechanism based on the requirements of the V2X data traffic. However, the problem is that a vehicle cannot remain in the managed mode at all instants of time and also if it has to stay connected with the network infrastructure, it comes at an additional subscription cost and signalling time delays.

The SB-SPS algorithm in the unmanaged mode is extremely efficient in achieving lower latency due to a reduced amount of signalling overhead. Also, it facilitates a

[3]Market information as of August 2023.

possibility for communication irrespective of whether a vehicle is located within the region of cellular network coverage or not. However, the concept of pre-allocating radio resources for future transmissions is not always the best approach considering the resource utilization aspects and the potential risks for radio resource collisions as explained in Section 1.3.2.

Weighing the benefits offered by both the modes, it can lead to a good argumentation to consider the idea of implementing mode switching between the sidelink modes and also between the sidelink and cellular (Uu) mode. However, the switching procedure is not so easy because if a vehicle has to switch from the sidelink unmanaged mode to sidelink managed or to the cellular (Uu) mode, it should drive to a region where cellular network coverage is available which cannot happen instantaneously. In order to switch from the managed to the unmanaged mode in areas such as tunnels where Global Navigation Satellite System (GNSS) is not available for synchronization, the vehicles experience large synchronization latencies with the proposed *SyncRef* UE option in the standards [31].

1.4 Research questions

In this section, we discuss about the research questions (RQs) and practical perspectives which influence the choice of our methodology to tackle the problems discussed in Section 1.3.

To evaluate the robustness in the performance of any radio resource scheduling algorithm it is important to understand its adaptability for different types of V2X data traffic patterns. In the first step, we studied the generation rules of the V2X messaging protocols in terms of their triggering conditions, format, number of containers along with the size & frequency of each container.

RQ 1 *What are the parameters and metrics that influence the performance efficiency of the radio resource allocation modes in different Cellular V2X environments?*

The main discussion points related to RQ 1 are: *(a)* What is the baseline condition where both the radio resource allocation modes perform to their best efficiency? *(b)* How does each mode behave when we vary the V2X data traffic patterns and vehicular density conditions? What are corresponding parameters and metrics that help us to quantify the points *(a)* and *(b)* and how are they formulated & measured in simulations?

RQ 2 *How does a UE select a particular mode of operation and what are the different strategies for mode switching?*

The main discussion points related to RQ 2 are: *(a)* What are the factors that affect a mode selection decision and what are the events that trigger a necessity for mode switching? *(b)* What are the different possibilities to switch between the sidelink modes

and between the sidelink and the cellular (Uu) mode? In the event that a successful mode switch happens, what are the phases involved in a mode switch procedure and the corresponding latencies (or delays) in each phase? *(c)* Which is the preferred mode of operation and can a UE be able to conveniently switch to this mode if it cannot meet the radio resource requirements in its current operating mode?

RQ 3 *How can we improve the efficiency of radio resource allocation in the unmanaged mode? What are the qualitative improvements that can be achieved by employing suitable AI based approaches?*

The main discussion points related to RQ 3 are:
A collaborative approach for radio resource allocation is considered to be a big step forward both in the research and standardization domains [56]. However in the standards, it still remains unclear as to how this can be accomplished within the SB-SPS algorithm. The 3GPP standardization [56], considers the introduction of an "Inter-UE coordination" message type that facilitates the sharing of different radio resource related parameters.

Some of the aspects that are currently under discussion are: *(i)* How often and in what events do the vehicles send this "Inter-UE coordination" message? *(ii)* What is the time needed (in terms of number of slots) at the receiving UE to process such a message and accordingly alter its current and future resource allocations/reservations? *(iii)* Is it mandatory for all the UEs in a network to transmit this message or is it sufficient for those UEs which see a potential risk of radio resource collision? *(iv)* What are the additional overheads in terms of resources and latency needed to incorporate an additional message for coordinating the task of radio resource allocation?

Thinking further about the idea of introducing an additional message to coordinate the radio resource allocation task, we understand that such a message can definitely improve the extent of awareness about radio resource utilization but does not necessarily alleviate the chances of potential radio resource collisions especially under aperiodic traffic conditions in densely crowded road traffic scenarios. When each vehicle has configured a different RRI and adopts random values for re-selection counters, all parameters cannot be synchronized by the adoption of "Inter-UE coordination" message. Therefore, there needs to be a constantly evolving mechanism where the vehicles learn by means of interaction with the other road traffic participants to improve their radio resource allocation. The Reinforcement Learning (RL) facilitates such a mechanism where the obtained rewards in each of the previous grant period play a significant role in adjusting the parameters for the subsequent allocations. To implement such a radio resource scheduler, the following aspects need to be carefully assessed:
(a) How do we train the RL based schedulers - online or offline? *(b)* How can the RL based schedulers improve the efficiency of radio resource allocation in the events of dynamically changing V2X data traffic patterns? *(c)* How to establish common knowledge between decentralized agents that have only limited awareness of their

environment? *(d)* Is it a good idea to switch back to the rule based resource scheduling algorithms under appropriate situations?

1.5 Structure of the thesis

The remainder of this PhD thesis is organized as follows:

Chapter 2 provides technical details about the fundamental concepts related to radio resource allocation modes in Cellular V2X and also reviews the scientific state-of-the-art. Additionally, we also discuss about the emergence of different AI based approaches for radio resource allocation in vehicular communication networks and understand their advantages and uncertainties.

Chapter 3 discusses the requirements needed to realize a combined simulation framework that couples the network simulator with a realistic road traffic model. The system architecture consisting of the Cellular V2X protocol stack layers, channel modeling approaches and the V2X messaging services are presented in this chapter. Also, this chapter further elaborates on the architecture to extend the simulator with a Deep Reinforcement Learning (DRL) based environment where different AI algorithms can be implemented and tested.

An in-depth analysis of the limitations and challenges of the sidelink resource allocation modes under various types of V2X data traffic patterns is presented in Chapter 4. The measurable parameters and metrics are formulated analytically which serve as a basis for performance evaluation of the radio resource allocation modes throughout this thesis.

Following a detailed evaluation of the sidelink resource allocation modes, we discuss the possibilities for mode switching in Chapter 5. The procedure is decomposed into subsequent phases and specific strategies are formulated for mode switching. The latency in each of the mode switching phase and the overall impact of mode switching on the reliability of Cellular V2X communication links is further studied by means of simulations.

With an objective to improve the robustness of the radio resource allocation in the unmanaged mode, Chapter 6 investigates the application of decentralized multi agent DRL techniques. Simulation studies are further carried out to evaluate the advantages of the AI based radio resource schedulers in comparison to the rule based SB-SPS in the unmanaged mode.

Chapter 2

Fundamentals

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In this chapter, we present the fundamental technical concepts on which the PhD thesis develops in the subsequent chapters. This chapter is divided into two main parts: *(i)* Technical background and *(ii)* State-of-the-art. In the technical background section, we discuss about the radio resource allocation algorithms in Cellular V2X and introduce the different types of European Telecommunications Standards Institute (ETSI) compliant V2X messaging services and protocols.

In the state-of-the-art section, we perform a detailed literature review on the existing approaches related to the study of radio resource allocation in Cellular V2X, evaluation methodologies at different levels of abstraction and the emergence of Artificial Intelligence (AI) based techniques in the field of vehicular communication networks.

2.1 Technical background

The concept of Device-to-Device (D2D) communication was first introduced in the Long Term Evolution-Advanced (LTE-A) (i.e., in the Third Generation Partnership Project (3GPP) Release 12/13) which focused on proximity services and public safety applications. It further evolved in the subsequent Releases 14 and 15, where the support for automotive applications were included with the priority of improving road traffic safety and efficiency. In the more recent Fifth Generation New Radio (5G-NR) V2X release (i.e., Release 16), the sidelink extends to connect more devices at the edge-providing new classes of services and user experiences. In the following subsections, we present the technical details about the radio resource allocation modes and the rule based scheduling algorithms with compliance to the ETSI 5G-NR V2X standards [45] and also highlight the relevant improvements with reference to the previous LTE V2X standards [42]. Further, we elaborate on the V2X messaging services and their corresponding protocol definitions, data structure and triggering conditions which we consider to be an integral part of this work.

2.1.1 Radio resource allocation modes

The sidelink (PC5) is continuously evolving since its introduction in the LTE V2X. The 5G-NR V2X improves the functional capabilities of the sidelink with the inclusion of variable numerologies, bandwidth parts and technical enhancements to the radio resource scheduling algorithms. It supports two modes of operation - managed mode and unmanaged mode.

In the managed mode, both the resource allocation and scheduling is performed by the base station (Next Generation Node B (gNB)) in a centralized manner. It configures the sidelink parameters such as carrier frequency, subchannels, and time slots in order to enable transmission of messages between different User Equipments (UEs). The process of activation, de-activation and modification of allocated resources is done dynamically

based on the feedback received from a UE about the size, priority and transmission frequency of its message.

In the unmanaged mode, a UE selects its resources autonomously from a pre-configured radio resource pool independent of the base station. To do so, the UE continuously monitors the resource usage by other UEs before it selects resources for itself. Although the standards specify the methodology for sensing and parameter sharing within the Sidelink Control Information (SCI), the UE still has only partial knowledge of the resources selected & utilized by other UEs. There exists no central unit like the base station that coordinates and manages the resource allocation process.

To understand the operation of the radio resource allocation modes and improve their efficiency, it is important to obtain a thorough understanding of the configurable entities and their parameters which affect the radio resource allocation and scheduling decisions. The configurable entities discussed in the following subsection are: *(i)* Radio resource pool and *(ii)* Physical channels and signals in sidelink.

Radio resource pool

A radio resource pool can be defined in two dimensions - time (slots or subframes) and frequency (subchannels). A Resource Block (RB) has a bandwidth of 180 kHz consisting of 12 subcarriers in the frequency domain and has a length of one slot (or subframe) in the time domain. In the frequency domain, the RBs are grouped into subchannels. The number of subchannels, their size and the duration of the slots are determined in accordance to the ETSI specifications [40].

Numerologies:
Two frequency bands are supported for operation in 5G-NR V2X [40] namely,

- Frequency range (FR I): $410 - 7.125$ MHz.
- Frequency range (FR II): $24.25 - 52.6$ GHz.

In comparison to LTE V2X [31], the slot lengths in 5G-NR V2X can vary based on the subcarrier spacing (SCS) parameter μ. The slot lengths based on different values of SCS are listed in Table 2.1. Depending on the nature of the V2X application, appropriate SCS and slot lengths can be adopted. Additionally, two configurations for cyclic prefix lengths are supported - normal and extended.

In Figure 2.1, we illustrate the structure of a radio frame (of length 10 ms), the number of slots per subframe along with their duration for each type of numerology under normal cyclic prefix conditions. It can be seen that as the SCS increases from 15 kHz to 120 kHz, the slot duration decreases from 1 ms to 0.125 ms. The slot structure consisting of 14 symbols is depicted in Figure 2.2. Each symbol is responsible to carry particular information related to control (Physical Sidelink Control Channel (PSCCH)), data

(Physical Sidelink Shared Channel (PSSCH)), feedback (Physical Sidelink Feedback Channel (PSFCH)), reference (Demodulation Reference Signal (DMRS)), Automatic Gain Control (AGC) and guard intervals.

Need for variable numerologies

For lower range of carrier frequencies ranging from 1 GHz to few GHz, smaller numerologies, i.e., SCS ranging from 15 kHz to 30 kHz, are beneficial where low latency requirements can be satisfied. For higher range of carrier frequencies especially in milli-meter wave bands, the phase noise becomes more critical and hence it is beneficial to have larger subcarrier spacings.

Table 2.1 – Numerologies supported in 5G-NR V2X.

μ	SCS [kHz]	Symbols per slot	Slot duration [ms]	Max BW [MHz]
0	15	14	1	50
1	30	14	0.5	100
2	60	14,12	0.25	200
3	120	14	0.125	400

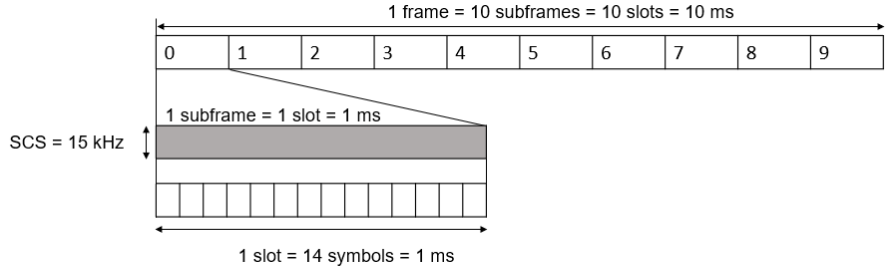
Sidelink Bandwidth Part (SL-BWP):

Supporting larger bandwidths create additional computational resources for a UE in terms of power, Radio Frequency (RF) and base band signal processing capabilities. Extending the concept of bandwidth (BW) part from the 3GPP Release 15, the concept of Sidelink Bandwidth Part (SL-BWP) was introduced in Release 16 [40]. A SL-BWP refers to a contiguous portion of the carrier bandwidth (refer to Figure 2.3) where a single numerology is applied. All the assigned resources, physical channels and synchronization signals are expected to be contained within the SL-BWP.

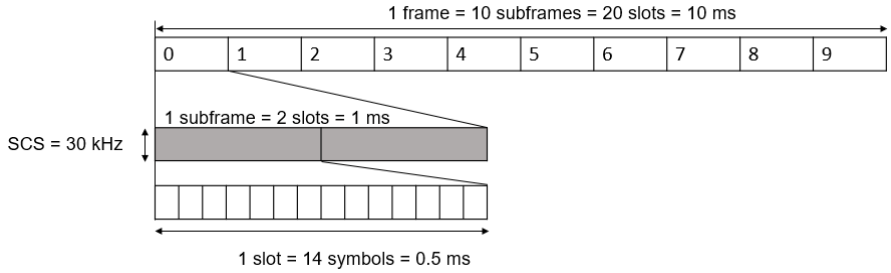
Physical channels and signals in sidelink

Two broad categories of physical channels for sidelink are specified by the standards [32, 33] that carry different types of information: *(i)* Sidelink Transport Channel (STCH) and *(ii)* Sidelink Broadcast Channel (SBCH).

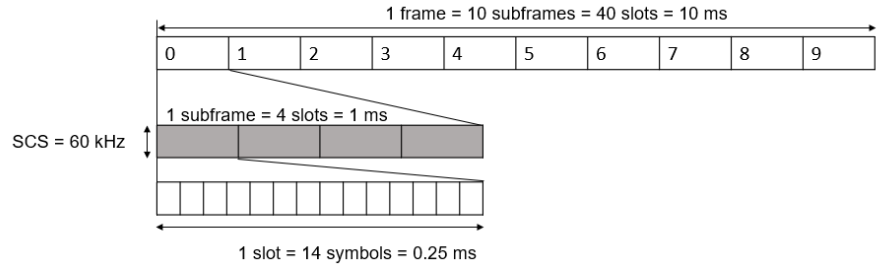
The STCH is responsible for carrying all the data related information and it interfaces with the Physical Sidelink Shared Channel (PSSCH). The SBCH is responsible for carrying information related to the synchronization signals when a UE is located outside the region of cellular network coverage. It interfaces with the Physical Sidelink Broadcast Channel (PSBCH). Additionally, there also exists the Physical Sidelink Control Channel (PSCCH) that is dedicated to the transport of all control related information. In addition to the physical channels, the following signals are defined in the 5G-NR V2X [48] as illustrated in Figure 2.2.



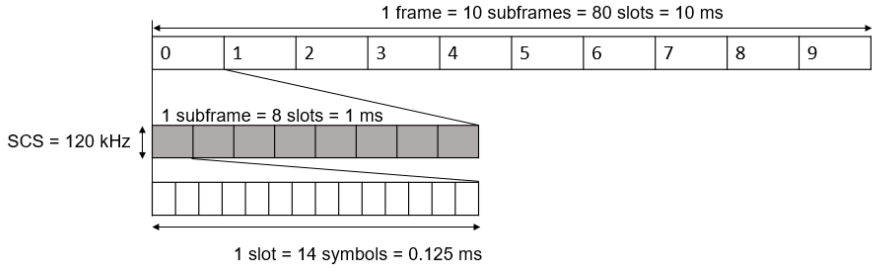
(a) $\mu = 0$



(b) $\mu = 1$



(c) $\mu = 2$



(d) $\mu = 3$

Figure 2.1 – Number of slots for different numerologies in 5G-NR V2X.

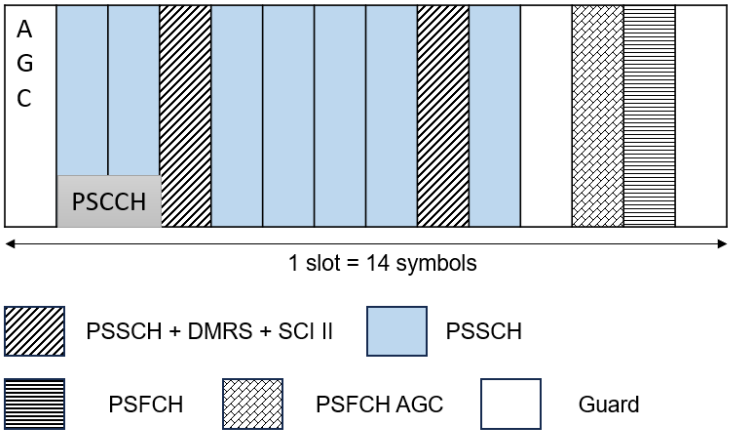


Figure 2.2 – Slot structure in 5G-NR V2X.

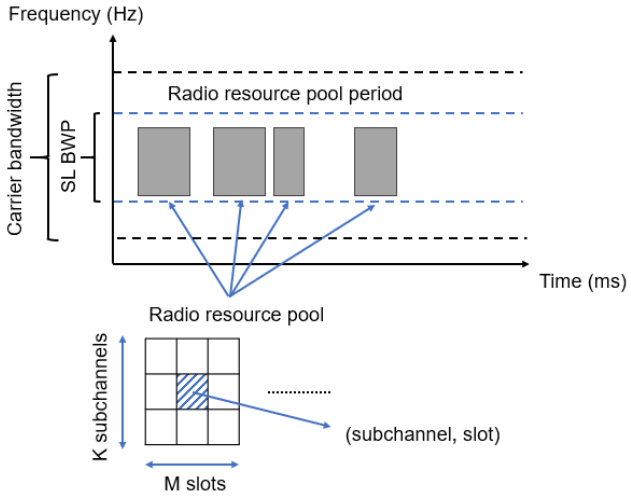


Figure 2.3 – Radio resource pool and sidelink BWP.

- Demodulation Reference Signal (DMRS): Utilized by the receiver for decoding the information in PSSCH and PSCCH.
- Sidelink Primary Synchronization Signal (S-PSS) and Sidelink Secondary Synchronization Signal (S-SSS): These are required for time synchronization between transmitter and receiver UEs.
- Sidelink Channel State Information Reference Signal (SL-CSI-RS): The channel state information between the transmitter and receiver UE is measured by the receiver UE and given as a feedback to the transmitter UE.
- Sidelink Phase Tracking Reference Signal (SL PT-RS): This is used to mitigate the effect of phase noise resulting from imperfections in the oscillator.

PSCCH in 5G-NR V2X:
The PSCCH in 5G-NR V2X carries the Sidelink Control Information (SCI) component which is divided into two stages. The stage-1 SCI carries information related to allocation of radio resources, priority, format and size of the required radio resources. The stage-2 SCI carries information related to sidelink Hybrid Automatic Repeat Request (HARQ).

The fields in the stage-1 SCI [56] are as follows:

- Priority
- Frequency resource assignment
- Time resource assignment
- Resource Reservation Interval (RRI)
- DMRS
- Modulation and Coding Scheme (MCS)
- Stage-2 SCI format
- Beta offset indicator
- Number of DMRS ports
- Reserved

The fields in the stage-2 SCI are as follows:

- HARQ process ID
- New data indicator

- Redundancy version
- Source ID
- Destination ID
- CSI request

How does it differ from LTE V2X?
In LTE V2X, two types of SCI formats are defined - SCI format 0 and SCI format 1. The SCI format 1 is used for the radio resource scheduling in PSSCH. The total size of the SCI is fixed to 32 bits. The fields in the SCI format 1 are as follows:

- Priority
- Frequency resource location of initial transmission and re-transmission
- Time gap between initial transmission and re-transmission
- RRI
- Re-transmission index
- MCS
- Reserved

For the sidelink operation, LTE V2X supports a fixed length SCI format which is sent only once in contrast to the two stages in 5G-NR V2X. The reserved bits field in both the stages of the SCI in the 5G-NR V2X allows for inclusion of additional information which helps the receiver to get better knowledge of the nature of the V2X data traffic.

PSSCH in 5G-NR V2X:
The PSSCH contains the stage-2 SCI along with the data payload in the form of transport block (TB). The advantage in 5G-NR V2X is that the stage-1 SCI contains all the information required to decode the stage-2 SCI and hence no blind decoding of SCI is required. By including the source and destination IDs, the receiving UE has knowledge of the identity of the transmitting UE and also the indication of new/re-transmitted data.

2.1.2 Radio resource scheduling algorithms

The mechanism involved in providing the selected/allocated radio resources in a timely manner for a UE is referred to as resource scheduling. Following the steps involved in the configuration of the sidelink parameters, the UE chooses to operate in one of the sidelink modes depending on the availability of cellular network coverage, safety critical requirements of the V2X data traffic and also the channel state conditions. The specific criteria for mode selection are explained in Chapter 5.

2.1.2.1 Managed mode

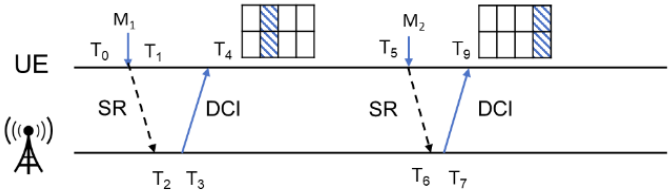
The managed mode in LTE V2X is capable of supporting two types of scheduling - dynamic and Semi Persistent Scheduling (SPS). The dynamic scheduling offers more flexibility and accuracy because the exact amount of radio resources are allocated by the base station (gNB) every time a UE wants to transmit a V2X message. The UE requests radio resources from the gNB by sending a Scheduling Request (SR) as shown in Figure 2.4a. The gNB configures radio resources separately for each V2X message $[M_1, M_2, \cdots]$ as indicated in Figure 2.4a. This type of scheduling incurs larger signalling overheads and sometimes increased latencies.

Considering the periodic nature of the V2X data traffic (based on some variants of the Cooperative Awareness Message (CAM) in the initial stages of development), it was understood that a certain amount of radio resources can be pre-allocated for a deterministic number of future transmissions. This led to the development of the SPS algorithm. Simulation studies [83] have indicated that the SPS algorithm was very efficient for periodic messages where it incurred less signalling overheads and delivered shorter End-to-End (E2E) latencies that made it suitable for safety-critical V2X applications. Moving to the advanced Use Cases for sensor data sharing (based on the Collective Perception Message (CPM) and CAMs that take into account of several dynamic factors of the vehicle), pre-allocation of radio resources becomes challenging because messages are no longer periodic with deterministic data sizes.

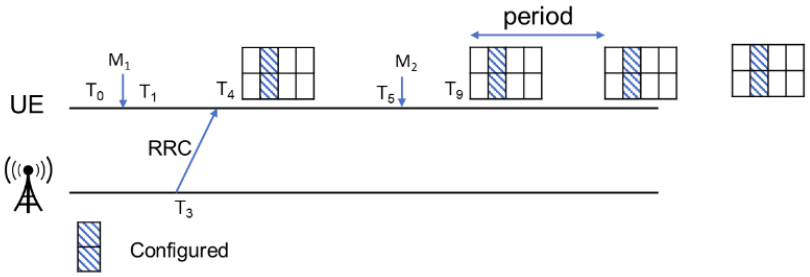
Hence, the 5G-NR V2X standards [48] have replaced the SPS with Configured Grant (CG) scheduling (refer to Figure 2.4) for the managed mode. Two variants of CG scheduling are - CG type I and CG type II.

- **Configured Grant Scheduling type I**
  The gNB is continuously aware of the V2X data traffic information of its connected users such as the periodicity of sidelink traffic, Transport Block (TB) sizes and Quality of Service (QoS) information (latency, reliability and priority). It configures a set of radio resources for future transmissions of the messages $[M_1, M_2, \cdots]$ as shown in Figure 2.4b via the RRC signalling. This set of resources is referred to as configured grant. These radio resources can be immediately utilized by the UE depending on the requirements of the Transport Block (TB).

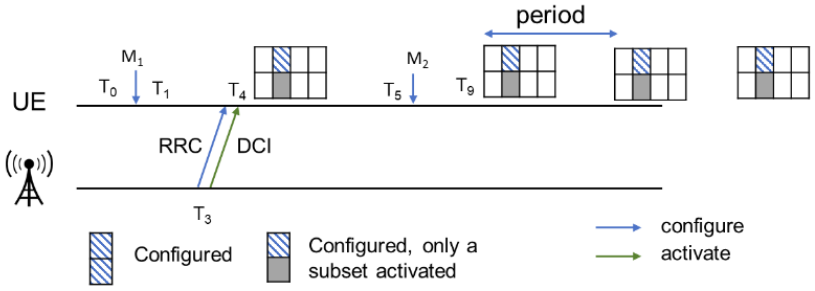
- **Configured Grant Scheduling type II**
  The radio resources are configured similarly to CG type I algorithm via the RRC signalling but the difference is that a UE can use the radio resources only after they are activated by the gNB until their deactivation. The gNB notifies of the activation and deactivation using the Downlink Control Information (DCI) signalling [45]. The DCI also includes information of the CG index and time-frequency allocation of CG type II. The CG type II algorithm can configure



(a) Dynamic scheduling



(b) Configured grant type I scheduling



(c) Configured grant type II scheduling

Figure 2.4 – Radio resource scheduling in the managed mode of 5G-NR V2X.

multiple CGs for a UE and only activate a subset of the CGs (via RRC+DCI signalling as shown in Figure 2.4c) based on the UE requirements. Resources in non-active CGs can be allocated to other UEs. Considering the advantages of the activation and deactivation mechanisms, this work adopts the implementation of the CG type II algorithm for the managed mode in all its simulation studies.

How it differs from the managed mode in LTE V2X?

The managed mode in 5G-NR V2X retains the possibility for dynamic scheduling (refer to Figure 2.4a) similar to the managed mode in LTE V2X. The procedure has not undergone any specific changes within the intermediate releases.

However, the SPS algorithm in the managed mode of LTE V2X is now replaced by CG type I and CG type II scheduling algorithms. Both these algorithms consider

pre-allocation of radio resources for future transmissions as indicated in the configured grant. The CG type II algorithm however is more efficient because it activates portions of the allocated radio resources depending on the nature of the V2X data traffic. The non-utilized resources can be distributed among other connected users. In both the CG algorithms, a UE is allowed to utilize the radio resources in the configured grants even in situations when it wants to operate in the cellular (Uu) mode until the expiration of a specific timer T_{310} [45]. Following that, it has to compulsorily switch to the unmanaged mode of operation.

2.1.2.2 Unmanaged mode

A UE operates in the unmanaged mode when it is located outside the coverage area of a base station. The sensing mechanism enables it to gain knowledge of the radio resources utilized by other UEs along with the time domain spacing between them. Using this information, the UE allocates its own radio resources by means of the SPS algorithm. Jointly, it is known as Sensing Based Semi Persistent Scheduling (SB-SPS). The fundamental idea of the SB-SPS algorithm in 5G-NR V2X remains same as compared to LTE V2X, except that 5G-NR V2X aims towards achieving better awareness among the UEs. This is accomplished by introducing a two stage SCI format that allows for the inclusion of certain configuration parameters within the SCI. Some interesting simulation studies in [10, 24] demonstrate the benefits of sharing these parameters and accordingly adapting the SB-SPS algorithm based on the dynamically changing traffic and radio resource availability conditions.

Sensing Based Semi Persistent Scheduling (SB-SPS):
A UE is capable of sensing the SL resources in all time slots except the slot in which it is transmitting. During the sensing process, it decodes the stage-1 SCI received from other UEs in the sensed SL resources. This indicates the radio resources that other UEs have reserved for their subsequent transmissions in the PSSCH slots (indicated in Figure 2.2). The UE stores this sensed information and utilizes it for candidate resource selection. For SB-SPS, the length of the sensing window is specified to be between $1,000-1,100$ ms. In case of dynamic scheduling, the length of the sensing window can be as small as 100 ms.

In order to start allocating radio resources, the UE first defines a selection window (refer to Figure 2.5) of duration $[m+T_1, m+T_2]$ where T_1 accounts for the processing time required for start of resource selection and T_2 is the maximum allowed latency or the Packet Delay Budget (PDB). For an SCS of 15 kHz, $T_1 \leq 3$ ms. Allowable minimum values for T_2 are $[1,5,10,20] * 2^{\mu}$ slots based on the chosen numerology.

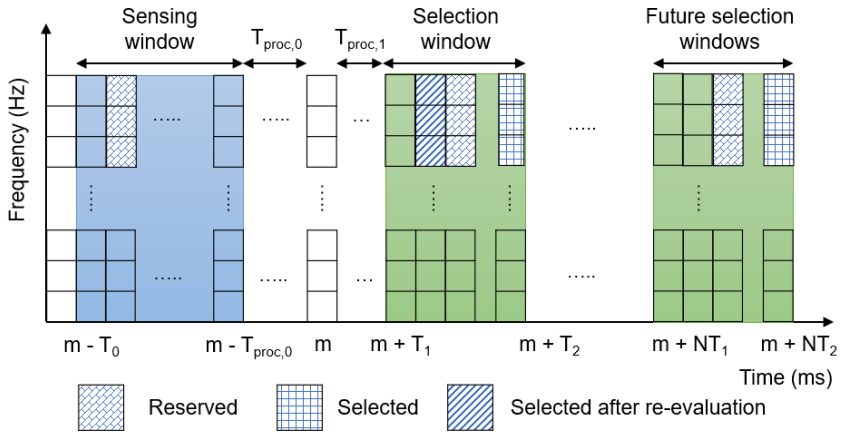


Figure 2.5 – Radio resource scheduling in the unmanaged mode of 5G-NR V2X.

A configured radio resource is represented in terms of slot and the number of subchannels available for SCI and TB per slot. The UE implements a two step procedure to allocate the Candidate Slot (or subframe) Resource (CSR):

- Step 1: The UE excludes all the candidate resources in the selection window based on these two conditions: *(i)* A resource in the selection window happens to be allocated by some other UE for its future transmission (based on the received stage-1 SCI in the sensing window). *(ii)* In the condition *(i)*, the UE reports to have measured a Reference Signal Received Power (RSRP) value that is higher than a prescribed threshold. After executing step 1, the UE checks whether the percentage of available candidate resources in the selection window is equal or higher than 20%. If not, the RSRP thresholds are increased by 3 dB and the process is repeated iteratively until the percentage of available candidate resources in the selection window is at least equal to 20%.

- Step 2: After the UE has obtained a list of candidate resources in step 1, it randomly selects a radio resource for transmission.

Re-evaluation of selected resource: A UE which has completed the selection of the radio resource in the above two steps, still continues to sense in the selection window interval. Based on the updated sensing information, it has the possibility to re-do the selections in case it detects that another UE has chosen the same resource and also has measured an RSRP value higher than the prescribed threshold. The UE can make a decision to re-select the resources only in cases where it gets to know atleast 3 slots prior to the location of the chosen radio resource. Otherwise, the UE will continue to maintain its previous selection and the radio resource collision cannot be avoided. It is to

be noted that such a re-evaluation can be performed only once when a UE configures the radio resources for a certain grant period. For the subsequent selection windows within the configured grant, it cannot re-select the radio resources in the events of suspected resource collisions. Re-selections are permitted only when the size of the data does not fit into the previously allocated radio resources or when the value of re-selection counter reaches zero.

How it differs from the unmanaged mode in LTE V2X?

The unmanaged mode in 5G-NR V2X differs from that of LTE V2X in the following aspects:

- The number of steps in CSR selection is limited to two. The third step that involves ranking of selected resources based on their Received Signal Strength Indicator (RSSI) values in LTE V2X is eliminated in the unmanaged mode of 5G-NR V2X.
- In LTE V2X, the SCI is limited to 32 bits. 5G-NR V2X introduces a two stage SCI with more bits in reserved fields that can help to encode more control related information.
- LTE V2X does not facilitate the re-evaluation of selected radio resources.

2.1.3 V2X messaging services

By closely aligning with the ETSI compliant definitions of the V2X messaging services [34, 35, 43], in this section we explain some of the salient features such as the containers in the data structure, generation models and triggering conditions which are considered within the scope of this thesis. Although the standards consider several conditions for generation and trigger, we make certain adaptations in the modeling of these messages such that they are relevant to our simulated road traffic environment.

2.1.3.1 Cooperative Awareness (CA) service

The objective of the CA service is to allow vehicles to gain and maintain awareness of other vehicles in proximity. This is accomplished by means of the CAM protocol. A CAM is exchanged between different road traffic participants (e.g., vehicle, Road Side Unit (RSU) etc.) to create and maintain awareness of each other within a road traffic network. A CAM typically contains status and attribute information of the originating ITS-Stations (ITS-S). The content varies depending on the type of the ITS-S. For vehicle, the status information includes time, position, motion state, activated systems and many more. The attribute information includes data about the dimensions, vehicle type and role in the road traffic, etc. On reception of a CAM, the receiving ITS-S

becomes aware of the presence, type, and status of the originating ITS-S. The received information can be used by the receiving ITS station to support several ITS applications. For example, by comparing the status of the originating ITS-S with its own status, a receiving ITS-S is able to estimate the collision risk with the originating ITS-S and if necessary may inform the driver of the vehicle via the Human Machine Interface (HMI).

CAM data structure

The specific containers of the CAM data structure are shown in Figure 2.6. The ITS PDU header consists of the station ID, protocol version and message ID information. The contents transmitted by the basic container include: *(i)* Type of originating ITS-S *(ii)* Last geographic position. All the CAMs generated by vehicles include atleast one high frequency container which consists of information about all the dynamically changing parameters such as vehicle speed, heading angle etc. The low frequency container transmits the parameters which do not change that frequently such as the vehicle lights. The special vehicle container which is an optional container, is sent only when the vehicle has a specific role in public traffic such as transporting of dangerous goods, roadworks vehicle, emergency service vehicle or any other as specified in [35].

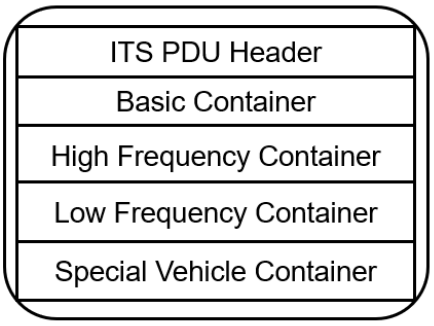


Figure 2.6 – CAM data structure [35].

CAM triggering conditions

Each vehicle equipped with a CA service, generates one to ten CAMs per second depending on its own dynamics and the prevalent channel congestion. Vehicle data originating from the road traffic model are evaluated every 100 ms if any of the following three vehicle dynamics rules triggers:

- Heading has changed by more than 4 degrees.
- Position differs by more than 4 m.
- Absolute speed difference exceeds 0.5 m/s.

Whenever one of these rules trigger, the determined CAM update rate is kept for the next three subsequent CAMs. Hence, the CA service does not immediately reduce its generating rate even if the vehicle dynamics are changing less frequently. Also, the Decentralized Congestion Control (DCC) has an explicit influence on the message generation rate [30]. While the triggering rules mentioned above describe the desired message generation rate by the CA service, this rate may get limited when the DCC module detects a congestion and thereby imposes a lower rate. However, a CAM will be generated atleast once per second. Thus, the effective message rate ranges from 1 Hz to 10 Hz. The length of a CAM also varies over time as its low-frequency container is only appended every 500 ms. Typically, the length of generated CAMs ranges from $41 - 242$ bytes.

2.1.3.2 Decentralized Environmental Notification (DEN) service

The DEN service informs the road traffic participants about the road hazards or any abnormal road conditions [36]. In contrast to the CAMs, the occurrence of a Decentralized Environmental Notification Message (DENM) cannot be predicted because they are always linked to events. Typical use cases of the DENM service include adverse weather conditions, dangerous situations because of hard braking, stationary vehicles such as broken-down or crashed vehicles, and traffic jams. Many triggering conditions are way beyond the scope of network simulations, because it is not feasible to simulate the weather additionally. However, we can take advantage of what all DENMs have in common - they begin at a certain time point and are valid for a limited period and region.

2.1.3.3 Collective Perception (CP) service

The CP service [25, 34] enables vehicles and RSUs to exchange the perception of their environment by sharing the objects they detect with their sensors. The objective here is to improve the vehicles' awareness of their environment which is achieved by means of the CPM protocol. In addition to the information provided by the CAMs, the CPMs help the vehicles to develop a perception beyond own sensor field-of-view (FOV) thereby resulting in better situational awareness of the road traffic environment. For example, when a vehicle is making an exit from a parking lot, it is very difficult for the vehicle to obtain the road traffic information just by means of its on-board sensor perception. Hence, if there is a nearby RSU or another vehicle sending this information, it will be

very beneficial. The information perceived by the vehicle on-board sensors is fused together using different sensor fusion techniques to create Local Environmental Model (LEM), in which they track the information from other vehicles in the sensor perception range. The objects tracked in the LEM are utilized in the generation of CPMs. By combining the information from the onboard sensors and that received from the CPMs, vehicle next develops a Global Environmental Model (GEM). This results in GEM having more objects than the LEM thereby providing an increased perception range for the vehicle. The objects sent by the CPMs can be used to validate the information that is tracked. As multiple vehicles/RSUs send information about the same object in a short period of time, it results in higher accuracy in the perception of the environment for the ego vehicle.

CPM data structure

Separate containers are assigned to transfer specific information within the CPM protocol as shown in Figure 2.7. The ITS-PDU header is common for all V2X messages and consists of a version of the message protocol - e.g., CAM, CPM, or DENM and also a unique identification number that recognizes the ego vehicle. Following the ITS-PDU header, different CPM parameter containers such as Station Data & Management Container (SMC), Sensor Information Container (SIC), Perceived Object Container (POC) and the free space addendum container are included. The ITS-PDU header, management container, and, depending on the station type, the station data container is mandatory. Other containers such as sensor information, perceived objects, and free space addendum are optional to be added in the CPMs.

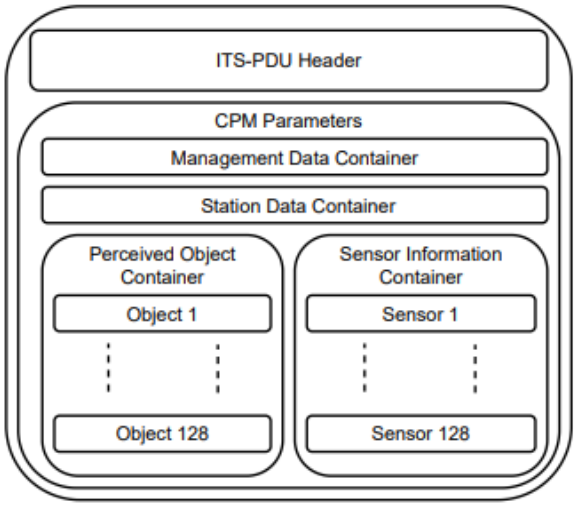


Figure 2.7 – CPM data structure [34].

CPM triggering conditions

The SIC contains information about the sensing capabilities of a transmitting V2X station. The sensing capabilities are described in the form of a list based on the capabilities of each of the sensors mounted on the vehicle. Since this information is time invariant, the SIC does not need to be repeated with a high frequency and is included only once every second. The second and the most relevant container is the POC, which contains all objects that a vehicle perceives with its local sensors.

An object is selected for inclusion in the POC if it fulfills at least one of the following conditions [25]:

1. The object was never sent previously, i.e., it is considered new for the transmitting station.
2. The object's position changed by more than 4 m (absolute Euclidian distance) since its last inclusion in a CPM of the transmitting station.
3. The object's speed changed by more than 0.5 m/s since its last inclusion.
4. The object's heading changed by more than 4 degrees since its last inclusion.
5. The object was previously included in a CPM of the transmitter more than one second ago.

The SMC contains information about the vehicle mobility such as position and velocity. Following the message generation rules in [34], a CPM is generated whenever the SIC needs to be transmitted, the POC contains at least one object for transmission or both. However, the CPM generation interval cannot be higher than 1,000 ms or lower than 100 ms. Following these message generation rules, the size and the time a CPM is generated can considerably vary within the interval. This represents a challenge for the radio resource allocation mechanism at the access layers where the radio resource scheduling algorithms should be carefully optimized in order to make it suitable for the CP service application.

