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A Systematic Literature Review in Distributed Resource Allocation for C-V2X

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ABSTRACT

Vehicular networks are the key paradigm of the Internet of Vehicles (IoV) as the extension of the Internet of Things (IoT) notion in Intelligent Transportation Systems (ITS) which can assist in the development of autonomous driving in smart cities. This technology can provide a wide variety of onboard data services, such as road safety, and increase traffic efficiency by connecting vehicles with road infrastructure and pedestrians. However, it is a challenging task to provide a satisfactory quality of service (QoS) to this network due to a number of limiting factors such as resource collision, resource interference, and congested channels because of the network topology and rapid changes produced by the high mobility as well as hardware imperfections and the anticipated growth of vehicular network devices. As a result, it will be essential to ensure that the resources of the available cellular network are allocated and used in the most efficient possible way. To achieve these goals, 3GPP has standardized the cellular vehicle to everything (C-V2X) with two versions, the long-term evolution-V2X (LTE-V2X) in Release 14 and the new radio-V2X (NR-V2X) in Release 16, as prominent technologies to improve resource allocation for vehicular networks. In order to capture the continuous effort for improving resource allocation, we present a systematic literature review (SLR) on distributed resource allocation (DRA) schemes for the two cellular-based vehicular network technologies. First, we discuss the technical configuration of resource allocation in the light of LTE-V2X and NR-V2X technologies and classify the state-of-the-art for each technology. Afterward, we explain the impact of machine learning (ML) and congestion control (CC) on the DRA. Then, we point out the primary performance metrics and simulation tools that were used in the related work. Ultimately, we highlight the challenges, open issues, and opportunities for DRA in C-V2X and outline several promising future research directions.

1. INTRODUCTION

Road traffic injuries pose a substantial burden on public health in terms of morbidity, mortality, and disability. Annually, over 1.2 million people perish and an additional 50 million suffer injuries as a result of road accidents worldwide. Accidents involving motor vehicles are the leading cause of death for individuals aged 15 to 29. Over 90% of all deaths are estimated to occur in low-and middle-income countries, which account for roughly half of the world's registered vehicles. Road traffic accidents are projected to be the seventh-leading cause of death by 2030 if the current trend continues and no proper action is taken [1]. The growing quantity of vehicles on the roadways, as a result of the growing human population, strains the world's transportation networks and causes a variety of problems, including parking difficulties, accidents, long commute times, traffic congestion, and increased pollution. Therefore, a reliable and secure transportation system is of utmost importance. Vehicular networks play a vital role in the Internet of Things (IoT), giving rise to the Internet of Vehicles (IoV) [1], a sophisticated extension of IoT in Intelligent Transportation Systems (ITS). IoT is regarded as a fundamental enabling technology for smart cities, where intelligent devices can interact with one another [2]. IoV is primarily intended to facilitate a real-time network between vehicles, pedestrians, and roadside infrastructure.

Despite the enormous potential of smart cities, vehicular networks are currently confronted with a multitude of technological obstacles in terms of their performance and security. In light of this, vehicular cellular technology, also referred to as cellular-V2X (C-V2X) [3], which operates in both the 5.9-GHz range and the licensed spectrum allocated for cellular networks, has emerged to enable vehicular networks and overcome these obstacles. Third Generation

Partnership Project (3GPP) Release 14 outlined the initial C-V2X technology, also known as the long-term evolution-V2X (LTE-V2X). Release 16 of the 3GPP has introduced NR-V2X as the most recent version of C-V2X technology. C-V2X provides exceptional performance in coverage range, reliability, throughput, and latency. Although C-V2X holds promise for improving communication between vehicles, effectively using this technology requires overcoming hurdles in allocating resources.

Consequently, the C-V2X resource allocation has attracted the researcher's interest over the past few years. Radio frequencies, being valuable and scarce resources, require careful management to minimize interference and collisions. In addition, resources allocation in C-V2X networks encounters unique challenges as a result of the dynamic and diverse characteristics of vehicular environment. These challenges arise from factors such as different vehicle densities, unpredictable mobility patterns, and diverse quality-of-service (QoS) requirements. To tackle such challenges, it is necessary to employ advanced resource allocation strategies that can dynamically adjust to changing network environments while simultaneously catering to the varying requirements of different applications. A key requirement in C-V2X networks is to guarantee reliable connectivity for safety-critical applications, such as cooperative awareness and collision avoidance. These applications require fast and reliable communication, which means that communication resources need to be allocated efficiently to give priority to significant messages. Moreover, these kinds of networks are capable of accommodating a diverse array of applications that have various requirements in terms of bandwidth and latency. These applications include traffic management, infotainment, and autonomous driving. Optimizing network utilization and meeting different quality of service (QoS) requirements of applications requires efficient resource allocation. This allocation must ensure fairness and maximize total system throughput. Therefore, resource allocation in C-V2X is crucial for enhancing the performance of IoV applications.