CPM generation models

The message generation models for CPMs considered as a part of this thesis are listed in Table 2.2. The purpose of considering multiple generation models is to observe the variations in the number of CPMs generated per second, the time gap between subsequent CPMs and the variations in data sizes which have an impact on the efficiency of the radio resource scheduling algorithms in both the sidelink modes.

In case of Fixed models ($100, 300, 500$ ms), the CPMs are generated at a fixed time interval irrespective of the content updates in the SIC and POC. In case there are no

Table 2.2 – CPM generation models.

Model	Message characteristics
Fixed 100	Periodicity of 100 ms
Fixed 300	Periodicity of 300 ms
Fixed 500	Periodicity of 500 ms
ETSI	According to ETSI specifications in [34]
ETSI-K	According to ETSI specifications in [34] + ego vehicle kinematics

updates in the SIC and POC, only the contents of the SMC are sent periodically within the interval of $[100; 1,000]$ ms. Although realistically any number of objects can be detected at any instant of time, this traffic model is designed such that a certain fixed size is allocated for the SIC and POC. Therefore, only a limited number of detected objects can be accommodated and sent periodically.

The ETSI-K model differs from other models in the sense that in addition to sending objects in the POC, the CPM generation rules also take into account of the vehicle driving dynamics. In this model, the contents of the SMC are not transmitted periodically within the interval of $[100; 1,000]$ ms. They are restrictively sent along with the updates in the SIC only every 1 s. So within the interval of $[100; 1,000]$ ms, CPMs are generated only when objects are perceived by the vehicles. This results in large variations in the sizes of the CPMs sent within the generation interval of $[100; 1,000]$ ms.

CPMs generated according to different models have a significant impact on how resources are utilized in the channel. The message sizes of all the models depends on the number of objects included in the perceived object container of the CPM and whether the sensor container is included or not.

2.1.3.4 Vulnerable Road User Awareness (VA) service

The objective of the VA service [43] is to enhance the safety of the VRUs on the road. This is accomplished by introducing a dedicated class of messaging service for VRUs with a new message type, the VRU Awareness Message (VAM). VA service has some specific characteristics: *(i)* Flexibility of the VAM in length and content where the message containers are customized based on the class of VRU including pedestrian, cyclist etc. *(ii)* Adaptable periodicity of the messages depending on the irregularities in the spatial distribution of VRUs and their unpredictable behavior.

VAM data structure

The VAM data structure as specified in [43] is depicted in Figure 2.8. A brief description of the different VRU containers with some example fields are listed in Table 2.3.

Depending on the number of containers and the respective fields, the size of the VAMs is reported to vary between 74 – 116 bytes [79].

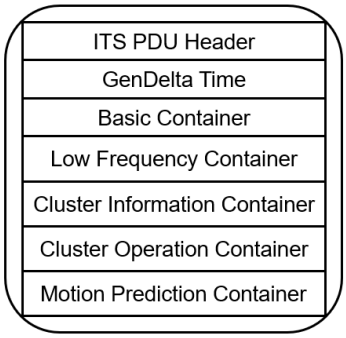


Figure 2.8 – VAM data structure [43].

Table 2.3 – VAM containers and their description [43].

Container	**Description**	**Examples**
Basic	VRU profile type	Pedestrian, cyclist etc.
High frequency	Fast changing VRU data	Speed, heading, yaw rate, position on lane etc.
Low frequency	Slow changing VRU data	Exterior lights.
Cluster information	VRU cluster specific	Cluster id, shape.
Cluster operation	Change of cluster state	Join and leaving the cluster (id, time) with reasons.
Motion prediction	VRU motion prediction	Path history, path prediction, safe distance etc.

VAM triggering conditions

The triggering conditions for the generation of a VAM are as follows:

- When a VRU gets onto its vehicle and starts driving (e.g., bicycle). Here the speed of the VRU increases from low to high.
- When a VRU gets off its vehicle and starts walking or remains stationary (e.g., a pedestrian standing or crossing the road). Here the speed of the VRU decreases from high to low.
- When VRU enters/leaves a protected environment - subways, traffic protected zones, tram stations etc.

- Extreme weather conditions where there are chances that the vehicle sensors may not detect a VRU.

The choice of the V2X messaging services and protocols depend on the road traffic environment, application support by the Cellular V2X hardware and also the geographical location of the ITS-stations. One or more combinations of the above mentioned services can be suitably deployed in different V2X application scenarios. We acknowledge that additional V2X messaging protocols such as MAP (topology) Extended Message (MAPEM) and Signal Phase And Timing Extended Message (SPATEM) exist in the ETSI specifications which are currently out of scope within the context of this PhD thesis.

2.2 State-of-the-art

In this section, an overview of the scientific works related to radio resource allocation modes in Cellular V2X are presented. A brief introduction to the development of a system level simulation environment is provided. Subsequently, we also discuss the recent advances in the AI based techniques in vehicular communications and analyze their challenges and uncertainties especially when they are to be deployed in decentralized partially observable environments [94].

2.2.1 Simulation environment

Discrete-event simulation (DES) is a technique of modeling systems as a series of events at discrete time steps that can efficiently represent the potential change to the system's state [47]. The first successful discrete event based network simulator developed in the mid-1990s is the `Network Simulator` version 2 (*ns-2*) [68] which was used in several research areas such as for simulation of reliable transport protocols, congestion control and wireless adhoc routing. The `Network Simulator` version 3 (*ns-3*) [99] project was launched in 2006 and focused on supporting parallel simulation capabilities for the predecessor *ns-2*. The Open Modular Network Testbed in C++ (OMNeT++) framework [113] was published in the year 1997, a C++ based network simulation framework that supports modeling of communication networks, multiprocessors and other distributed or parallel systems.

One of the key challenges in modeling a vehicular communication network is that it requires integration of a diverse set of components, including vehicle mobility, environmental perception, radio propagation and related effects along with the specific V2X services and communication protocols. In principle, two levels of abstractions are possible namely, the link level and the system level. When we want to study the characteristics of the communication link between one or more transmitters and receivers

at the physical layer, it becomes necessary to develop a link level simulation model as done in [117]. In a system level simulation, we measure the performance of a large scale communication system/network consisting of many UEs and base stations that are operating in different deployment configurations (e.g., frequency bands, scheduling policies etc.) [10]. In this PhD thesis, a system level abstraction is considered to study the performance of the radio resource allocation modes in Cellular V2X communication networks.

One of the most well established simulation frameworks in the VANET and ITS domain is the `Veins` [106], which was launched in the year 2006. It is employed by both academia and industry around the globe. The OMNeT++ based simulation framework `Artery` [97] – was originally developed for the standard-compliant, WLAN-based V2X communication. In the beginning, it was developed as an extension for the simulator `Veins`, but today it can run independently and is capable of providing an elaborated environment for carrying out large scale system level V2X network simulations. It provides a clear separation of facilities, application layer and vehicular scenarios, which makes it an ideal base framework even for Cellular V2X simulations. `Artery` utilizes the `Vanetza` stack to provide Basic Transport Protocol (BTP) and Geo-Networking (GN) features, along with the Decentralized Congestion Control (DCC) and security according to ETSI specifications. To model the data plane functionalities of the LTE V2X Radio Access Network (RAN) and Evolved Packet Core (EPC), we have utilized and extended the user plane of the simulation framework `SimuLTE` [115]. Additionally, we have implemented the control plane functions, and integrated both user and control plane into `Artery`, resulting in `Artery-C`. The salient features of the network simulator `Artery-C` are presented in Chapter 3. Recently, the user plane of the `SimuLTE` got upgraded with 5G components and modules (resulting in `Simu5G` [91]), however we consider the implementation of only relevant sidelink components from the 5G-NR V2X protocol stack.

In addition to modeling of the communication protocol stack, it is equally important to consider a realistic modeling of the road topology and mobility patterns of different participants such as vehicles and VRUs (pedestrians, bicycle etc.). Different types of traffic scenarios have been developed by the transportation community for a while such as [22, 23] and many more, but their scope does not extend towards evaluating VANET simulations. To perform a co-simulation of the communication network and the road traffic model, it demands a deeper understanding of the mobility patterns, analysis of vehicle position and driver behavior and their impact on the V2X message generation rules. This is referred to as microscopic modeling approach. Ingolstadt Traffic Scenario (InTAS) is a microscopic road traffic model for the city of Ingolstadt which is developed using `SUMO`. `InTAS` [80] considers an accurate mapping for all city roads according to categories of residential, public, and highway roads. It also includes modeling of bridges and tunnels which are important locations where the V2X communication needs to be

evaluated. In the recent years, the InTAS has been updated to include basic mobility patterns of pedestrians such as walking on a straight road, making right & left turns and coming to a stop in front of the traffic lights. The InTAS traffic model is developed on the basis of real-world data collected from the government office in the city of Ingolstadt, Germany. We would like to acknowledge that more sophisticated pedestrian locomotion models are developed in the research community such as the Vadere [72, 103] which incorporates various mathematical techniques to model the pedestrian steps, density, movements and behavior in different types of road traffic environments.

2.2.2 System level evaluation of radio resource allocation modes

A system level perspective on modeling and simulation of D2D communication in LTE and LTE-A networks was initially studied in [114]. The user plane features of the LTE/LTE-A networks were enhanced in the subsequent implementations of SimuLTE [98, 115] which could later support the simulation of Cellular V2X communication networks.

Analytical studies on the unmanaged mode in the LTE V2X traces back to the contributions in [50]. The authors analytically model the types of errors that arise in the SB-SPS scheduling algorithm under varying traffic density conditions and verify them by means of simulations. A detailed analysis of the influence of difference radio resource allocation parameters in SB-SPS were carried out in [87, 88, 90]. An use-case based analysis of the components contributing to resource allocation latency in the managed and unmanaged modes of the LTE V2X networks were studied in [77]. Some of the notable studies that compare the performance of Cellular V2X (LTE V2X) and WLAN-V2X (ITS-G5) access technologies from a technical and use-case perspective are [20, 71].

Following the performance evaluation studies, there was a keen interest in the research community to investigate the impact of certain factors that challenged the performance of the radio resource scheduling algorithms in LTE V2X networks. The studies carried out in [12] clearly explain how the misalignment between message generation and radio resource allocation impacts the performance of the radio resource scheduling algorithm. Rule based methods to tackle the problems of radio resource collisions are proposed in [15, 69]. A detailed analysis on the reliability bounds of SB-SPS in LTE V2X networks is performed in [120]. Another rule based approach to optimally schedule the radio resources based on different groups of message sizes is illustrated in [13]. The joint optimization of radio resource selection and power allocation presented in [108] shows promising results in simultaneously balancing the distribution of radio resources between cellular UEs and vehicular UEs.

With the emergence of the 5G-NR V2X standards in the subsequent 3GPP Releases 15 and 16, some changes were made to incorporate a two stage SCI format which

facilitates the transmission of more fields related to radio resource allocation such as the RRI, re-selection counter *cResel* etc. The studies carried out in [10] provide a detailed comparison on the performance of different variants of the SB-SPS scheduling algorithm over the subsequent standards - LTE V2X and 5G-NR V2X. The scientific studies presented in [83] provides a technical level comparison of the implementation and performance of the SB-SPS algorithm in the unmanaged mode with the possible variants of the dynamic scheduling algorithms in the managed mode. The effectiveness of the SB-SPS algorithm with regard to handling aperiodic traffic with variable data sizes is studied in [84].

The possibilities of switching between the cellular (Uu) and the sidelink mode in 5G-NR V2X is considered as a part of the standardization efforts in [2]. The standards also list the operational frequency bands and explain the concept of frequency re-use between uplink and sidelink interfaces. The possibilities of switching between the sidelink modes in 5G-NR V2X for a platooning scenario are studied by means of field trial experiments in [85]. The idea to share the frequency resources between sidelink and cellular (Uu) modes of 5G-NR V2X is thoroughly analyzed in [9].

Considering the contributions from the previous works on LTE V2X and more recently in the 5G-NR V2X, it has been found that the rule based scheduling algorithms in both the sidelink modes are unable to perform to their best efficiency when the nature of the V2X data traffic is aperiodic with variable data sizes. Although different approaches of tuning the resource allocation parameters exist, by careful considerations we infer that it still results in radio resource collisions and misinformed resource allocation decisions in the events of aperiodic data traffic.

The considerations for mode switching in LTE V2X were not included as a part of standardization, nor in the scientific works at that point of time. Considering the fact that a vehicle cannot remain within the region of cellular network coverage throughout, we believe that it is essential to consider the possibilities for mode switching in Cellular V2X communication networks. A systematic approach to implement a mode switching procedure and the analysis of the resulting overheads in terms of latency and link reliability are required to be developed.

2.2.3 AI based techniques in vehicular communication networks

The next generation wireless networks (beyond 5G and 6G) are driven by a large increase in the number of connected devices, the growing demand for high data rate applications, low latency requirements and the convergence between communications and computing. In the context of V2X communication networks, AI is recognized as an useful tool for solving problems related to traffic flow control, congestion control, radio resource allocation, Predictive Quality-of-Service (pQoS) and many more [26]. The recent success of two AI techniques [46] - Machine Learning (ML) and Deep Learning

(DL) have created interest in the development of an interactive-learning based approach to solve wireless control and management problems.

Machine learning comprises of three stages - training and testing. In the training stage, a model is learnt based on the available training data. In the testing stage, the model is deployed in the environment where it is expected to make predictions. ML techniques can be divided into broadly three categories: *(i)* Supervised *(ii)* Unsupervised and *(iii)* Reinforcement Learning (RL).

Supervised learning is a technique where a labelled data set is used to train algorithms that can predict and classify the outcomes. Since it is not possible to obtain labelled data sets all the time, unsupervised learning technique was developed. This method aims to find efficient representation of the data samples, represented either by means of hidden structures or hidden variables, which can be learnt by Bayesian learning methods. The reinforcement learning technique differs from supervised and unsupervised techniques in the sense that it does not require any data sets but rather focuses on decision making by means of exploration and interaction with the environment. Several variants of the supervised, unsupervised and reinforcement learning techniques are studied along with their mathematical representations [86]. Deep Learning describes algorithms that analyze data with a logical structure similar to how a human brain would draw conclusions. Note that this can happen both through supervised, unsupervised and reinforcement learning techniques. The deep learning applications utilize a layered structure of neural networks consisting of several neurons in each layer.

The studies carried out in [111] address three generic challenges for deploying AI based algorithms for radio resource allocation in vehicular networks: *(i)* Fast response needed during handovers, synchronizations and re-selection of radio resources, *(ii)* Accuracy in environmental modeling - both communication network and road traffic model and *(iii)* Self adaptability - radio resource allocation algorithms should allow for exploration but at the same time be self adaptive.

Considering the large amounts of useful data generated by several components in a vehicular communication network - e.g., sensors, road side monitoring units (such as RSU) and other sources, the usage of ML techniques is desirable in the implementation of data driven decisions within a vehicle. Some of the potential use-cases include traffic flow prediction, network congestion control and channel quality prediction [119].

The usage of Deep Reinforcement Learning (DRL) based algorithms for the radio resource allocation in mobile communication networks goes way back to the research studies carried out in the late nineties [92]. The authors have taken into consideration various influencing conditions such as heterogeneity in traffic distributions, time-varying traffic patterns, and channel failures and developed a Q-learning based radio resource scheduler. Owing to the non-stationary behavior of the environment in a vehicular communication network, establishing cooperation between multiple vehicles to carry out different tasks (e.g., radio resource selection) brings joint benefits to learn and

improve the performance of the complete system. The survey studies in [11] indicate the qualitative benefits of using Multi-Agent Reinforcement Learning (MARL) techniques to improve the collaboration between vehicles in a fast changing V2X communication network. One of the major issues in vehicular communication networks is that each vehicle has only partial or zero knowledge about the decisions taken by other vehicles. Also they can only partially observe the global environment. Therefore in such a Multi Agent System (MAS) where each agent is capable of own decision making, it becomes extremely important to formally define the concept of "uncertainty". The different types of uncertainty which decentralized partially observable environments should cope with are:

- Result uncertainty: In many situations, the effects of actions may be uncertain. To simplify the design, we can try to formulate all the possible outcomes of each action and even assign some probability but since the state of the environment changes stochastically, it becomes very difficult to pre-determine all the outcomes of every action.
- State uncertainty: In some of the real-world problems, it becomes very difficult to pre-determine how the state changes over a period of time. For example, it is not possible to know in advance whether cellular network coverage will be available for a vehicle or not.
- Uncertainty with respect to other agents: In a multi agent system, each agent is not sure of the outcomes of the actions performed by other agents. Also they have no knowledge of each others' state information (or input parameters) which lead them to choose certain actions.

Depending on the extent of uncertainty, knowledge of the environment, availability of input variables to represent the environment state, number of actions and the method to evaluate the consequence of actions there can be different types and variants of RL algorithms. A detailed introduction to the different types of RL algorithms is presented in [110].

The radio resource allocation task in Cellular V2X communication networks is one example where the vehicular agents have only partial knowledge of the global state space (ie., road traffic environment) and are also not clearly aware of the actions (i.e., radio resource allocation) executed by other agents. A similar concept was already addressed by the researchers in one of the early works [16] where they present a survey of different techniques ranging from decision-theoretic planning to reinforcement learning and further highlight some interesting issues that arise with regard to coordinating the policies of individual agents. The studies in [73] describe a set of scalable techniques that enable different agents to learn in a collaborative manner. In the more recent days, the contributions in [21] introduces a technique called "experience sharing" which

aims in addressing the problem of uncertainty in partially observable environments where agents explicitly cooperate with each other. The Chapter 6 in this thesis further elaborates on the multi agent reinforcement learning techniques that can be applied to improve the radio resource scheduling in the unmanaged mode of Cellular V2X and answers some important issues related to deployment of AI based radio resource schedulers.

2.3 Summary

The technical background section in this chapter discussed in-depth about the sidelink radio resource allocation modes and the scheduling algorithms complying with the ETSI specifications. Different types of V2X messaging services along with their protocol formats and triggering conditions are also explained with suitable examples.

Within the state-of-the-art section, we have presented an overview of the simulation based approaches used in Cellular V2X communication networks. A brief introduction to the microscopic road traffic model for the city of Ingolstadt (`InTAS`), Germany is provided. Scientific works related to the performance evaluation of the rule based radio resource scheduling algorithms in Cellular V2X were reviewed. Lastly, this section introduced some of the recently developed AI based techniques in vehicular communications and identified their uncertainties in the context of decentralized partially observable environments.

Chapter 3

Simulation framework: `Artery-C`

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Network simulations provide an opportunity to evaluate the performance of different communication protocols and system architectures (e.g., centralized, decentralized, hybrid etc.) before deploying them in the real world settings. For a vehicular adhoc network (VANET), a network simulator provides a common platform for designing and understanding a complete system that consist of two key components: *(i)* Communication network and *(ii)* Road traffic model. Although test-bed implementations are more realistic than simulations, they involve substantially high costs and are less scalable. For example, it is not easy to deploy Cellular V2X radio modules in several vehicles and measure the performance of each link. The simulations also offer an opportunity for repetition of different experiments which can be particularly helpful when we want to study the influence of certain specific parameters. In this chapter, we present the salient features of the Cellular V2X network simulator, `Artery-C`[4] which has been used to study the performance of the radio resource allocation modes for different types of road traffic environments, vehicular densities and V2X messaging services at a system level of abstraction.

3.1 Preliminaries

A baseline implementation of the Device-to-Device (D2D) communication within an OMNeT++ based framework was carried out in `SimuLTE` [115]. Subsequently, the `SimuLTE` was extended to include the unmanaged mode in the `OpenCV2X` [84] framework. Similar developments also took place with the `ns-3` based frameworks, the `Cellular-VCS` [75] implements the protocol stacks of both WLAN-V2X (ETSI ITS-G5 [29]) and Cellular V2X (LTE V2X [42]) access technologies within one framework. The `LENA` simulator implements the LTE and the Evolved Packet Core (EPC) functionalities but does not include the sidelink interface. Another important framework widely used in research is the `VSimRTI` [104]. It provides a sophisticated environment for large scale V2X simulations where multiple simulators (both network and road traffic models) can be combined to study various aspects of the future Intelligent Transport Systems (ITS).

With the emergence of the 5G-NR V2X standards, the `SimuLTE` got upgraded to `Simu5G` and the frameworks such as the `OpenCV2X` currently implement some selected features from the 5G-NR V2X protocol stack. The `LENA` simulator has also undergone upgrades to be known as `5G-LENA` [74, 95] where it currently supports the sidelink unmanaged mode in 5G-NR V2X [10].

Another notable MATLAB based V2X simulator is the `LTEV2Vsim`. It provides a detailed model of the physical layer of the LTE V2X particularly to study the V2V links.

[4] `Artery-C` public repository: `https://github.com/anupama1990/Artery-C`

Recently, it was extended to include the features from the 5G-NR V2X protocol stack resulting in a new simulator known as the `WiLabV2Xsim` [112].

All the above mentioned frameworks support the simulation of a single resource allocation mode at a time, in most cases only the unmanaged mode. These network simulators do not consider systematic implementation (according to ETSI specifications) of V2X messaging services & protocols. Within the scope of this PhD, we study the efficiency of radio resource allocation mechanisms in both the sidelink modes and also investigate the possibilities for mode switching which has not been considered so far in any of the above mentioned works. Therefore, it is important to consider the dynamically changing V2X data traffic patterns originating from different V2X messaging protocols, such as Collective Perception Message (CPM) service and VRU Awareness Message (VAM) in addition to Cooperative Awareness Message (CAM) and Decentralized Environmental Notification Message (DENM).

The `Artery` framework discussed in Section 2.2.1 provides a comprehensive implementation of the ETSI compliant V2X messaging services (and protocols) along with the integration of specific road traffic scenarios. Also, it provides a structured implementation of the networking and transport protocols. Hence by choosing `Artery` as the base framework, we have further extended the `SimuLTE` framework to incorporate the control and data plane functionalities of the LTE/5G-NR Radio Access Network (RAN) and the Evolved Packet Core (EPC). This resulted in our new simulator `Artery-C` [60]. A feature level comparison of the `Artery-C` with other open source simulation frameworks is presented in Table 3.1.

Table 3.1 – Comparison between different Cellular V2X simulation frameworks.

Framework	**Access technologies**	**Modes**	**Messaging protocols**[5]
`SimuLTE`	LTE, LTE-A	Uu, D2D	-
`OpenCV2X`	LTE/5G-NR V2X	SL-UM[6]	CAM, DENM
`Cellular-VCS`	LTE, LTE-A	Uu, SL-M	CAM, DENM
`LENA`	LTE	Uu	-
`LTEV2Vsim`	LTE V2X	Uu, SL-UM	CAM, DENM
`Simu5G`	5G-NR	Uu, D2D	-
`5G-LENA`	5G-NR V2X	Uu, SL-UM	CAM, DENM
`WiLabV2Xsim`	ITS-G5, 5G-NR V2X	Uu, SL-UM	-
`Veins`	ITS-G5, 5G-NR V2X	Uu, SL-UM	CAM, DENM
`Artery-C`	LTE/5G-NR V2X	Uu, SL-UM, M	CAM, DENM CPM, VAM

[5] ETSI compliant V2X messaging protocols.
[6] Abbreviations: SL-UM = sidelink unmanaged, SL-M = sidelink managed.

Contributions

The Section 3.2 and Section 3.4.1 are based on the ideas developed in one of our conference publication [60]. The Section 3.4.3 includes direct excerpts from our article [64]. Section 3.4.4 is based on our journal article [63]. The specific author contributions along with the copyright note for these publications are provided in Appendix C.

The main contributions in this chapter are as follows:

1. Definition of requirements for the development of the `Artery-C` simulation framework.
2. Software design and implementation of the different planes and layers of the Cellular V2X protocol stack.
3. Techniques to model cellular network infrastructure within a road traffic scenario in `SUMO`.
4. Channel modeling approaches for Cellular V2X and derivation of the Signal-to-Interference Noise Ratio (SINR).
5. Extension of the `Artery-C` framework with a Deep Reinforcement Learning (DRL) based environment.

3.2 Requirements

For the development of a comprehensive simulation framework that comprises the Cellular V2X protocol stack that integrates with different types of V2X messaging services (and protocols) and road traffic scenarios, we classify the requirements [27] broadly into two categories: *(i)* Functional and *(ii)* Non-functional.

3.2.1 Functional requirements

Based on the inputs, these requirements define the functions to be performed by different modules within the simulation framework in order to arrive at the desired output. For the development of the `Artery-C`, the functional requirements are listed as follows:

1. Cellular V2X communication: This involves the implementation of the control and user planes of LTE/5G-NR V2X access technologies according to ETSI specifications [42, 45]. Modeling of the wireless channel characteristics for different types of V2X links (e.g., Vehicle-to-Vehicle (V2V), Vehicle-to-Pedestrian (V2P) and Vehicle-to-Network (V2N)) need to be done at a system level abstraction.

2. V2X messaging services and protocols: Ability to support different types of V2X messaging services such as Cooperative Awareness (CA), Collective Perception (CP), Decentralized Environmental Notification (DEN) and VRU Awareness (VA) along with their respective messaging protocol implementations.

3. Road traffic scenarios: Modeling of highway and urban road traffic scenarios in `SUMO` along with the cellular network infrastructure.

4. Extensions for Deep Reinforcement Learning (DRL): Coupling of `Artery-C` with a DRL based environment in `TensorFlow` `Python`.

3.2.2 Non-functional requirements

These requirements define the quality constraints to be satisfied by the simulation framework in order to ensure a smooth deployment, operation and maintenance. The non-functional requirements identified prior to the development of `Artery-C` are:

1. Modularity and re-usability: Specific modules need to be defined for each of the nodes (such as car, pedestrian, gNB etc.) and also the global road traffic environment. The V2X services along with the networking and transport protocols need to be re-used from the `Artery` simulator. The Cellular V2X protocol stack needs to be extended from `SimuLTE` in a manner that the modules can be suitably adapted to incorporate the relevant 5G-NR V2X features.

2. Scalability: Support for the simulation of a large number of vehicles - around $1,500 - 2,000$.

3. Portability: Seamless integration with `Artery`, `SimuLTE`, `INET` along with further possible extensions.

4. Performance: The smallest unit time step for simulations should be set as one millisecond which corresponds to one subframe/slot length in LTE/5G-NR V2X. The full scale simulations should be able to complete within a reasonable time frame along with automated storage of results in an SQL data base.

5. Maintainability: By regularly upgrading to the recent versions of the OMNeT++ software, it is possible to experience the latest performance improvement features. Synchronizing with the updates in other dependent software such as `Artery`, `Vanetza`, `INET` and `SimuLTE`, the `Artery-C` simulator can be useful for studying different types of research problems in Cellular V2X communication networks.

3.3 Software design

Based on the functional and the non-functional requirements listed in Section 3.2, a high-level design of the `Artery-C` framework is illustrated in Figure 3.1. The planes and layers of the Cellular V2X protocol stack are built on the OMNeT++ platform and the road traffic model along with the cellular network infrastructure are realized in `SUMO`. The bi-directional coupling between the OMNeT++ and `SUMO` is achieved by means of the Traffic Command Interface (TraCI). The modules for the V2X messaging services along with the network & transport protocols are re-used from the `Artery` and `Vanetza` [96] frameworks, respectively. The compatible versions of these frameworks along with other dependent packages are listed in the Table A.1 of Appendix A.

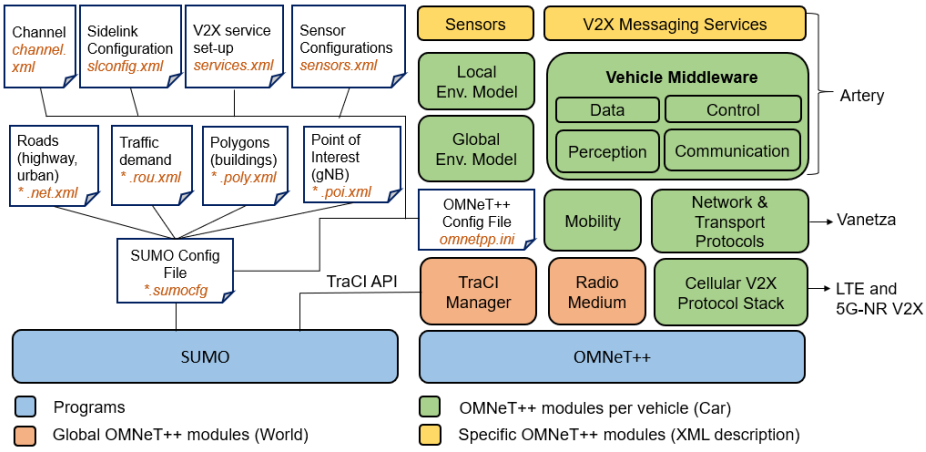

Figure 3.1 – High-level design of the `Artery-C` framework.

A brief description of the different building blocks in the `Artery-C` framework are as follows:

- Sensors: Two types of radar sensors are modeled in `Artery-C`: forward facing (range 160 m with a field-of-view (FOV) of 35°) and backward facing (range 80 m with an FOV of 325°) [97]. The sensor perception model is based on the implementation in `Artery` [54, 55]. This is an idealistic model where all the information about an object (dimensions, velocity and position) is available without any inaccuracies in their measurements. The sensor related configurations are included in the *sensors.xml* file. The local environment model in Figure 3.1 contains information of the objects perceived by the on-board sensors of each vehicle. The global environment model serves as a database containing the information of all the objects in a simulation. Further details about the object perception, filtering and construction of local and global environment models are explained in `Artery` [55].

- V2X messaging services: Specific services such as Cooperative Awareness (CA), Collective Perception (CP), Decentralized Environmental Notification (DEN) and VRU Awareness (VA) can be enabled according to an external configuration file (*services.xml*), which lists the required services for each vehicle. This feature enables the user to specify the services to be activated during the set-up process of the simulation without the need for re-compilation. It provides an environment to simulate different types of V2X services (or even different variants of the same service) within the same simulation.

- Vehicle middleware: This component is same as that of the ITS-G5 middleware implemented in `Artery` [97] which serves as a backbone for any V2X messaging service. Upon the creation of a service, its initialization procedures are called by the middleware. This module is responsible for the collection of information from V2X messaging services (communication) & on-board sensors (perception, data) and triggering of reactions and vehicle control functions (e.g., such as stopping, braking etc.).

- Networking & transport protocols: Two types of networking and transport protocols are originally implemented in `Vanetza`: *(i)* Geo-Networking (GN) and *(ii)* Basic Transport Protocol (BTP). `Vanetza` is a stand-alone implementation of the ETSI ITS-G5 protocols which comprises the GN, BTP and Decentralized Congestion Control (DCC) mechanisms. An advantage of `Vanetza` is that it can function independent of OMNeT++ and can even be deployed on embedded hardware.

- TraCI manager: The TRaCI protocol [81] allows for the bi-directional coupling between `SUMO` and OMNeT++ programs. A sophisticated implementation of the TraCI manager module can be found in `Veins` [106]. The attributes of the vehicles (e.g., speed, location, lane number, size etc.) and base stations (cell ID, location, transmit power etc.) can be continuously exported from the `SUMO` into the OMNeT++ environment by means of the TraCI protocol.

- Mobility: On receiving the information about the vehicle and the point-of-interest (POI) attributes from `SUMO`, the mobility module in OMNeT++ manages the storage and updates of these attributes. When vehicles dynamically enter and exit the road traffic environment in `SUMO`, their attributes need to be accordingly added or deleted within the OMNeT++ environment.

- Radio medium: This module provides the implementation of different types of Fixed-to-Mobile (F2M) and Mobile-to-Mobile (M2M) channel models which are further explained in Section 3.4.2.1 and Section 3.4.2.2, respectively. A system level modeling of the multipath propagation effects such as delay spreads and

Doppler shifts are included for the V2V, V2I and V2P communication links. All the channel related parameters can be configured in the *channel.xml* file.

- Cellular V2X protocol stack: Both simulators `Artery` and `Veins` originally implemented the WLAN-V2X protocol stack which was built by extending the `INET` framework. In case of `Artery-C`, we have extended the `SimuLTE` plane that models the conventional Uu interface. A dedicated implementation of the control plane comprising the Radio Resource Control (RRC) module plays a key role in cell search, mode selection and mode switching control. The access layers in the user/data plane implement the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), Medium Access Control (MAC) and the Physical layer (PHY) layers of the LTE V2X and the 5G-NR V2X [42, 45] protocol stacks. The sidelink related parameters are configured in the *slconfig.xml* file.
- V2X scenarios: The `InTAS` [80] road traffic model is chosen for the modeling of dense urban and highway road traffic environments throughout this thesis. The specific road network parameters such as number of lanes, directions etc. are included in the * *.net.xml* file. The traffic flow generation model parameters are defined in the * *.rou.xml* file. The road topology parameters such as buildings, trees and other obstacles are represented using polygons within the * *.poly.xml* file. The gNB attributes such as the coordinates, cell IDs, antenna transmit power etc. are listed * *.poi.xml* file. All these files are combined together into the *.*sumocfg* file which is subsequently called from the OMNeT++ config file (*omnetpp.ini*).

3.4 Implementation

Following a brief introduction into the high level design of the `Artery-C` framework in Figure 3.1, this section provides finer details of the implementation of the planes & layers of the Cellular V2X protocol stack, channel models, cellular network infrastructure and the extensions with a DRL based environment.

3.4.1 Cellular V2X protocol stack

The protocol stack is broadly divided into two planes: *(i)* Control and *(ii)* User plane. The control plane is responsible for the management and the control of the radio interface, establishment of the identity with the cellular network infrastructure and selection of appropriate sidelink modes of operation. The user plane is responsible for the handling of data (segmentation and framing), assigning of appropriate acknowledgement modes, allocation and scheduling of radio resources and many more functions across different layers of the protocol stack within the Network Interface Card (NIC) as shown in Figure 3.2.

3.4.1.1 Control plane – Radio Resource Control (RRC)

The RRC component is modeled in accordance with the ETSI specifications for 5G-NR V2X [41]. It is responsible to carry out three primary functionalities, i.e., system information acquisition, cell search & mode selection and mode switching control.

1. System Information (SI) acquisition:
   The process of SI acquisition involves the exchange of network related messages between an User Equipment (UE) and a base station. Subsequently, the gNB preconfigures a set of time and frequency resources in the form of System Information Block (SIB). The synchronization related information [7, 48] between a UE and a base station are exchanged immediately after the establishment of successful connection.

2. Cell search & mode selection:
   The cell search module identifies the possibility to establish connection with a nearby base station and accordingly switches between the states *IDLE*, *CONN* and *INACTIVE*. In the *IDLE* state, the UE is not connected to the base station. Therefore, it is only possible to operate in the unmanaged mode. In both *INACTIVE* and *CONN* states, the UE is connected to the base station. Therefore, it is possible to operate in cellular (Uu) mode and also in the sidelink managed mode. Different combinations of state transitions and mode selections are explained in Chapter 5.

3. Mode switching control:
   The mode switching control module is responsible to regulate the dynamic switching between the sidelink modes (i.e., managed and unmanaged) and also between the sidelink and the cellular (Uu) mode.

3.4.1.2 User/data plane

Packet Data Convergence Protocol (PDCP)

The PDCP is the connecting component between the Cellular V2X access technology and the networking & transport layer. It processes both the IP and non-IP packets. In case of IP traffic, it performs Robust Header Compression (ROHC) and assigns/creates the Connection Identifier (CID) that uniquely identifies, together with the UE ID, a connection in the whole network. When an IP packet arrives at PDCP, a Logical Connection Identifier (LCID) is attached to it and forwarded to the RLC layer. In case

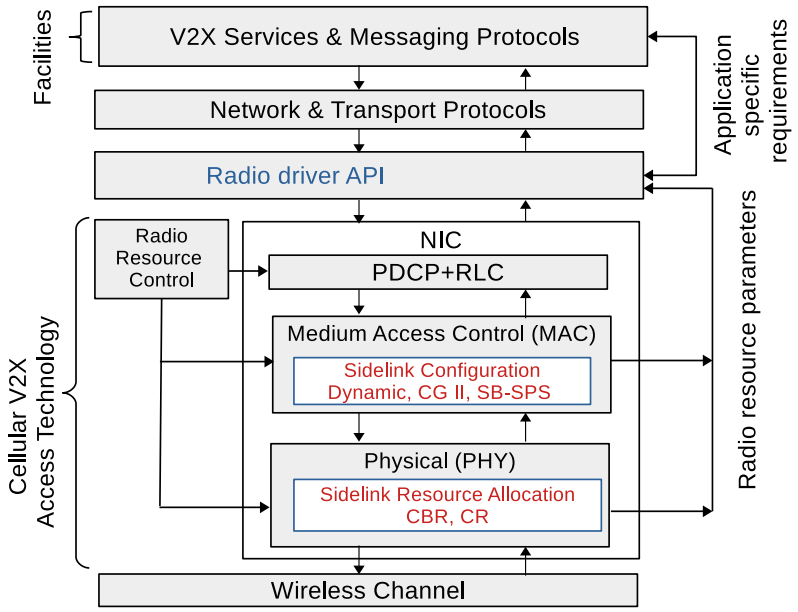

Figure 3.2 – Cellular V2X protocol stack.

of a non-IP-based packet[7] the PDCP performs ROHC, creates an entry in the non-IP connections table and forwards the packet as a PDU to the RLC.

The PDCP consists of two separate gates for data input from IP and non-IP traffic. Additionally, it has a separate gate to receive control related messages from the control plane. For interaction with the RLC, similar to [115], three different gates are connected with the PDCP-RRC module, one for each RLC mode.

Radio Link Control (RLC)

The RLC operates in three modes - acknowledged , un-acknowledged and the transparent mode. The key functionality of this component is to multiplex and de-multiplex MAC Service Data Units (SDUs) to and from the MAC layer. The implementation of the RLC has not been modified with reference to `SimuLTE` [115]. For the sidelink broadcast operation, an acknowledgement is not necessary to be applied [45] and hence we use the un-acknowledged mode.

[7] In the European C-ITS standards, non-IP packet transport is realized by GeoNetworking [37], an adhoc network protocol based on geographic positions, and Basic Transport Protocol (BTP) , an UDP-like transport protocol [38]. Both are implemented in the simulation framework `Artery-C`.

Medium Access Control (MAC)

The design of the MAC layer in the UE and gNB is modified in a way that the sidelink scheduling algorithms co-exists with the conventional uplink and downlink implementations as shown in Figure 3.3. Additionally, the MAC layer consists of a separate gate to receive the control related information from the RRC. It implements an OMNeT++ sub-module called the Sidelink Configuration (SC) which configures the grant related parameters based on the inputs received from the Sidelink Resource Allocation (SRA) submodule in the PHY layer.

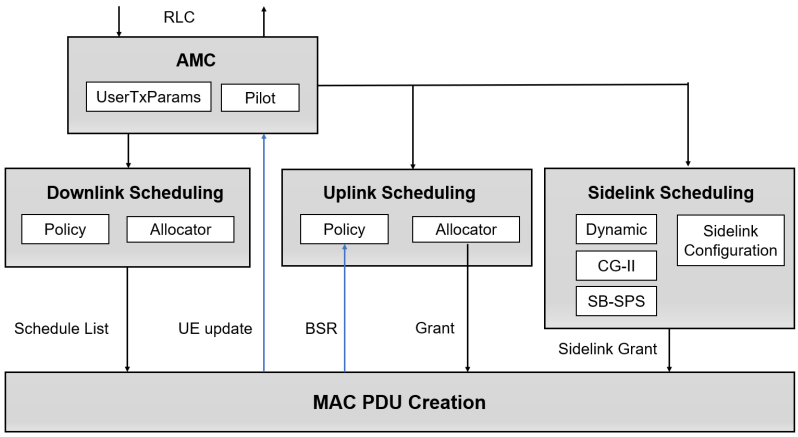

Figure 3.3 – Functional block diagram of the MAC scheduler in `Artery-C`.

The Adaptive Modulation and Coding (AMC) module in the gNB stores the channel status information, which is based on the periodic feedback from its connected UEs via up-/downlink interfaces. The AMC module in the UE determines the modulation scheme for sidelink operations. In addition to the existing scheduling policies in the `SimuLTE` framework [115] - Maximum Carrier to Interference Ratio (MAXCI), Proportional Fair Queuing (PF) and Deficit Round Robin (DRR), we have implemented dynamic and Configured Grant (CG) type II scheduling algorithms for the managed mode and Sensing Based Semi Persistent Scheduling (SB-SPS) algorithm for the unmanaged mode.

Managed mode operation: When a UE wants to transmit data on the sidelink, it requests for time and frequency resources from the gNB. The UE reports to the gNB about the size of the data (through a Buffer Status Report (BSR)), periodicity and maximum allowed latency based on the type of V2X application. The sidelink configuration (SC) submodule in the MAC of the gNB configures the sidelink grant parameters. These parameters are required in the PHY layer to allocate the Candidate Slot (or subframe) Resources (CSRs) and generate a corresponding Sidelink Control Information (SCI) message.

On receiving the CSRs from the PHY layer, the MAC of the gNB updates the resource related information in the sidelink grant and proceeds with the scheduling of radio resources for sidelink. The gNB selects the scheduling algorithm depending on the nature of the V2X data traffic and the extent of radio resource utilization by its connected users.

Unmanaged mode operation: In the unmanged mode of operation, the MAC of the UE handles the scheduling of resources independent of the base station. The channel related cost metrics such as SINR, the Reference Signal Received Power (RSRP) and the Received Signal Strength Indicator (RSSI) are computed in the PHY layer, which play an important role in determining the list of CSRs. On receiving the pool of CSRs from the SRA module in the PHY layer, it handles the SPS information and schedules time-frequency resources for both the transport block and the SCI. Detailed information on the flow of packets and creation of Protocol Data Unit (PDU) are explained in [60].

Physical layer (PHY) layer

The PHY layer contains information about the antenna power characteristics, standard channel models and cell related information (macro, micro and pico cells). The functional components of the PHY layer are depicted in Figure 3.4. The Sidelink Resource Allocation (SRA) module handles the following operations: *(i)* Selection of candidate radio resources. *(ii)* Evaluation of the selected resources & re-selection. *(iii)* Calculation of congestion control parameters.

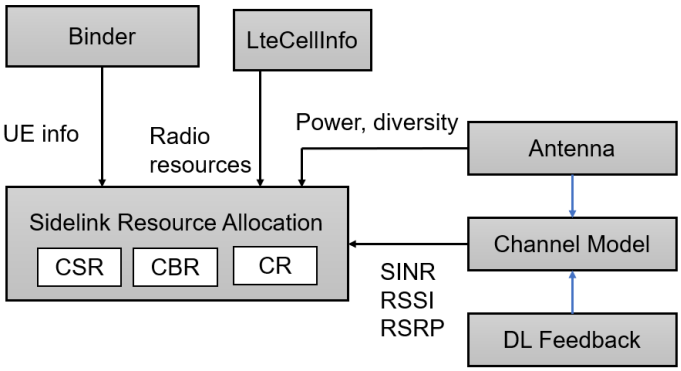

Figure 3.4 – Function components of the physical layer in `Artery-C`.

Sidelink Resource Allocation (SRA)

The calculation of the AMC and the sizes of the transport blocks is done with reference to the Modulation and Coding Scheme (MCS) table provided in the ETSI specifications [42]. The time and frequency resources for the sidelink modes are selected in the following manner:

- Time resources: A time resource is indicated in the form of a logical slot offset (Time Resource Indicator Value (TRIV)) depending on the value of the field *sl-MaxNumberPerReserve* $N_{sl-mnpr}$. The possible values are $N_{sl-mnpr} = 1,2,3$. For the sake of simplicity, we have considered only $N_{sl-mnpr} = 1,2$ as shown in Table 3.2.

  Table 3.2 – Time Resource Indicator Value (TRIV).

$N_{sl-mnpr}$	**Range**	**TRIV**
1	0	0
2	$1 \leq t_1 \leq 31$	t_1

  Here, t_i corresponds to the ith time resource within the logical time slots M in a radio resource pool.

- Frequency resources: The number of subchannels allocated in each time slot is represented by the Frequency Resource Indicator Value (FRIV) field in the SCI message. The calculation of FRIV is also based on the *sl-MaxNumberPerReserve*,

$$FRIV = n^{start}_{subCH,1} + \sum_{i=1}^{k_{subCH}-1} (K-1+i) \tag{3.1}$$

  where K is the total number of subchannels in the radio resource pool and $n^{start}_{subCH,1}$ represents the starting subchannel index for the first resource. The number of contiguously allocated subchannels with in a defined $N_{sl-mnpr}$ is represented by k_{subCH}.

- SB-SPS procedure:
  The following parameters are provided from the higher layers which influence the process of resource selection for PSCCH and PSSCH. The parameters are: *(i)* Radio resource pool, *(ii)* Packet Delay Budget (PDB), *(iii)* Number of subchannels k_{subCH} available for usage in a given slot m, *(iv)* Subset of eligible resources for pre-emption, and *(v)* Resource Reservation Interval (RRI) $P_{rsvp-TX}$.

  Consider that the sidelink radio resource pool consists of a total of M time slots indexed as $(m_0, m_1, \cdots m_M)$. A radio resource is characterized by $R_{k,m}$ where k denotes the number of continuous subchannels and m denotes the time slots

intended for transmission(s) in the selection window(s) (note: $k \in K$ and $m \in M$). The selection window ranges between the time slots $[m+T_1, m+T_2]$. The start of selection window T_1 lies within the range $0 \leq T_1 \leq T_{proc,1}$. The end of the selection window lies within the range $T_{2,min} \leq T_2 \leq T_{PDB}$ where $T_{2,min}$ ranges between $20-100$ ms [45]. The number of slots in the sensing window is denoted by $[m-T_0, m-T_{proc,0}]$ as depicted in Figure 3.5. For our considered numerology, $T_{proc,1} = 1$ slot and $T_{proc,0} = 3$ slots. The values of the processing delays T_{proc}^{SL} for other numerologies can be found in [40].

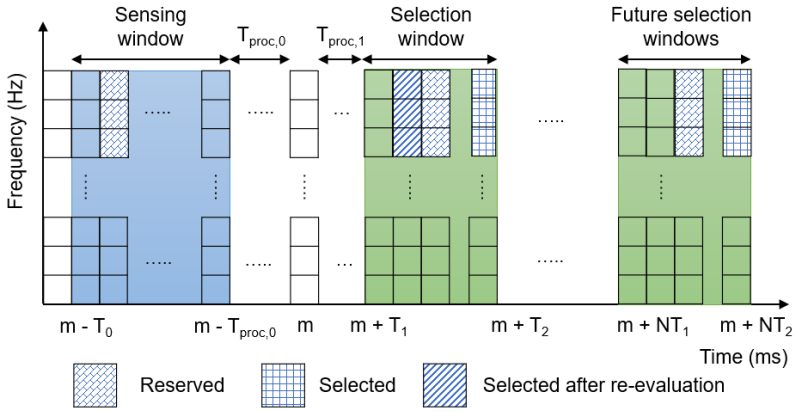

Figure 3.5 – Sensing and selection windows during an SB-SPS procedure.

The set of assigned resources for transmission is represented by S_A. The resources are excluded from S_A under the following conditions:

1. If a certain slot m has not been monitored/sensed. This can happen in the initial time slots when a vehicle has entered the road traffic environment. Also those slots that are used for own transmissions are not sensed.
2. Overlapping radio resources between sensing and selection window slots based on RSRP measurements:

$$R_{k,z+q\times P'_{rsvp-RX}} = R_{k,m+c\times P'_{rsvp-TX}} \tag{3.2}$$

where the sensing window component $q = 1,2,\cdots Q$, $Q = \frac{T_{sel}}{P_{RSVP-RX}}$. The number of future reservations in the selection window is governed by the value of re-selection counter *cResel*. The variable c in Equation 3.2 takes the values $c = 0,1,\cdots$ *cResel*-1. Here, the variabbles m and z refer to time slots present in the sensing and selection windows, respectively (where, $m,z \in M$).

3. Following the elimination of overlapping resources, the UE checks if the number of radio resources in the list is not less than 20% of the total number of radio resources. In that case, it increases the RSRP threshold by 3 dB and performs the re-selection.

- Re-evaluation of selected resources and pre-emption: After selecting a candidate radio resource, the UE continues to sense the transmissions from other UEs in the subsequent slots. One of the improvement features in 5G-NR V2X is the resource re-evaluation mechanism which allows a UE to drop its chosen candidate radio resource and select another resource when it senses that there is a possibility for another UE to have chosen the same resource. This decision should however be taken within a certain number of slots prior to the slot chosen for transmission. It provides higher flexibility in the management of resources and better capacity to cope with the variability in transmitted messages and previously undetected radio resource collisions between one or more vehicles.

  Pre-emption is another novel feature in 5G-NR V2X that allows better management of radio resources based on the priority requirements of the V2X application. When a UE estimates that there exists one or more other UEs that intend to transmit a higher priority traffic, it is expected to free its radio resources so that they are available for other UEs.

- Calculation of congestion control parameters: The two parameters to quantitatively analyse channel resource conditions are Channel Busy Ratio (CBR) and Channel Occupancy Ratio (CR) [44]. The channel busy ratio is defined as the ratio of the number of occupied subchannels to the total number of configured subchannels.

  A subchannel is considered occupied if the measured RSSI is higher than the prescribed threshold. The CR parameter is used to describe channel occupancy of the transmitting UE. The CR at a slot m is measured as the number of subchannels used for transmissions in the slot interval $[m-a, m-1]$ and granted in future slots $[m, m+b]$, divided by the number of configured subchannels in the transmission pool over the slots $[m-a, m+b]$ subject to constraints $a, b \geq 0$, $a \geq 500$ and $a + b + 1 = 1000$.

3.4.2 Channel modeling

Channel models play a vital role in understanding the statistical properties of the medium between a transmitter and a receiver in a communication system. So far, the channel modeling approaches for uplink and downlink channels focus on path loss, delay spreads due to multi-path propagation effects and Doppler shifts due to movement of the UEs. The channel propagation characteristics of V2X links differ in a number of ways in

comparison to the conventional cellular communication links. Specifically, both the transmitter and the receiver are continuously moving due to which they exhibit rapid temporal variability and inherent non-stationarity in their statistical parameters. The antennas placed on top of vehicles are usually at a height between $1.0 - 1.55$ m. Massive dense scatters nearby to the vehicle transmitters and receivers create different propagation characteristics in comparison to cellular links where the base station is fixed and only the receiver is mobile.

In the recent past, both simulation and experimental approaches have been conducted to model the V2X channels. The experimental studies carried out by Molisch et al. in [89] address the importance of using well characterized measurement-based V2V channel models to describe vehicular communication channels. Furthermore, the authors in [116] have proposed a variety of simulation approaches to describe different V2V channels. The most popular Winner II model is discussed for various types of environments in [76]. In order to model V2P channel characteristics, the approach proposed by the Deutsches Zentrum für Luft- und Raumfahrt (DLR) [101] is another good example where it considers specific pedestrian locomotion parameters (such as height, orientation, gathering up in crowds and many more) that contribute to the channel propagation characteristics.

In this thesis, we primarily consider the channel modeling methodology proposed in the ETSI specifications for 5G-NR V2X communication networks [39]. This modeling approach relies on the Winner II model [76] for cellular environments. To model the V2X channel characteristics primarily for V2V and V2I communication links, the ETSI specification in [39] recommends to extend the Winner II approach and include the large scale scattering effects due to the presence of other vehicles, buildings and objects on the road. Based on the complexity, four categories of channel modeling approaches are studied in the literature [89]:

- Deterministic path loss models
- Statistical models
- Geometry Based Stochastic Channel Model (GBSCM)
- Geometry Based Deterministic Channel Model (GBDCM)

In deterministic path loss models, we consider only losses incurred when a signal travels from the transmitter to receiver in free space. We do not take into account of any nearby objects that cause scattering, reflections etc. This channel model is considered as the most idealistic channel model.

The deterministic channel models can be extended by incorporating the loses due to fading effects (large and small scale) in the form of certain statistical distributions. Such models are called statistical channel models. A simple example for such a model is the single tap flat fading Rayleigh channel model [70].

In addition to modeling path loss and fading in vehicular communication environments, it is also important to consider the effects of multi path delay spread and Doppler shifts due to continuous motion of both the transmitter and the receiver. Tap delay line based implementations [70] are popularly used to model statistical channels that exhibit time and frequency selectivity. It is the most suitable form of implementation for statistical channels that satisfy the property of Wide Sense Stationary and Uncorrelated Scattering (WSSUS). These models assume that although the channel characteristics vary with time, the second order statistics remain wide sense stationary and the scattering effects due to obstacles are uncorrelated in nature.

In a vehicular communication environment, it becomes essential to consider the large scale correlated scattering effects due to the presence of nearby obstacles on the road which are taller than the vehicle antenna height - for example, when there is a truck or a bus in between two vehicles. Such correlated scattering effects are very specific to the road traffic scenario and time of the day. In the GBSCM method, the geometry of the propagation environment is randomly generated according to specified statistical distributions for each type of vehicular scenario [39]. Although it is possible to modify the tapped delay line to specific scenarios, it is still difficult to incorporate all the parameters related to large scale scattering effects from different obstacles - e.g., Angle of Arrival (AoA), Angle of Departure (AoD) and many more.

The GBDCM method uses pure ray tracing or ray launching to determine the channel's characteristics. It requires us to provide information about 3D building data to search for all possible paths between a transmitter and a receiver. The transmissions, reflections, diffraction, and scattering effects are modeled very specifically based on real world data from measurement campaigns or maps. A classical example is the $GemV^2$ channel model [14]. A more recent model based on a holistic approach to simulate large-scale three-dimensional VANET scenarios is presented in [18, 19]. The complexity of GBDCMs increases with the number of transmitters and receivers in a road traffic scenario and their levels of interactions with other objects.

3.4.2.1 Fixed-to-Mobile (F2M) channel environments

The F2M channel environments refer to the channel between a fixed Base Station (BS) and a moving Mobile Station (MS). The MS can be a vehicle or a pedestrian. The BS antennas are located at a greater height in comparison to the antenna located on the vehicle. To develop a GBSCM model for the F2M channel environment, we have implemented two variants of the Winner II [76] model within the `Artery-C` framework: *(i)* Bad urban micro cell - B2. *(ii)* Rural macro cell - D1.

The specific parameters (such as the distance between transmitter and receiver d, height of base station h_{BS} and height of mobile station h_{MS}, lane width w and carrier frequency f_c) for Winner II variants implemented in `Artery-C` can be configured

according to Table 3.3. The suitable scenarios for which the Winner II model variants can be adapted are listed in Table 3.4. Note that the scenarios listed in Table 3.4 can be modified to support even the sidelink unmanaged mode. The fading parameters in Table 3.3 are obtained from the Winner II channel model specifications defined in [76].

Table 3.3 – Configuring path loss and fading parameters for Winner II [76] variants.

Winner II	State	Path loss variables	Fading [dB]
B2	NLOS	$10\,\text{m} < d < 1\,\text{km}$, $f_c = 5.9\,\text{GHz}$, $w = 20\,\text{m}$, $10\,\text{m} < h_{BS} < 40\,\text{m}$, $h_{MS} = 1.5\,\text{m}$	4
D1	LOS	$10\,\text{m} < d < 1\,\text{km}$, $f_c = 5.9\,\text{GHz}$, $30\,\text{m} < h_{BS} < 40\,\text{m}$, $h_{MS} = 1.5\,\text{m}$	$4-6$
D1	NLOS	$50\,\text{m} < d < 1\,\text{km}$, $f_c = 5.9\,\text{GHz}$, $30\,\text{m} < h_{BS} < 40\,\text{m}$, $h_{MS} = 1.5\,\text{m}$	8

Table 3.4 – Winner II variants and suitable scenarios.

Winner II	State	Modes	Scenarios
B2	NLOS	Uu, managed	Urban
D1	LOS	Uu, managed	Highways (rural, urban)
D1	NLOS	Uu, managed	Dense highways (rural, urban)

3.4.2.2 Mobile-to-Mobile (M2M) channel environments

The M2M channel refers to the channel characteristics between two or more mobile UEs where both the transmitter and the receiver are continuously moving. Typically, the V2V and V2P communication links belong to this category. To develop M2M channel models, we have adopted the GBSCM approach suggested in the ETSI specifications [39] for the urban and highway environments.

Three types of path propagation conditions are considered originally in `SimuLTE`. They are as follows:

- Line of Sight (LOS): There are no obstacles in the path between the transmitting and the receiving vehicle.
- Non Line of Sight (NLOS): There are one or more obstacles (e.g., buildings, trees etc.) in the path between the transmitting and the receiving vehicle.
- NLOSv: There are one or more obstacles in the form of other taller vehicles in the path between the transmitting and the receiving vehicle - e.g., a truck is located in between two cars that intend to communicate with each other.

For the simulation scenarios in this thesis, we extend the NLOSv propagation condition that models the pathloss and vehicle blockage loss as recommended in the ETSI specifications [39].

1. Path loss: The path loss equations for highway PL_H and urban PL_{Ur} environments under NLOSv PL_{nlos} conditions are calculated as:

$$PL_H = 32.4 + 20\log_{10}(d) + 20\log_{10}(f_c) \tag{3.3}$$

$$PL_{Ur} = 38.77 + 16.7\log_{10}(d) + 18.2\log_{10}(f_c) \tag{3.4}$$

   Here, d is the distance between transmitter and receiver (in m) and f_c is the carrier frequency.

2. Vehicle/obstacle blockage loss: In addition to the path loss for the highway and urban environments as calculated in Equation 3.3 and Equation 3.4, respectively, we need to statistically add the loss due to vehicle blockage component in an M2M channel environment. Typically, vehicle blockage loss occurs in NLOSv environments when the antenna height of the blocking vehicle is greater than the antenna heights of transmitting and receiving vehicles. The ETSI standards [39] recommend the calculation of the mean vehicle blockage loss $\bar{V}_{bl}$ as:

$$\bar{V}_{bl} = 9 + max(0, 15\log_{10}(d) - 41) \tag{3.5}$$

   with a standard deviation of 4.5 dB.

3. Losses due to shadow fading: The shadow fading parameters for V2V and V2I links are considered based on the specifications and parameters mentioned in [39].

4. Large and small scale correlated scattering effects: To model the correlated scattering effects due to the presence of obstacles in specific road traffic scenarios, GBSCM considers the usage of Cluster Delay Line (CDL) models. The details of generating a CDL profile are presented in [39, 70]. Since we consider only system level simulations as a part of this thesis, we have directly adopted the CDL profiles defined for highway and urban scenarios in [39].

3.4.2.3 Signal-to-Interference Noise Ratio (SINR)

Consider a multiuser sidelink broadcast scenario, where we have N transmitting UEs each with a transmit power P_{SIG}.

The signal received at one of the intended receiver UE j in time domain can be expressed as a superposition of signal and interference components from the set of N transmitting UEs,

$$y^j(n) = \sum_{i=0}^{N-1} \sum_{l=0}^{L_{taps}-1} h^i(n,l)x^i(n-l)p^i(n) + \zeta(n) \tag{3.6}$$

where $h^i(n,l)$ is the channel impulse response of a time-frequency selective channel between transmitter i and receiver j. The time shifted input data signal from the transmitting UE i is $x^i(n-l)$. The total number of channel taps is L_{taps} and $p^i(n)$ is the power component for the ith transmitter at time index n. The term $\zeta(n)$ represents the Additive White Gaussian Noise (AWGN).

The Inter Symbol Interference (ISI) resulting from the previous symbol in a multipath channel environment is removed by a time-domain windowing technique at the receiver. The interferences due to Inter Carrier Interference (ICI) and Adjacent Channel Interference (ACI) present in the currently received symbol will be extracted in frequency domain.

By taking the Fast Fourier Transform (FFT), we have the received signal $Y^j(p)$ at the pth subcarrier as,

$$\begin{aligned} Y^j(p) = & \underbrace{G^i(p,p)X^i(p)P^i(p)}_{\text{Signal}} \\ & + \underbrace{\sum_{f=0,f\neq p}^{N_t-1} G^i(p,f)X^i(f)P^i(f)}_{ICI} \\ & + \underbrace{\sum_{f'=0,f'\neq p}^{N_t-1} \sum_{r=0,r\neq i}^{N-1} A(p,f')G^r(p,f')X^r(f')P^r(f')}_{\text{ACI from other transmitting UEs}} + \underbrace{\zeta^i(p)}_{\text{AWGN}} \end{aligned} \tag{3.7}$$

In Equation 3.7, the total number of subcarriers is N_t. The frequency domain channel response for the transceiver link (i,j) is obtained by taking the FFT along both time and frequency dimensions. The Doppler variant channel frequency matrix is denoted by G^i.

The first term in Equation 3.7 represents the signal component. The main diagonal elements of G_i contain the signal relevant information ($G^i(p,p)$) corresponding to our transmit UE i. The frequency domain representation of data signal and the transmit power components at the pth subcarrier is given by $X^i(p)$ and $P^i(p)$, respectively. The off-diagonal elements ($G^i(p,f)$) of G_i contain the ICI contributed by another subcarrier f (refer to the second term in Equation 3.7). The frequency domain data and the transmit power components at the fth subcarrier is given by $X^i(f)$ and $P^i(f)$, respectively.

The third term in Equation 3.7 corresponds to the ACI resulting from other non-intended UEs r that transmit on an adjacent subcarrier f'. The frequency domain

representation of the data signal and the transmit power components at subcarrier $f^{'}$ is given by $X^{r}(f^{'})$ and $P^{r}(f^{'})$, respectively. The ACI parameter is influenced by the power amplifier and the transmission scheme. We formulate a generic ACI mask $A(p, f^{'})$ which is an element-wise inverse adjacent channel interference ratio (ACIR) matrix. It is obtained by taking the ratio of the received power on the frequency slot p and $f^{'}$. The term $\zeta^{i}(p)$ represents the channel noise power at the pth subcarrier.

By taking the ratio of the signal power P_{SIG} to the sum of the powers due to all interference components ISI (P_{ISI}), ICI (P_{ICI}), ACI (P_{ACI}) and noise (P_N), we calculate the SINR as,

$$\text{SINR} = \frac{P_{SIG}}{P_{ISI} + P_{ICI} + P_{ACI} + P_N} \tag{3.8}$$

3.4.3 Modeling cellular network infrastructure

In addition to developing road traffic models in SUMO to model vehicle and pedestrian movements and behaviour, there also arises a need to model the network infrastructure. With a long term goal to study different application scenarios of Cellular V2X communication in the city of Ingolstadt, we hereby extend the InTAS by modeling cellular coverage sites in one of the densely crowded area (the urban district Ingolstadt Mitte), which is a good choice for modeling an urban macro cell environment [64]. Specific reasons to introduce the modeling of cell sites in a road traffic scenario are as follows:

- Get a clear understanding of the availability of cellular network coverage in different areas of the city, i.e., which providers are operating, their frequency bands, etc.
- Retrieve the number of vehicles currently served by a certain base station in a specific cell. This information is helpful to study the occupancy of a cell at a given time during the day and to further optimize the allocation of radio resources.
- Develop a better understanding of the cell coverage and interference characteristics at different points within a cell site, e.g., within the cell close to base station, near cell borders, overlapping regions etc.

Continuing with the same high level architecture of Artery-C shown in Figure 3.1, the addition of the cellular layer helps us to generate a record consisting of mobility events (interactions between road traffic participants and gNBs) for routable entities such as vehicles and pedestrians that can be utilized to analyse the vehicle behaviour, accuracy of message transmission and reception in case of events that took place in the recent past. In the following subsections, we discuss the details about the structure of the cell sites, how to model them in SUMO environment and also the types of antennas deployed.

3.4.3.1 Implementation

For modeling the geographic environment and for defining the application scenario, we rely on the International Telecommunication Union - Radiocommunication (ITU-R) specifications [66], which define test environments for the evaluation of cellular networks, specifically for Enhanced Mobile Broadband (eMBB), Ultra Reliable and Low Latency Communication (URLLC) and Massive Machine-to-Machine Type Communication (mMTC), namely *(i)* indoor hotspot-eMBB, *(ii)* dense urban-eMBB, *(iii)* rural-eMBB, *(iv)* urban macro-mMTC and *(v)* urban macro-URLLC. These test environments correspond to the major application scenarios in the 3GPP specifications for 5G cellular networks and define target Key Performance Indicators (KPI) for every scenario. We have developed a *dense urban-eMBB* test environment, which is characterized by high density traffic load comprising of fast moving vehicles and pedestrians. In the proposed

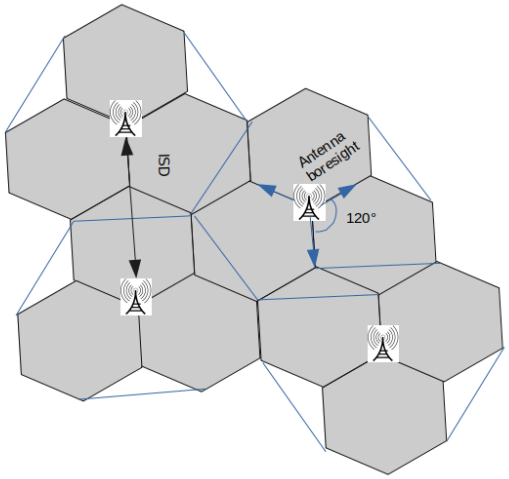

Figure 3.6 – Dense urban macro cell layout [64].

cellular coverage layer in `SUMO`, each cell site comprises three transmission-reception points (TRxP) that are placed in a regular hexagonal grid as shown in Figure 3.6. A cell site is served by a base station (gNB) that covers three cells through three sectors at an angle of 120 degrees.

3.4.3.2 Generation of cell sites in `SUMO`

The workflow to create cell sites in a `SUMO` scenario is illustrated in Figure 3.7, using `InTAS` with `Ingolstadt.net.xml` as an example. In general, the process of modeling cellular coverage involves the following aspects:

1. Definition of gNB as a point-of-interest (POI) in the `InTAS` model. The geospatial coordinates of the gNBs (latitude, longitude) are obtained from the crowdsourcing database *Cellmapper*.[8]
2. Creation of a hexagonal layout utilizing the `polygon` feature in `SUMO`.
3. Creation of boundaries to distinguish different areas such as cell borders and sectors.
4. Assigning attributes to the gNB and the corresponding cells in an `.xml` file.

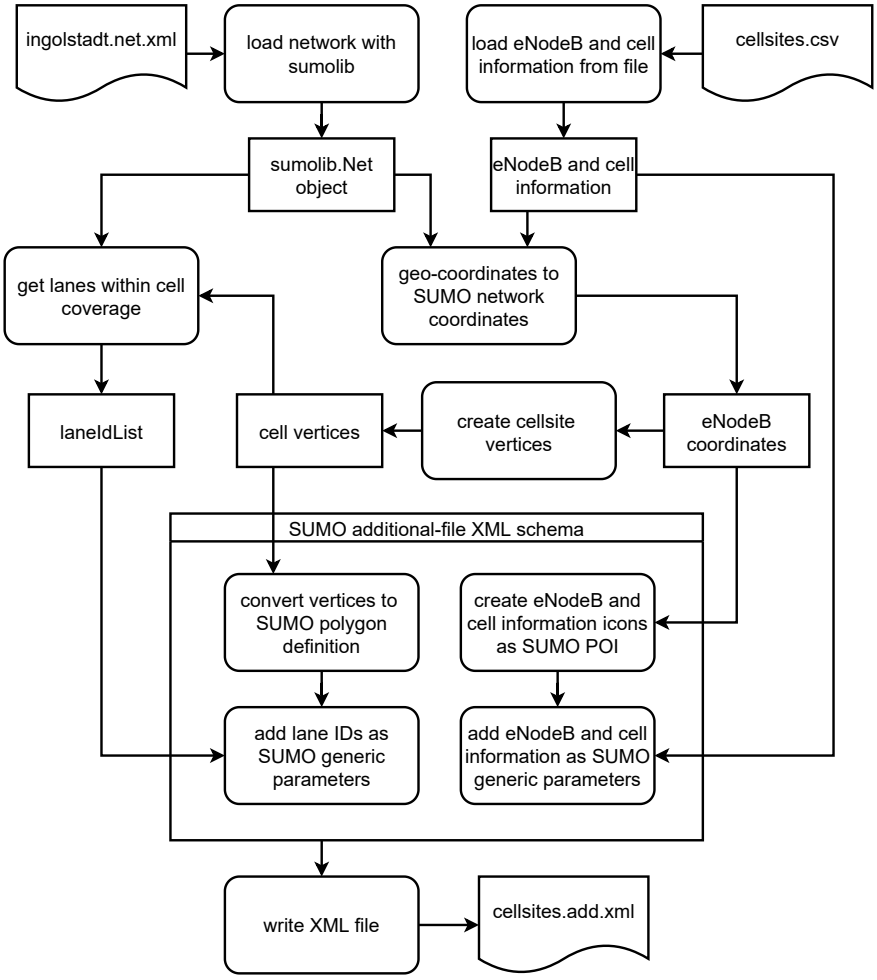

Figure 3.7 – Workflow for the creation of cell sites [64].

In Figure 3.7, the first step is to create a cell information file (`cellsites.csv`) that consists of the base stations and cell related attributes such as operational bands,

[8] `https://www.cellmapper.net`

district, duplex mode, support for sidelink, geographical location and the gNB/cell identifiers along with their telecom service provider names [64]. Then, we convert the geospatial coordinates of the gNB into SUMO recognizable network coordinates. The logic for the generation of cell vertices is written in a separate Python-based script, which takes the coordinates of the gNB as an input parameter and generates the cell site vertices to construct the hexagon grid (polygon) inside the ingolstadt.net.xml file. We use different colors to indicate the cells, cell boundaries and sectors. We add the lane IDs of the lanes traversed by the hexagonal cells as generic parameter because later this information is useful to obtain the details of the vehicles, which are inside the cellular coverage area and their mobile event logs. The gNB and cell information is subsequently written into the cellsites.add.xml file, which gets loaded along with the intas.sumocfg file during the start of simulation. This workflow allows the user to include any number of attributes inside the cellsites.csv file, generate the hexagon grid of appropriate cellular environment and automatically generate the cellsites.add.xml file.

In order to determine the data traffic load in each cell, we first retrieve the list of lane IDs traversed by the polygon and subsequently obtain the list of vehicle IDs present in that lane. Since vehicles can dynamically enter and exit the cellular coverage region, it becomes important to monitor the road traffic flow in order to get an idea of the number of users (vehicles, pedestrians, etc.) connected to a given base station and the radio resources utilized by the users in the particular cell site.

3.4.4 Extension for Deep Reinforcement Learning (DRL)

As explained in the previous sections of this chapter, the network simulator Artery-C originally implements rule based radio resource scheduling algorithms for the managed and the unmanaged modes. To study the performance of Artificial Intelligence (AI) based radio resource allocation in Cellular V2X, we have extended the existing simulation environment by a DRL environment that executes an AI based radio resource scheduler.

3.4.4.1 Coupling of Artery-C and TensorFlow

To couple the network simulation in Artery-C with a DRL based environment that implements an AI based resource scheduler, two types of approaches are possible - online and offline. The core idea here is to maintain a high degree of realism from the existing open-source simulation frameworks Artery-C and SUMO, and also to utilize the capabilities of the well-established AI environment TensorFlow [6].

In the offline method, several simulation runs on Artery-C can be conducted by varying the network and road traffic parameter settings (for example, message generation frequency, vehicular traffic density in number of vehicles/m/lane) and other scheduling parameters (for example, RRI). Once we have the data collected from large scale

simulation runs, the state parameters are extracted and fed into the DRL environment. This method benefits the car manufacturers in a way that algorithms can be pre-trained in a simulation environment and then deployed into the cars. Diagnostic information can be collected to measure the performance of the algorithm in real world deployment scenarios and then the algorithm can be tuned for improvements. This method is relatively fast but more suited to deterministic environments.

Typically, in a road traffic environment with varying number of vehicles, changing network coverage situations and dynamic environmental perception by sensors, it is not possible to practically simulate all scenarios. Also there is a justified need to switch between rule and AI based schedulers depending on the traffic flows and V2X data traffic patterns. Hence an online method is more appropriate.

The integration of network simulators (such as `ns-3` and OMNeT++) and a neural network based learning environment (such as `PyTorch` or `TensorFlow Python`) has been previously carried out in [49, 102]. In comparison to these frameworks, our approach differentiates in the following manner:

1. Possibility to support an AI based scheduler within the OMNeT++ environment by the integration of `TensorFlow C++` library. This feature is particularly efficient to perform ML tasks by the network simulator when it does not require many computational resources.

2. Seamless bi-directional communication to handle multiple simultaneous vehicular clients by a single server.

3. The MAC module of the Cellular V2X protocol stack allows for switching between the rule based (refer to Figure 3.3) and AI based schedulers in different situations. Further details about the design of AI based schedulers are covered in Section 6.4.1 and Section 6.4.2.

3.4.4.2 Implementation

The high-level architecture of the coupled simulation framework is depicted in Figure 3.8. From a DRL perspective, the network simulator `Artery-C` contains information describing the environment, input parameters related to the states observed by the vehicles and the obtained rewards. Considering `Gym` as a standard API to model the environment in Reinforcement Learning (RL) [17], the network simulation in `Artery-C` should be converted as an equivalent `Gym` environment in order to train and run the AI algorithms. Taking into account that `Artery-C` is implemented in `C++` and we use `TensorFlow Python` for the DRL environment, `Artery-C` is extended by an equivalent `Python` stub, where the vehicular attributes related to the states are exchanged in the form of a `ProtoBuf` message which is a flexible and an efficient mechanism for serializing structured data [51]. On the DRL-side, a multi-agent custom `Gym` environment is created and

the agent related attributes are imported from the Python-stub equivalent of Artery-C. Within this environment, the agents learn to select their radio resources in a collaborative manner.

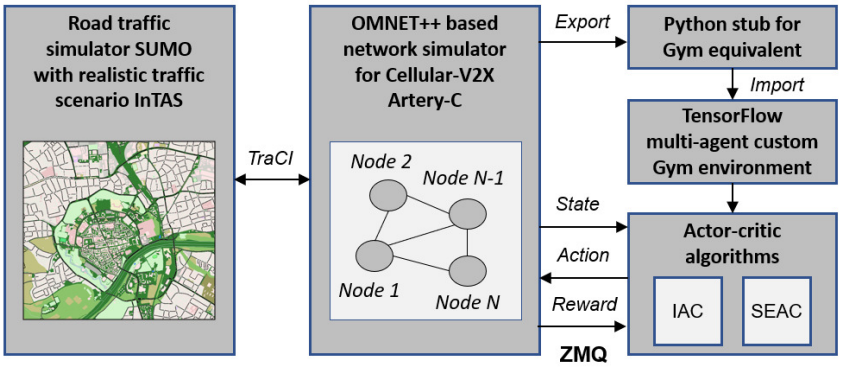

Figure 3.8 – Simulation environment for AI based radio resource allocation [63].

Inter Process Communication (IPC)

The simulation environment uses IPC to link the network simulation with the DRL environments and to synchronize their actions. In Section 3.4.4.1, we implement a message passing paradigm where the processes – one running in Artery-C and the other running in TensorFlow Python – send and receive messages utilizing ZMQ, a flexible asynchronous messaging library for distributed applications based on socket communication paradigm [65]. One of the key advantages of the ZMQ library is that there are interfaces to many common programming languages. For example, a complex application can be built in the Python environment and intermediate results can be exchanged with another process running in the C++ environment.

The information exchange relies on the client-server paradigm with the REQ-REP pattern, where a client sends a request and the server responds with a reply. As depicted in Figure 3.8, vehicular agents (clients) in the OMNeT++ environment encode the state information as ProtoBuf messages and send a request (ZMQ-REQ) to the DRL environment. The Python based server processes the request and sends appropriate action back to OMNeT++ in the form of ZMQ-REP. The speed of the simulation varies with the size of the road traffic scenario, length of the episode and the number of vehicles that execute rule and AI based schedulers.

3.5 Validation

To demonstrate the functional capabilities of the `Artery-C` framework, we present a sample screenshot of a Cellular V2X communication network simulated in an urban road traffic environment within the city of Ingolstadt [80], Germany. The UEs mainly comprise of cars, buses and trucks indicated by red color in Figure 3.9 along with Vulnerable Road Users (VRUs) such as pedestrians and bicycle riders. As we can observe, there are certain areas covered by the cellular base stations where the vehicles can either operate in the cellular (Uu) mode or the sidelink managed mode. In those portions of the city where cellular network coverage is absent, the vehicles operate in the sidelink unmanaged mode.

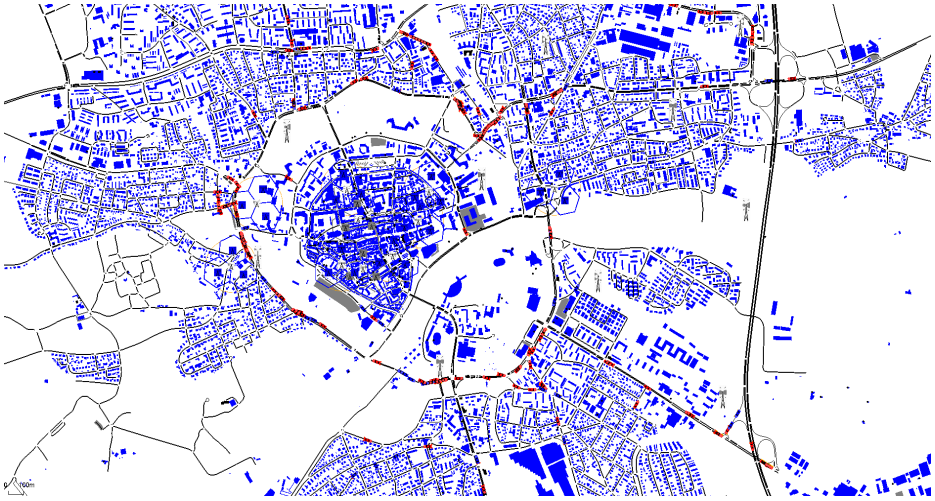

Figure 3.9 – Urban road traffic scenario [80].

The road traffic scenario related parameters are listed in Table 3.5 and the Cellular V2X communication parameters along with the messaging protocols are listed in Table 3.6.

When the vehicles switch from the sidelink unmanged to the managed or the cellular (Uu) mode, the process of connection establishment and timing synchronization with gNB is relatively faster and hence the vehicles are able to obtain the radio resources within the maximum allowed latency constraints. This ensures that almost up to 90% of the generated messages are successfully transmitted and also received. On the other hand, when the vehicles move out-of-coverage of the base station, they are forced to operate in the sidelink unmanaged mode. They experience significant delays due to synchronization and radio resource allocation which directly impacts the probability of message transmission and reception. Particularly at higher vehicular densities ($0.28 \leq B < 0.45$), the probability of message reception reduces to nearly 0.6 in the unmanaged mode of operation as illustrated in Figure 3.10. A detailed analysis on the

efficiency of the radio resource allocation in sidelink and possibilities for a mode switch operation are carried out in Chapter 4 and Chapter 5, respectively.

Table 3.5 – Simulation parameters: Urban road traffic scenario.

Parameter	Value
Vehicle speed [km/h]	30 – 50
Range of sidelink broadcast [m]	500 – 800
Number of lanes	2 – 4
Types of vehicles	Cars, buses, trucks
VRUs	Pedestrians and bicycle riders
Time of the day [am]	8:30 - 9:30
Backward facing radar (range, FOV)	80 m and 325°
Forward facing radar (range, FOV)	160 m and 35°
Pedestrian mobility model	`Striping`[9]
Vehicle density (B) [Veh/m]	Low: 0.07, med: $(0.14 - 0.21)$ high: $(0.28 - 0.45)$

Table 3.6 – Simulation parameters: Cellular V2X [45].

Parameter	Value
Protocol stack	5G-NR V2X
Frequency band [GHz]	5.9
Subcarrier spacing [kHz]	15
Frame structure	Frequency Division Duplexing (FDD)
Modulation scheme	QPSK
Channel model	WINNER II - B2 (urban)
Cellular mode supported	Yes
Sidelink modes	Managed and unmanaged
V2X messaging	CAM, CPM, DENM and VAM
Possibility for mode switch	Yes

The overall time taken for a certain simulation to synthesize depends on a number of factors such as the complexity of the road traffic scenario, details in the implementation of the Cellular V2X protocol stack and most importantly the number of nodes (here it refers to vehicles and VRUs) and their data traffic patterns in a communication network. The simulation synthesis times for the nodes executing rule based radio resource schedulers are illustrated in Figure 3.11.