As there is always an absence of base station (BS) services in some places, two types of resource allocation have been proposed by C-V2X, which are the centralized mode and the decentralized mode. In the context of LTE-V2X, these modes are referred to as modes 3 and 4, whereas in NR-V2X, they are described as modes 1 and 2. For the centralized mode, resources are scheduled and assigned to vehicles by either the evolved Node B (eNB) in LTE or the generation Node B (gNB) in NR. In addition, in dynamic vehicle environments, traditional centralized resource allocation systems may encounter scalability and latency issues. Centralized algorithms necessitate a centralized controller to gather and analyze global network data, which can result in increased communication overhead and delay, especially in large-scale networks with significant mobility. On the other hand, DRA methods provide a more scalable and responsive solution for C-V2X networks in the decentralized mode, vehicles autonomously pick their resources using the sensing-based semi-persistent scheduling (SB-SPS) algorithm by considering local data, such as channel conditions, traffic density, and application needs. Furthermore, distributed techniques enable the delegation of decision-making, allowing for swift adaptation to local changes in network conditions and minimizing dependence on centralized coordination. Moreover, DRA facilitates proactive and opportunistic sharing of resources among nearby vehicles, hence promoting collaborative and efficient utilization of the resources. This adaptability is especially beneficial in dynamic vehicular environments where the structure of the network and the conditions of traffic might change rapidly.

Numerous solutions for LTE-V2X and NR-V2X modes have been presented in the past, concentrating primarily on mode 4 and mode 2, respectively. It is worthwhile to highlight that eNB/gNB control is the main reason why mode 3 and mode 1 are less challenging. In contrast, mode 4 and mode 2 present a variety of collision, congestion control, and interference issues induced by their decentralized structure.

According to our literature, several survey articles [4-14] are concerned with resource allocation for vehicular networks. The work by the authors [6, 7, 9] provided information regarding the resource allocation for the C-V2X sidelink (SL) specifications detailed across different 3GPP Releases. However, they do not report or include any discussion of the related research types that have flourished in recent years, nor do they acknowledge the crucial reality of SL requirements in latency and reliability for vehicular network applications.

An analysis of the research literature review has been presented in the study by the authors [9, 10], which have a broad focus on V2X and a negligible concentration on SL resource allocation. Noor-A-Rahim et al. [7] provided a broad overview of resource allocation for vehicular communication, their focus on C-V2X is limited by considering both dedicated short-range communication (DSRC) and C-V2X technologies. They do not explore all the proposed algorithms for managing resources in both centralized and decentralized C-V2X modes. Furthermore, Allouch et al. [12] concentrated on the resource allocation of C-V2X in their study. The limitation is that they focused exclusively on LTE-V2X technology, thereby excluding the latest research concepts related to resource allocation for NR-V2X. In addition, Le and Moh [11] demonstrate the various resource allocation algorithms that can be implemented in an NR-V2X scenario, as do Sehla et al. [13], where the authors present a comprehensive overview of resource allocation in all modes for LTE-V2X and NR-V2X. Finally, the most recently published article is presented by Shin et al. [14], which addressed the key features of resource allocation for V2X in terms of LTE and NR. Table 1 depicts the summary of the most relevant and important survey articles.

As a result, the absence of a systematic literature review (SLR) focusing on distributed resource allocation (DRA) for LTE mode 4 and NR mode 2 in the context of C-V2X communications presents a critical gap in the current body of knowledge. As C-V2X technology continues to gain momentum in the realm of Intelligent Transportation Systems (ITS), understanding how to efficiently allocate resources in a distributed manner is paramount to ensuring reliable and effective communication among vehicles and infrastructure. By conducting this SLR, our objective is to fill this void and make significant contributions to the advancement of C-V2X DRA techniques.

Our comprehensive analysis will begin by examining the relevant 3GPP specifications, such as LTE mode 4 and NR mode 2, which define the standards for C-V2X communication. We will then delve into the existing literature, covering research publications from 2017 onwards. This approach ensures that our review captures the latest developments and insights in the field.