It can be observed that for up to $1,000$ vehicles, the synthesis time during one simulation run is less than or equal to 10 hours. As the number of vehicles grow, the synthesis time increases exponentially and especially when we want to include several instances of our simulation by varying different parameters, it can take up to one week when nearly $1,500$ vehicles are simulated. By utilizing the parallel execution features

[9] `SUMO` striping model: `https://sumo.dlr.de/docs/Simulation/Pedestrians.html`

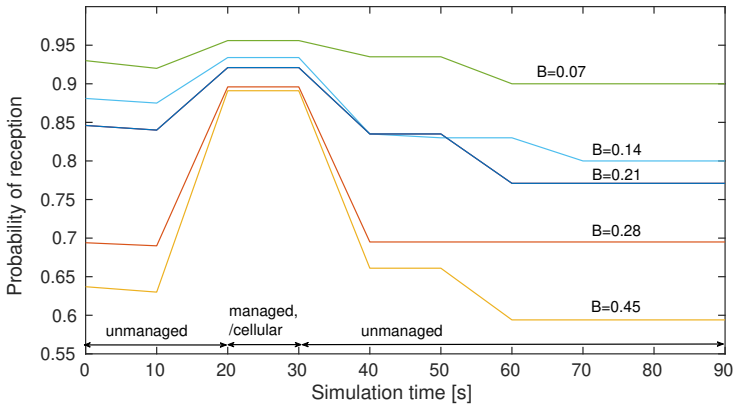

Figure 3.10 – Mode switching and its impact on link reliability.

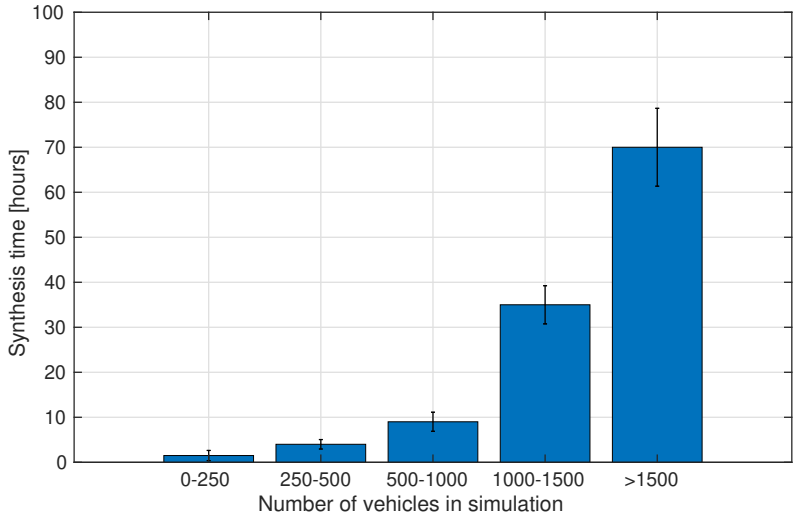

Figure 3.11 – Evaluation of scalability and synthesis time of a large scale V2X simulation in `Artery-C`.

of the OMNeT++ framework, we have managed to simulate multiple instances of our simulation scenario and obtain results within a reasonable amount of time (less than 20 hours) even with $1,500$ nodes. This satisfies the scalability and performance requirements (measured in terms of synthesis time) of the simulation framework. By closely aligning with the ETSI specifications during the implementation of each submodule of the Cellular V2X protocol stack, it becomes possible to re-use (and further extend if necessary) these modules in order to incorporate latest features from the subsequent releases.

When Artery-C is coupled with a DRL environment (as done in Chapter 6), the performance of the simulation framework suffers from scalability issues beyond 30 vehicles. This is mainly due to the time overheads caused by the complexity of the IPC mechanisms handled within the ZMQ sockets. Therefore, we believe that development of efficient communication protocols and IPC paradigms are an important next step when such a simulator is to be coupled with an AI based environment. Another aspect to note here is that the OMNeT++ kernel is inherently single threaded and hence is not suited for deployment in real-time applications. The mismatches between the simulator time and the wall clock time as studied in [93] is another technical limitation that leads to time inconsistencies when such a simulator is coupled with real hardware.

3.6 Summary

This chapter discussed in-depth about the requirements, salient features of the network simulator Artery-C and its coupling with the road traffic simulator InTAS. Artery-C implements both the control and user planes of the Cellular V2X protocol stack (LTE/5G-NR V2X). It integrates dedicated channel models for the simulation of different types of Cellular V2X links (V2V, V2P and V2I). Both the sidelink resource allocation modes and the corresponding resource scheduling algorithms are implemented with a possibility to perform mode switching. Another distinguishing feature of Artery-C is that it supports different types of ETSI compliant V2X messaging protocols such as CAM, DENM, CPM and VAM. In the application layer, the generation rules and the triggering conditions of these protocols can be varied in order to generate different types of V2X data traffic patterns. An enhancement to Artery-C includes the extension with a DRL based environment that supports the development of AI based algorithms. The concepts and the features described in this chapter are utilized in different capacities to study the performance of the rule- and AI based radio resource allocation algorithms in the following chapters of this thesis.

Chapter 4

Radio resource allocation modes: a performance evaluation

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In order to to guarantee a high reliability in the Cellular V2X communication links, it is important to ensure successful transmission and reception of messages among the road traffic participants (e.g., vehicles, Road Side Units (RSUs) and Vulnerable Road Users (VRUs)). In addition to acquiring the radio resources in a timely manner within the maximum latency (or the Packet Delay Budget (PDB)), it is equally important that the User Equipments (UEs) are able to utilize them appropriately for their transmissions (and receptions).

The radio resource allocation in the managed mode is better coordinated because the Base Station (BS) has a complete view of the radio resources utilized by its connected users. On the other hand in the unmanaged mode, the UEs are not informed of the radio resource allocation decisions by other UEs. Other time varying factors such as high mobility and varying levels of sensor perceptions make it challenging for the Configured Grant (CG) type II and the Sensing Based Semi Persistent Scheduling (SB-SPS) algorithms in the managed and unmanaged modes, respectively, to adapt their parameters to make future resource reservations in the events of aperiodic V2X data traffic.

In this chapter, we identify and derive the metrics and parameters that help to us to assess the performance of the sidelink radio resource allocation modes. By varying the generation rules of the standardized V2X messaging protocols, we characterize the resulting V2X data traffic patterns along with the variations in their data sizes. By carrying out large scale system level simulations within the `Artery-C` framework, we determine the baseline conditions where both the modes perform to their best efficiency and further understand their robustness in handling different types of V2X data traffic.

4.1 Preliminaries

System level simulation studies of the unmanaged mode in [59, 87, 112] indicate that the SB-SPS algorithm is efficient in scheduling the radio resources when the vehicles transmit periodic messages whose data sizes are deterministic. The algorithm is able to withstand some extent of variations with regard to the periodicity and data sizes of the messages. Studies in [10, 13, 24, 84, 112] have demonstrated that by tuning different parameters of the SB-SPS algorithm such as Resource Reservation Interval (RRI), *cResel* and probability of resource keep, it is possible to optimize the radio resource allocation under different vehicular density conditions. However, when simulated for a realistic traffic scenario consisting of several vehicles with constantly changing kinematics and environmental perception [59], it has been observed that the nature of V2X data traffic is largely aperiodic with non-deterministic data sizes. This results in poor radio resource utilization and frequent resource re-allocations because the data sizes are not fitting properly within the previously allocated radio resources. To be able to explain the concept of radio resource utilization, it is important to formally

characterize some observations such as such the number of allocated radio resources that are utilized/wasted, how many times a re-allocation is taking place and the number of successful transmissions per sidelink (SL) grant.

When vehicles operate in the unmanaged mode, the sensing mechanism does not guarantee that all the vehicles have complete knowledge of the radio resources utilized by other vehicles. In one of the leading research studies [50], they have reasoned out that resource collisions are prone to happen due to the following reasons:
(i) In resource congested situations where more number of vehicles are competing for a fewer number of available radio resources. *(ii)* When several vehicles re-select their radio resources at the same time (the value of their *cResel* has reached zero). *(iii)* New vehicles entering the traffic environment do not have knowledge of the resource allocation decisions of other vehicles. In [57, 69], the authors propose approaches to tackle the problem of radio resource collisions by implementing parameter sharing mechanisms for the SB-SPS algorithm. Fundamentally, the radio resource collision problem exists even in a non congested situation. The mechanisms suggested in the above mentioned works for parameter sharing partially helps to mitigate the resource collision but is not an adequate solution. This is because in the events of aperiodic traffic, the vehicles need to re-allocate their radio resources several times. The parameters such as RRI and *cResel* continuously change and this leads to inconsistencies in radio resource allocation decisions for neighboring vehicles. In this chapter, we study the problem of radio resource collision in a more structured manner where we develop analytical approaches to calculate the probability of radio resource collision caused by different influencing parameters.

The unmanaged mode is extensively studied so far in all the previous works. A careful examination of the advantages of the managed mode in favourable conditions (for example, when cellular network coverage is available) needs to be carried out in order to obtain a comparison on the performance of the radio resource allocation in Cellular V2X communication networks.

Contributions

The V2X data traffic models formulated in Section 4.2 are direct excerpts from our journal article [63] and some selected measurement results obtained within the IN²Lab project [67]. The metrics formulated in Section 4.3.2 are based on our conference publications [59, 60]. The specific author contributions along with the copyright note for these publications are provided in Appendix C.

The main contributions in this chapter are as follows:

1. Formulation of V2X data traffic models to characterize the patterns resulting from different types of V2X messaging services.

2. Derive analytical expressions to calculate the following metrics: Radio Resource Utilization (RRU), Probability of Resource Collision (PRC), Transmission Success Ratio (TSR) and Probability of Reception (P_R).

3. With regard to the above defined metrics, we compare the performance of the managed and the unmanaged modes under dynamically changing vehicular density conditions and V2X data traffic patterns.

4.2 V2X data traffic characterization

Heterogeneity in the nature of the data traffic generated by different V2X messaging protocols (such as Cooperative Awareness Message (CAM), Collective Perception Message (CPM) and VRU Awareness Message (VAM)) makes it challenging for the managed and the unmanaged modes to allocate and schedule the radio resources. Practically, it is not feasible to have separate radio resource schedulers for each type of V2X data traffic or even a separate Cellular V2X radio device for each mode of operation. Therefore, it is necessary to understand the V2X message characteristics (refer to Table 4.1) and their impact on the radio resource allocation mechanism in each of the sidelink modes.

Table 4.1 – Characteristics of V2X messaging protocols.

Protocol	Message size [bytes]	Periodicity [ms]	Category
CAM static	$250 - 300$	100	A
CAM dynamic	$250 - 600$	$100 - 1,000$	B,C
CPM fixed	$180 - 250$	100, 300, 500	A
CPM ETSI	$200 - 400$	–	B
CPM ETSI-K	$50 - 800$	–	C
VAM	$74 - 116$	–	B, C
DENM	50	–	C

Within the scope of this PhD thesis, we consider the V2X messaging services that are standardized by the ETSI for CAM, CPM and VAM [34, 35, 43]. In Table 4.1, we provide details about the data traffic characteristics of different message generation models (and their variants) for these protocols. We acknowledge that other standardized V2X messaging services exist, but we consider the models listed in Table 4.1 since they are more safety critical and need to be transmitted frequently.

The different containers of the messaging protocols listed in Table 4.1 were explained in Chapter 2 and Chapter 3. It is to be noted that not every container needs to be included in every message. For example, the "low-frequency container" in a CAM contains static vehicle data and may be included only in every n-th message to reduce the message size. Also in case of RSUs that remain stationary, it is sufficient to send CAMs one time per second. A similar rule exists for the inclusion of the Sensor Information Container (SIC)

in a CPM. The size of the Perceived Object Container (POC) in a CPM depends on the number of detected objects. This is directly dependent of the sensor field-of-view (FOV) of a vehicle or an RSU. Therefore, the message size and the Inter Arrival Time (IAT) of CAMs, CPMs and VAMs can vary depending on the road traffic scenario, sensor perception capabilities and the corresponding message container configurations.

A Cumulative Distribution Function (CDF) plot of the message sizes resulting from CPMs transmitted by one of the RSUs in the example scenario of Figure 1.1 [67] is illustrated in Figure 4.1. The sensor perception module [105] on the RSU detects the objects on the road, classifies them and sends as object list to the Cellular V2X radio module[10], which further broadcasts it as a CPM to all the Intelligent Transport Systems (ITS) stations nearby (other RSUs and vehicles).

Table 4.2 summarizes the data traffic characteristics of the CPMs transmitted from one of the RSU. It is to be noted that these characteristics vary for different RSUs based on their geographical location and perception capabilities of their on-board sensors. Hence the data presented in Table 4.2 should be treated as a representative example based on the averaged diagnostics collected at different times of the day between the months of March and July 2023. Similarly, in case of a vehicle, the data traffic patterns of both CAMs and CPMs vary based on the vehicle driving dynamics and extent of environmental perception by the on-board sensors.

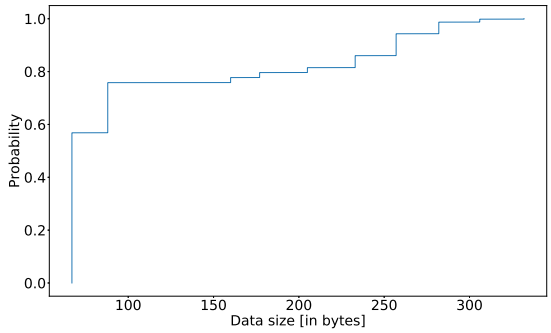
Table 4.2 – V2X data traffic characteristics summary.

Time	Message size [bytes]	CPMs per second
09:00 - 12:00	$50-260$	$1-3$
12:00 - 15:00	$80-260$	$2-4$
15:00 - 17:30	$120-420$	$7-8$

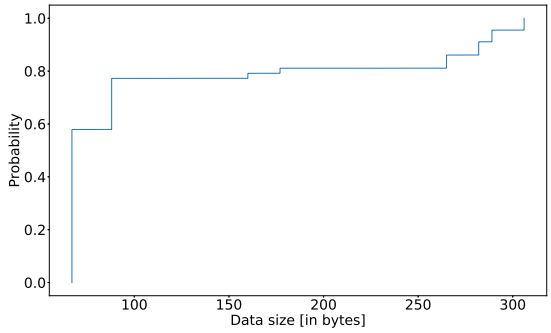
Based on the nature of the V2X data traffic pattern resulting from different messaging protocols listed in Table 4.1, we have developed three broad categories of V2X data traffic models which is used throughout the subsequent chapters to evaluate different metrics and parameters.

- **Type A: Periodic and deterministic**
  The message IAT is fixed at a certain value such as $[100, 300, 500]$ ms and also the size of the data (transport block and SCI) is limited to a fixed size (Figure 4.2a). Typically, static CAMs and CPM fixed as listed in Table 4.1 are considered as a part of this model. Although this model is quite far from reality, the objective here is to evaluate the conditions under which the SB-SPS and the CG type II algorithms perform most efficiently.

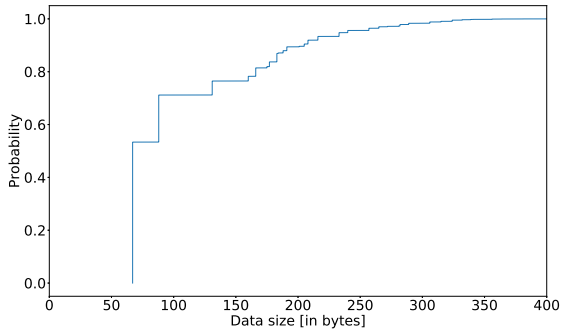
[10]Commsignia ITS-RS4 - `https://www.commsignia.com`.



(a) Time slot for measurement: 9:00 - 12:00

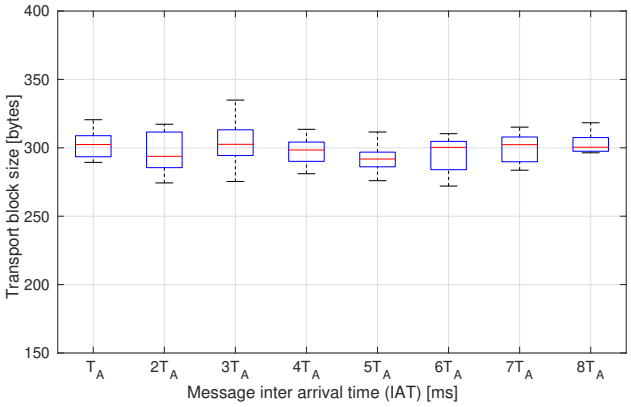


(b) Time slot for measurement: 12:00 - 15:00

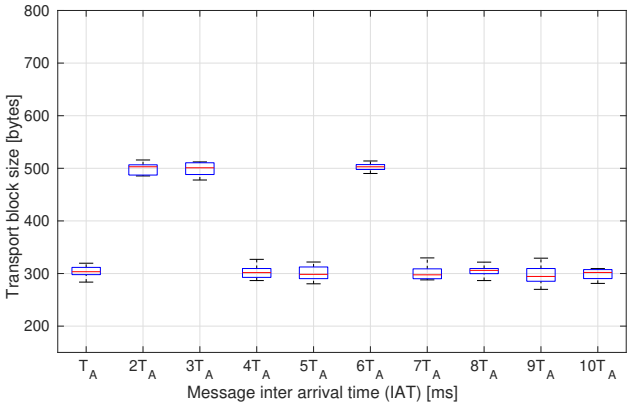


(c) Time slot for measurement: 15:00 - 17:30

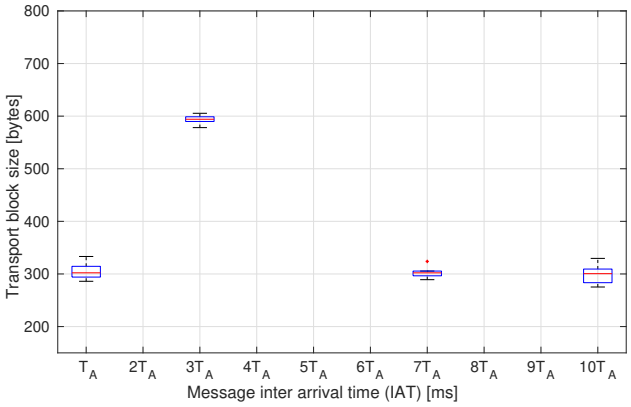
Figure 4.1 – V2X data traffic patterns as observed at one of the RSUs in the example scenario of Figure 1.1 [67].



(a) Type A data traffic model



(b) Type B data traffic model



(c) Type C data traffic model

Figure 4.2 – V2X data traffic models.

- **Type B: Periodic and non-deterministic**
  Messages are generated at a fixed IAT similar to the type A model, but the size of the data varies based on the number and size of the containers of the V2X messaging protocols. This type of traffic originates from a certain configuration and usage scenarios of CAMs and CPMs (Figure 4.2b). For a CAM, a fixed IAT is applied when the ego vehicle drives at a constant speed. In case of CPM, the messages are generated at smaller spaced equidistant intervals when the perceived objects move at a high speed, for example, on a highway.

  This fixed message IAT allows the reservation capabilities of the CG type II and the SB-SPS algorithms to be exploited. However, when the size of the data does not fit into the previously allocated radio resources, a re-allocation must be performed.

- **Type C: Aperiodic and non-deterministic**
  The message IATs do not follow any specific patterns and also the size of the data varies depending on the extent of environmental perception. This model typically illustrates (refer to Figure 4.2c) the data traffic generated by CAMs in scenarios with high dynamics of the ego vehicle and by the CPMs with varying levels of environmental perception. The variable message IATs and non-deterministic data sizes render the rule based radio resource allocation algorithms in both modes inefficient even in a non-congested scenario. A potential problem here is the poor resource utilization in low vehicular density (and perception) conditions and frequent re-allocations in high vehicular density conditions with changing levels of environmental perception (e.g., inclusion of more number of objects in the POC of a CPM). In the unmanaged mode, since the vehicles are only partially aware of the resource allocation decisions of other vehicles, the SB-SPS algorithm is highly susceptible to radio resource collisions.

4.3 Evaluation

A Discrete Event Simulation (DES) based approach is adopted to study the performance of the radio resource allocation modes under different vehicular density conditions and V2X data traffic patterns. The variants of the V2X messaging protocols described in Table 4.1 are implemented in the facilities layer of the Cellular V2X protocol stack in the `Artery-C` framework as shown in Figure 3.2 . The criteria for the selection of the appropriate road traffic scenario within the `InTAS` model along with the parameter settings are explained in this section. We derive the analytical expressions for the calculation of metrics which help us to quantitatively analyze the performance of both the radio resource allocation modes. Representative examples are provided to further

help in the visualization of these metrics and to formally characterize some observations occurring in simulations.

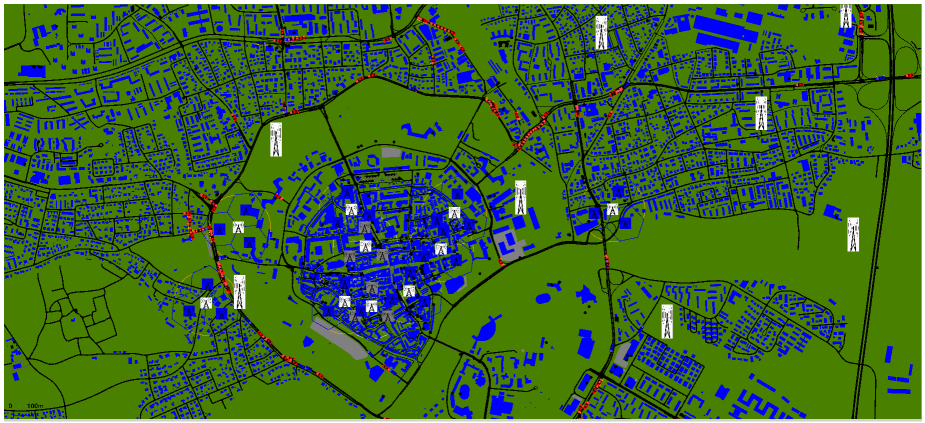


Figure 4.3 – Dense urban road traffic scenario.

4.3.1 Simulation environment

The dimensions of the original `InTAS` [80] road traffic model are $13,574.18 \times 11,092.15$ meters which includes also the smaller villages located in close proximity to the city of Ingolstadt, Germany. Based on the real traffic data collected from the city of Ingolstadt, we have made the following considerations to select a certain portion of the `InTAS` as depicted in Figure 4.3. It has a dimension of $4,500 \times 4,250$ meters to qualify as a dense urban traffic scenario that exhibits the following characteristics: *(i)* Changing vehicular density patterns (red color objects in Figure 4.3 represent vehicles) at different times during the day. *(ii)* Dynamically varying cellular network coverage conditions that requires for the operation in the managed and unmanaged modes. *(iii)* Reasonable simulation synthesis time to accommodate around $1,500 - 2,000$ vehicles and several VRUs.

Using the methodology discussed in Section 3.4.3.2, we model the cellular network infrastructure and consider the operation of both the sidelink managed and unmanaged modes. The road traffic and Cellular V2X related simulation parameters are listed in Table 4.3 and Table 4.4, respectively. In our simulations, the vehicles are equipped with sensors that have two radars: forward and backward facing (refer to the specifications in Table 4.3). The number of vehicles equipped with Cellular V2X capabilities is referred to as Vehicle Penetration Rate (VPR) as mentioned in Table 4.3.

Table 4.3 – Simulation parameters: Urban road traffic scenario.

Parameter	Value
Vehicle speed [km/h]	40 – 60
Sidelink broadcast range [m]	500 – 800
Number of lanes	2
Vehicle Penetration Rate (VPR)	100
Types of Vehicles	Cars, buses, trucks
Number of RSUs	11
RSU height [m]	4.55
VRUs	Pedestrians and bicycle riders
Time of the day [am]	8:30 - 9:30
Backward facing radar (range, FOV)	80 m and 325°
Forward facing radar (range, FOV)	160 m and 35°
Pedestrian mobility model	`Striping`
Vehicle density [Veh/m]	Low: 0.07, med: $(0.14 - 0.21)$, high: $(0.28 - 0.45)$

Table 4.4 – Simulation parameters: Cellular V2X [45].

Parameter	Value
Protocol stack	5G-NR V2X
Frequency band [GHz]	5.9
Subcarrier spacing [kHz]	15
Frame structure	Frequency Division Duplexing (FDD)
Modulation scheme	QPSK
Channel model	WINNER II - B2 (urban)
Number of subchannels (K)	2
Subchannel size	10
Slot length [ms]	1
Probability of resource keep	0.8
Operational modes	Managed & unmanaged
V2X messaging	CAM, CPM and VAM broadcast
Mode switching	No
Message size [bytes]	50 – 800
Re-selection counter ($cResel$)	[5,15]
Selection window size (M) [ms]	[20,100]
RRI [ms]	100
Adjacency SCI+Data	Yes

4.3.2 Metrics

The following metrics are analytically derived and subsequently measured from simulations: *(i)* Radio Resource Utilization (RRU), *(ii)* Probability of Resource Collision (PRC), *(iii)* Transmission Success Ratio (TSR) and *(iv)* Probability of reception (P_R).

The RRU measures the extent of utilization of the allocated radio resources for the successful transmission (and reception) in both the sidelink modes. Two additional parameters that directly affect the RRU are grant break and grant wastage which are characterized directly from simulations. The measurement of the PRC metric helps us to understand the robustness of the allocation modes in adjusting their parameters to allocate radio resources for V2X messages that have diverse generation rules, patterns and triggering conditions.

The combined measurements of the RRU and PRC together have an impact on the successful transmission of a V2X message which is quantified by means of TSR. The P_R metric helps us to evaluate the reliability of a communication link - what is the probability with which the transmitted messages are successfully received in sidelink broadcast communication links?

4.3.2.1 Radio Resource Utilization (RRU)

It is computed as the ratio of the number of radio resources utilized for transmissions (and receptions) to the total number of radio resources configured within a grant period. For a given N vehicles in the simulation, the RRU η is computed as:

$$\eta = \sum_{i=1}^{N} \frac{C_u^i}{C_c^i} \tag{4.1}$$

where C_u^i and C_c^i represent the number of radio resources utilized and the number of radio resources configured (within a sidelink grant), respectively, for a given vehicle i.

In order to elaborate further on the RRU metric, we formally characterize two observations:

1. Grant break: A configured grant is said to be broken when a UE requires re-allocation of radio resources. This happens in the following three situations: *(i)* The data sizes of the V2X messages do not fit within the previously allocated radio resources. *(ii)* When the value of the *cResel* reaches zero - i.e., all the allocated radio resources are utilized for transmission and new resources need to be allocated. *(iii)* When a radio resource collision is reported.

2. Grant wastage: When a UE is unable to transmit messages by utilizing the allocated radio resources, it leads to wastage of resources in the sidelink grant. Another subsequent problem is that it creates unnecessary blocking of radio resources for other vehicles leading to misinformed allocation decisions.

The CG type II algorithm (explained in Chapter 2) in the managed mode handles the effects of grant breaks and wastage in a better manner compared to the SB-SPS in the unmanaged mode because the pre-allocated radio resources are activated only when

a UE intends to transmit/receive data. This way, the gNB manages to re-distribute the non-utilized radio resources among other connected users. For the SB-SPS algorithm in the unmanaged mode, both the effects (i.e., grant breaking and wastage) are significant because the UE has only partial information of the resources utilized by other UEs and also re-distribution of non-utilized radio resources is not possible within the current implementation [45].

To illustrate the concept of grant wastage and radio resource blocking in the unmanaged mode, a sample screenshot of the sensing and selection windows for three vehicles (A, B and C) in the simulation (refer to Figure 4.4) are presented in Figure 4.5. The message arrival times for the vehicles A, B and C are indicated as T_n, T_m and T_p at the slot indices n, m and p, respectively. The number of future reservations (selection windows) is governed by the *cResel* value (represented as c in Figure 4.5). This can be either same or different for each of the vehicles in the simulation. Depending on the geographic location, driving dynamics, perception capabilities and presence of VRUs, each vehicle can transmit (and receive) one or more type of V2X messages (or their variants) listed in Table 4.1. The processing delays are indicated as $T_{proc,0}$ and $T_{proc,1}$. The lengths of $T_{proc,0}$ and $T_{proc,1}$ depend on the chosen subcarrier spacing (SCS) [45]. It can be observed in Figure 4.5a that based on the slots in which vehicle A receives messages from the neighboring vehicles B and C, it reserves resources for future transmissions according to the SB-SPS mechanism formulated in Equation 3.2. Suppose it fails to transmit in one of the intended future slots (e.g., situations where a vehicle is stationary or did not perceive any new objects etc.), the allocated resources go non-utilized for vehicle A (indicated in orange color in Figure 4.5a) and blocked for vehicles B and C as shown in Figure 4.5b and Figure 4.5c respectively. In high vehicular density scenarios where several neighboring vehicles are transmitting aperiodic messages with varying data sizes (similar to the type C data traffic model), it leads to an increased blocking in the selection windows thereby rendering only fewer options for resource selections.

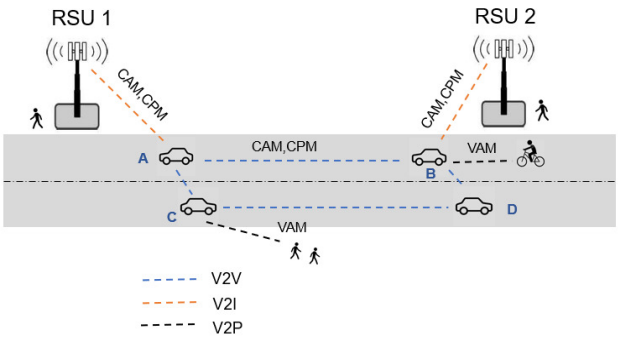
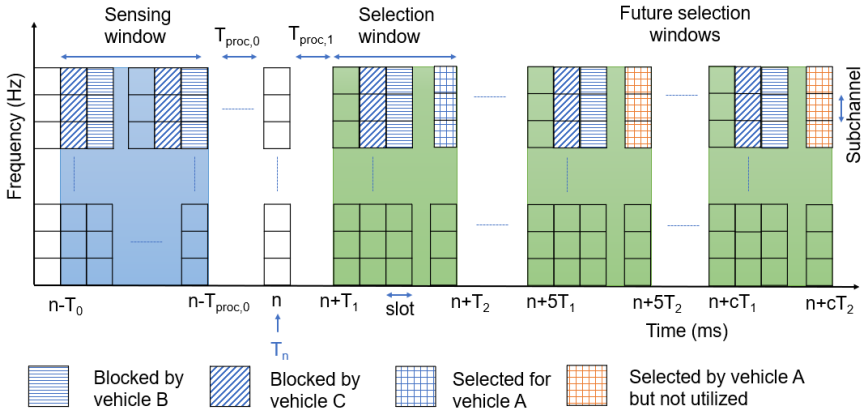
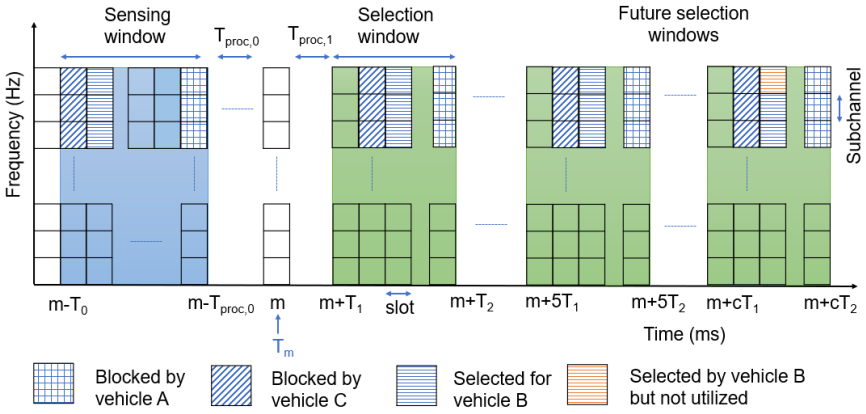


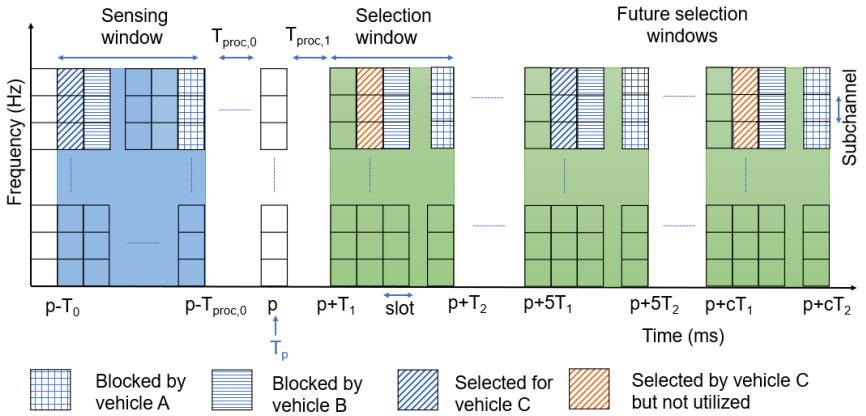
Figure 4.4 – V2X application scenarios in a dense urban environment.



(a) Resource allocation: Vehicle A



(b) Resource allocation: Vehicle B



(c) Resource allocation: Vehicle C

Figure 4.5 – Illustration of radio resource blocking for vehicles that operate in the unmanaged mode.

4.3.2.2 Probability of Resource Collision (PRC)

When more than one UE selects the same set of subchannels k (where $k \in K$) and the slot m (where $m \in M$) for its transmission, we refer to it as radio resource collision. Three sources of resource collisions can be identified from our simulations: *(i)* Extent of overlapping in selection windows of different vehicles, *(ii)* Insufficient or no sensing, and *(iii)* Grant breaks and resource blocking by aperiodic traffic.

Extent of selection window overlap

When the message IATs for different vehicles are less than 1 RRI apart, it leads to greater extent of overlapping in their corresponding selection windows. It is particularly observed under high vehicular density scenarios where several vehicles are transmitting at closely spaced time intervals. This type of collision is prevalent in all the three types of V2X data traffic models A, B and C (illustrated in Figure 4.2). One intuitive way to reduce this type of collision is that based on the application requirements and chosen data traffic model, vehicles intelligently choose their RRI and *cResel* value such that the extent of overlap can be relatively reduced if not completely avoidable. In a road traffic environment consisting of a total of N vehicles, there exist L neighboring vehicles to the ego vehicle i within the sidelink broadcast range (here $L \in N$). The extent of overlap of selection window ($S_{i,n}$) for the vehicle i with n (here $n \in L$) neighboring vehicles in the system can be represented as:

$$S_{i,n} = \begin{pmatrix} 0 & S_1 \cap S_j & \cdots & S_1 \cap S_n \\ \vdots & \vdots & \ddots & \vdots \\ S_i \cap S_1 & S_i \cap S_j & \cdots & S_i \cap S_n \\ \vdots & \vdots & \ddots & \vdots \\ S_n \cap S_1 & S_n \cap S_j & \cdots & 0 \end{pmatrix} \tag{4.2}$$

The collision probability Z_{ij} that any two vehicles i and j choose the same set of k subchannels present in e_{ij} overlapping slots (radio resource pool consisting of a total of K subchannels and M number of time slots within a selection window T_{sel}) is calculated as,

$$Z_{ij} = Z_{ji} = \sum_{p=1}^{ke_{ij}} \frac{pe_{ij}}{(KT_{Sel})^2} \tag{4.3}$$

Here, p refers to the subchannel index from $1, 2, \cdots k$ where $k \in K$. Utilizing Equation 4.3, the average probability that vehicle i and n other vehicles have overlapping selection windows can be calculated as:

$$\bar{Z}_i = \sum_{j=1}^{n} \frac{S_{ij}}{n(KT_{Sel})^2} \tag{4.4}$$

Equation 4.4 indicates that the average PRC measured among n vehicles directly depends on the extent of overlap in their selection windows.

Insufficient sensing

There are two situations when proper sensing fails: *(i)* When vehicles enter the simulation for the first time, their sensing window does not contain sufficient information about the resource utilization of other neighbouring vehicles. Hence the new vehicles tend to choose the same radio resources which are selected by other existing vehicles. Unfortunately in the current specifications of the managed and the unmanaged modes in 5G-NR V2X [45], there exist no mechanism for the vehicles to announce or interact with other vehicles in order to select the radio resources. *(ii)* The half-duplex constraint of the radio does not allow a vehicle to transmit and receive simultaneously in the same slot. For example, when the number of receptions per vehicle is high, it results in larger blocking of resources in the corresponding selection window(s). Also it is to be noted that the vehicle cannot sense those slots which are blocked for the reception of messages.

Grant breaks & resource blocking by aperiodic traffic.

In both the sidelink resource allocation modes, the resources are always pre-allocated for a certain number of future transmissions. When the nature of traffic is aperiodic and non-deterministic (such as the type C data traffic model shown in Figure 4.2c), the pre-allocated resources in the grant cannot be utilized and hence resource re-allocations have to be made. When such re-allocations happen frequently, it creates unpredictable blocking of resources for the neighbouring vehicles leading to misinformed resource allocation decisions as illustrated in Figure 4.5.

4.3.2.3 Transmission Success Ratio (TSR)

A ratio of the number of successful transmissions of a message to the total number of messages generated per sidelink grant is referred to as Transmission Success Ratio (TSR). When a vehicle is able to utilize the allocated radio resource(s) and successfully transmit all the generated messages within the grant period, it records the best value of TSR close to 1.0.

4.3.2.4 Probability of reception

The reliability of the sidelink broadcast communication link is measured in terms of probability of reception, P_R. From simulations, it can be measured as the ratio between the number of messages successfully received by the recipients (one or more) to the total number of messages sent by a transmitter UE (can be a vehicle, RSU or VRU). Considering a dynamically changing V2X sidelink broadcast communication network, the probability that a vehicle i receives messages transmitted by L neighboring vehicles

is calculated as:

$$P_R^i = \frac{1}{L}\sum_{j=1}^{L}\{\gamma_t^{jj} \geq \gamma^{th}\} \tag{4.5}$$

Here, $L \in N$, where N represents the total number of vehicles in the simulation. The component γ_t^{jj} is the received Signal-to-Interference Noise Ratio (SINR) at time t for a vehicle j, which is computed according to the formula:

$$\gamma_t^{jj} = \frac{P|H_t^{ij}|^2}{\sigma_l^2 + \sum_{l\in L} P|H_t^l|^2} \tag{4.6}$$

where H_t^{ij} represent the channel gain between the vehicles i and j at time instant t. The interference channel gain between l colliding neighboring vehicles with the ego vehicle i is represented as H_t^l and the noise component is given by σ_l.

The P_R at the receiving UE is impacted by the following factors: *(i)* Channel characteristics that cause stochastic bit errors - e.g., when there exists tall buildings/trees and other obstacles that lead to poor channel characteristics. *(ii)* Availability of sufficient radio resources at the receiving UE in order to successfully receive the messages within the latency requirements - here we refer to all the problems related with radio resource allocation (grant breaks, resource collisions) and also half duplex constraints. Therefore, in order to achieve reliability in a sidelink communication network, it is extremely important to address the resource allocation related challenges to ensure that messages are transmitted and received within the permissible latency limits.

4.4 Result analysis

The simulation results discussed in this section provide insights about the performance efficiency of the sidelink resource allocation modes with regard to the metrics formulated in Section 4.3.2. It is to be considered that the managed and the unmanaged modes are simulated separately in the `Artery-C` framework without enabling the mode switching option. Separate discussions about the performance of the metrics in each of the modes are presented in order to have a comparative assessment of their behavior and robustness under different parameter settings of the V2X data traffic and vehicular densities.

4.4.1 Radio Resource Utilization (RRU)

Managed mode

The CG type II algorithm in the managed mode is extremely efficient in achieving an RRU in the range between $90-96\%$ (at a confidence level of 98%) for the type A data traffic model under low, medium and high vehicular density conditions. Also for this

data traffic model, the performance of the SB-SPS algorithm is comparable to that of CG type II as observed in Figure 4.6a.

In Figure 4.6b, it can be inferred that the CG type II algorithm achieves a better RRU than the SB-SPS for all the three types of vehicular density conditions. In the CG type II algorithm, although the radio resources are allocated for future use within a sidelink grant, the gNB activates only a subset of these resources based on the V2X data traffic requirements. This way, when some extent of periodicity is observed in the V2X data traffic and the data sizes do not get larger than the allocated radio resources, the gNB is able to balance the allocation and re-distribute the non-utilized resources with other connected users.

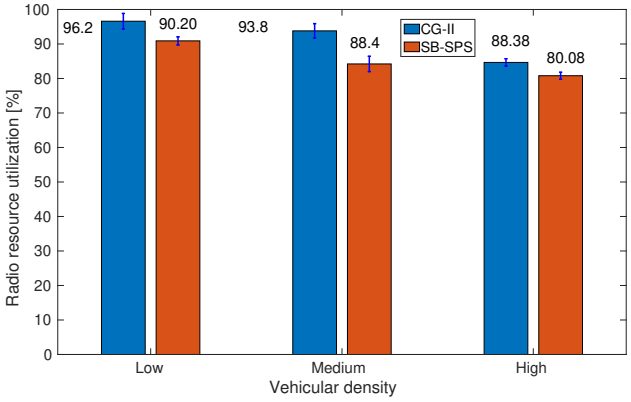
The RRU performance of the CG type II algorithm starts to worsen when the nature of the V2X data traffic is aperiodic with dynamically varying data sizes. When the allocated radio resources are not sufficient to accommodate the data sizes, new radio resources need to be allocated by breaking the previously configured sidelink grant. This results in poor RRU values lower than 25% as shown in Figure 4.6c. One of the options for the gNB is to switch to dynamic scheduling where radio resources are allocated for each message. Although this can potentially improve the RRU, it causes considerable amount of signalling overhead to make new allocations for each message.

Unmanaged mode

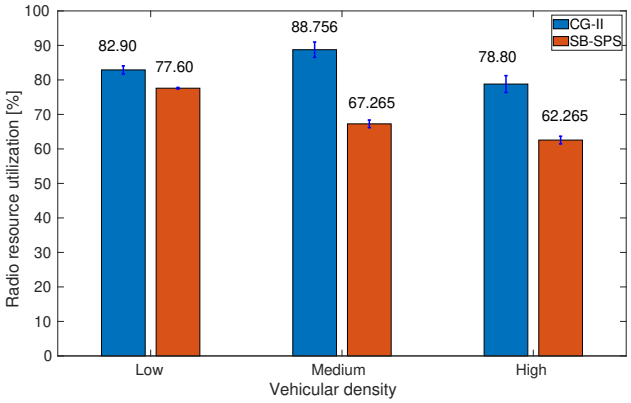
The SB-SPS algorithm in the unmanaged mode achieves nearly same RRU performance as that of the CG type II in the managed mode for type A data traffic model as shown in Figure 4.6a. In these situations the SB-SPS is very efficient which makes it an ideal choice for safety-critical applications that demand low End-to-End (E2E) latency requirements. The only reason for non-utilization of radio resources is due to half duplex constraints when a vehicle has to receive a message in the same slot that it intends to transmit.

For the type B data traffic model shown in Figure 4.6b, the SB-SPS algorithm manages to achieve RRU values close to 77%, 67% and 62% (at a confidence level of about 98%) for low, medium and high vehicular density conditions, respectively. When the V2X data traffic follows a periodic pattern displaying some variations in the data sizes, there is no need for re-allocation as long as the data sizes can fit into the previously allocated radio resources. Only when the data sizes get larger (e.g., due to inclusion of more number of objects in the Perceived Object Container (POC) of the CPM or large number of VRUs gathering up in crowds and sending VAMs), a re-allocation needs to be performed by breaking the configured sidelink grant.

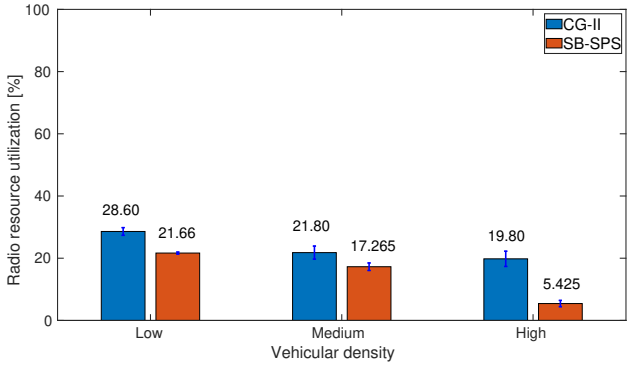
When the nature of the V2X data traffic becomes largely aperiodic with non-deterministic data sizes as that of the type C data traffic model, the performance of the SB-SPS algorithm degrades severely where the RRU is measured below 25% for



(a) RRU: Type A data traffic model



(b) RRU: Type B data traffic model



(c) RRU: Type C data traffic model

Figure 4.6 – Comparison of RRU measurements for sidelink modes.

all the three types of vehicular density conditions as shown in Figure 4.6c. The allocated sidelink grants need to be frequently broken in order to perform re-allocations for nearly every message due to their diverse generation rules and triggering conditions (as discussed in Section 2.1.3 and listed in Table 4.1).

4.4.2 Probability of Resource Collision (PRC)

Managed mode

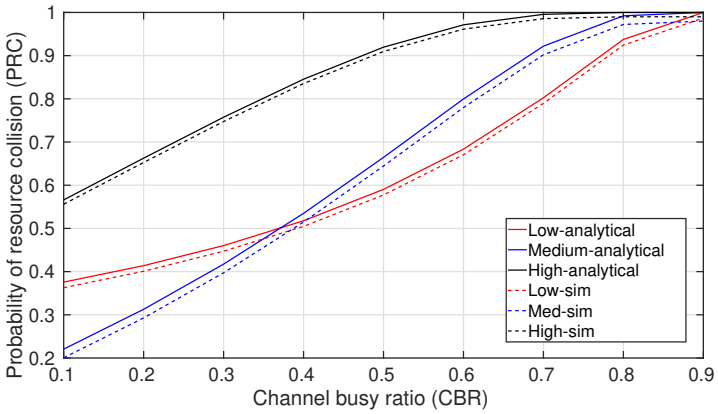
In the managed mode, the average PRC values under low and medium vehicular density conditions are lower than 0.2 for all the three types of V2X data traffic models. Under high vehicular density conditions, the type A and B data traffic models still manage to keep the PRC as low as 0.2. For the type C data traffic model the average values of PRC are measured in the range between $0.30 - 0.35$ under high vehicular density conditions.

The significantly low values of PRC in the managed mode is attributed to the fact that the gNB is completely aware of the resources utilized by all its connected users. The only reason for radio resource collision occurs due to half duplex constraints - for example, when a scheduled transmission overlaps with an unexpected reception of a message sent by another neighboring vehicle in an aperiodic manner. Owing to the consistency in the measured values of PRC for all the vehicular density conditions (i.e., low, medium and high) as well as the V2X data traffic models (i.e., A, B and C), we have not illustrated the corresponding graphs for the managed mode.

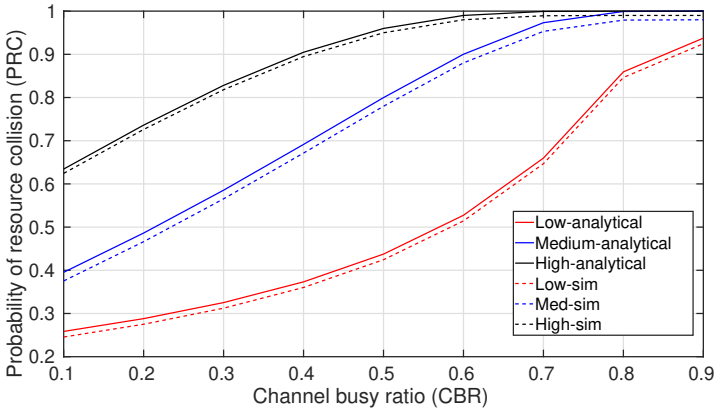
Unmanaged mode

When all the vehicles are transmitting only periodic messages with deterministic data sizes (similar to the type A data traffic model in Figure 4.2), the average PRC measured per vehicle is consistently lower than 0.40 even when the measured CBR exceeds 0.65. At lower CBR values, the average PRC values are lower than 0.20. Radio resource collisions are reported only in the situations when new vehicles enter the road or when the *cResel* value for multiple vehicles reach zero at the same time.

When we vary the parameters of the V2X messaging protocols listed in Table 4.1 to generate diverse V2X data traffic patterns (similar to the type B and C models in Figure 4.2), the reported average PRC measurements lie in the range between $0.60 - 0.70$ for a CBR of about 0.65 under low vehicular density conditions (as illustrated in Figure 4.7a and Figure 4.7b, respectively). As the vehicular density increases from medium-to-high, there is a higher number of vehicles transmitting V2X messages at closely spaced IATs. In addition to an increase in the extent of selection window overlap, the new vehicles also do not contain sufficient information in their sensing windows. Hence, there is a greater probability of two or more vehicles selecting the same radio resource. In a high vehicular density environment with vehicles reporting



(a) PRC: Type B data traffic model



(b) PRC: Type C data traffic model

Figure 4.7 – Comparison of PRC measurements for data traffic models.

higher values of CBR (above 0.65), the PRC measurements for type B and type C models (refer to Figure 4.7a and Figure 4.7b) are reported to be higher than 0.8 which greatly affects the chances of successful transmission. The frequent grant breaks caused by aperiodic data traffic (as in case of type C data traffic model), leads to several misinformed resource allocation decisions and unnecassary blocking of radio resources for neighboring vehicles. This results in fewer options for resource selections within the selection windows thereby increasing the risks for potential radio resource collisions.

The studies in [24, 69] recommend the sharing of the *cResel* values among vehicles to provide advance information about the radio resource selections. The results have proven that these enhancements are able to partially resolve the extent of PRC when all vehicles are transmitting periodic data traffic with deterministic data sizes. However, in the events of aperiodic data traffic (following type B or C data traffic models) observed in our simulations, it results in several vehicles frequently performing re-allocations

and updating their *cResel* values to the neighboring vehicles. The SB-SPS algorithm does not allow for re-allocations once a resource has been selected for a certain sidelink grant period. When the vehicles receive several updates of the *cResel* values from the neighboring vehicles, they cannot change their allocation decisions until the sidelink grant period has expired. Therefore, the suggested methodology in [24, 69] could not completely resolve the problem of radio resource collisions when the nature of V2X data traffic is aperiodic with variable data sizes.

4.4.3 Transmission Success Ratio (TSR)

Following the results from the RRU and PRC measurements, we obtain statistics about the number of successful transmissions per sidelink grant from the simulations. Here we present the selected results from a high vehicular density scenario where all the observations such as grant breaking, wastage, radio resource collisions and frequent re-allocations are significant. With reference to the TSR measurements in Table 4.5, the CG type II algorithm in the managed mode achieves TSR in the range between $0.85 - 0.95$ for type A and type B data traffic models.

Table 4.5 – Comparison of TSR measurements for the sidelink modes.

Mode	Type A	Type B	Type C
Managed	0.95 - 0.98	0.85 - 0.89	0.5-0-.6
Unmanaged	0.91 - 0.96	0.62 - 0.75	<0.4

For the type A traffic model, the SB-SPS algorithm in the unmanaged mode achieves nearly same TSR as that of CG type II algorithm in the managed mode. In case of the type B and C data traffic models, the lower values of the TSR resonate with the RRU and PRC measurements which prevent the successful transmission of a messages utilizing the radio resources configured within a sidelink grant period. It is to be noted that performing frequent re-allocations as a result of grant breaks renders the previously allocated radio resources not useful for transmitting the V2X messages. The poor values of the TSR (lower than 0.4) especially in case of the type C data traffic model indicate that the unmanaged mode cannot perform to its best efficiency when the V2X data traffic pattern is unpredictable. Also, the managed mode is not entirely robust in handling aperiodic data traffic (type C data traffic model) as observed from the TSR measurements in Table 4.5.

4.4.4 Probability of reception

The probability of reception metric has been previously studied for highway and urban road traffic environments in our publications [59, 60]. In this chapter, this metric is analyzed within the context of a dense urban road traffic environment (refer to Sec-

tion 4.3.1) by suitably varying the two conditions: *(i)* V2X data traffic model type and *(ii)* Distance between transmitter and receiver.

The effect of the changing V2X data traffic patterns contribute to additional latency in radio resource allocation thereby impacting the transmission and reception of V2X messages. Stochastic bit errors resulting from the time-varying channel conditions increase when the transmitter and receiver are further apart from each other. Dense urban environments are typically Non Line of Sight (NLOS), hence the attenuation due to the presence of a large number of obstacles such as buildings, bridges, trees and other tall vehicles such as trucks & buses degrades the quality of the received signal strength. While keeping the focus on the V2V and V2P links, the results in Figure 4.8 compare the P_R performance for both the CG type II and the SB-SPS algorithms under varying data traffic patterns discussed in Section 4.2.

Managed mode

In the managed mode, there exists two types of communication links: *(i)* Between vehicles and the base station to request and obtain the radio resources, and *(ii)* Between one or more vehicles (RSUs and VRUs) where V2X messages are exchanged. When the vehicles are driving in the region near cell borders or experiencing handovers between base stations, the main factor contributing to reduction in the P_R values is the inter-cell interference. When users in neighbouring cells attempt to simultaneously use the same radio resources, it results in inter-cell interference. This is caused by the limitation that the gNBs optimize the resource allocation for the UEs in their cell and are not informed about the allocation in neighbouring cells, which can be specifically harmful for UEs located at the cell borders. It is to be noted that the inter-cell interference is particularly higher in a densely crowded urban environment where vehicles move between different types of cell sites. In order to achieve higher values of P_R in the managed mode of the Cellular V2X, it is beneficial to incorporate the inter-cell interference (ICIC) coordination mechanism.

Interpreting the results in Figure 4.8, it was observed that when a large number of vehicles are sending aperiodic V2X data traffic in adjacent cell sites, it becomes difficult for the gNBs to optimize the radio resource allocations without coordinating with the neighboring gNBs. Hence, without ICIC, the measured values of P_R in Figure 4.8 falls slightly below 0.8 for all the three types of data traffic models when the transmitter and the receiver are apart by a distance of $1,000$ meters.

Unmanaged mode

In addition to the interference contributed by the multipath propagation conditions, two more components need to be considered for the vehicles operating in the unmanaged mode - Co-channel interference and Adjacent Channel Interference (ACI). Both effects

are prominent in the unmanaged mode because the UEs are unaware of the slots chosen by the neighboring UEs for their transmissions.

As studied in one of our previous publications [58], co-channel interference shows up during radio resource collisions. When one or more vehicles located close to each other are transmitting (or receiving) in the same slot, it results in co-channel interference. Since the PRC values for the type C data traffic model as observed in Figure 4.7b are higher than 0.7, these slots are more prone to co-channel interference.

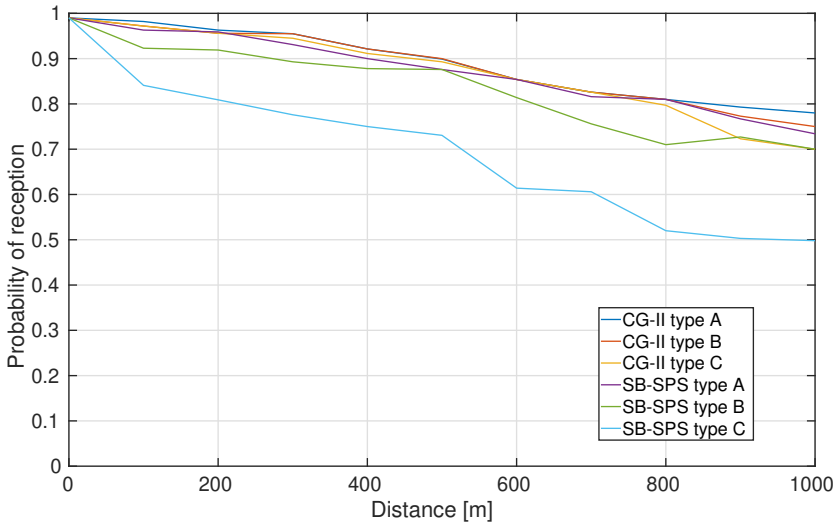


Figure 4.8 – Comparison of P_R measurements for the sidelink modes in a dense urban road traffic environment.

ACI occurs when neighboring vehicles are transmitting in adjacent frequency slots with a higher transmit power than the ego vehicle. Whenever a transmitting UE (i.e., a vehicle, RSU or VRU) is far away from the intended receiving UE and the interfering UEs are in close proximity, the ACI effect becomes more significant.

In case of the type A traffic model where the vehicles are transmitting only periodic traffic and are able to achieve adequate sensing, the P_R measurements are closer to the managed mode because of the less chances for co-channel interference. The only contributing factor for the reduction in P_R is the stochastic bit error caused by the time-varying channel conditions as the distance between the transmitting and the receiving UE increases.

In the type B and type C data traffic models, the chances of radio resource collision are high thereby leading to an increase in co-channel interference and also the ACI. Subsequently, it results in the degradation of the measured P_R values even at shorter distances between the transmitter and receiver. At a distance of $200 - 400$ m, the performance of the SB-SPS algorithm in the unmanaged mode is still lower than the

managed mode where the measured P_R lies in the range between $0.8 - 0.9$ for the type B data traffic model and between $0.75 - 0.8$ for the type C data traffic model.

At larger distances of $800 - 1{,}000$ m, the vehicles experience P_R values in the range of $0.6 - 0.7$ for the type B data traffic model and between $0.48 - 0.65$ for the type C data traffic model. In addition to co-channel interference and the ACI, the channel propagation conditions in a dense urban environment result in higher stochastic bit error rates.

4.5 Summary

This chapter quantitatively examined the challenges of the sidelink resource allocation modes in dynamically changing Cellular V2X environments. Three broad categories of V2X data traffic models were formulated by considering the periodicity and data sizes contributed by different V2X messaging protocols (e.g., CAM, CPM, DENM and VAM). Analytical expressions to calculate the metrics such as radio resource utilization, probability of resource collision, and probability of message reception have been derived and also measured by means of simulations.

The performance evaluation results indicate that both the sidelink resource allocation modes perform very efficiently when the nature of the data traffic exhibits some extent of periodicity. They achieve a radio resource utilization greater than 90% and a transmission success ratio close to 100%. Also very minimal resource collisions are reported.

When the V2X data traffic is aperiodic with variable data sizes, the performance of the SB-SPS algorithm degrades significantly. The evaluation results indicate poor resource utilization (less than 25%) under low vehicular density conditions and frequent grant breaks under high vehicular density conditions. These effects lead to unnecessary blocking of radio resources for the neighboring vehicles with an increased risk of resource collision between two or more vehicles. On the other hand, the managed mode handles the resource collisions in a better manner through explicit coordination by the base station. We also analyze the types of interferences that impact the communication link reliability in both sidelink modes of operation.

Although the managed mode performs better in all evaluations presented in this chapter, it cannot always be the default choice of operation. A vehicle cannot remain connected to the base station throughout its journey and therefore it is important to consider the improvements needed for the unmanaged mode so that it can become equally efficient. To derive the qualitative benefits of both sidelink modes and the cellular mode, it is important to investigate the criteria for appropriate mode selection and develop mechanisms for switching between the modes in different Cellular V2X scenarios.

Chapter 5

Mode switching in Cellular V2X

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Safety and traffic efficiency applications rely on a periodic exchange of messages with low latency requirements; e.g., typical values for the maximum latency are 100 ms for forward collision warning and $10-25$ ms for high-density platooning [1, 3, 48]. These values can be achieved in either the managed or the unmanaged mode of Cellular V2X. However, the managed mode may not always be available due to insufficient base station coverage (e.g., in rural outdoor, tunnels), low signal reception, or inaccessible network infrastructure (e.g., network overload, disaster). In such cases, a vehicle needs to choose the unmanaged mode.

In order to support continuous transmission and reception of messages, a vehicle should be able to select the best mode (one of the sidelink modes or the cellular mode) in its current situation and dynamically switch to any other appropriate mode when required. Mode switching invokes procedures for synchronization, resource allocation & scheduling, during which a vehicle is not able to send or receive messages. At the application, it is seen as longer message latency and message loss. Mode switching is unavoidable but should affect the communication as little as possible. In this chapter, we elaborate on the technical aspects involved in a mode switch procedure, the resulting overheads in terms of longer latencies and investigate if it is a viable option to switch the mode in case radio resources are not available in a particular mode. Further, we also provide a discussion about the feasibility of mode switching in the real-world implementation.

5.1 Preliminaries

Initial scientific studies carried out in [50] analytically models the types of errors with the Sensing Based Semi Persistent Scheduling (SB-SPS) in the unmanaged mode of LTE V2X. The operational frequencies and the co-existence of sidelink with the cellular mode are discussed in 3GPP standardization [2]. ETSI also addresses the requirement to perform a mode switch operation between cellular and sidelink modes as discussed in [5]. From both research and practical perspectives, it is essential to understand the factors that affect a mode selection decision and the events that trigger a mode switching operation. To the best of our knowledge, none of the prior works provide any structured approach for mode switching so far. 3GPP standardization considers it as a possibility [2] but does not suggest any approaches.

Contributions

The decomposition of the mode switch procedure into subsequent phases as explained in Section 5.2.3 includes direct excerpts from two of our conference publications [58, 61]. The calculation of the mode switch latency metric in Section 5.4.2.1 is based on our conference publication [61]. The specific author contributions along with the copyright note for these publications are provided in Appendix C.

The main contributions in this chapter are as follows:

1. Analyze the factors that lead to a mode switch operation between the sidelink managed and the unmanaged modes and also between the sidelink (PC5) and the cellular (Uu) mode.
2. Decomposition of the mode switch procedure into subsequent phases and calculation of latency in each phase.
3. Evaluation under realistic road traffic environments.
4. Discussion of some practical perspectives in real-world deployment.

5.2 Possibilities for mode switching

Dynamic switching between the sidelink (PC5) modes or between the sidelink and the cellular (Uu) mode based on the changing cellular network conditions, V2X data traffic requirements and physical location of an User Equipment (UE) is known as mode switching. On a particular section of the road there can be UEs that operate in the managed mode, unmanaged mode or in the cellular mode. This is referred to as the mixed mode operation.

The 3GPP standards [2] address the concurrent operation between the cellular and the sidelink modes along with some conditions that allow for switching between them. The PC5 interface operates in the Intelligent Transport Systems (ITS) band, N_{47} and the Uu interface is set to operate in the N_{71} band. The possibilities for a mode switch include:

- Switching between sidelink and the cellular mode: Involves a mode switch between the 5G-NR V2X sidelink in the ITS band and cellular mode that operates in the Frequency Range (FR) 1 band (refer to Section 2.1.1).
- Switching between the sidelink modes: managed mode to unmanaged mode and vice-versa.

5.2.1 Switching between sidelink and cellular mode

The possibility for a simultaneous operation of the cellular and the sidelink modes in the FR1 frequency band is discussed in [2]. The standards propose two configurations:

1. Operation of the sidelink (PC5) modes in the N_{47} ITS spectrum and the cellular modes in the licensed N_{71} spectrum.
2. Operation of the sidelink (PC5) modes in the N_{38} spectrum and the cellular mode in the licensed N_{38} spectrum – currently not operational in the EU until 2025 [2].

In configuration 1, the sidelink modes can be operated for safety-critical applications with low latency and data rate requirements whereas the cellular mode can be operated for high data rate and non-safety critical applications. The studies carried out by Albonda and Romero in [8] propose an efficient strategy to perform mode selection in a way that improves the radio resource utilization in Cellular V2X communication networks.

5.2.2 Switching between sidelink modes

In a continuously changing network scenario, a vehicle selects an appropriate resource allocation mode based on the link quality parameters such as received signal strength, traffic load etc. Studies carried out in [58] investigate possible strategies and situations to perform switching between the sidelink managed mode and the unmanaged mode.

- Switching from managed mode to unmanaged mode: When a vehicle moves away from the region of cellular network coverage (e.g., tunnels), it becomes important that it operates in the unmanaged mode. This leads to a situation of forced mode switching.
- Switching from unmanaged mode to managed mode: When cellular network coverage is available, it becomes beneficial for the vehicle to switch to the managed mode in the sense that gNB manages the radio resource allocation process by taking into consideration channel state information, Signal-to-Interference Noise Ratio (SINR) and V2X data traffic load. If needed, it can even decide to re-use the resources between uplink and sidelink.

The event of a mode switch can lead to extra delays based on the establishment of connection with a nearby base station, allocation of radio resources and obtaining time synchronization. These latencies eventually affect the probability of message reception thereby affecting the reliability of the communication link.

5.2.3 Mode switching phases

In order to understand the latency involved in a mode switch procedure, we decompose a mode switch event into subsequent phases as shown in Figure 5.1. The calculations of

the latencies in each of the phase namely, T_{Det}, T_{Syn}, T_{RA} and T_{SL} are further explained in Section 5.4.2.1.

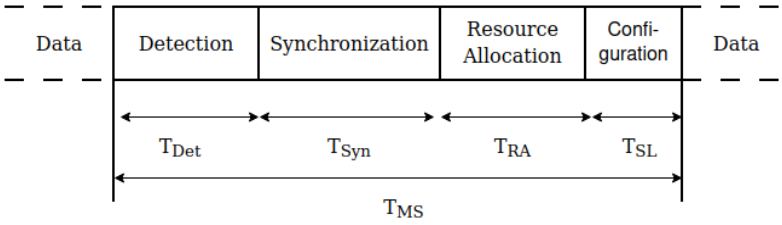


Figure 5.1 – Mode switching phases.

Detection: This phase corresponds to the establishment of the connection with a nearby base station and acquisition of System Information (SI). This SI can be either related to the operation in the cellular mode or in the sidelink managed mode. Separate formats of the Master Information Block (MIB) and System Information Block (SIB) are defined in the ETSI specifications for both cellular and sidelink modes.

Synchronization: When multiple UEs want to communicate with each other, it is important to obtain precise timing alignment between them. In most cases, it happens by means of an onboard Global Navigation Satellite System (GNSS) of the vehicle (or a Road Side Unit (RSU)) or the internal clock of a base station. In special road scenarios like tunnels where GNSS is not available, the UEs inside the tunnels should get connected with some other UE (referred to as the *SyncRef* UE [45]) which is synchronized to a nearby base station.

Resource allocation: In this phase, the candidate radio resources are allocated for a UE for the transmission of V2X messages. When it operates in the sidelink managed or the cellular mode, the radio resources are allocated and scheduled by the base station. In the sidelink unmanaged mode, the UE autonomously configures its resources from a pre-allocated pool of radio resources.

Configuration: The configuration phase corresponds to the activation of the radio resource scheduling algorithm at the Medium Access Control (MAC) layer and the generation of the resource grant.

It is to be noted that the duration of the detection, synchronization and the resource allocation depends on the current mode of operation and the availability of the possible mode switching options. The configuration phase is fixed and set as equivalent upto four slots as defined in the LTE V2X standards [42].

5.3 Implementation

In our prior work [58], we have studied the possibilities for a mode switching between the sidelink modes where three strategies have been formulated. In this section, we explain the events that trigger a mode switching between different modes (i.e., sidelink and cellular) and the appropriate strategies to be deployed in each case. The influencing factors identified here are: availability of network coverage, SINR conditions and V2X data traffic load. These three factors are considered as the input parameters (in Table 5.1) which drive the Finite State Machine (FSM) inside the mode switching control module of the Cellular V2X protocol stack. In principle several combinations of inputs and outputs are possible, but taking into account that the RRC can reside in only one state at a given instant of time, we limit ourselves to the state transitions depicted in Figure 5.2.

Table 5.1 – Mode switching control: input parameters.

Parameter	**Values**
Network coverage (N)	0 or 1
SINR (S)	Low (L), medium (M), high (H) or don't care (x)
Data traffic load (D)	0, low (L), medium (M), high (H) or don't care (x)

In Table 5.1, the SINR inputs "low", "medium" and "high" correspond to the values: ≤ 0 dB, $0-20$ dB and ≥ 20 dB, respectively. When the network coverage is totally absent, the value of the SINR is not applicable (N.A.) to be considered. The data traffic load is characterized by the size of the transport block. The inputs "low", "medium" and "high" correspond to $50-1,000$ bytes, $1,000-5,000$ bytes and order of megabytes, respectively.

The FSM of the mode switching control module comprises five discrete states as described in Table 5.2. The state transitions that are triggered within the mode switching control module are illustrated in Figure 5.2. The mode switching strategies associated with each of these state transitions are further listed in Table 5.3. A detailed description of the events and actions related to a state transition is included in Appendix B.

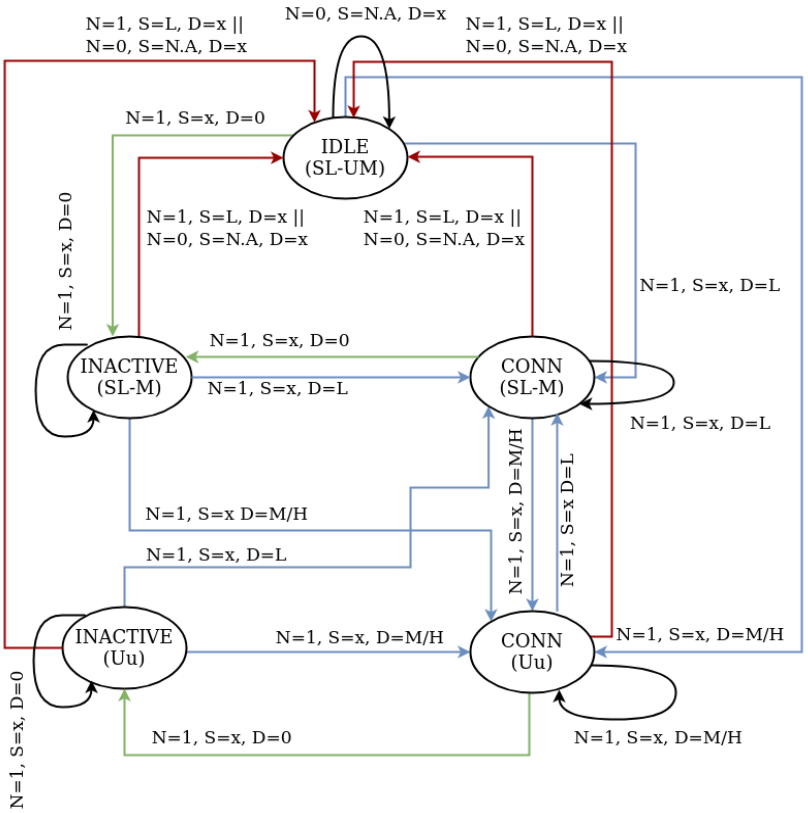


Figure 5.2 – Mode switching control: state transitions.

Table 5.2 – Mode switching control: state description.

State name	Description
IDLE(SL-UM)	RRC state is *IDLE* and UE operates in sidelink unmanaged mode
INA(SL-M)	RRC state is *INACTIVE* and UE operates in sidelink managed mode
INA(Uu)	RRC state is *INACTIVE* and UE operates in the cellular mode
CONN(SL-M)	RRC state is *CONN* and UE operates in the sidelink managed mode
CONN(Uu)	RRC state is *CONN* and UE operates in the cellular mode

Table 5.3 – Mode switching strategies.

Network	SINR	Data	Current	Strategy	Next
0	N.A	x	IDLE(SL-UM)	None	IDLE(SL-UM)
1	x	0	IDLE(SL-UM)	SINR	INA(SL-M)
1	x	L	IDLE(SL-UM)	Data	CONN(SL-M)
1	x	M/H	IDLE(SL-UM)	Data	CONN(Uu)
1	x	0	INA(SL-M)	None	INA(SL-M)
1	x	L	INA(SL-M)	Data	CONN(SL-M)
1	x	M/H	INA(SL-M)	Data	CONN(Uu)
1	L	x	INA(SL-M)	SINR	IDLE(SL-UM)
0	N.A	x	INA(SL-M)	Forced	IDLE(SL-UM)
1	x	L	CONN(SL-M)	None	CONN(SL-M)
1	x	0	CONN(SL-M)	Data	INA(SL-M)
1	x	M/H	CONN(SL-M)	Data	CONN(Uu)
1	L	x	CONN(SL-M)	SINR	IDLE(SL-UM)
0	N.A	x	CONN(SL-M)	Forced	IDLE(SL-UM)
1	x	0	INA(Uu)	None	INA(Uu)
1	x	L	INA(Uu)	Data	CONN(SL-M)
1	x	M/H	INA(Uu)	Data	CONN(Uu)
1	L	x	INA(Uu)	SINR	IDLE(SL-UM)
0	N.A	x	INA(Uu)	Forced	IDLE(SL-UM)
1	x	M/H	CONN(Uu)	None	CONN(Uu)
1	x	0	CONN(Uu)	Data	INA(Uu)
1	x	L	CONN(Uu)	Data	CONN(SL-M)
1	L	x	CONN(Uu)	SINR	IDLE(SL-UM)
0	N.A	x	CONN(Uu)	Forced	IDLE(SL-UM)

1. Forced mode switching: This strategy focuses on scenarios where there is a chance to operate in only one mode at a given time, i.e., sidelink (managed mode or the unmanaged mode) or the cellular mode. In Table 5.3, we can observe that when network coverage is not available, a UE is forced to operate in the unmanaged mode. It can switch to the managed mode or the cellular mode only after it has driven to an area where the network coverage is sufficiently available. Similarly, while operating in the cellular mode or the sidelink managed mode, if it loses the network coverage (for example, movement into a tunnel) then it has to switch to the sidelink unmanaged mode.

2. SINR based switching: The factors that contribute to the calculation of SINR in a typical Cellular V2X communication network are defined in Equation 3.8.

Whenever a transmitting UE is far away from the intended receiving UE and the interfering UEs are in close proximity, the ACI effect becomes more significant. Inter cell interference can be avoided by appropriately scheduling non-overlapping frequency resources in each time slot. The SINR varies in different regions depending on how close the UEs are located to the base station and the underlying multipath propagation conditions. The decision to switch from the managed to the unmanaged mode is done by evaluating the cost incurred as a result of weighted contributions of different interference parameters as calculated in Equation 3.8.

3. Data traffic load based switching: The mobility of the vehicles and other road users in various traffic condition events such as traffic jams, road accidents, construction activities, rush hour etc. affect the triggering rules of different V2X messaging protocols. This causes the V2X data traffic load to vary dynamically in a given Cellular V2X communication network. Operation in the cellular mode is preferable when the V2X data traffic load is relatively high. Considering the limited radio resource pool in the sidelink, it is more suited for safety-critical applications having low data size requirements.

5.4 Evaluation

To evaluate the feasibility of a mode switch procedure, we consider a highway-tunnel road traffic scenario with varying cellular network conditions and vehicular densities. The vehicles operate in the cellular mode and in the sidelink modes at different locations and instants of time. The impact of the mode switch procedure on the End-to-End (E2E) latency of a V2X application is studied by measuring the mode switch latency T_{MS} parameter for each of the vehicles in the simulations. In the next step, we also plot the probability of message reception P_R versus the T_{MS} values to analyze the extent of link reliability in the events of mode switch.

5.4.1 Simulation environment

The simulation environment is modeled as a highway-tunnel road traffic scenario that consists of regions with varying cellular network coverage conditions. It consists of two lanes with four regions labeled as R_1, R_2, R_3 and R_4. In Figure 5.3, it can be seen that regions R_1 and R_3 lie outside the coverage area of base stations and hence the vehicles should operate in the unmanaged mode. The regions R_2 and R_4 are covered by base stations (modeled as an urban macro cell) and hence a vehicle has the possibility to operate both in the cellular and the sidelink managed mode.

The simulation parameters related to the highway-tunnel road traffic scenario are listed in Table 5.4 and the corresponding Cellular V2X protocol stack related parameters are listed in Table 5.5. The vehicles in the simulation primarily transmit periodic CAMs

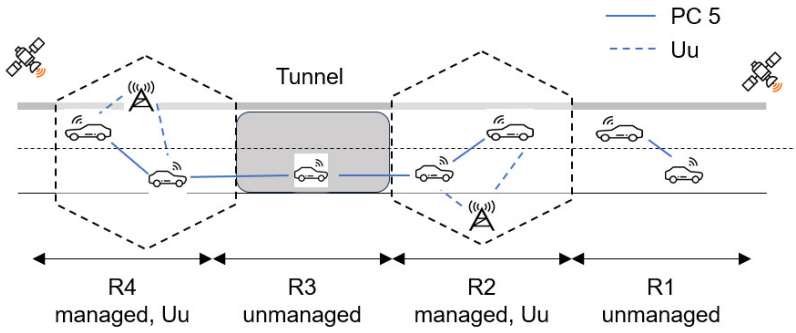


Figure 5.3 – Highway-tunnel scenario with intermittent gNB coverage and mode switching.

for 80% of the time with variable sizes in the range of 190 – 300 bytes and occasionally also transmit larger data sized messages whose sizes can range from several kilobytes to one megabyte for which it is more suitable to operate in the cellular mode.

Table 5.4 – Simulation parameters: Highway-tunnel road traffic scenario.

Parameter	**Road type**	
	Highway	Tunnel
Vehicle speed [km/h]	100 – 130	60 – 80
Inter-vehicle distance [m]	50	
Vehicle density [Veh/Km/lane]	45 (high), 30 (medium), 15 (low)	
Sidelink broadcast range [m]	500-800	80-150
Regions (Figure 5.3)	R_1, R_2, R_4	R_3
Types of vehicles allowed	Cars, buses and trucks	
Pedestrians/slow moving vehicles	No	

5.4.2 Metrics

In order to quantitatively understand the significance of performing a mode switch operation driven by different time varying conditions, we consider the following two metrics: *(i)* Mode switch latency T_{MS} and *(ii)* Probability of reception (P_R). The calculation of mode switch latency helps us to visualize the latencies in each phase of the mode switch procedure and decide whether a UE should switch to another mode or not. The probability of reception metric helps us to determine whether the communication link reliability can be guaranteed in the events of mode switching - for example, if the measured value of T_{MS} is very large, the vehicle may not be able to successfully transmit

Table 5.5 – Simulation parameters: Cellular V2X [45].

Parameter	Values
Protocol stack	5G-NR V2X
Frequency band [GHz]	5.9
Frame structure	FDD
Modulation scheme	QPSK
Channel model	WINNER II - D1 (highway, urban)
Number of subchannels (K)	2
Subchannel size	10
Slot length [ms]	1
Probability of resource keep	0.8
Operational modes	Managed, unmanaged & cellular
V2X messaging	Periodic CAM broadcast
Mode switching	Yes
Re-selection counter ($cResel$)	[5,15]
Selection window size (M) [ms]	[20,100]
RRI [ms]	100
Adjacency SCI+Data	Yes

(or receive) the intended message because the radio resource allocation has not yet taken place.

5.4.2.1 Mode switch latency

The mode switch latency corresponds to the sum of the latencies in each of the phase of the mode switch procedure. It is to be noted that not all phases shown in Figure 5.1 are relevant for each of the mode switch operation presented in Table 5.3. The calculation of the latencies in each phase of mode switching is formulated as follows:

Detection latency T_{Det}

It comprises the time it takes for a UE to detect cellular coverage, successfully establish the connection with a nearby base station and acquire the SI. Depending on when a UE first establishes a connection with the gNB, it has to wait for the subsequent cycle of the MIB/SIB broadcast to obtain the SI from the gNB. When a UE makes a transition from the *IDLE* to the *CONN* state, its identity and connection are freshly established with the gNB. Correspondingly, when a UE executes a transition from *INACTIVE* to *CONN* state, the detection latency is short because the UE's identity is already known to the gNB. The remaining task is to only exchange system related information.

Considering that the gNB transmits the MIB periodically, the UE experiences a uniform waiting period of $[0, T_w]$. On successfully decoding the MIB-SL, the UE requests the SIB from the gNB. The detection latency T_{Det} for the managed mode can be calculated as $T_{Det} = T_{SIB21} - T_{RRC_{CRQ}}$, i.e., the time interval between sending a

connection request to the gNB at $T_{RRC_{CRQ}}$ and receiving the reply at T_{SIB21}. In case of the sidelink unmanaged mode, the UE operates independently of the base station and hence calculation of T_{Det} is not relevant.

Synchronization latency T_{Syn}

The time it takes to obtain the timing alignment between the transmitting and receiving UEs is referred to as the synchronization latency. In the context of sidelink managed mode and the cellular mode, the UE synchronizes directly with the base station (gNB) by means of a simple Random Access Channel (RACH) procedure [42, 45] at the time of connection establishment. After obtaining the synchronization related information from the gNB, it transmits this to all other intended receivers. Hence, the delay incurred due to synchronization is minimal.

In the sidelink unmanaged mode, the UE can either obtain its timing from the GNSS or connect to another UE which is already synchronized to a base station. In either case, it generates periodic signalling information related to synchronization (in the form of Sidelink Primary Synchronization Signal (S-PSS) and Sidelink Secondary Synchronization Signal (S-SSS)) . Depending on when it intends to transmit data, it has to wait for the subsequent cycle of the synchronization signals which leads to inevitable delays. GNSS is the preferred mode of synchronization when available. When a UE depends on the *SyncRef* mechanism for synchronization, the value of T_{Syn} starts increasing.

Resource allocation latency T_{RA}

In Figure 5.4, we can observe that when the physical layer receives a new message frame at time T_M, the resource allocation starts at time T_1. The interval between the times $[T_1, T_M]$ can be in the range of $[0, 4]$ ms as specified in the standards [45]. The maximum allowed latency T_2 is defined by the higher layers depending on the type of application. The time difference between the start of first transmission T_S and the arrival time of the message frame T_M is referred to as resource allocation latency T_{RA}. With reference to Figure 5.4 it is calculated as, $T_{RA} = T_s - T_M$.