Table 1. Summary of the most related survey articles

Reference	Author	Year	LTE/NR	Objective
[4]	Zeadally et al.	2020	LTE and NR	Concise explanation to 802.11p/bd, PC5 LTE-V2X, and PC5 NR-V2X
[5]	Lien et al.	2020	NR	Specifics on the NR-V2X physical layer as well as its control channels
[6]	Ashraf et al.	2020	LTE	Enhancement to PC5 LTE-V2X in Release 16
[7]	Noor-A-Rahim et al.	2020	LTE	Survey on vehicular network resource allocation schemes
[8]	Gyawali et al.	2021	LTE and NR	Review of the research activities related to C-V2X
[9]	Garcia et al.	2021	LTE and NR	3GPP specifications for PC5 LTE-V2X and NR-V2X
[10]	Bazzi et al.	2021	LTE and NR	Review of PC5 for LTE-V2X and NR-V2X
[11]	Le and Moh	2021	NR	Survey of resource selection schemes for NR-V2X communications
[12]	Allouch et al.	2022	LTE	Overview on the LTE-V2X resource allocation techniques
[13]	Sehla et al.	2022	LTE and NR	Review of resource allocation in LTE-V2X and NR-V2X for all modes
[14]	Shin et al.	2023	LTE and NR	Review the key features of resource allocation in LTE and NR for V2X
	This Review		*LTE and NR*	*Systematic literature review on distributed resource allocation for C-V2X*