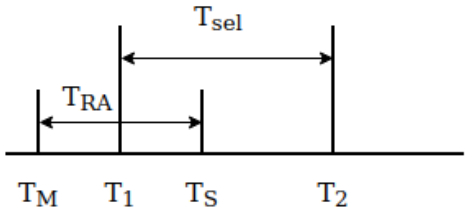


Figure 5.4 – Resource allocation latency [61],©2020, IEEE.

Dynamic scheduling in the cellular mode allocates new resources for every V2X message based on the message size and sending periodicity. For the CG type II and the SB-SPS algorithms in the sidelink, the maximum resource allocation latency depends on the following factors: *(i)* Selection window size based on the type of V2X application. *(ii)* Number of resource re-allocations in the events of aperiodic data traffic.

Configuration latency T_{SL}
The configuration latency is defined as the time taken for activation of CG type II or the SB-SPS at the MAC layer and generation of a sidelink grant. Since it is a system-related internal procedure, it can be as long as four slots (or 4 ms equivalent time) for both sidelink modes.

5.5 Result analysis

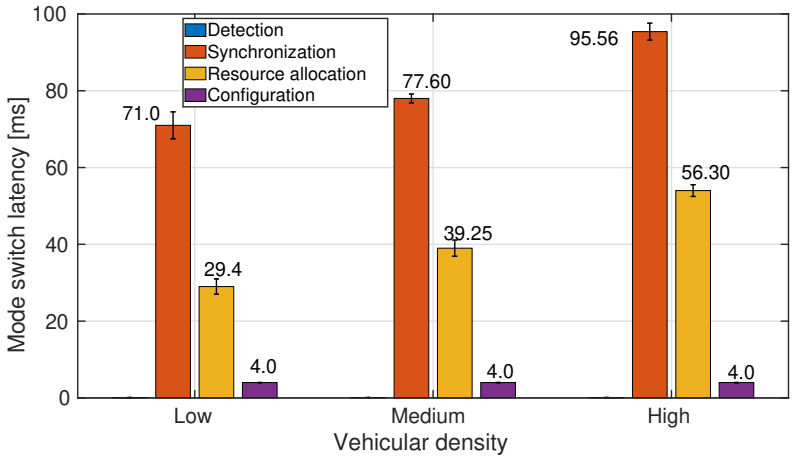
In this section, we discuss the mode switch latency measurements for the switching between the sidelink modes and also between the sidelink and the cellular mode for different vehicular density conditions specified in Table 5.4. To simplify the analysis, we consider that all the vehicles are broadcasting only periodic CAMs that resemble the type A data traffic model. We have selected the scenarios where the mode switch latencies are longer than the permissible delay budget and evaluate its impact on the reliability of the communication link. In situations where mode switching takes place seamlessly, we do not consider any additional evaluations.

5.5.1 Mode switch latency

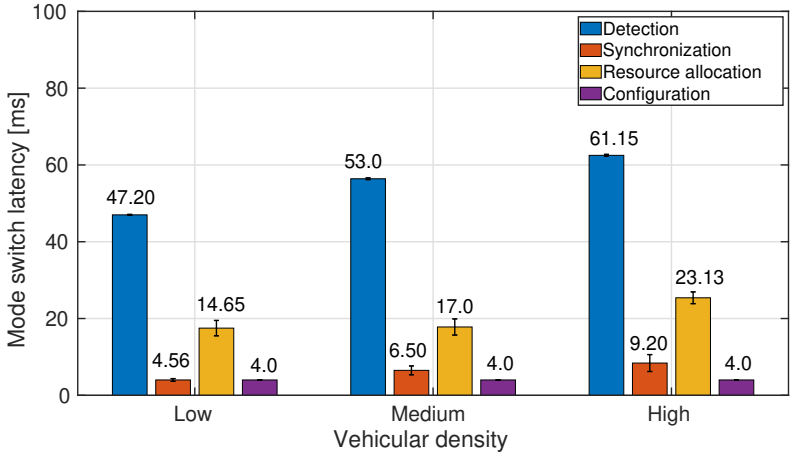
The graphs plotted in Figure 5.5 represent the mean latency measurements for each stage of the mode switch procedure when vehicles switch between the sidelink managed and the unmanaged modes. In Figure 5.5a, it can be observed that longer synchronization latencies are measured when vehicles switch to the unmanaged mode. Typically when vehicles leave the highway environment and enter the tunnel, GNSS is not available inside and hence the *SyncRef* mechanism should be adopted for time synchronization. The exchange of synchronization related signals results in waiting times of around $40 - 160$ ms (confidence $\geq 95\%$) for the vehicles. At higher vehicular densities, it can take as long as 160 ms which results in T_{MS} values to be larger than 200 ms. However when vehicles drive from region R_2 to R_1, the synchronization latencies are much shorter due to the availability of GNSS. The measured values of T_{MS} consistently ranges between $80 - 100$ ms for all three types of vehicular density conditions.

When a vehicle switches from the sidelink unmanaged mode to the managed mode as shown in Figure 5.5b, the values of T_{Det} lie in the range between $47 - 62$ ms (at a confidence level of 98%) across different vehicular densities. The synchronization

procedure is instantaneously handled by the base station and also the resource allocation latency is lower than the measurements in Figure 5.5a for all three types of vehicular density conditions.



(a) Managed to unmanaged mode: vehicles drive from regions R_2 and R_4 to R_1 or R_3.

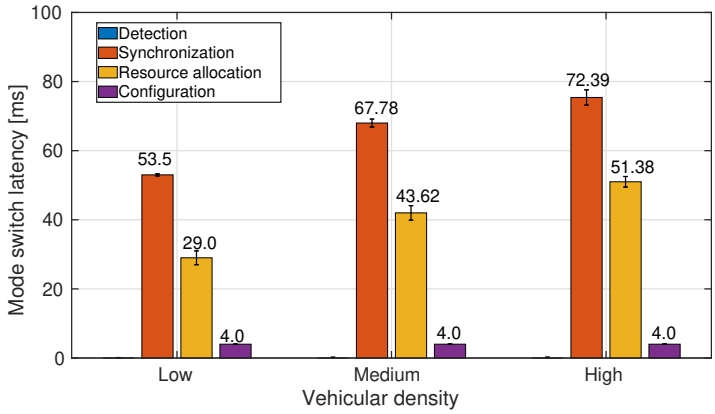


(b) Unmanaged to managed mode: vehicles drive from regions R_1 and R_3 to regions R_2 or R_4.

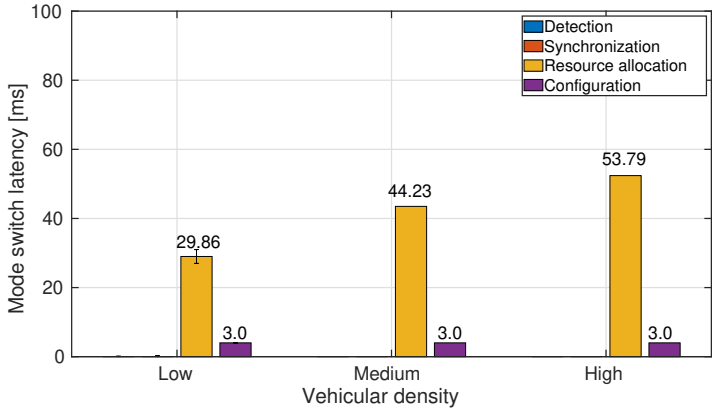
Figure 5.5 – Mode switching between sidelink modes: mean T_{MS} measurements.

When vehicles switch from the cellular mode to the sidelink unmanaged mode as shown in Figure 5.6a, the values for T_{MS} are similar to the measurements in Figure 5.5a. In some outlier scenarios, the T_{MS} values are as large as $250 - 350$ ms inside the tunnels.

The measurements in Figure 5.6b indicate that the switching procedure from the cellular mode to the sidelink managed mode is almost seamless in the sense that vehicles remain connected to the gNB and hence the values of T_{Det} and T_{Syn} are zero because these steps need not be initiated again. The measurement results for mode switching from



(a) Uu to unmanaged mode: vehicles drive from regions R_2 and R_4 to R_1 or R_3



(b) Uu to managed mode: vehicles are driving within the regions R_2 and R_4

Figure 5.6 – Mode switching between cellular and sidelink modes: mean T_{MS} measurements.

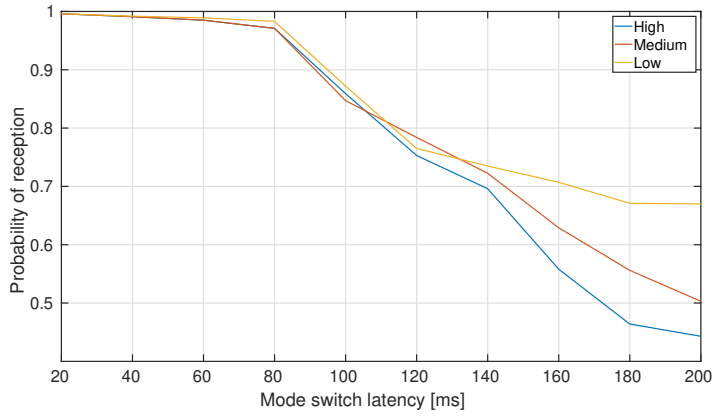
sidelink managed mode to the cellular mode are almost similar to the results obtained in Figure 5.6b. On switching from the sidelink unmanaged to the cellular mode, the measurement results are similar to the results obtained in Figure 5.5b. The similarity in the results are contributed to the fact that only type A traffic model is considered in this chapter. When detection and synchronization phases are successfully established, the values of T_{RA} are within the allowable latency limits and the gNB is capable of balancing the distribution of radio resources without causing any radio resource collisions.

Summarizing the observations from Figure 5.5 and Figure 5.6, it can be inferred that performing a mode switch between the cellular mode and sidelink managed mode is quite seamless with a total T_{MS} ranging between $30-55$ ms. The switching to the sidelink unmanaged mode (either from cellular (Uu) or the managed mode) incurs moderate T_{MS} ranging between $70-120$ ms (with a confidence level greater than 95%) for low-

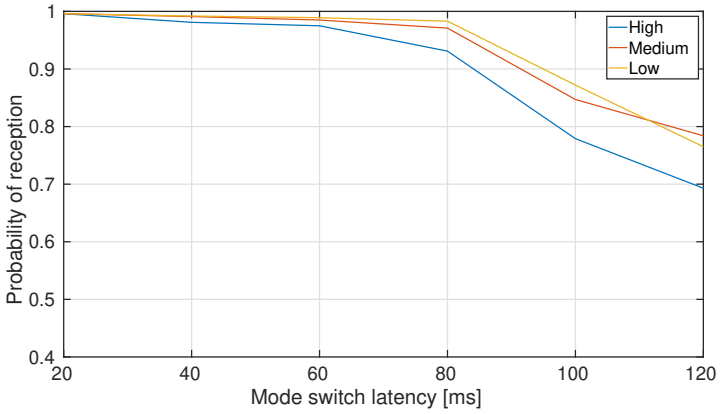
to-medium vehicular density conditions on an urban road which is still acceptable. However, under high vehicular density conditions and longer synchronization delays inside the tunnels, we have measured values of T_{MS} as large as $250 - 300$ ms which makes it challenging for safety-critical applications.

5.5.2 Probability of reception

By taking into account the mode switch latency results obtained for different scenarios in Figure 5.5 and Figure 5.6, we consider the calculation of the probability of message reception P_R under different mode switch latencies for two specific cases where the vehicles switch to the unmanaged mode (either from the cellular (Uu) or the sidelink managed mode): *(i)* Switching to sidelink unmanaged mode without GNSS availability and *(ii)* Switching to sidelink unmanaged mode with GNSS availability. Here again we consider three different vehicular density conditions namely, low, medium and high.



(a) Switching to unmanaged mode without GNSS



(b) Switching to unmanaged mode with GNSS

Figure 5.7 – P_R measurements with mode switching.

On switching from the cellular (Uu) to unmanaged mode as depicted in Figure 5.7a, it can be observed that P_R suffers at high vehicular densities when the mode switch latency is relatively high. In regions where GNSS is unavailable and a large number of vehicles are operating in the sidelink unmanaged mode, a sharp increase in T_{MS} is mainly due to longer synchronization latencies. A larger value of T_{MS} leads to delays in radio resource allocation because a vehicle cannot allocate radio resources in the new mode until the switching procedure is successfully completed. Hence vehicles are unable to transmit and receive a message during this period.

The P_R measurement results in Figure 5.7b indicate that when the vehicles switch to the unmanaged mode with GNSS availability, the resulting values of T_{MS} are much shorter in comparison to Figure 5.7a. Subsequently, the vehicles are able to achieve a higher P_R of above 0.8 even under high vehicular density conditions. This corresponds to situations in which the vehicles drive from region R_2 to R_1 as shown in Figure 5.3.

At low and medium vehicular densities and good availability of GNSS, the mode switching procedure does not significantly affect the message reception at the receiver much because the vehicle has obtained its radio resources within the maximum allowed latency limits. We regard this as successful message reception without any delay constraints. It can be observed that for low vehicle densities, even at a mode switch latency of $70-100$ ms, we are able to achieve a P_R value close to 0.9. Under larger mode switch latency conditions combined with high vehicular densities, it can be noticed in Figure 5.7b that P_R deteriorates below 0.5 which degrades the reliability of the communication link.

Comparing the results from Figure 5.7, we can see that at lower vehicular density conditions and fast switching intervals, it is possible to achieve a P_R up to 0.98 for all switching scenarios listed in Table 5.3. If switching to the unmanaged mode incurs larger mode switch latencies, it is beneficial for the vehicles to rather operate in the sidelink managed mode especially when they intend to transmit safety-critical V2X messages. Switching from the sidelink managed mode to the cellular mode is preferable when a vehicle intends to transmit information with larger data size requirements.

5.6 Practical considerations for deployment

The evaluation studies carried out in this chapter and in our previous works [58, 61] indicate the advantages and the different possibilities to perform a mode switching operation from the technology perspective. By taking into account the currently available Cellular V2X hardware, it is to be acknowledged that some of the challenges listed below need to be analyzed for real-world deployment:

- When a vehicle is located completely outside the region of cellular network coverage, it becomes mandatory to operate in the sidelink unmanaged mode. Switching to the sidelink managed mode or to cellular mode becomes feasible

only when it drives to a region where network coverage is available. Hence all the challenges of the radio resource allocation (as studied in Chapter 4) need to be addressed for the reliable operation in the sidelink unmanaged mode.

- From the radio resource allocation perspective, our results in this chapter and in our publication [61] have indicated that managed mode is preferable for operation when it is available. This is mainly because the base station has complete knowledge about its connected users and it is capable of optimizing the process of resource allocation. However, if vehicles have to stay connected to the base station and send fast periodic V2X messages like CAMs and CPMs it leads to additional subscription costs. Hence, the real-world deployment scenarios in our public funded project [67] consider the usage of sidelink modems that operate in the unmanaged mode independent of the cellular network infrastructure.

- Our simulation results have indicated that switching between sidelink and cellular mode depending on the data sizes and SINR conditions along with the QoS requirements (latency and reliability) of V2X messages helps to achieve a better balance in the utilization of radio resources. However, the practical challenges for such a switching procedure needs to be further evaluated in terms of subscription costs, radio resource utilization and relevant hardware support.

5.7 Summary

This chapter investigated in-depth the different possibilities for mode selection and switching where the procedure was decomposed into different phases. The latency at each phase of the mode switch procedure was calculated analytically and measured under different vehicular density conditions in a realistic network simulation. Other measurable parameters such as the mode switch latency and probability of reception were used to characterize the extent of reliability of the communication link in different mode switching events.

The sidelink unmanaged mode showed promising results in achieving short end-to-end latencies as studied in Chapter 4 and it is extremely beneficial for the UE to switch or remain in this mode when cellular network coverage is not available (or when the signal strength is in-sufficient). When cellular network coverage is sufficiently available, the results presented for the mode switch latency and probability of reception indicate that it is beneficial for the UE to switch to the sidelink managed mode for safety-critical V2X applications and the cellular mode for large data sized applications.

However, we still believe that it is important to consider the practical perspectives involved in the deployment of V2X hardware which support such switching operations. Therefore, a balanced approach is needed to adapt the strategies mentioned in this chapter to fit the requirements of the real-world Cellular V2X communication networks.

Chapter 6

Multi agent actor-critic based radio resource scheduler

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The diverse generation rules and triggering conditions of the V2X messaging protocols make it challenging for rule based radio resource scheduling algorithms in both the sidelink modes to perform to their best efficiency. The results of the evaluation studies in Chapter 4 have indicated that when the size and periodicity of the V2X messages vary, the Configured Grant (CG) type II and Sensing Based Semi Persistent Scheduling (SB-SPS) algorithms cannot efficiently adapt their parameters to reserve the radio resources for both current and future use. Particularly the SB-SPS algorithm in the unmanaged mode shows poor performance in terms of inefficient radio resource utilization and a greater probability of radio resource collisions between two or more vehicles. In such situations, it results in misinformed resource allocation decisions for the neighbouring vehicles in one or more subsequent slots resulting in unnecessary blocking of radio resources. This happens because the sensing window does not provide full information to the vehicles about the radio resource allocation decisions of other vehicles. Also, switching to the managed mode or the cellular (Uu) mode cannot happen instantaneously as discussed in Section 5.6. Our simulation studies in [59] have further shown that in high vehicular density conditions, the probability of reception is reduced to about 50% [61] thereby impacting the reliability of the communication link severely.

Due to several time varying factors such as geographical position of the vehicles, triggering rules for different V2X messages, safety critical situations and many more, it is not straightforward to implement a decision making strategy in the rule based radio resource allocation algorithms. The "Inter-UE-coordination message" proposed in the 3GPP standards [56] cannot be directly adopted to achieve a mutual interaction based radio resource allocation in Cellular V2X communication networks as discussed in Section 1.4. Hence, there is a strong motivation to investigate mechanisms that allow for independent exploration, learning and decision making capabilities for vehicles to allocate and schedule their radio resources independent of the cellular network infrastructure.

Reinforcement Learning (RL) techniques provide a mechanism for independent learning by means of interaction with the environment [109]. Some of the main advantages of applying RL techniques in wireless communications are: *(i)* Mathematical model of the environment is very hard to define (or does not exist) due to a large number of time varying factors. *(ii)* Difficulty in obtaining labelled data sets for training. *(iii)* Desired outcomes or goals can be expressed as a scalar reward. In this chapter we model the Cellular V2X communication network as a networked multi agent Markovian Decision Process (MDP) where each vehicle can execute an actor-critic based resource scheduler in addition to the existing rule based SB-SPS. Developing the actor-critic methodology [110] for the radio resource allocation problem, we derive two variants namely, Independent Actor Critic (IAC) and Shared Experience Actor Critic (SEAC). Depending on the time varying factors such as V2X data traffic pattern, vehicular traffic density and the radio resource utilization, the scheduler can either function as an IAC or

SEAC scheduler. Also, there is a possibility for the vehicle to switch between the ETSI standard compliant [42, 45] SB-SPS and the AI based schedulers (IAC and SEAC).

6.1 Preliminaries

As presented in Chapter 3 and Chapter 4, adopting a simulation based evaluation methodology has benefits us in terms of: *(i)* Ability to model large network sizes with nodes exchanging heterogeneous V2X data traffic. *(ii)* Adaptation of the V2X message generation rules in order to study the performance of different radio resource allocation algorithms. *(iii)* Study some of the key parameters and metrics that are otherwise impractical to determine by just performing field measurements. *(iv)* Chance to repeat and reproduce the errors and inconsistencies by means of conducting multiple independent simulation runs of a particular scenario.

The SB-SPS algorithm in the unmanaged mode has proven itself to be extremely efficient in achieving low latencies when the vehicles exchange periodic messages with fairly deterministic data sizes. To improve the performance of SB-SPS for aperiodic traffic and tackle resource collision problems, the inclusion of additional fields in the sidelink control information (SCI) of the SB-SPS were studied in [24, 84]. These approaches have shown promising results in reducing collisions in selective situations but so far none of these works have considered the heterogeneity in the nature of the V2X data traffic (unpredictable patterns in message Inter Arrival Time (IAT) and variable data sizes).

6.1.1 Application of Deep Reinforcement Learning (DRL)

From an implementation perspective, reinforcement learning offers the flexibility to design both model-based and model-free behavior among the agents. In the model-based approach, an agent interacts with the environment and creates a model. This approach helps the agent to predict the rewards of the actions even before performing them. In the model-free behavior, an agent interacts with the environment, performs certain actions and improves its policies based on the consequence (reward or penalty) of the actions taken. When the size of the state space and the action spaces increase, it becomes complicated to achieve direct mapping between the states and actions. Hence it is difficult for an RL agent to learn and make decisions. Therefore, Deep Neural Networks (DNNs) have been widely used as function approximators to achieve a mapping between the states and the actions within an RL environment. This approach is referred to as Deep Reinforcement Learning (DRL) [110]. In a model-free RL environment, DNNs are used to learn the policy function that achieves the mapping between the current state and the possible actions for a given system.

When a system consists of only one intelligent central entity that learns by interacting with the environment and chooses actions to be executed by its connected agents, it is referred to as centralized architecture. Here, the agents remain connected with the central entity and follow the actions. They do not interact with the environment nor even with each other. Typically, single agent systems (SAS) are placed under this category [46].

There can also be systems where the learning takes place at a centralized entity but the actions are executed in a decentralized manner by each agent. This is referred to as centralized training and decentralized execution based architecture. This methodology is further investigated for the radio resource allocation problems in Cellular V2X communication networks in [122]. The main advantage here is that a central entity such as the base station is able to completely observe the V2X environment and has knowledge of the radio resources selected by its agents. Both single and multi agent systems can be modeled in this approach.

Considering the dynamically varying number of nodes in a vehicular adhoc network (VANET), fast changing road traffic environment and sporadic availability of network coverage, it is not possible for a vehicular agent to stay connected to a central entity (for example, gNB) at all instants of time and follow the decisions for radio resource allocation. Also, the environment observed by each agent varies with time and it is not possible for all agents to choose actions based on a single policy definition. Hence it becomes essential for each vehicular agent to independently interact with the environment and develop an own policy for the selection of radio resources. This is referred to as a fully decentralized architecture. Typically, multi agent systems (MAS) are modeled in this manner.

In all the three types of systems discussed above, two broad categories of Deep Reinforcement Learning (DRL) methods can be applied [109, 110]: *(i)* value based or *(ii)* policy based. The goal of the value based approach is to determine the value of a state or an action. This can be mathematically represented as a value function or a table (such as the Q-table [109]). In the policy based approach, the goal is to directly train a policy which tells the agent which action to choose in a given state. Different types of policies that can be applied in DRL environments are further discussed in [109, 118].

In one of the recent works [52], the authors have designed a Q-learning based multi agent DRL radio resource scheduler where they address the problem of partial observability in Cellular V2X communication networks. However, they do not consider the impact of the varying V2X data traffic patterns for radio resource allocation. Other notable works that employ multi agent DRL approaches for V2X communication networks can be found in [53, 78]. In both these works, they have specifically investigated the value based multi agent DRL methods for radio resource allocation in different application scenarios.

In order to specifically formulate a fully decentralized Multi-Agent Reinforcement Learning (MARL) based model for radio resource allocation in Cellular V2X, the following requirements are considered within the scope of this chapter: *(i)* Make vehicles aware of the positions of their neighbors, *(ii)* Interpret the V2X data traffic pattern of other vehicles, *(iii)* Calculate the number of radio resources reserved, utilized and wasted in each grant period, *(iv)* Apply a certain mechanism to forecast radio resource occupancy for future transmissions, and *(v)* Re-evaluate the selected radio resource and choose new resources if required. These tasks cannot be achieved using only the classical value based methods (for example, Deep Q Learning, DQN) [110] as implemented in [52] or the policy based methods as discussed above. Actor-critic based methods provide a middle ground between pure value based and pure policy based approaches where the "critic" network can be designed to evaluate the effectiveness of the chosen action. They can be applied in independent learning situations or in shared-experience based learning situations as introduced in Section 2.2.3. Also, they can be implemented in mixed environments where each agent displays a different behavior (e.g., cooperative, competitive etc) as discussed in [82].

In this chapter, we consider a fully decentralized multi agent DRL environment where the vehicular agents are connected by a possibly time-varying communication network. This serves as a channel for the agents to exchange information in the absence of a central controller. At each time step, the agent executes an action based on its local observations, receives some rewards (positive or negative) and creates an "on-policy" trajectory referred to as experience. The experience parameters are exchanged between the agents through a communication network. This architecture is referred to as a networked agent MDP in the literature [121]. The advantage provided by the networked MDP architecture is that the DNNs learn by means of independent exploration to estimate the state and action value functions among several spatially distributed agents.

Contributions

This chapter is developed based on the ideas and formulations from our journal publication [63] and also includes direct excerpts. The specific author contributions along with the copyright note for the publication are provided in Appendix C.

The main contributions in this chapter are as follows:

1. Formulation of a multi agent networked MDP model to represent a Cellular V2X communication network with dynamically moving vehicular nodes.

2. Design of an actor-critic based radio resource scheduler to be deployed in each vehicular agent which performs the task of radio resource allocation.

3. Simulation based performance evaluation to compare the effectiveness of rule based scheduling with the IAC and SEAC variants of the actor-critic based scheduler for different vehicular traffic density scenarios.

6.2 Actor-critic based radio resource scheduler

While designing an AI based resource scheduler for a Cellular V2X communication network, certain simplifications must be made to obtain a model that can be trained by consuming a reasonable amount of computational resources (sizes of state space and action space), the extent of stationarity in the parameters that we intend to forecast (for example, vehicle speed, position, nature of V2X data traffic) and dynamically changing number of nodes in a network. At a basic level, we consider that the vehicular agents share a common road traffic environment that they can observe. Since the road traffic conditions change dynamically, the local observations alone do not guarantee the best action selection decisions for the vehicles at all instants of time. Our model is said to be decentralized in the sense that actions are taken based on each agent's local observations and the obtained rewards are also local with respect to each agent. All the agents in the network have a common reward function that is to achieve successful transmission of V2X messages within the chosen radio resource in such a way that they do not cause resource collisions with other agents and also meet the required latency constraints. The individual components of an actor-critic scheduler are formulated as follows:

6.2.1 State

Before arriving at the definition of the state, we consider pre-processing of the input parameters that affect the action selection decision for the vehicle. This is illustrated in Figure 6.1. The time-varying input parameters are listed as follows:

- Distance to neighboring vehicles: This factor determines how radio resources can be re-used between different vehicles. When the vehicles are far apart at a distance greater than the sidelink broadcast range, it is possible for them to transmit on the same radio resource. For example, in Figure 6.1, vehicles A and E can select the same radio resources.

- Forecast indicator of the possibility of an object (in this context, it refers to another vehicle) present within the sensor field-of-view (FOV) for an ego vehicle. In Figure 6.1, it can be observed that vehicle C is approaching vehicle A, and vehicle B is also within the sensor FOV of vehicle A. Hence by having a predictive estimation of the mobility patterns of the neighboring vehicles (vehicle B and C in Figure 6.1), vehicle A can expect to receive aperiodic CPMs from these vehicles over the next time slots.

- Radio resource occupancy in the previous 1 s time window as a result of V2X messages received from other vehicles and the messages scheduled for own transmissions.

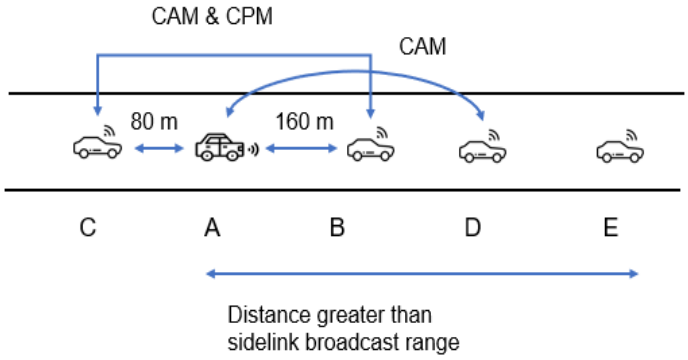


Figure 6.1 – Parameters that determine the state pre-processing.

The temporal variations in the above input parameters over the previous time window (for example, $[1,2,..5]$) s are captured using a Long Short Term Memory (LSTM) based Recurrent Neural Networks (RNN) as shown in Figure 6.4. The relative distance to neighboring vehicles and the pattern of received V2X messages are jointly processed as multi-dimensional inputs by the LSTM cells. The output of the LSTM is a forecast (future predictions) of radio resource occupancy for the next $500-1,500$ ms. The number of past time-steps can be best adjusted by tuning the "momentum" hyperparameter of the LSTM such that it allows the accumulation of the gradients of a certain number of past steps to determine the direction to go with, instead of using the gradient of only the current step. The State s_t at a time-step t is expressed as follows:

$$s_t = [C^{k\times m}, \Delta d, I_{sf}] \tag{6.1}$$

Here, $C^{k\times m}$ refers to the number of radio resources (i.e., the number of occupied subchannels k in each time-slot m) within the selection window T_{sel}. In principle, the selection window length can vary between $20-100$ ms and the number of resource blocks can be as large as 100 [42, 45]. This results in large dimensions of the state and action spaces. Hence we limit the size of K to two subchannels and M to ten slots having a total of 20 radio resources.

The term Δd in Equation 6.1 corresponds to the distance of the neighboring vehicle normalized to the length of the road under consideration. Here we only consider the distances of those neighboring vehicles which are forecasted to transmit in one of the intended slots. The term I_{sf} indicates if the neighboring vehicle is within the sensor FOV or not.

6.2.2 Action

The action space for a given agent is represented by the radio resource pool consisting of $C^{K\times M}$ available radio resources as shown in Figure 6.2. Here, K denotes the number of subchannels (consisting of groups of resource blocks, RBs) and M denotes the number of slots. Additionally, the two possible categories of re-selection counter ($cResel_1, cResel_2$) values are considered, which determine how long the vehicle decides to hold these selected resources for future transmissions - $cResel_1 \sim \mathrm{U}[5,9]$ and $cResel_2 \sim \mathrm{U}[10,15]$ where U represents an uniform distribution [45].

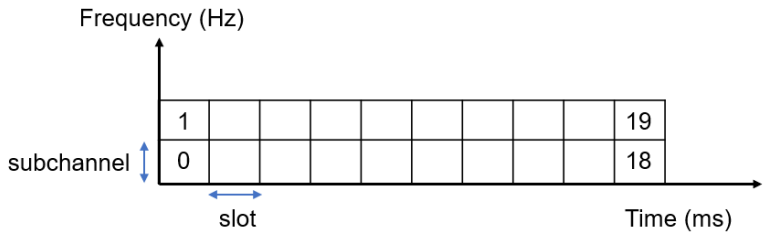


Figure 6.2 – Radio resource pool.

Each vehicle performs the action of selecting one radio resource from $C^{K\times M}$ and one category of *cResel* value. The specific goals of the action selection mechanism are:

1. Selection of radio resource and decision to use the same resource for a certain number of future transmissions. This is done by taking into account the V2X data traffic pattern as forecasted by the LSTM cells.

2. Detection of a potential resource collision risk and re-evaluation of resource selection within the Packet Delay Budget (PDB).

3. The agents should take care that when collisions happen in one of the intended transmission slots, the same radio resource should not be scheduled for subsequent transmissions and also other agents should be made aware. This can be done by means of sharing rewards and experience parameters with other agents.

4. Adaptation of *cResel* based on V2X data traffic pattern in a manner that reserved resources do not go under/over utilized.

Action selection: The actor network selects a radio resource based on the softmax probability values as shown in Figure 6.4. As an effect of the action, the state values at time steps t and $t+1$ are computed by the critic network that helps in evaluating the impact of the chosen action. The critic network continuously evaluates the state and provides updates to the actor about the choice of actions. The state value calculated by the critic provides an idea of how good is the next state (after the one or more actions

are performed) in comparison to the previous state. In a Cellular V2X communication network, it refers to the number of reserved resources that are not getting utilized, number of free resources and changes in V2X data traffic patterns (message arrival times and their respective sizes).

6.2.3 Reward

Two aspects are considered while designing the reward function as discussed in our work [63] - immediate rewards that can be collected per sidelink grant (which is referred to as one episode) and the overall long term reward that has a connection to the short term rewards which are obtained in each episode.

Here the short term reward directly corresponds to the number of successful transmissions per episode length T_g (calculated as the Transmission Success Ratio (TSR)). A successful transmission is said to be achieved when a vehicle is able to transmit within the allocated radio resource, without causing any resource collisions to the neighbouring vehicles.

The reward r_t^i for each agent $i \in N$ at time t is calculated as:

$$r_t^i(a_t^i|s_t^i) = \begin{cases} N_{txs}^i & N_c^i = 0, T_{RA}^i \leq T_{PDB} \\ N_{txs}^i - N_{re}^i & N_c^i \geq 1, T_{RA}^i \leq T_{PDB} \\ -N_{txf}^i & N_c^i \geq 2, T_{RA}^i \geq T_{PDB}, \\ & \Delta d(N_i^c) \leq D \\ 0 & N_c^i \geq 1, \Delta d \geq D. \end{cases} \tag{6.2}$$

Here a_t^i is the action taken by an agent i in the state s_t^i.

- An agent i receives the best reward when all its transmissions per grant N_{txs}^i are successful and the resource allocation latency T_{RA}^i in each of the transmissions is within the allowed PDB. The reward numerically is equal to the number of successful transmissions per grant N_{txs}^i. The number of vehicles whose resources collide with the ego vehicle N_c^i is zero.

- An intermediate reward is received when an agent detects collisions during any of its transmission but manages to re-evaluate the selected resources and chooses new resources within the PDB. The number of successful transmissions after re-selection of resources is given by N_{re}^i. Here the reward is calculated by taking the difference between N_{txs}^i and N_{re}^i.

- Suppose there are more than two neighbouring vehicles choosing the same radio resource within a grant period and the agent is unable to re-select the resources within the PDB, it receives a negative reward. The reward is numerically equal

to the number of failed transmissions N^i_{txf}. This is observed in situations where many vehicles nearby compete for the same radio resources.

- A reward of 0 is assigned to an agent when another agent whose distance is larger than the range chooses the same resource as agent i. This does not create much interference and hence the transmission can still be possible.

The long term rewards are computed at the system level for all the N agents after the completion of a certain total number of episodes E_T. The two measurable rewards in the long term are:

- Radio resource utilization η per transmission
- Probability of reception P^i_R

The radio resource utilization over a total length of E_T episodes is calculated as:

$$\eta = \sum_{e=1}^{E_T} \sum_{i=1}^{N_{T,e}} \frac{C^i_{u,e}}{C^i_{c,e}}, \tag{6.3}$$

where $C^i_{u,e}$ and $C^i_{c,e}$ represent the number of radio resources utilized and the number of radio resources configured for a given agent i in the episode e. The total number of agents in a given episode e is denoted by $N_{T,e}$.

The probability of reception for an agent i in a sidelink broadcast communication network is calculated as:

$$P^i_R = \frac{1}{L} \sum_{j=1}^{L} \{\gamma^{ij}_t \geq \gamma^{th}\}. \tag{6.4}$$

Here, L represents the number of neighbouring vehicles to agent i at time t which receive the messages sent by agent i. The term γ^{th} is the SINR threshold. The component γ^{ij}_t is the received signal-to-interference noise ratio (SINR) for agent j, which is computed according to the formula:

$$\gamma^{ij}_t = \frac{P|H^{ij}_t|^2}{\sigma^2 + \sum_{l \in L} P|H^l_t|^2}, \tag{6.5}$$

where H^{ij} represent the channel gains between agents i and j. The interference channel gain between l colliding agents with the agent i is represented as H^l. The term σ corresponds to the noise at the receiver.

6.2.4 Experience

Each vehicular agent takes independent actions based on local observations. It receives a reward (either positive or negative) and generates one “on-policy” trajectory consisting of resulting observations after performing the actions in each episode. This “on-policy” trajectory is referred to as experience.

6.3 Algorithm design

An Actor-critic model typically consists of two components: *(i)* Actor and *(ii)* Critic. The actor network selects the action and the critic network computes the value for the network. This value can be a state value or an action value. When an action value is considered to update the actor's policy then it is known as Advantage Actor-Critic (A2C). When a state value is computed in order to evaluate the action, it is referred to as Temporal Difference (TD) learning based actor-critic. This work considers the latter approach as shown in Figure 6.3. Computing the state values allows us to evaluate the quality of a state compared to the previous state after taking a certain action. In connection to the radio resource allocation task, the calculation of state values provide insights about the proportion of resources utilized by the agents, the number of successful transmissions and the amount of wasted resources.

The actor network's policy determines the degree of exploration for the actor. Using the calculated state values, the policy in the actor network is updated to increase the probability of selecting actions with favorable values as illustrated in Figure 6.3.

There are several policies for actor-critic methods discussed in the ML literature [109], but for our approach, we have chosen the "softmax" policy. Using this policy, it is possible to explore actions and states considering their relative expected value as opposed to randomly selecting an action as done in the "epsilon-greedy" policy. The overall DNN architecture of the actor-critic algorithm is illustrated in Figure 6.4.

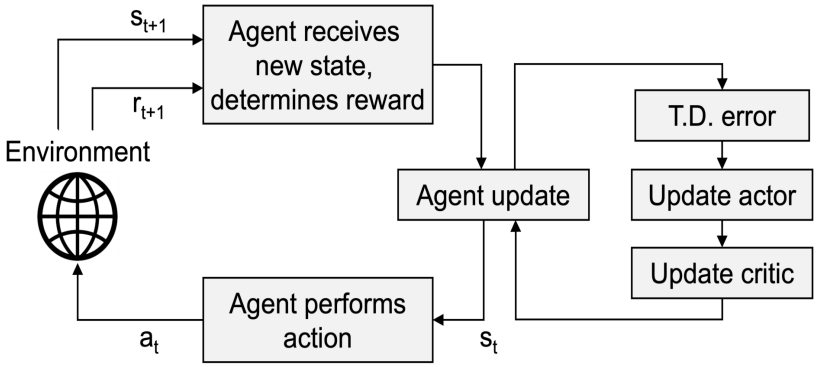


Figure 6.3 – Learning mechanism in actor-critic (T.D.=temporal difference) [63].

Each vehicular agent is deployed with two separate DNNs – one for the actor and one for the critic as illustrated in Figure 6.4. Prior to the selection of actions in the actor network, we introduce a state processing unit that is composed of LSTM cells which identify patterns in the input parameters over a defined number of past time steps. The state processing unit is commonly shared between the actor and the critic networks. We choose to use the convolutional LSTM variant as it effectively captures patterns and features in multi-dimensional input data through convolution operations [100].

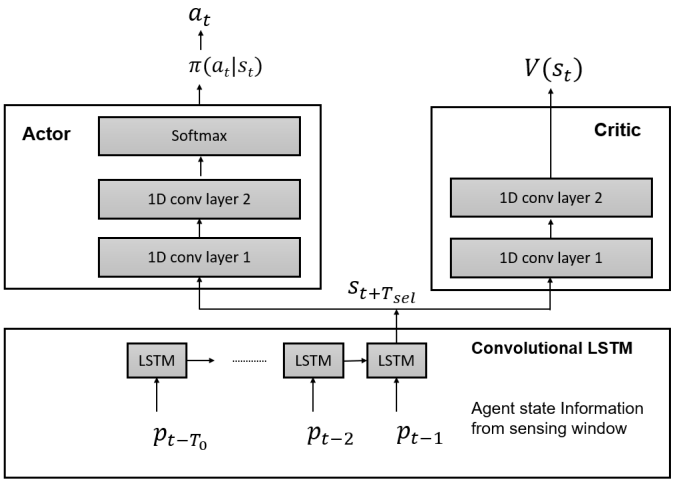


Figure 6.4 – Actor-critic algorithm implementation [63].

Once future state information for the next one second is obtained, the features are independently processed by a one-dimensional Convolutional Neural Networks (CNN) in a series of layers. These CNN layers extract relevant features from the input data, which are then used to select a radio resource through the softmax probabilities. The critic network evaluates the action by calculating the state value function, which updates the actor network through a policy gradient descent. This update process ensures that the actor network learns from the experience and improves its decision-making capabilities over time.

1. Temporal difference (δ_t):

$$\delta_t = R_{t+1} - \bar{R} + \hat{V}(s_{t+1}) - \hat{V}(s_t) \tag{6.6}$$

where $\hat{V}(s_{t+1})$ is the state-value function at time-step $t+1$. It is represented by the sum of Q-values of all actions in state s_{t+1}. The average reward $\bar{R}$ is updated according to:

$$\bar{R} \leftarrow \bar{R} + \alpha \bar{R} \delta_t \tag{6.7}$$

2. Critic update ($\hat{V}(s_t, a_t)$):

$$\hat{V}(s_t, a_t) \leftarrow \hat{V}(s_t, a_t) + \alpha_c \delta_t \tag{6.8}$$

3. Actor policy update (θ_{s_t}):

$$\theta_{s_t} \leftarrow \theta_{s_t} + \alpha_a \delta_t \nabla ln \pi(a_t|s_t, \theta_{s_t}) \tag{6.9}$$

The term $\nabla ln\pi(a_t|s_t,\theta_{s_t})$ represents the gradient and indicates the direction in which the individual action of the actor should be updated based on the policy parameters θ_{s_t}. The terms α_a and α_c refer to step-sizes for actor and critic updates, respectively. To further explain the calculation of gradient in the context of the softmax policy,

$$\nabla ln\pi(a_t|s_t,\theta_{s_t}) = x_h(s_t,a_t) - \sum_b \pi(b|s_t,\theta_{s_t})x_h(s_t,b) \tag{6.10}$$

where $x_h(s_t,a_t) \in \mathbb{R}^{1\times n}$ is the one-hot encoded vector of the action index chosen at time t. The second term in Equation 6.10 refers to the sum of the probability of taking other b actions in state s_t under a policy π multiplied by the corresponding one-hot encoded vector of that action index.

6.4 Networked multi agent MDP model

Considering the fundamental concepts of the actor-critic algorithm explained in Section 6.3 for a single agent case, we formulate a networked multi agent MDP model of the Cellular V2X communication network and design two variants of the actor-critic radio resource schedulers namely, IAC and SEAC to be deployed in each agent.

A networked multi agent MDP is represented by a tuple consisting of the following components $<S,\{A^i_{i\in N}\},P,R^i_{i\in N},\{G_t\}_{t\geq 0}>$. Here, S is the common state space or environment where N agents are currently performing a set of tasks. The action space A consists of the set of actions an agent i can execute. The joint action space of all agents is calculated as $A = \sum_{i=1}^{N} A^i$. The locally observed reward function for each of the agent is given by $R^i = S \times A \rightarrow \mathbb{R}$. The state transition probability P is represented by $P : S \times A \times S \rightarrow [0,1]$. The existence of a time-varying communication network between N agents is represented as an undirected graph, G_t where $G_t = (N,E_t)$. The set of vertices is represented as the number of agents N and the edge set E_t at time t is denoted by $\{E_t \subset (i,j) : i,j \in N, i \neq j\}$. This edge set formulation can be visualized as any two vehicular agents (i,j) or (j,i) which can share parameters with each other at time t.

6.4.1 Independent Actor Critic (IAC)

The joint action space of N agents in the system at time t is denoted as $a_t = (a^1_t, a^1_t \cdots a^N_t)$, where $a_t \in A$. Based on the action, each agent $i \in N$ receives a reward r^i_{t+1}. It is a random variable with expectation given by $R^i(s_t,a_t)$. As an effect of the action(s) taken by one or more agents, the MDP transitions to the next state $s_{t+1} \in S$. The joint policy function $\pi(s,a)$ of the system can be factorized as a product of local policies executed by each agent because the random actions chosen by each agent are statistically independent of

each other.

$$\pi(s,a) = \sum_{i \in N} \pi^i(s,a) \tag{6.11}$$

where $\{\pi^i : S \times A^i \rightarrow [0,1]\}, \forall\ i \in N$.

Considering that the policies of agents belong to a parametric function class with parameter θ, the policy function in Equation 6.11 is represented as $\pi_\theta(s,a)$. It is to be noted that $\pi_\theta(s,a)$ is continuously differentiable w.r.t θ.

The joint objective function in a multi agent IAC network is to collaboratively find a policy π that can achieve maximum global averaged returns in the long term. The joint objective function is formulated as:

$$\max_\theta J(\theta) = \lim_T \frac{1}{T} \mathbb{E}(\sum_{t=0}^{T-1} \frac{1}{N} \sum_{i \in N} r^i_{t+1}) \tag{6.12}$$

The global expected action value function $Q_\theta(s,a)$ is calculated as:

$$Q_\theta(s,a) = \sum_t \mathbb{E}[\bar{r}_{t+1} - J(\theta) | s_0 = s, a_0 = a; \pi_\theta] \tag{6.13}$$

The global state value function $V_\theta(s)$ represents the sum of the Q-values resulting from actions taken by all agents over different states. It is given by:

$$V_\theta(s) = \sum_{a \in A} \pi_\theta(s,a) Q_\theta(s,a) \tag{6.14}$$

Based on the Temporal Difference (TD) learning algorithm of the actor-critic [109], the TD parameter, critic and actor updates are done according to Equation 6.6, Equation 6.8 and Equation 6.9 respectively.

The objective is to find policies for each agent in $\pi = (\pi_1, \pi_2, \cdots \pi_N)$ such that the discounted reward in each agent i is maximized w.r.t to the policies in π. Over a length of episode T, the total discounted (with a discount factor β) reward for each agent is given by:

$$R^i = \sum_{t=0}^{T-1} \beta^t r^i_t \tag{6.15}$$

The joint objective function is derived as:

$$\max_{\pi'_i} \mathbb{E}[R^i | \pi'_i, \pi_{-i}] \forall i \in \pi_i \tag{6.16}$$

In the first step, the individual loss function at the actor and critic is obtained by taking into account the partial observability factor. The actor network in each of the agents evolves towards taking actions by learning the policy π_ϕ where ϕ is a parameter. The critic network computes the observed state value function parameterized $V_\pi(o,\theta)$

where $\{o \in O\} \subseteq S$. The actors loss or the policy gradient loss $L(\phi_i)$ for agent i executing the IAC scheduler is computed as:

$$L(\phi_i) = -log\pi(a_t^i|o_t^i;\phi_i)(r_t^i + \beta(V(o_{t+1}^i;\theta_i) - V(o_t^i;\theta_i))) \tag{6.17}$$

The critic loss $L(\theta_i)$ for agent i executing the IAC scheduler is computed as:

$$L(\theta_i) = ||V(o_t^i;\theta_i) - y_i||^2 \tag{6.18}$$

where $y_i = r_t^i + \beta(V(o_{t+1}^i;\theta_i))$.

The DNNs shown in Figure 6.4 approximate V and π by sampling several trajectories in parallel.

for timestep $t = 1 \cdots T$ **do**
  Observe $o_t^1, o_t^1, \cdots o_t^N$
  Sample actions $a_t^1, a_t^1, \cdots a_t^N$ from $P(o_t^1, \phi_1), \cdots P(o_t^N, \phi_N)$
  Execute actions and observe $a_t^1, a_t^1, \cdots a_t^N$ and $o_t^1, o_t^1, \cdots o_t^N$
  for agent $i = 1, \cdots N$ **do**
    for timestep $t = n, \cdots T_g$ **do**
      Observe $o_{t-nT_0}^i, o_{t-nT_0+1}^i, \cdots o_t^i$ ▷ Local observations
      Execute action a_t^i from $P(o_t^i, \phi_i)$
    end for
    Perform gradient step on ϕ_i by minimizing Equation 6.17
    Perform gradient step on θ_i by minimizing Equation 6.18
  end for
end for

Algorithm 6.1 – IAC algorithm.

The pseudo-code for the IAC algorithm is presented in Algorithm 6.1. In each episode, the agents execute actions based on their local observations $(o_t^1, o_t^1, \cdots o_t^N)$ within a grant period T_g and train on the policy parameter ϕ. Own experience trajectories are collected which are used to make updates to the policy parameters and minimize the actor and critic losses as calculated in Equation 6.17 and Equation 6.18, respectively. The IAC based actor-critic variant works to its best efficiency in environments where the agents can observe the global state at all instants of time t. Typically, in a Cellular V2X communication network the agents can only observe a subset of the global state S. Hence, the actions taken based simply on local observations (o_t^i) cannot guarantee in achieving best long term rewards at a global system level.

6.4.2 Shared Experience Actor Critic (SEAC)

While formulating an SEAC variant of the actor-critic algorithm, we take into account the partial observability factor [94] and modify the representation of the multi agent

networked MDP as $<S, \{O^i_{i\in N}\}, \{A^i_{i\in N}\}, P, R^i_{i\in N}, \{G_t\}_{t\geq 0}>$. Here the component $\{O^i_{i\in N}\}$ is known as the observation space of each agent i. The observation space O can be visualized as a subset of the global state space as observed locally by each agent.

Experience sharing: Each agent in the network takes an action based on local observations and trains its policy accordingly. As a result, it generates a trajectory of actions per episode. When experience sharing is enabled, it also considers the sampled trajectories of actions from other agents as "off-policy data" and further minimizes the loss functions of both its actor and critic networks. The actor loss and critic loss computed in Equation 6.17 and Equation 6.18 respectively, are further extended by incorporating the experience trajectories of other agents.

The actor loss $L_{se}(\phi_i)$ for an agent i after enabling experience sharing is computed as:

$$L_{se}(\phi_i) = L(\phi_i) - \lambda \sum_{k\neq i} \frac{\pi(a^k_t|o^k_t;\phi_i)}{\pi(a^k_t|o^k_t;\phi_k)} [log\pi(a^k_t|o^k_t;\phi_i)(r^k_t + \beta(V(o^k_{t+1};\theta_i) - V(o^k_t;\theta_i)))] \quad (6.19)$$

The critic loss $L_{se}(\theta_i)$ for agent i after enabling experience sharing is computed as:

$$L_{se}(\theta_i) = L(\theta_i) - \lambda \sum_{k\neq i} \frac{\pi(a^k_t|o^k_t;\phi_i)}{\pi(a^k_t|o^k_t;\phi_k)} ||V(o^k_t;\theta_i) - y_k||^2 \quad (6.20)$$

where $y_k = r^k_t + \beta(V(o^k_{t+1};\theta_i))$.

---

for timestep $t = 1 \cdots T$ **do**
  Observe $o^1_t, o^1_t, \cdots o^N_t$
  Sample actions $a^1_t, a^1_t, \cdots a^N_t$ from $P(o^1_t, \phi_1), \cdots P(o^N_t, \phi_N)$
  Execute actions and observe $a^1_t, a^1_t, \cdots a^N_t$ and $o^1_t, o^1_t, \cdots o^N_t$
  for agent $i = 1, \cdots N$ **do**
    for timestep $t = n, \cdots T_g$ **do**
      Observe $o^i_{t-nT_0}, o^i_{t-nT_0+1}, \cdots o^i_t$ ▷ Local observations
      Execute action a^i_t from $P(o^i_t, \phi_i)$
    end for
    Observe $o^{k\neq i}_{t-nT_0}, o^{k\neq i}_{t-nT_0+1}, \cdots o^{k\neq i}_t$ ▷ Trajectories from other agents
    Perform gradient step on ϕ_i by minimizing Equation 6.19
    Perform gradient step on θ_i by minimizing Equation 6.20
  end for
end for

Algorithm 6.2 – SEAC algorithm.

The pseudo-code for the SEAC algorithm is presented in Algorithm 6.2. Similar to the Algorithm 6.1, the agents execute actions based on their local observations

$(o_t^1, o_t^1, \cdots o_t^N)$ within a grant period T_g and train on the policy parameter ϕ. In addition to improvising the policy training based on own experience trajectories, the SEAC considers the shared experience trajectories from other vehicles. The gradient step is performed similar to Algorithm 6.1 and the corresponding actor and critic losses are calculated according to Equation 6.19 and Equation 6.20, respectively.

The "off-policy data" from other agents executing different policies (represented by another policy parameter ϕ_k) than the given agent i is chosen in the form of the weighted parameter λ. The generalized expressions in Equation 6.19 and Equation 6.20 can be useful even in environments where each agent executes different policies. Theoretically, the system can benefit when all agents are sharing their experiences. However, by considering the cost factor involved in explicit cooperation between agents [94], the experience sharing is enabled only in selected situations based on V2X data traffic pattern and vehicular density. Also, it can happen that not every experience trajectory from other agents can provide useful learning directions at all instants of time. The hyper parameter λ weighs the experiences of other agents. The sensitivity of the SEAC algorithm can be further explored by varying the values for λ. In our experiments, we consider a λ value close to 1.0.

6.5 Evaluation

To study the performance of AI based radio resource allocation in Cellular V2X, we extend the `Artery-C` framework with a DRL based environment and integrate it with the `InTAS` road traffic model in `SUMO`. The principles to couple a network simulator with a DRL based environment (running in `TensorFlow Python`) is discussed in Section 3.4.4.1. The vehicles have an option to execute a rule based or an AI based radio resource scheduler depending on the V2X data traffic patterns, possible modes of operation and the availability of radio resources. In this section, we discuss the selection of different parameters related to the road traffic model, Cellular V2X communication network along with the parameters and hyper parameters necessary to tune the actor-critic based radio resource schedulers.

6.5.1 Simulation environment

The co-simulation of `Artery-C`, `SUMO` and the DRL environment requires appropriate tuning of the road traffic model related parameters listed in Table 6.1, 5G-NR V2X related parameters as mentioned in Table 6.2, and the hyper parameters for actor-critic schedulers listed in Table 6.3.

As indicated in Table 6.1, a specific time during the day is chosen for simulations which makes it possible to observe the changing V2X data traffic patterns within the city of Ingolstadt [80], Germany. For each agent, the length of one episode depends on

Table 6.1 – Simulation parameters: Urban road traffic scenario [63].

Parameter	Value
Vehicle speed [km/h]	40 - 60
Sidelink broadcast range [m]	500
Number of lanes	2
Vehicle Penetration Rate (VPR)	100
Types of vehicles	Cars, buses and trucks
Time of the day [am]	8:30 - 9:30
Backward facing radar [range, FOV]	80 m and 325 °
Forward facing radar [range, FOV]	160 m and 35°
Vehicle density [Veh/m]	Low: 0.07, med: $(0.14 - 0.21)$, high: $(0.28 - 0.45)$

Table 6.2 – Simulation parameters: Cellular V2X [45].

Parameter	Value
Protocol stack	5G-NR V2X
Frequency band [GHz]	5.9
Subcarrier spacing [kHz]	15
Frame structure	FDD
Modulation scheme	QPSK
Channel model	WINNER II - B2 (urban)
Number of subchannels (K)	2
Subchannel size	5
Slot length [ms]	1
Probability of resource keep	0.8
Operational mode	Unmanaged
V2X messaging	CAM and CPM broadcast
Mode switching	No
Message size [bytes]	50 – 800
Reselection counter ($cResel$)	[5,15]
Selection window size (M) [ms]	10
Resource reservation interval RRI [ms]	100
Adjacency SCI + data	Yes

the sidelink grant period which varies between $500 - 1,000$ ms or between $1,000 - 1,500$ ms for a fixed RRI of 100 ms. For scalability reasons, we limit the road traffic participants to comprise only vehicles which transmit CAMs and CPMs that have the characteristics listed in Table 4.1.

Although the offline training method is fast and scalable as discussed in Section 3.4.4.1, it is more suitable for deterministic road traffic environments – for example, in highways where lane discipline is followed, and the relative speed of vehicles do not vary much.

Table 6.3 – Parameter settings for actor-critic schedulers [63].

Parameter	Value
Duration of the simulation [s]	10,000
Episode duration [ms]	500 – 1,500 depending on the value of *cResel*
γ	0.99
λ	1
Adam epsilon	0.001
α_a	[1e-3 – 3e-3]
α_c	[1e-3 – 3e-3]
Number of repetitions	10

In a dynamically changing road traffic environment with random movements of agents, it is not possible to simulate every scenario methodically. The pre-trained agents will not be able to foresee or adapt to such changes easily and hence wrong decisions will be made. When the number of agents increase or decrease, there will be a need to perform re-training. This can lead to a considerable wastage of computational resources and time for decision making among agents. Hence an online method is considered to be the better choice.

6.5.2 Metrics

To compare the performance of the rule-and the AI based schedulers, we consider the same metrics as defined in Section 4.3.2. The metrics Radio Resource Utilization (RRU) and probability of reception P_R directly translate to the long term rewards obtained by the agents at the system level (over a collection of episodes). The RRU along with the TSR measurements indicate the extent of utilization of the allocated radio resources for successful transmission of V2X messages. A comparison in the variation of the Probability of Resource Collision (PRC) metric from analysis and simulations helps us to evaluate the collaborative behavior among the vehicular agents when they select their radio resources. The measurement of the P_R metric in two time levels helps us to analyze the qualitative benefits achieved by the AI based radio resource schedulers with regard to the reliability of the communication link.

6.6 Result analysis

The results to be discussed in this section are obtained after the deployment of the rule-and the AI based radio resource schedulers in an online setting within the network simulator `Artery-C` as explained in Section 6.5.

Three categories of results are presented in this section: *(i)* Access layer measurable parameters for Cellular V2X. *(ii)* LSTM performance. *(iii)* Comparison of the learning

curves. The calculation of the access layer measurable parameters (metrics) listed in Section 4.3.2 are useful to obtain a comparison between the performance of the rule and AI based radio resource schedulers under different vehicular density conditions and V2X data traffic patterns. The evaluation of the LSTM performance helps us to understand the benefits offered by the state pre-processing layer. The learning curves allow assessment the time taken for the training of the AI based radio resource schedulers and their convergence.

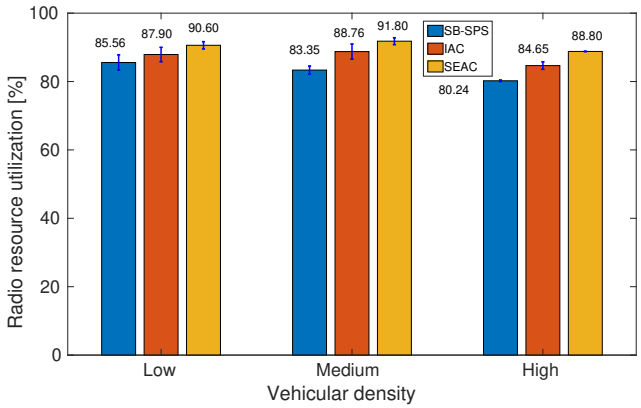
6.6.1 Radio Resource Utilization (RRU)

In Cellular V2X communication, the radio resources are configured for a certain number of transmissions that are contained within a sidelink (SL) grant. The RRU parameter was previously studied in Section 4.3.2 by means of formally characterising two observations - grant break and grant wastage. Here, the RRU parameter is measured for the rule (SB-SPS) and the AI based schedulers (IAC and SEAC) under varying vehicular density conditions and V2X data traffic patterns within the simulation. It is to be noted that all vehicles in the simulation operate in the sidelink unmanaged mode.

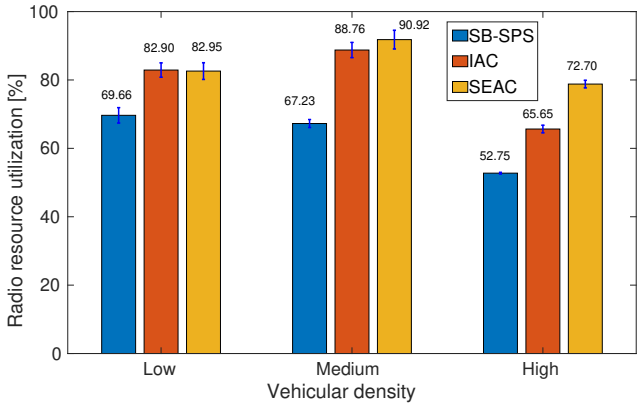
Figure 6.5a shows that the RRU measurements are fairly similar for the vehicles executing the rule based SB-SPS and the AI based schedulers, IAC & SEAC. When the nature of the V2X data traffic is periodic with deterministic data sizes (as in the type A traffic model), SB-SPS is capable of performing to the best efficiency by achieving a mean RRU greater than 80% (at a confidence level of 95%) for all the three types of vehicular density scenarios. The only reason for grant break is when new vehicles enter the simulation environment where they are unaware of the resources utilized by other pre-existing vehicles.

For the type B traffic model as depicted in Figure 6.5b, the performance of SB-SPS starts to recede when the vehicle density increases. The IAC based scheduler shows $10 - 15\%$ overall improvement in the mean RRU values but the vehicles are still making decisions only based on local observations and own experience trajectories. The performance of the SEAC scheduler is more noticeable in high vehicular density scenarios where the mean RRU is around 72% (at a confidence level of around 98%). The vehicles share their experiences in the form of local observation trajectories and thereby learn to improve their resource selection and adapt the *cResel* values accordingly. In this manner, the extent of resource blocking in the neighboring vehicles can be reduced.

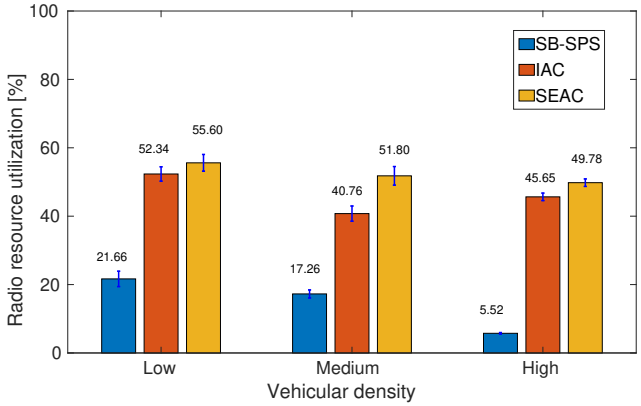
The advantage of the DRL based scheduling can be observed more prominently in Figure 6.5c where the nature of the V2X data traffic is completely aperiodic with variable data sizes. This corresponds to situations where the vehicle driving dynamics and environmental perception change frequently resulting in the transmission of several aperiodic CAMs and CPMs. In such a case, instead of pre-allocating a large number of future resources by means of SB-SPS, it is beneficial for the vehicles to adopt the



(a) RRU: Type A data traffic model



(b) RRU: Type B data traffic model



(c) RRU: Type C data traffic model

Figure 6.5 – Comparison of RRU measurements between rule and AI based schedulers [63].

SEAC variant of the actor-critic method for resource allocation. The LSTM unit in the state pre-processing layer provides future predictions about the locations of neighboring vehicles and hence the ego vehicle can estimate if it will receive a CPM from other vehicles within the next $1, 2 \ldots 5$ s. Additionally, based on the rewards obtained per episode (or grant), the agent can learn how efficiently its radio resources were utilized. This experience can be shared between agents and the value of *cResel* can be adapted accordingly.

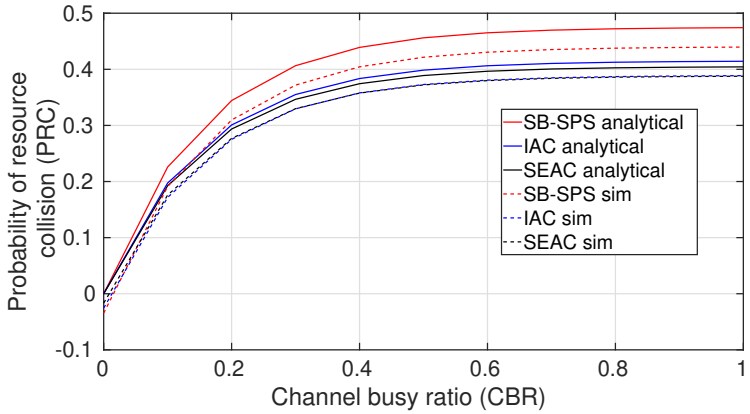
6.6.2 Probability of Resource Collision (PRC)

When two or more vehicular agents select the same radio resource for their transmission (slot and subchannel), it results in a radio resource collision. This causes co-channel interference which renders the radio resource unsuitable for transmission. As explained in Section 2.1.2.2, the SB-SPS algorithm so far does not formally address the need for re-allocation in the event of a resource collision [45].

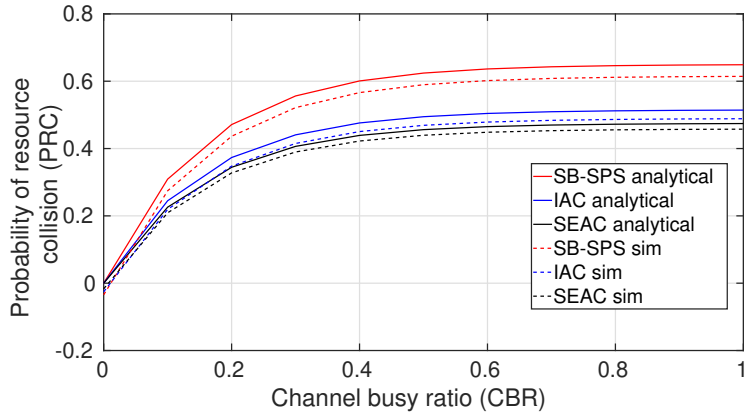
During the process of radio resource allocation, the SB-SPS algorithm uses the information in the sensing window to ensure that there is no resource collision within the current selection window. However it does not have a mechanism to guarantee that future transmissions are collision free. Also when new vehicles enter the environment and select the same resource, the ego vehicle cannot become aware of this situation and hence is unable to transmit the message within the chosen resource. The conditions leading to a resource collision are formulated analytically and discussed in Section 4.3.2.

The previous results in Section 4.4.2 employing the SB-SPS algorithm for the type B and type C data traffic models have shown that even under medium CBR conditions i.e., $0.45 \leq \text{CBR} \leq 0.65$, the PRC is greater than 0.5 for high vehicular density conditions. In this subsection, we discuss the PRC measurement results when AI based schedulers are deployed in aperiodic data traffic environments (with reference to the type C data traffic model). This is accomplished by evaluation of the following parameters: *(i)* Immediate rewards within an episode (or grant) and *(ii)* Experience trajectory of other agents. The immediate rewards within an episode are calculated in Equation 6.2. When an agent repeatedly receives bad rewards, the experience sharing is enabled and the critic network evaluates the experience trajectories of other agents and its impact on the state. In this way, the agent acquires knowledge about the radio resource utilization of other agents and learns to avoid those resources.

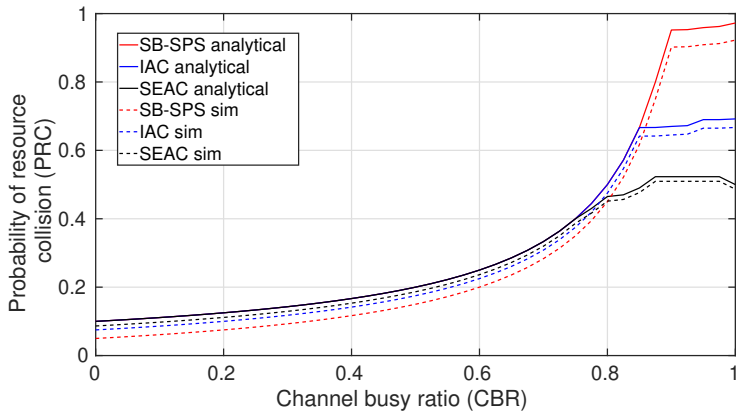
Considering that the size of the radio resource pool is fixed, we vary the vehicular density within the simulations to measure the PRC when vehicular agents adopt the type C data traffic model. Under low and medium vehicular density conditions as shown in Figure 6.6a and Figure 6.6b, both IAC and SEAC show comparable values of PRC (around 0.4) even in high CBR conditions. When there are fewer number of vehicles,



(a) PRC: measured in low vehicular density conditions



(b) PRC: measured in medium vehicular density conditions



(c) PRC: measured in high vehicular density conditions

Figure 6.6 – Variation of PRC under changing CBR conditions for the type C data traffic model [63].

the extent of blocking of resources in selection window is considerably lower and hence there is a sufficient number of resources for each vehicle to choose.

In high vehicular density scenarios, the SEAC technique has an advantage over the IAC technique with a potential to decrease the chances for a resource collision between agents. In the IAC technique, the decision is made only on the basis of local observations which may not be sufficient and accurate in all situations. Also, when new vehicles enter the simulation environment, their local observation space is insufficient. This leads to a larger probability of resource collision higher than 0.6 as observed in Figure 6.6c. This technique achieves optimal efficiency after a certain number of episodes, during which every vehicle in the simulation gathers enough information through their sensing windows.

In the SEAC technique, the decision is made by considering the experience trajectories of other agents in addition to own experiences. This is the fundamental reason that the performance of the SEAC scheduler as depicted in Figure 6.6c is between $15 - 20\%$ higher than that of the IAC scheduler. In contrast, the rule based SB-SPS does not have any mechanisms for the vehicles to interactively select their radio resources and hence the chances of resource collisions correspondingly increase at higher CBR conditions.

In the considered partially observable networked MDP environment, the experience sharing technique is a means for explicit cooperation between the agents [94]. To realise this type of cooperation, additional delays and resources (here we refer to radio resources) need to be taken into account. Based on the local rewards, it can be determined when to switch between the IAC and the SEAC schedulers so that it results in minimal usage of resources. For example, an IAC scheduler achieves nearly same performance as an SEAC scheduler in low-to-medium vehicular density scenarios. In high vehicular density scenarios, it is appropriate to switch to the SEAC scheduler. The decision of when to enable experience sharing for a subset of agents and for how many episodes is an open question that should be addressed in a more structured manner. Also, the time taken for stabilization of the learning mechanism depends on the number of agents and the specific road traffic environment perceived by each agent.

6.6.3 Transmission Success Ratio (TSR)

When the allocated radio resources are completely utilized for transmission of all the generated messages within a sidelink grant period, an agent measures a TSR value close to 1.0.

Table 6.4 – TSR measurements for V2X data traffic models [63].

Scheduler	Type A	Type B	Type C
SB-SPS	0.90 - 0.95	0.60 - 0.7	<0.4
IAC	0.90 - 0.95	0.80 - 0.85	0.65
SEAC	0.90 - 0.95	0.80 - 0.85	0.75 - 0.85

Table 6.4 documents the mean TSR measurements for the type A, B and C data traffic models under high vehicular density conditions. In case of the type C traffic model, the rule based SB-SPS records poor values of TSR (lower than 0.4) because the allocated grants have to be frequently broken and new resources should be chosen. In the IAC method, the vehicular agents interact and learn to adapt their radio resource allocation parameters in order to better utilize the allocated resources. The experience sharing mechanism in SEAC allows agents to collaboratively select their radio resources which eventually results in improved TSR values in the range between $0.75 - 0.95$ for the considered data traffic models.

6.6.4 Probability of reception

The reliability of the sidelink broadcast communication network is measured in terms of probability of reception, P_R. Here specifically, we refer to the reception of V2X messages such as CAMs and CPMs mentioned in Table 6.2. Intuitively, P_R can be measured as the ratio between the number of messages successfully received by one or more recipients to the total number of messages transmitted by one or more senders.

In the considered Cellular V2X communication network, the P_R values are directly impacted by the following issues: *(i)* Number of successful transmissions per sidelink grant, *(ii)* Number of radio resource collisions. *(iii)* Channel characteristics causing stochastic bit errors, and *(iv)* Half duplex constraints. In the chosen scenario where all vehicles generate V2X traffic as in the type A, B and C models, the channel characteristics are considered to be Wide Sense Stationary and Uncorrelated Scattering (WSSUS) given the fact that the speed of the vehicles do not vary much and only few obstacles/slow moving objects create blockages on the road. Here, the P_R values are measured in two time scales, that is, *(i)* Episode level and *(ii)* Average P_R over time after repeated simulation runs.

Episode level: The vehicular densities are made to vary throughout the length of the simulation. At the end of each episode, the P_R values are computed for each V2X data traffic model under consideration. From the plots in Figure 6.7, it can be inferred that at lower vehicular traffic densities, the SB-SPS technique fairly achieves a P_R value greater than 0.95 for each of the three data traffic models. Although the traffic model types B and C generate aperiodic traffic, there are still sufficient radio resources that can be allocated to all vehicles for both transmissions and receptions. The P_R values are only impacted by the number of radio resource collisions.

The performance of the SB-SPS scheduler for the type B traffic model declines as traffic density increases beyond the medium-to-high level. However, the IAC and SEAC schedulers demonstrate a significant improvement in performance, with an approximate $10 - 20\%$ increase in comparison to the SB-SPS scheduler.

For the type C traffic model, the metrics RRU and PRC show large differences in measurements based on the scheduler that is deployed. The rule based SB-SPS measures poor RRU values under low vehicular density conditions and larger PRC values under high vehicular density conditions. This results in a low P_R value for the SB-SPS as indicated in Figure 6.7c.

Average P_R measurements:
Considering the varying nature of the vehicular densities in the simulation, one simulation run is not sufficient to benchmark the P_R measurements. Hence, multiple simulation runs are carried out and the average P_R values over time are measured for each of the three scheduling mechanisms and data traffic models. This approach helps to evaluate the advantages of using AI based schedulers in comparison to the rule based scheduler.

Scheduler	Low	Med	High
SB-SPS	0.985 - 0.995	0.925 - 0.969	0.915
IAC	0.989 - 0.995	0.947 - 0.965	0.925 - 0.95
SEAC	0.989 - 0.995	0.947 - 0.965	0.925 - 0.95

(a) Type A data traffic model

Scheduler	Low	Med	High
SB-SPS	0.943 - 0.985	0.875 - 0.894	<0.85
IAC	0.965 - 0.985	0.856 - 0.925	0.865 - 0.890
SEAC	0.965 - 0.985	0.856 - 0.925	0.895 - 0.925

(b) Type B data traffic model

Scheduler	Low	Med	High
SB-SPS	>0.956	0.725 - 0.834	<0.75
IAC	0.96 - 0.99	0.856 - 0.925	0.795 - 0.825
SEAC	0.96 - 0.99	0.856 - 0.925	0.895 - 0.925

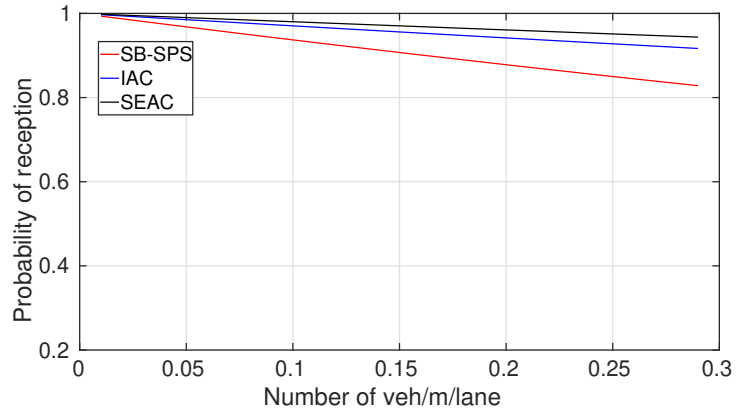
(c) Type C data traffic model

Table 6.5 – Average P_R measurements for different V2X data traffic models [63].

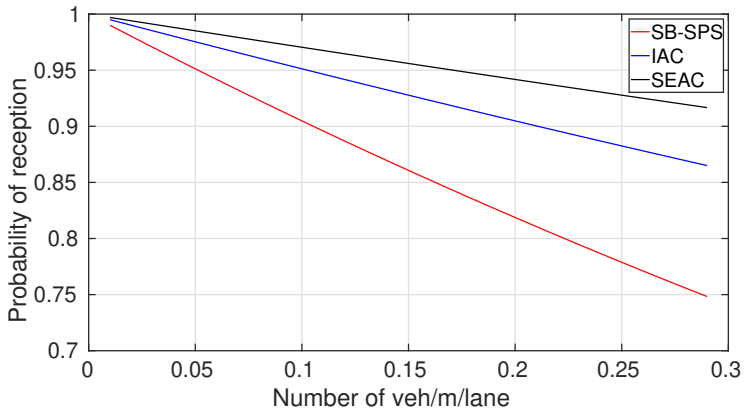
The values of P_R in Table 6.5 demonstrate that vehicles deploying the AI based schedulers are successful in achieving about $15-20\%$ greater probability of message reception in comparison to the vehicles deploying the SB-SPS for the V2X data traffic models B and C.

6.6.5 LSTM performance

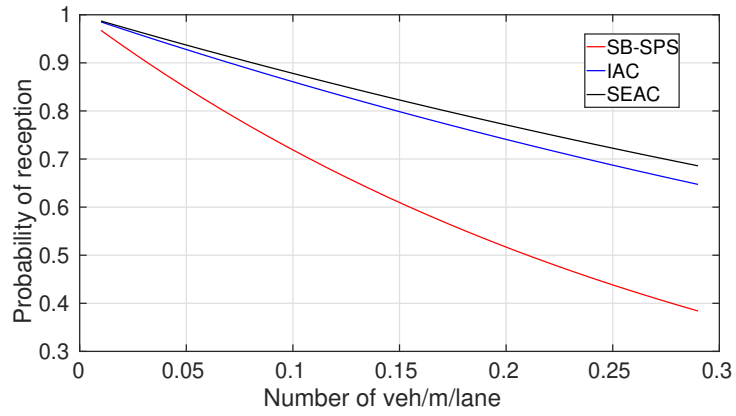
To measure the performance of the functional blocks of the state pre-processing unit shown in Figure 6.4, it is necessary to tune the parameters and hyper-parameters of the LSTM cells. It is to be noted that different variants of hyper parameter tuning can yield multiple interpretations of the results, we have carefully selected a smaller subset of



(a) P_R measurements: Type A data traffic model



(b) P_R measurements: Type B data traffic model



(c) P_R measurements: Type C data traffic model

Figure 6.7 – Variation of P_R under changing vehicular densities [63].

hyper-parameters that produce the most optimal results for the chosen Cellular V2X simulation environment.

LSTM prediction accuracy

The LSTM layer within the state processing unit plays a crucial role in predicting the future positions of the ego vehicle and its neighbors based on their previously tracked positions. The positions of the individual vehicles change over time. When considering a road traffic scenario where vehicles drive under prescribed speed limits, it has been measured from simulations that the relative distances between vehicles are wide sense stationary. This property allows for the successful deployment of LSTM in predicting future positions of the vehicles.

When the LSTM provides future time step predictions, it helps the ego vehicle to know in advance if other vehicles will come closer and appear within the range of the sensor FOV. Also, it provides an estimate of whether a vehicle will move out of the sensor FOV after a certain number of time steps (in seconds). This knowledge enables the vehicles to anticipate the nature and size of the V2X data traffic and accordingly reserve resources for shorter or longer intervals by adjusting the values of the re-selection counter *cResel*.

Figure 6.8 displays an example prediction of the LSTM from our work [63] for the future relative distance between the ego vehicle and one of its neighboring vehicles in a simulation. At time $t = 17$ s, the prediction shows that the neighboring vehicle is expected to move further away from the ego vehicle. Such predictions can be valuable in scenarios where the number of nodes in a network are constantly changing.

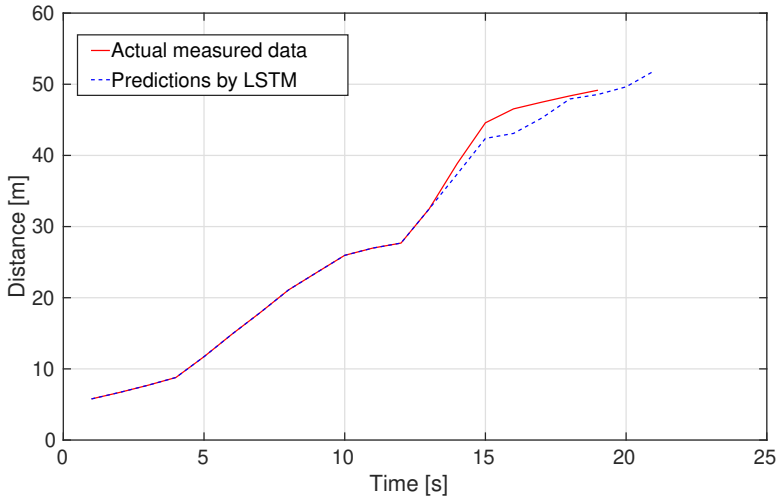


Figure 6.8 – Prediction of future vehicle positions [63].

To evaluate the performance of the LSTM layer, we measure the Mean Absolute Performance Error (MAPE) E_{mape}, which is calculated by taking the absolute difference between the actual value A_t and the predicted future value F_t, divided by the actual value, and then averaged over the total number of data points N_D.

$$E_{mape} = \frac{100}{N_D} \sum_{n=1}^{N_D} \left| \frac{A_t - F_t}{A_t} \right| \tag{6.21}$$

Table 6.6 – LSTM hyper-parameters [63].