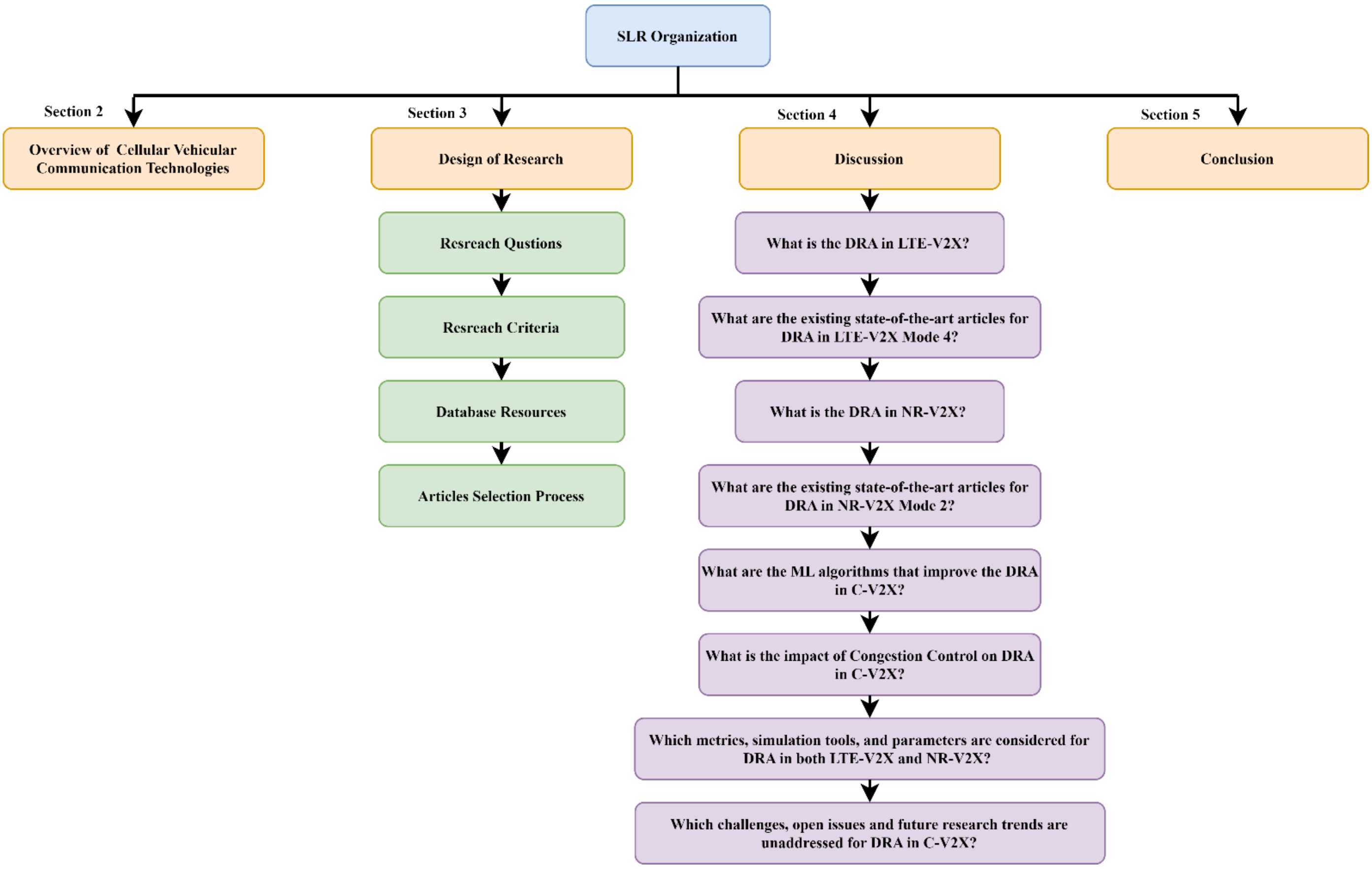

Figure 1. SLR organization

The SLR will provide valuable insights into a range of methodologies employed for DRA in C-V2X networks. We will assess existing techniques to identify their strengths and limitations, while also exploring modifications and proposing new alternatives to improve resource allocation performance. Additionally, we will investigate the integration of machine learning (ML) algorithms to enhance the efficiency and adaptability of DRA schemes. This analysis will shed light on the potential of ML in optimizing resource allocation decisions based on real-time network conditions, traffic patterns, and application requirements.

Moreover, the SLR will address the challenges and considerations associated with implementing DRA for C-V2X. This includes aspects such as dynamic channel conditions, diverse quality-of-service (QoS) requirements, scalability, interference management, besides fairness among competing users. Understanding these challenges will provide valuable insights into the design and optimization of DRA schemes that can effectively meet the unique requirements of C-V2X communication. Furthermore, we will investigate the integration of DCC mechanisms to optimize resource allocation decisions and mitigate congestion effects in C-V2X networks.

By bridging the current knowledge gap through this systematic review, our research endeavors aim to drive innovation and enhance the performance of C-V2X systems. The insights gained from this review will serve as a solid foundation for future studies and developments in this rapidly evolving field. Ultimately, our work strives to pave the way for a more efficient, connected, and safer future in intelligent transportation by optimizing resource allocation in C-V2X networks.

The remainder of this SLR article is structured as follows; Section 2 presents an overview of cellular vehicular communication technologies, i.e., LTE-V2X and NR-V2X. Section 3 presents the design for the SLR. In Section 4, We provide an in-depth analysis of the research questions related to DRA in LTE-V2X and NR-V2X, with a specific emphasis on modes 4 and 2, respectively. Our analysis aims to provide a thorough overview of current state-of-the-art in this field, as well as the new technologies that improve DRA (i.e., machine learning), the impact of CC in DRA, and the performance metrices and simulation tools used. This section also addresses the unresolved issues, challenges, and future interesting research concepts regarding the DRA in C-V2X. Ultimately, we conclude our SLR study by presenting a final section that summarizes the findings and provides insights for future research. The SLR organization can be seen in Figure 1.

2. OVERVIEW OF CELLULAR VEHICULAR COMMUNICATION TECHNOLOGIES

Prior to addressing the main concern of DRA in C-V2X, this part begins by providing an overview of cellular communication technologies used in vehicle networks. 3GPP has standardized the LTE-V2X as a new communication technology in Release 14. The key advantage of LTE-V2X is its utilization of cellular infrastructure, specifically roadside units (RSUs), and its reliance on device-to-device (D2D) connections [15]. The SL interface, also known as the PC5 interface, is specifically designed for D2D communication to handle the mobility nature of vehicle environments, particularly for high velocities. An enhancement has been implemented in this interface to fulfill these requirements. This enhancement comprises integrating demodulation reference symbols (DMRS) into resource frame structure in order to mitigate the impact of the Doppler effect.

Moreover, LTE-V2X supports the combination of both D2D communication, i.e., vehicle-to-infrastructure (V2I) and vehicle to-vehicle (V2V), utilizing the Uu interface, the communication between vehicles and the network is dependent on SL and cellular connectivity, specifically vehicle-to-network (V2N), as illustrated in Figure 2. In order to facilitate V2X communications, the LTE core network design incorporates two main parts: the V2X application server and the V2X control function [16]. The first component manages V2X network data, while the second offers a user equipment (UE) with required settings of V2X communication. The 3GPP introduced two communication modes in LTE-V2X, referred to as modes 3 and 4. In mode 3, the eNB schedules and assigns resources to vehicles. Meanwhile, vehicles reserve their own resources autonomously, utilizing the SB-SPS algorithm in mode 4 [17]. It is important to mention that mode 3 performs effectively because it utilizes the cellular network, whereas mode 4 operates independently of the cellular network. The various abbreviations used throughout this article are detailed in Table 2.

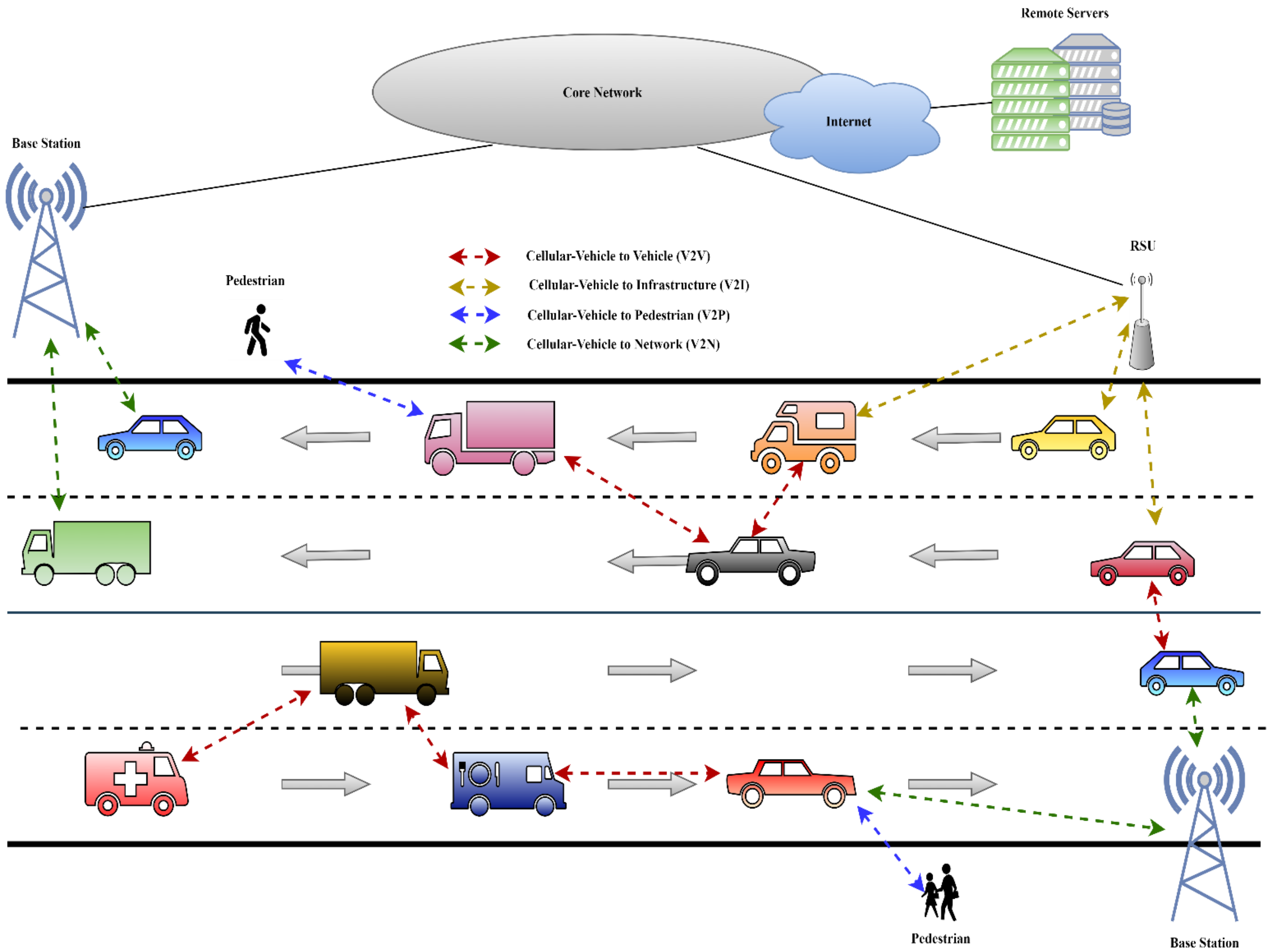

Figure 2. Overview of cellular vehicular network

Table 2. Abbreviations

Abbreviation	Definition	Abbreviation	Definition
3GPP	Third Generation Partnership Project	PAoI	Peak Age-of-Information
5G	Fifth Generation	PDR	Pocket Delivery Ratio
AFD-DRL	Adaptive Full-Duplex Deep Reinforcement Learning	PIR	Packet Inter-Reception
AM	Adaptive Modulation	pKeep	Probability of Keeping a Radio Resource
AMCD	Adaptive Modulation and Collision Detection	PPS	Packets Per Second
AoI	Age-of-Information	PRB	Physical Resource Block
ATOMIC	Adaptive Transmission Power and Message Interval Control	PRESS	Predictive Assessment of Resource Usage
A-TPC	Adaptive-Transmit Power Control	PRR	Packet Reception Ratio
BLER	Block Error Rate	PSCCH	Physical Sidelink Control Channel
BS	Base Station	PSSCH	Physical Sidelink Shared Channel
BSM	Basic Safety Messages	QAM	Quadrature Amplitude Modulation
BWP	Bandwidth Part	QPSK	Quadrature Phase-Shift Keying
CAM	Cooperative Awareness Message	RB	Resource Block
CBR	Channel Busy Ratio	RBP	Resource Block Pair
CDF	Cumulative Density Function	RC	Reselection Counter
CH	Cluster Head	RE	Resource Element
CLR	Counter Learning and Reselection	RRI	Resource Reservation Interval
CP	Cyclic Prefix	RSRP	Reference Signal Received Power
CR	Channel Occupancy Ratio	RSSI	Received Signal Strength Indication
CSR	Single-Subframe Resource	SB-SPS	Sensing-Based Semi-Persistent Scheduling
C-V2X	Cellular-V2X	SC-FDMA	Single Carrier Frequency Division Multiple Access
DENM	Decentralized Environmental Notification Message	SCI	Sidelink Control Information
DOCA	Delimited Out-of-Coverage Area	SCS	Sub-Carrier Spacing
DSRC	Dedicated Short-Range Communication	SL	Sidelink
E-ERRA	Extended Estimation and Reservation Resource Allocation	SLR	Systematic Literature Review
eNB	Evolved Node B	S-RSSI	Sidelink-Received Signal Strength Indicator
ERRA	Estimation and Reservation Resource Allocation	STS-RS	Short-Term Sensing-based Resource Selection
FDM	Frequency-Division Multiplexing	SW	Selection Window
FDPS	Full-Duplex Prioritized Scheduling	TA-SPS	Traffic-Aware SPS
gNB	generation Node B	TB	Transport Block
ICI	Inter-Carrier Interference	TBS	Transport Block Size
IoT	Internet of Things	TCH	Transport Channel
ISI	Inter-Symbol Interference	TDM	Time-Division Multiplexing
KPI	Key Performance Indicators	TS	Time Slot
LBT	Listen Before Talk	TTI	Transmission Time Interval
LTE	Long-Term Evolution	UD	Update Delay
MAC	Medium Access Control	V2I	Vehicle-to-Infrastructure
MCS	Modulation and Coding Scheme	V2P	Vehicle-to-Pedestrians
ML	Machine Learning	V2V	Vehicle-to-Vehicle
NR	New Radio	V2X	Vehicle-to-Everything
OFDM	Orthogonal Frequency Division Multiplexing	WBS	Wireless Blind Spot
ORLA	Online Reinforcement Learning Approach	WHO	World Health Organization

Table 3. Advanced V2X service applications QoS requirements

V2X Services	Automation Level	Latency (ms)	Tx Rate (msg/sec)	Reliability (%)	Data Rate (Mbps)
Vehicle platooning	High	10-500	30-50	90-99.99	80-350