Parameter	Values
Number of LSTM layers	2
Number of units in each LSTM	100
Number of units in dense layer	50
Activation function	Rectified Linear Unit (ReLU)
Drop out rate	0.2
Batch size [samples]	32

Figure 6.9 illustrates the values of E_{mape} over a certain number of epochs, based on the hyper-parameter settings presented in Table 6.6. During the training phase, E_{mape} measures around $10 - 25\%$ for the first 25 epochs. Subsequently, by the 75th epoch, E_{mape} drops to less than 0.01%. In the validation phase, E_{mape} is consistently less than 5%, and eventually becomes close to zero.

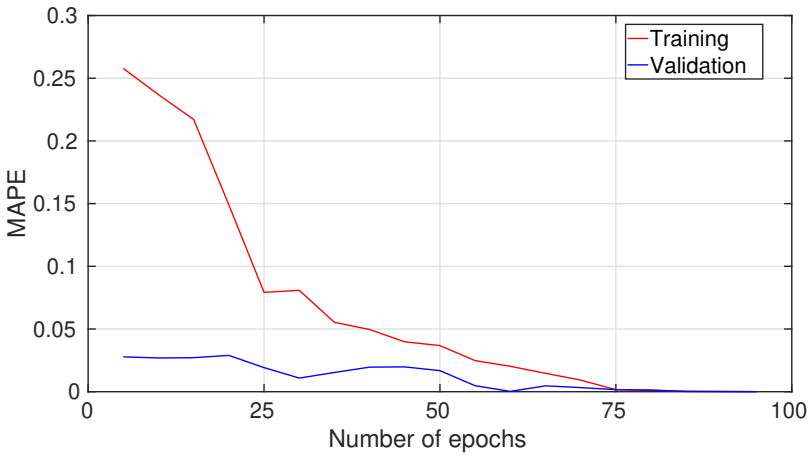
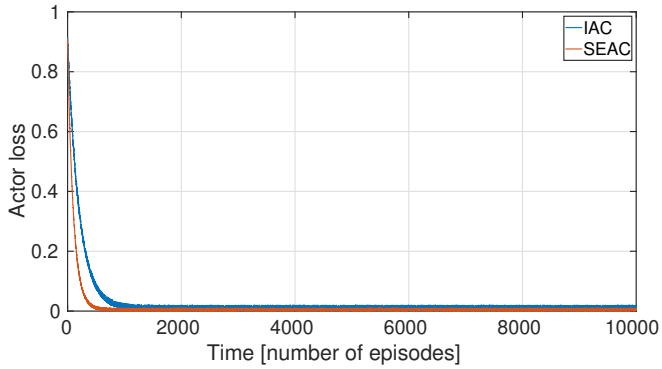


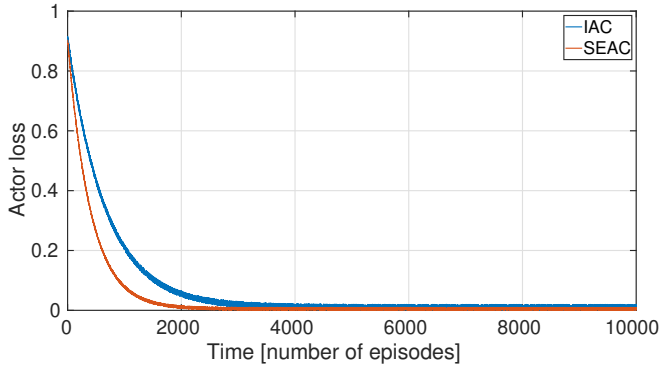
Figure 6.9 – Prediction accuracy of LSTM [63].

6.6.6 Learning curves

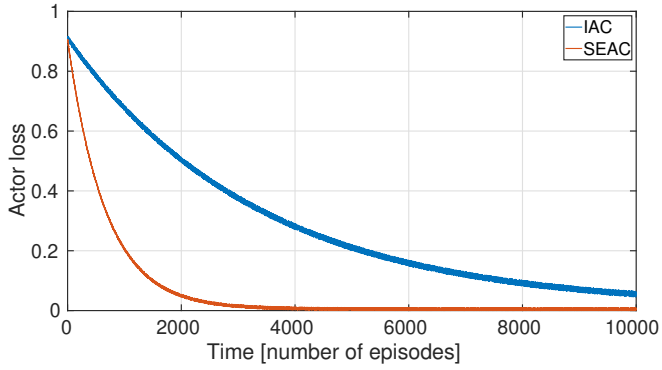
In order to compare the learning performance of the IAC and the SEAC schedulers, the actor loss and the average rewards are plotted for a significant number of episodes as shown in Figure 6.10 and Figure 6.11, respectively.



(a) Type A data traffic model

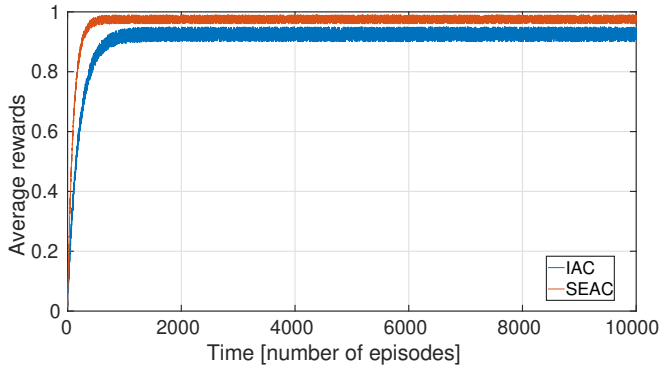


(b) Type B data traffic model

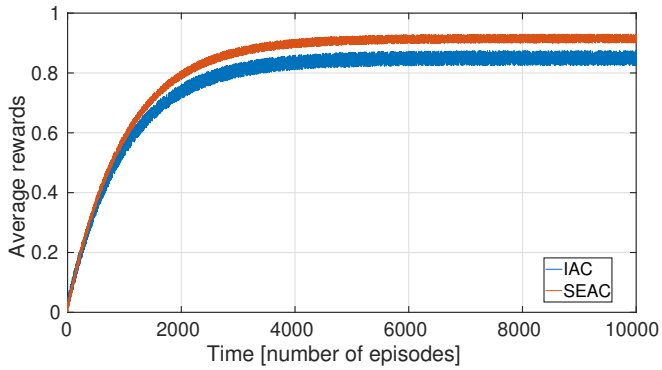


(c) Type C data traffic model

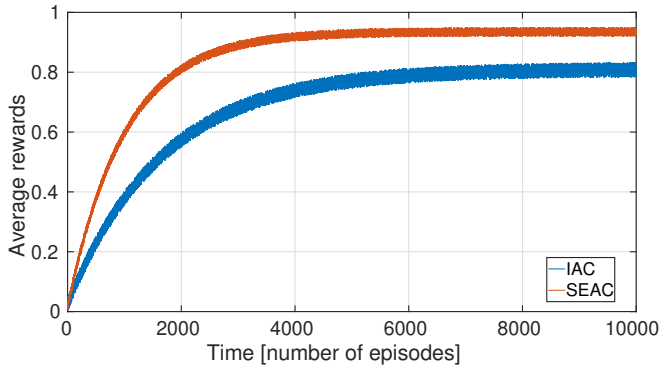
Figure 6.10 – Actor loss measurements for different types of V2X data traffic models [63].



(a) Type A data traffic model



(b) Type B data traffic model



(c) Type C data traffic model

Figure 6.11 – Average reward measurements for different types of V2X data traffic models [63].

The results shown in these two figures are obtained for a high vehicular density scenario with changing V2X data traffic patterns. The actor losses for the IAC and SEAC schedulers are computed according to Equation 6.17 and Equation 6.19, respectively,

and the average number of long term rewards corresponds to the probability of reception metric as calculated according to Equation 6.4.

The actor loss measurements in Figure 6.10 indicate that it takes a couple of episodes for the actor to start learning about the radio resource utilization of different vehicular agents and making appropriate resource selection decisions. For the data traffic models of type A and B as shown in Figure 6.10a and Figure 6.10b, the actor losses for the IAC and SEAC schedulers show fast convergence within a number of initial episodes. This directly corresponds to the average rewards as depicted in Figure 6.11a and Figure 6.11b, respectively. When the nature of the V2X data traffic shows some sort of periodic behavior as in case of the type A and B data traffic models, the IAC scheduler is able to make appropriate decisions based on local observations. There is no need for explicit cooperation by means of sharing experiences between the agents. In these two situations, it is more favourable to deploy IAC schedulers since they do not require additional overhead that comes with experience sharing.

The advantage of the SEAC scheduler can be clearly observed in case of type C data traffic model as shown in Figure 6.10c and Figure 6.11c. The fast convergence of the SEAC scheduler in Figure 6.10c (prior to 2000 episodes) improves the action selection decisions by means of experience sharing between the vehicular agents. When the nature of the data traffic is aperiodic with changing data sizes, it becomes very difficult for the IAC scheduler to make future allocation decisions just by means of local observations and own experience trajectory. Hence, it is required to switch to the SEAC scheduler that enables explicit cooperation by means of experience sharing in order to achieve higher average rewards for the agents.

6.7 Further enhancements

In a partially observable decentralized environment (such as a Cellular V2X communication network), it is found that establishment of common knowledge sharing mechanisms between agents is one of the most challenging tasks. It takes a certain number of initial episodes for an agent to learn about its environment based on the information gathered as experiences from other agents. Any form of explicit cooperation in such an environment [94] incurs overhead in terms of delays and resources needed for parameter sharing. Hence, it is important to carefully understand the requirements for experience sharing and the possibilities to switch back to the rule based scheduling algorithm or the IAC when needed.

The two variants of the actor-critic based radio resource schedulers have shown significant improvements in achieving higher transmission success ratios and reducing the risks of resource collisions. Particularly in an environment consisting of agents that enter and exit randomly, it becomes difficult to determine the mechanism of experience sharing. Experiences from agents who are present for a very short duration do not provide

useful information for other agents. Although the system can benefit when all agents can share their experiences, it is however important to develop a systematic approach to select the agents who are better eligible to share their experiences in comparison to other agents. An immediate next step for any future works in this direction requires development of structured protocols for experience sharing where the following aspects need to be considered: *(i)* Selection of agents that participate in experience sharing. *(ii)* Determine the number of rounds of experience sharing and the computational resources for each round. *(iii)* Appropriate methods to determine the type of parameters that are needed to be shared without revealing actual information of any agent.

6.8 Summary

In this chapter, we have presented a novel approach for improving the radio resource allocation in the unmanaged mode based on multi agent deep reinforcement learning. Developing further the actor-critic methodology for the radio resource allocation problem in Cellular V2X, two variants were derived: Independent Actor Critic (IAC) and Shared Experience Actor Critic (SEAC). Specifically, we formulated the communication network as a multi agent networked MDP and employ actor-critic schedulers which can learn and dynamically adapt the radio resource allocation parameters based on the changing V2X data traffic patterns. This approach shows remarkable results in mitigating the risks of radio resource collisions particularly in the unmanaged mode. Our simulation results demonstrate the qualitative improvements offered by both the AI based schedulers in achieving higher reliability of message transmission and reception. The SEAC variant achieves a transmission success ratio of about $0.7 - 0.8$ under high vehicular density conditions and aperiodic data traffic patterns. Both the IAC and SEAC schedulers achieve about $15 - 20\%$ improvement in the probability of message reception in comparison to the rule based SB-SPS while operating in the sidelink unmanaged mode.

The future scope of this work requires us to develop efficient inter-process communication paradigms to improve the simulation efficiency with regard to processing time, scalability and parallelism. By designing structured protocols for collaboration among vehicular agents, it helps to achieve better consistency in the deployment of AI based radio resource schedulers for Cellular V2X communication networks.

Chapter 7

Conclusion

In this PhD thesis, we have quantitatively analyzed the performance of the sidelink radio resource allocation modes by means of analytical and simulation based approaches. The criteria for mode selection and the possibilities for a mode switching within the sidelink modes and also between the sidelink and the cellular modes are studied in this work. Fully decentralized Multi-Agent Reinforcement Learning (MARL) based approaches were developed where the vehicles learn, interact and collaborate with each other to select their radio resources while operating in the sidelink unmanaged mode.

The first step was to design a comprehensive simulation framework that supports the implementation of the resource allocation modes complying to the ETSI specifications for the LTE/5G-NR V2X access technologies. Subsequently, we identified the influencing parameters and the configurable entities (such as radio resource pool, frequency bands, sidelink bandwidth part etc.) within the access layers of the protocol stack. The selection of appropriate road traffic scenarios and parameters such as variations in vehicular density, sensor configuration etc., plays an equally important role because they directly impact the triggering conditions of different V2X messaging protocols.

On simulating the radio resource allocation modes under different vehicular density conditions and diverse V2X data traffic patterns, it was observed that the rule based scheduling algorithms namely, Configured Grant (CG) type II and the Sensing Based Semi Persistent Scheduling (SB-SPS) were not able to efficiently adapt their parameters to successfully transmit all the messages generated within a sidelink grant period. These algorithms were initially developed based on the assumptions that the V2X data traffic will follow a certain pattern with deterministic data sizes. However in a realistic traffic scenario, such assumptions are no longer valid. The allocated resources are either under utilized or frequent re-allocations have to be made because the dynamically changing data sizes cannot fit into the previous allocations. Most often, it was observed that more than one vehicle selected the same resource for its transmission which resulted in co-channel interference. This is more prominent for vehicles operating in the un-

managed mode because the sensing mechanism in the SB-SPS algorithm does not provide sufficient information about the radio resources utilized by other road traffic participants. These observations led us to formulate mathematical representations to formally characterize some effects such as sidelink grant breaks, grant wastage and radio resource collisions. Furthermore, by calculating the probability of message reception metric, it was possible to assess the reliability of the sidelink broadcast communication links within the simulation.

With a necessity to support continuous transmission and reception of messages, it is essential for a vehicle to choose the appropriate radio resource allocation mode and be able to switch between different modes seamlessly. After careful considerations of the involved procedures and the latency in each phase of mode switching, we have formulated specific strategies for mode switching. Simulation results have shown that switching from the sidelink unmanaged mode to the sidelink managed mode incurs relatively smaller mode switch latency in comparison to the reverse process. Also switching from the cellular (Uu) to the sidelink managed mode is seamless because the vehicle remains connected to the base station and does not have to perform the procedures of detection and synchronization separately. The switching from the Uu/sidelink managed mode to the unmanaged mode incurs large synchronization latency particularly when vehicles are located inside tunnels.

Following a detailed performance evaluation of the radio resource allocation modes and the strategies for mode switching, it was found that the challenges and the limitations of the unmanaged mode need to be addressed in order to make it suitable for diverse V2X data traffic patterns and achieve better radio resource utilization. Although the managed mode better coordinates the radio resource allocation mechanism, it is to be noted that the vehicle cannot remain connected to the cellular network infrastructure always and the mode switching from the unmanged mode to any other mode is not feasible in all situations.

One of the main limitations in the rule based SB-SPS algorithm is that there is no mechanism for vehicles to interact and share information about their radio resource selection. Although this aspect is extensively discussed in the research community and in standardization, we have found that the implementation of these mechanisms in a rule based setting does not solve the problems especially in scenarios with aperiodic data traffic patterns. This led us to investigate the feasibility of using MARL techniques for the radio resource allocation problem. We have formulated a decentralized multi agent networked Markovian Decision Process (MDP) model of the Cellular V2X communication network where each vehicle executes an Artificial Intelligence (AI) based scheduler. Two variants of the actor-critic schedulers are deployed in each agent namely, Independent Actor Critic (IAC) and Shared Experience Actor Critic (SEAC). Results have shown that these AI based schedulers are efficient in achieving about $15-20\%$ improvements in communication link reliability along with better radio resource utiliza-

tion and a lower probability of radio resource collisions in comparison to the rule based SB-SPS algorithm.

Putting everything together, this PhD thesis provided a detailed evaluation of the radio resource allocation modes in Cellular V2X and methodically addressed their challenges and limitations. The development of an AI based radio resource scheduler that operates in a fully decentralized environment is considered to be a valuable research contribution in this work. The analytical methods adopted in this thesis to formally characterize the V2X data traffic patterns and other measurable parameters will definitely be useful for real-world experiments as well. We further believe that field measurements can provide useful insights about the channel load variations caused by different types of V2X messaging protocols. In particular, we look forward to the introduction of the enhancements for radio resource allocation in the subsequent releases of the Cellular V2X standardization and at the same time work towards bringing systematic improvements to the AI based approaches so that they are more efficient, scalable and safe for deployment.

Appendix A

Artery-C dependencies

Artery-C currently uses the following software packages (please note the specific version):

Table A.1 – Artery-C dependencies

Software	Version
C++ compiler support	C++ 11 onwards
OMNeT++	5.7
SUMO	1.18.0
INET	3.6.5
Vanetza	-
PyBinds	11
Boost	1.65.1
GDB	8.1.1

The latest versions of the dependent packages can be downloaded at the following URLs [last accessed on 1.11.2023]:

1. Vanetza- https://github.com/riebl/vanetza.
2. INET- https://github.com/inet-framework/inet
3. Simu5G- https://github.com/Unipisa/Simu5G

The source code of the Artery-C framework can be publicly accessed at: https://github.com/anupama1990/Artery-C.

Appendix B

Mode switching control: description of events and actions

A description of events and actions that trigger different state transitions within the mode switching control module of Figure B.1) is provided as follows:

1. `IDLE(SL-UM)` => `IDLE(SL-UM)`
   Event: When a vehicle is not connected to the base station (marked as N=0, S=N.A, D=x).
   Action: RRC state remains as *IDLE* and the vehicle operates in the (SL-UM) mode.
   Note: This happens when a vehicle drives for long stretches where cellular network connection in not available or when a vehicle is refused a connection by the base station after multiple attempts.

2. `IDLE(SL-UM)` => `INACTIVE(SL-M)`
   Event: When a vehicle drives to an area of cellular network coverage and establishes connection with the base station but has not started transmitting yet (marked as N=1, S=x, D=0).
   Action: RRC state switches from *IDLE* to *INACTIVE* and the sidelink managed mode (SL-M) is chosen for radio resource allocation.
   Note: It can switch directly to `CONN(SL-M)` or `CONN(Uu)` states but remaining in the *INACTIVE* mode helps to save energy.

3. `IDLE(SL-UM)` => `CONN(SL-M)`
   Event: When a vehicle is connected to the base station and transmits V2X messages of smaller data sizes (marked as N=1, S=x, D=L).
   Action: RRC state switches from *IDLE* to *CONN* and the sidelink managed mode (SL-M) is chosen for safety-critical V2X services.
   Note: -

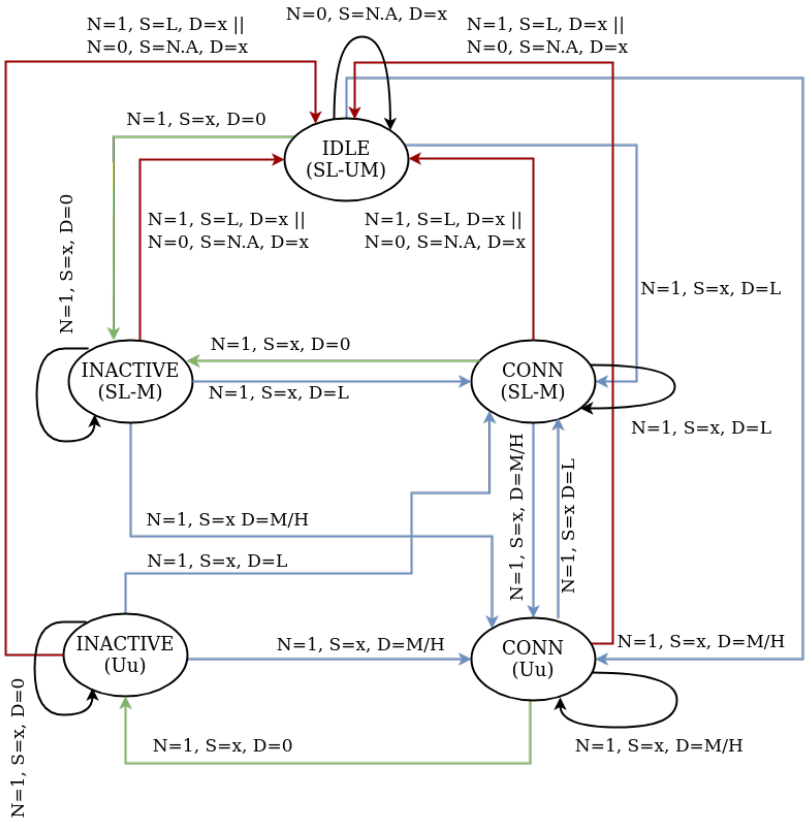


Figure B.1 – Mode switch control – state transitions

4. `IDLE(SL-UM) => CONN(Uu)`
   Event: When a vehicle is connected to the base station and transmits messages of larger data sizes (marked as N=1, S=x, D=M/H).
   Action: RRC state switches from *IDLE* to *CONN* and the cellular mode (Uu) is chosen when the vehicle wants to transmit messages of larger data sizes.
   Note: -

5. `INACTIVE(SL-M) => INACTIVE(SL-M)`
   Event: When a vehicle is connected to the base station and does not transmit any data (marked as N=1, S=x, D=0).
   Action: RRC state remains *INACTIVE* and the vehicle operates in the sidelink managed mode.
   Note: -

6. `INACTIVE(SL-M) => CONN(SL-M)`
   Event: When a vehicle is connected to the base station and transmits V2X messages of smaller data sizes (marked as N=1, S=x, D=L).

Action: RRC state switches from *INACTIVE* to *CONN* since the vehicle has started transmitting data. It continues to operate in the managed mode as long as the data traffic load does not get large.
Note: -

7. `INACTIVE(SL-M) => CONN(Uu)`
   Event: When a vehicle is connected to the base station and transmits messages of larger data sizes (marked as N=1, S=x, D=M/H).
   Action: RRC state switches from *INACTIVE* to *CONN* since the vehicle has started transmitting data. It switches to operate in the cellular (Uu) mode since the data traffic load increases.
   Note: -

8. `INACTIVE(SL-M) => IDLE(SL-UM)`
   Event: When a vehicle is not connected to the base station (marked as N=1, S=L, D=x || N=0, S=N.A, D=x).
   Action: RRC state switches from *INACTIVE* to *IDLE* since the vehicle is currently not connected to the base station.
   Note: This happens when the vehicle is driving in an area where network coverage is either not sufficient (e.g. cell borders) or completely unavailable.

9. `CONN(SL-M) => CONN(SL-M)`
   Event: When a vehicle is connected to the base station and transmits V2X messages of smaller data sizes (marked as N=1, S=x, D=L).
   Action: RRC state remains as *CONN* and the vehicle continues to operate in the sidelink managed mode.
   Note: -

10. `CONN(SL-M) => INACTIVE(SL-M)`
    Event: When a vehicle is connected to the base station and does not transmit data (marked as N=1, S=x, D=0).
    Action: RRC state switches from *CONN* to *INACTIVE* and the vehicle continues to operate in the sidelink managed mode.
    Note: -

11. `CONN(SL-M) => CONN(Uu)`
    Event: When a vehicle is connected to the base station and intends to transmit messages of larger data sizes (marked as N=1, S=x, D=M/H).
    Action: RRC state remains as *CONN* and the vehicle switches to operate in the cellular (Uu) mode since the data traffic load increases.
    Note: -

12. `CONN(SL-M) => IDLE(SL-UM)`
    Event: When a vehicle is not connected to the base station or experiences poor signal reception (marked as N=1, S=L, D=x || N=0, S=N.A, D=x).
    Action: RRC state switches from *CONN* to *IDLE* and the vehicle switches to operate in the sidelink unmanaged mode.
    Note: It autonomously selects its radio resources from a pre-configured pool.

13. `INACTIVE(Uu) => INACTIVE(Uu)`
    Event: When a vehicle is connected to the base station and operates in the cellular (Uu) mode but is currently not transmitting any data (marked as N=1, S=x, D=0).
    Action: RRC state remains as *INACTIVE* and the vehicle continues to operate in the cellular (Uu) mode until the V2X data traffic load changes.
    Note: -

14. `INACTIVE(Uu) => CONN(SL-M)`
    Event: A vehicle is connected to the base station and is transmitting safety-critical V2X messages of smaller data sizes (marked as N=1, S=x, D=L).
    Action: RRC state switches from *INACTIVE* to *CONN* and the vehicle chooses to operate in the sidelink managed mode since the data traffic load is low.
    Note: -

15. `INACTIVE(Uu) => CONN(Uu)`
    Event: When a vehicle is connected to the base station but needs to transmit messages of larger data sizes (marked as N=1, S=x, D=M/H).
    Action: RRC state switches from *INACTIVE* to *CONN* and the vehicle continues to operate in the cellular (Uu) mode since the data traffic load is high.
    Note: -

16. `INACTIVE(Uu) => IDLE(SL-UM)`
    Event: When a vehicle is no longer connected to the base station but needs to transmit data (marked as N=1, S=L, D=x || N=0, S=N.A, D=x).
    Action: RRC state switches from *INACTIVE* to *IDLE* and the vehicle operates in the sidelink unmanaged mode.
    Note: -

17. `CONN(Uu) => CONN(Uu)`
    Event: When a vehicle is connected to the base station and operates in the cellular (Uu) mode (marked as N=1, S=x, D=M/H).
    Action: RRC state remains as *CONN* and the vehicle continues to operate in the cellular (Uu) mode until the V2X data traffic load changes.
    Note: -

18. `CONN(Uu) => INACTIVE(Uu)`
    Event: When a vehicle is connected to the base station but is currently not transmitting any data (marked as N=1, S=x, D=0).
    Action: RRC state switches from *CONN* to *INACTIVE* and the vehicle continues to operate in the cellular (Uu) mode until the V2X data traffic load changes.
    Note: -

19. `CONN(Uu) => CONN(SL-M)`
    Event: When a vehicle is connected to the base station but is transmitting only safety critical V2X messages of smaller data sizes (marked as N=1, S=x, D=L).
    Action: RRC state remains as *CONN* and the vehicle switches to operate in the sidelink managed mode.
    Note: -

20. `CONN(Uu) => IDLE(SL-UM)`
    Event: When a vehicle is no longer connected to the base station but needs to transmit data (marked as N=1, S=L, D=x || N=0, S=N.A, D=x).
    Action: RRC state switches from *CONN* to *IDLE* and the vehicle switches to operate in the sidelink unmanaged mode since it is not connected to the base station.
    Note: -

Appendix C

Statement on contributions with regard to self-citations

The original peer-reviewed publications that lead to this PhD thesis are listed below along with the respective author contributions, copyright notes and the license information (wherever required).

[58] A. Hegde and A. Festag, *"Mode Switching Strategies in Cellular V2X,"* IFAC-PapersOnLine, vol. 52, no. 8, pp. 81–86, 2019 10th IFAC Symposium on Intelligent Autonomous Vehicles (IAV), Gdansk, Poland, doi: 10.1016/j.ifacol.2019.08.052, © 2019, IFAC (International Federation of Automatic Control) Hosting by Elsevier Ltd.

- Decomposition of the mode switch procedure into subsequent phases.
- Formulation of strategies for mode switching between sidelink modes.
- Simulation based evaluation & result analysis.

[60] A. Hegde and A. Festag, *"Artery-C – An OMNeT++ Based Discrete Event Simulation Framework for Cellular V2X,"* in ACM Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM), Alicante, Spain, Nov. 2020, pp. 450–456, doi: 10.1145/3416010.3423240, © 2023 ACM, Inc. Extended version on arXiv: (URL:) http://arxiv.org/abs/2009.05724, License information: published under CC0 1.0 Deed, copyright is held by the author(s). Software repository URL: https://github.com/anupama1990/Artery-C, License information: GPL-3.0, copyright (C) 2007 Free Software Foundation, Inc.

- Definition of the system architecture for a combined simulation of the Cellular V2X protocol stack and a realistic road traffic scenario.

- Development of Cellular V2X protocol stack layers and the control & user planes.
- Tuning of Cellular V2X and road traffic related parameters for evaluation and result analysis.

[61] A. Hegde and A. Festag, *"Mode Switching Performance in Cellular V2X,"* in 2020 IEEE Vehicular Networking Conference (VNC), 2020, p. 8, doi: 10.1109/VNC51378.2020.9318394, © 2020, IEEE.

- Formulation of latency calculations at each stage of mode switching.
- Tuning of Cellular V2X and road traffic related parameters for evaluation and result analysis.

[64] A. Hegde, S.Lobo, R. Stahl and A. Festag, *"Modeling Cellular Network Infrastructure in SUMO,"* in SUMO Conference 2021, pp. 99–113, doi: 10.52825/scp.v2i.97, copyright (c) 2022, Anupama Hegde, Ringo Stahl, Silas Lobo, Andreas Festag.

- Definition of the system architecture for modeling cellular network infrastructure within the Ingolstadt Traffic Scenario (InTAS).
- Modeling of hexagonal cell geometry and achieve automation in the generation of attributes related to a base station.

[62] A. Hegde, S. Lobo and A. Festag, *"Enabling Cellular V2X for Vulnerable Road User Protection in C-ITS,"* 2022 18th International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob), Thessaloniki, Greece, 2022, pp. 118-123, doi: 10.1109/WiMob55322.2022.9941707, © 2022, IEEE.

- Integration of the VRU Awareness (VA) service within the network simulator `Artery-C`.
- Define the concept of fairness in allocation of radio resources between different road traffic participants.
- Modeling of Vehicle-to-Pedestrian (V2P) channel characteristics.
- Tuning of Cellular V2X and road traffic related parameters for evaluation and result analysis.

[59] A. Hegde, D. Quentin, C. Mariyaklla, A. Festag, and F. Klingler, *"Radio Resource Allocation for Collective Perception in 5G-NR Vehicle-to-X Communication Systems,"* in 2023 IEEE Wireless Communication and Networking Conference (WCNC), Glasgow, Scotland, UK, Mar. 2023, p. 6, doi: 10.1109/WCNC55385.2023.10118606, © 2023, IEEE.

- Development of V2X data traffic models based on message generation frequency and data sizes.
- Integration of Collective Perception (CP) service within the network simulator `Artery-C`.
- Formulation of analytical models to formally characterize grant breaks, grant wastage and probability of radio resource collision.

[63] A. Hegde, R. Song and A. Festag, *"Radio Resource Allocation in 5G-NR V2X: A Multi-Agent Actor-Critic Based Approach"*, in IEEE Access, vol. 11, pp. 87225-87244, 2023, doi: 10.1109/ACCESS.2023.3305267. License information: published under CC BY-NC-ND 4.0 Deed and the copyright is held by the author(s).

- Development of an online learning based environment that combines the network simulator `Artery-C` with a Deep Reinforcement Learning (DRL) based environment in `Tensorflow Python`.
- Formulation of the Cellular V2X network as a multi-agent networked Markovian Decision Process (MDP) and derivation of two variants of actor-critic schedulers: Independent Actor Critic (IAC) and Shared Experience Actor Critic (SEAC).
- Design of the Deep Neural Network (DNN) architecture for the implementation of actor-critic algorithms.

Other publications

[107] R. Song, A. Hegde, N. Senel, A. Knoll and A. Festag, *"Edge-Aided Sensor Data Sharing in Vehicular Communication Networks,"* in 2022 IEEE 95th Vehicular Technology Conference (VTC2022-Spring), Helsinki, Finland, 2022, p. 7, doi: 10.1109/VTC2022-Spring54318.2022.9860849, © 2022, IEEE.

Acronyms

3GPP	Third Generation Partnership Project
5G-NR	Fifth Generation New Radio
A2C	Advantage Actor-Critic
ACI	Adjacent Channel Interference
ADAS	Advanced Driver Assistance Systems
AGC	Automatic Gain Control
AI	Artificial Intelligence
AMC	Adaptive Modulation and Coding
AoA	Angle of Arrival
AoD	Angle of Departure
AWGN	Additive White Gaussian Noise
BS	Base Station
BSR	Buffer Status Report
BTP	Basic Transport Protocol
C-ITS	Cooperative Intelligent Transport Systems
CA	Cooperative Awareness
CACC	Cooperative Adaptive Cruise Control
CAM	Cooperative Awareness Message
CBR	Channel Busy Ratio
CDF	Cumulative Distribution Function
CDL	Cluster Delay Line
CG	Configured Grant
CID	Connection Identifier
CNN	Convolutional Neural Networks
CP	Collective Perception
CPM	Collective Perception Message
CR	Channel Occupancy Ratio
CSR	Candidate Slot (or subframe) Resource
D2D	Device-to-Device

DCC	Decentralized Congestion Control
DCI	Downlink Control Information
DEN	Decentralized Environmental Notification
DENM	Decentralized Environmental Notification Message
DES	Discrete Event Simulation
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMRS	Demodulation Reference Signal
DNN	Deep Neural Network
DRL	Deep Reinforcement Learning
DRR	Deficit Round Robin
E2E	End-to-End
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
F2M	Fixed-to-Mobile
FFT	Fast Fourier Transform
FOV	field-of-view
FR	Frequency Range
FRIV	Frequency Resource Indicator Value
FSM	Finite State Machine
GBDCM	Geometry Based Deterministic Channel Model
GBSCM	Geometry Based Stochastic Channel Model
GEM	Global Environmental Model
GN	Geo-Networking
gNB	Next Generation Node B
GNSS	Global Navigation Satellite System
HARQ	Hybrid Automatic Repeat Request
HMI	Human Machine Interface
IAC	Independent Actor Critic
IAT	Inter Arrival Time
ICI	Inter Carrier Interference
InTAS	Ingolstadt Traffic Scenario
ISI	Inter Symbol Interference
ITS	Intelligent Transport Systems
ITS-S	ITS-Stations
ITU-R	International Telecommunication Union - Radiocommunication
LCID	Logical Connection Identifier
LEM	Local Environmental Model
LOS	Line of Sight

LSTM	Long Short Term Memory
LTE	Long Term Evolution
LTE-A	Long Term Evolution-Advanced
M2M	Mobile-to-Mobile
MAC	Medium Access Control
MAPE	Mean Absolute Performance Error
MAPEM	MAP (topology) Extended Message
MARL	Multi-Agent Reinforcement Learning
MAS	Multi Agent System
MAXCI	Maximum Carrier to Interference Ratio
MCS	Modulation and Coding Scheme
MDP	Markovian Decision Process
MIB	Master Information Block
ML	Machine Learning
mMTC	Massive Machine-to-Machine Type Communication
MS	Mobile Station
NIC	Network Interface Card
NLOS	Non Line of Sight
OMNeT++	Open Modular Network Testbed in C++
PDB	Packet Delay Budget
PDCP	Packet Data Convergence Protocol
PDU	Protocol Data Unit
PF	Proportional Fair Queuing
PHY	Physical layer
POC	Perceived Object Container
POI	point-of-interest
pQoS	Predictive Quality-of-Service
PRC	Probability of Resource Collision
PSBCH	Physical Sidelink Broadcast Channel
PSCCH	Physical Sidelink Control Channel
PSFCH	Physical Sidelink Feedback Channel
PSSCH	Physical Sidelink Shared Channel
QoS	Quality of Service
RACH	Random Access Channel
RAN	Radio Access Network
RB	Resource Block
RF	Radio Frequency
RL	Reinforcement Learning
RLC	Radio Link Control
RNN	Recurrent Neural Networks

ROHC	Robust Header Compression
RQ	research question
RRC	Radio Resource Control
RRI	Resource Reservation Interval
RRU	Radio Resource Utilization
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indicator
RSU	Road Side Unit
S-PSS	Sidelink Primary Synchronization Signal
S-SSS	Sidelink Secondary Synchronization Signal
SB-SPS	Sensing Based Semi Persistent Scheduling
SBCH	Sidelink Broadcast Channel
SC	Sidelink Configuration
SCI	Sidelink Control Information
SCS	subcarrier spacing
SDU	Service Data Unit
SEAC	Shared Experience Actor Critic
SI	System Information
SIB	System Information Block
SIC	Sensor Information Container
SINR	Signal-to-Interference Noise Ratio
SL	sidelink
SL PT-RS	Sidelink Phase Tracking Reference Signal
SL-BWP	Sidelink Bandwidth Part
SL-CSI-RS	Sidelink Channel State Information Reference Signal
SMC	Station Data & Management Container
SPATEM	Signal Phase And Timing Extended Message
SPS	Semi Persistent Scheduling
SR	Scheduling Request
SRA	Sidelink Resource Allocation
STCH	Sidelink Transport Channel
TB	Transport Block
TD	Temporal Difference
TraCI	Traffic Command Interface
TRIV	Time Resource Indicator Value
TSR	Transmission Success Ratio
UE	User Equipment
URLLC	Ultra Reliable and Low Latency Communication
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network

V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VA	VRU Awareness
VAM	VRU Awareness Message
VPR	Vehicle Penetration Rate
VRU	Vulnerable Road User
WSSUS	Wide Sense Stationary and Uncorrelated Scattering

Mathematical symbols

α_a	step-size for actor update
α_c	step-size for critic update
β	discount factor
γ^{th}	SINR threshold
γ_t^{jj}	received SINR for agent j
δ_t	temporal difference
Δd	normalized distance of the neighbor vehicle
$\zeta^i(p)$	channel noise power at the pth subcarrier
η	radio resource utilization per transmission
λ	weight factor for experience parameter
μ	subcarrier spacing parameter
π	mathematical constant whose value is 3.14159/ used to represent policy in machine learning algorithms
σ	receiver noise
a_t^i	action from agent i at time t
$cResel$	resource re-selection counter
e_{ij}	number of overlapping slots between vehicle i and another vehicle j
f_c	carrier frequency
h_{BS}	height of base station
h_{MS}	height of mobile station
i	agent index
k	number of occupied subchannels
k_{subCH}	number of subchannels allocated for a given value of $N_{sl-mnpr}$
m	number of occupied time slots
$n_{subCH,1}^{start}$	starting subchannel index for the first frequency resource
o_t^i	observation for an agent i at time t

r_t^i	reward for an agent i at time t
s_t^i	state of an agent i at time t
t	time step
w	lane width
$x^j(n-l)$	time shifted input data signal
A	action space
A_t	actual value
C_c^i	number of radio resources configured within a sidelink grant for vehicle i
$C_{c,e}^i$	number of radio resources configured by agent i per episode e
C_u^i	number of radio resources utilized by vehicle i within a sidelink grant
$C_{u,e}^i$	number of radio resources utilized by agent i per episode e
$C^{k\times m}$	radio resource pool showing k subchannels and m time slots occupied
$C^{K\times M}$	radio resource pool consisting of a total of K subchannels and M time slots
E_{mape}	mean absoulte performance error
E_t	number of edges at time t
E_T	total number of episodes
F_t	predicted future value
G^i	Doppler variant channel frequency matrix
G_t	undirected graph
H^{ij}	channel gain between agents i and j
H^l	interference channel gain between agents i and l other agents which choose the same radio resource
I_{sf}	indicator variable for sensor FOV
K	total number of available subchannels
L	number of neighboring vehicles (agents) to the ego vehicle (agent) in the simulation
L_{taps}	number of channel taps
M	total number of available time slots
N	total number of vehicles/agents in the simulation
N_c^i	number of agents which select same resource as that of vehicle/agent i
N_D	number of data points
N_{re}^i	number of successful transmissions after re-selections for agent i

$N_{sl-mnpr}$	*sl-MaxNumberPerReserve*
N^i_{txf}	number of failed transmissions for agent i
N^i_{txs}	number of successful transmissions for agent i
$N_{T,e}$	total number of agents per episode e
O	observation space
P	state transition probability
$P^i(f)$	transmit power component at the pth subcarrier
P_{ACI}	adjacent channel interference power
P_{ICI}	inter carrier interference power
P_{ISI}	inter symbol interference power
P_N	noise power
P^i_R	probability of reception for agent i
$P_{rsvp-TX}$	resource reservation period, transmit
P_{SIG}	signal power
PL_H	pathloss, highway
PL_{nlos}	pathloss, non line-of-sight
PL_{Ur}	pathloss, urban
$\bar{R}$	average reward
S	state space
S_A	set of assigned resources for transmission
$S_{i,n}$	selection window overlap matrix between vehicle i and another vehicle n
T	episode length
T_{Det}	detection latency
T_g	episode length/one sidelink grant period
T_M	message arrival time
T_{MS}	mode switch latency
T^{SL}_{proc}	sidelink processing delay in [ms]
T_{RA}	resource allocation latency
T^i_{RA}	resource allocation latency experienced by agent i
$T_{RRC_{CRQ}}$	RRC connection request time
T_{sel}	selection window
T_{SIB21}	time needed for acquisition of system information block (SIB) 21
T_{SL}	configuration latency
T_{Syn}	synchronization latency
$\bar{V}_{bl}$	mean vehicle blockage loss
$X^i(f)$	frequency domain representation of input signal
Z_{ij}	probability of radio resource collision between vehicle i and another vehicle j

List of Figures

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