Extended sensors	High	3-50	10	95-99.99	Oct-50
Advanced driving	Low	3-100	10	90-99.99	Oct-50
Remote driving	High	5	33-200	99.999	UL: 25 DL: 1

In Releases 15 and 16, NR-V2X was developed to manage sophisticated V2X applications. These applications maintain road safety by requiring low latency, high throughput, high reliability, and scalability. However, different V2X communications require varying degrees of quality of service (QoS), which depends on the transmitter and receiver for various V2X services; these services are described in greater detail below [18].

- *Vehicle platooning:* refers to several vehicles travelling in close proximity to one another as they form a single unit called a platoon. The leader vehicle leading the platoon relays messages to the other vehicles.
- *Extended sensors:* enable V2V, V2I, and vehicle-to-pedestrian (V2P) data exchanges for generating a comprehensive map of the surrounding area.
- *Remote driving:* enables people to control vehicles from a remote location.

Table 3 summarizes the requirements of the advanced V2X applications QoS.

Release 14 of the 3GPP standard introduced the radio resource allocation method necessary for V2X communication. This Release also described the technological enablers for V2X advanced service applications at the physical and MAC levels. 3GPP Release 16 [19] was designed to address the substantial needs of V2V services, which include high reliability, flexible transmission technology, and low latency. These criteria must be met in a highly dynamic environment. The NR-V2X services are supported by 3GPP Release 16, which focuses on enhancing V2X scenarios and implementing stricter criteria for advanced automation capabilities. These requirements include the management of resources and the physical frame structure [20]. As shown in Table 3, the NR-V2X advanced services demand an exceptionally high level of reliability, between 90 and 99.99%, and a low level of latency, between 100 and 10 milliseconds, or as low as 3 milliseconds.

NR-V2X technology now supports these newly developed applications, in addition to those currently supported by LTE-V2X technology and relating to essential safety services. If a vehicle is equipped with both cellular technologies, in this particular situation, RAT can be utilized for fundamental safety applications and for advanced service applications, respectively., which are also known as C-V2X RATs. The nature of the messages that are sent and received might either be periodic or aperiodic, depending on the application. Additionally, certain communications are transmitted for whole vehicles, whereas others are directed for a particular set of vehicles, for instance in the platooning scenario, wherein the commander interacts with the members within the platoon. To accomplish this objective, NR-V2X provides support for unicast and groupcast communication in addition to broadcast communication, which is already supported by LTE-V2X [21].

These new communications are operable both inside and outside the cellular service area. It is important to keep in mind that the vehicle is capable of simultaneously using both the groupcast and the broadcast communications. This indicates that the vehicle is capable of participating in groupcast communication, which involves communicating with a specific group of other vehicles. Additionally, it can convey messages to other vehicles using broadcast communication. The best example of this scenario is platooning, in which the leader member communicates with other members using groupcast communication to keep the platoon together as well as broadcasts periodic messages to vehicles that are not members of the platoon as part of the cooperative awareness service. NR-V2X technology includes the following essential features:

- *Supporting New Numerologies:* The new numerologies have been established for the NR in 3GPP Release 15 [22]. These numerologies are supported as well as the NR-V2X standard, which was presented in 3GPP Release 16. NR-V2X offers greater flexibility in subcarrier spacing (SCS) compared to LTE-V2X. Unlike LTE-V2X, which is fixed at 15 kHz, NR-V2X allows for SCS values that are multiples of 15 kHz, including 30 kHz, 60 kHz, and 120 kHz. Due to the fact that the SCS is a subject that is changeable, the time slot (TS), which is the time required for transmitting 14 OFDM symbols, is also subject to variation. This TS diminishes with an increase in the SCS; this procedure will lower the latency and, as a result, benefit applications that are crucial for latency. Table 4 provides a more detailed analysis of the differences and similarities between LTE and NR of V2X.
- *PSCCH and PSSCH Multiplexing in the Time Domain:* The second crucial and noteworthy characteristic is that PSCCH and PSSCH multiplex in the time domain. On one hand, this means that the PSCCH will be transmitted first, and then the PSSCH. On the other hand, LTE-V2X combines these channels in the frequency domain. Both features contribute to reducing latency.
- *Use of the PSFCH:* It is defined in NR-V2X as a novel channel aimed at guaranteeing the reliability of both unicast and groupcast communications.

In addition to the features listed above, the NR-V2X offers a number of features on its physical layer, such as a variable quantity of DMRS symbols within the slot and a high Modulation and Coding Scheme (MCS) level, capable of supporting up to 64 QAM coding.

In Section 4, we will present a detailed explanation of the DRA in both LTE-V2X and NR-V2X technologies.

Table 4. Features comparison of LTE-V2X and NR-V2X

Features	LTE-V2X	NR-V2X
SCS	15 kHz	15, 30, 60, and 120 kHz
Communication Modes	Broadcast	Unicast, Groupcast, and Broadcast
MCS	QPSK and 16QAM	QPSK, 16QAM, and 64QAM
Waveform	SC-FDMA	OFDM
PSCCH and PSSCH	FDM	TDM
Feedback Channel	No	PSFCH
DMRS	4	Flexible
Sidelink Modes	3 and 4	1 and 2

3. SLR DESIGN

This section of the research focuses on the methodology or framework that was utilized to complete this SLR. The structure is based on instructions to complete the SLR that was directed by Boell and Cecez-Kecmanovic [23] and reported in the study by Kamal et al. [24], with the emphasis on V2X DRA in LTE and NR. The primary focus of an SLR is on the formulation of research questions, in addition to the presentation of the many aspects of motivation that are included in this section. The included articles were selected from a variety of different data sources. Specifically, a research strategy was developed with the intent of focusing on articles associated with a particular domain, which will be discussed in the next part of the article. Then, the research articles were gathered for this study according to the inclusion and exclusion assessment criteria. As a means to significantly assess the state-of-the-art of DRA in both LTE-V2X and NR-V2X, motivations and research questions were developed.

3.1 Research questions

The following is a list of the main research issues that were explored and evaluated during this study:

(1) What is the DRA in LTE-V2X?

(2) What are the existing state-of-the-art articles for DRA in LTE-V2X Mode 4?

(3) What is the DRA in NR-V2X?

(4) What are the existing state-of-the-art articles for DRA in NR-V2X Mode 2?

(5) What are the ML algorithms that improve the DRA in C-V2X?

(6) What is the impact of CC on DRA in C-V2X?

(7) Which metrics, simulation tools, and parameters are considered for DRA of LTE-V2X and NR-V2X?

(8) Which challenges, open issues, and promising future directions are for DRA in C-V2X?

3.2 Research criteria

The primary focus of this SLR was on DRA in C-V2X since it is more closely associated with the IoT and enhanced vehicular network performance. The articles published in 2017 and onward were taken into account for this SLR since the 3GPP released the first official C-V2X specification in Release 14, which was complete in 2017. Focusing on 2017 onwards allows for the inclusion of research and developments following the standardization efforts, providing insights into how C-V2X technologies have evolved and been implemented in real-world scenarios. Many pilot projects and field trials of C-V2X technologies have been launched by automotive manufacturers, infrastructure providers, and government agencies worldwide since 2017. Research during this period can shed light on the practical challenges, solutions, and lessons learned from these deployment initiatives.

Table 5. Database sources

Publisher	URL
IEEE	https://ieeexplore.ieee.org
Google Scholar	https://scholar.google.com
Science Direct	https://www.sciencedirect.com
Springer	https://link.springer.com
Scopus	https://www-scopus-com

We gave the search keywords that were used for seeding the objectives to select the group of papers that will be taken into consideration. These search phrases are based on the research questions that were submitted and the planned subject. The study team used the phrases "C-V2X," "resource allocation," "LTE," and "NR" when doing the search. These phrases were nominated for use as primary keywords. In order to link the significant search phrases, we used the logical "OR" and "AND" operators. Eventually, after conducting a small number of tests, we chose the related search string that yielded a suitable number of relevant research papers by making use of the keywords to encase the search question that was displayed in Figure 3.

3.3 Database sources

Different data sources were examined. These databases, which include Scopus, Google Scholar, IEEE, Springer, and Science Direct, were primarily investigated for relevant conference papers, journal articles, review articles, and magazines, as illustrated in Table 5.

3.4 Articles selection process strategy

The perspectives presented in research papers were the most common criterion utilized in the selection of various quantitative types of studies. In order to determine whether particular articles should be included or not, standards of quality evaluation were applied to those pieces. As stated previously, the selection of papers began with the formulation of the research questions that would guide the study. The search and selection process were aided by outlining the string of searches that were conducted. In this review, only articles written in English were considered. The preferred reporting items for systematic reviews and meta-analyses (PRISMA) flowchart [25] was applied, as illustrated in Figure 4.

The data extraction process involved systematically collecting essential information from selected articles on DRA in C-V2X networks. Using a standardized template, details such as article title, authors, publication venue, research objectives, methodology, resource allocation techniques, application scenarios, performance metrics, results, challenges, and future research directions were recorded. This method ensured consistency and facilitated thorough analysis to meet the review's objectives efficiently.

After acquiring the main papers according to the keywords and strings, we examined each article to analyze how resource allocation techniques in vehicular networks were discussed. The classification of the resource distribution plan marked the conclusion of the search technique, which served to further validate the exhaustive nature of this study. There was a mismatch between the names of a few of the publications and the robustness of the measures that were used, which led to their exclusion. In addition, the inclusion of abstracts by themselves was not considered for this study.

It is clear from Figure 4 that the search query yielded a total of 507 published research articles. The articles were published in a variety of high-quality journals between the years 2017 and 2023, as shown in Table 5. Using the inclusion and exclusion criteria, the selection of compelling research articles has been carried out. These criteria are listed in Table 6, and they were used to reduce the number of research articles to 246 (after removing duplicates) and then to 76 (after filtering abstracts and titles). These 76 research articles were subsequently analyzed and classified according to their DRA technologies as LTE-V2X and NR-V2X, ML and CC for C-V2X.

The papers selected for this study are represented in Figure 5, which organizes them according to their publication year. The selection of these publications was further categorized by publisher and C-V2X resource allocation algorithms.

Finally, there were only 76 articles that were considered for the SLR study regarding the DRA in C-V2X. These papers were extracted from different widely known journals, like IEEE, Springer, Science Direct, Scopus, Google Scholar, and other publishers. Figure 6 illustrates the distribution of the 76 selected articles based on the SLR research questions, to be explained in Section 4.

As presented in Figure 7, the essential components of the specified C-V2X taxonomy are 1) Communication technologies, 2) Approaches, 3) Requirements, 4) Performance metrics, and 5) Objectives.

Table 6. The criteria of inclusion and exclusion

	Criteria
Inclusion	Research articles published in high-quality journals. Research articles peer reviewed. Research articles were written in English. Research articles were focusing on DRA in C-V2X. Research articles published by the abovementioned publishers.
Exclusion	Research articles were from editorials, keynote speeches, and white papers. Research articles were not in English language. Research articles do not peer reviewed. Research articles were not focusing on issues other than DRA in C-V2X.

(("Vehicle to everything") OR ("V2X") OR ("C-V2X") OR ("Cellular Vehicle to Everything")) AND (("Resource Allocation")) AND (("LTE") OR ("Long Term Evolution") OR ("New Radio") OR ("NR"))

Figure 3. Research query

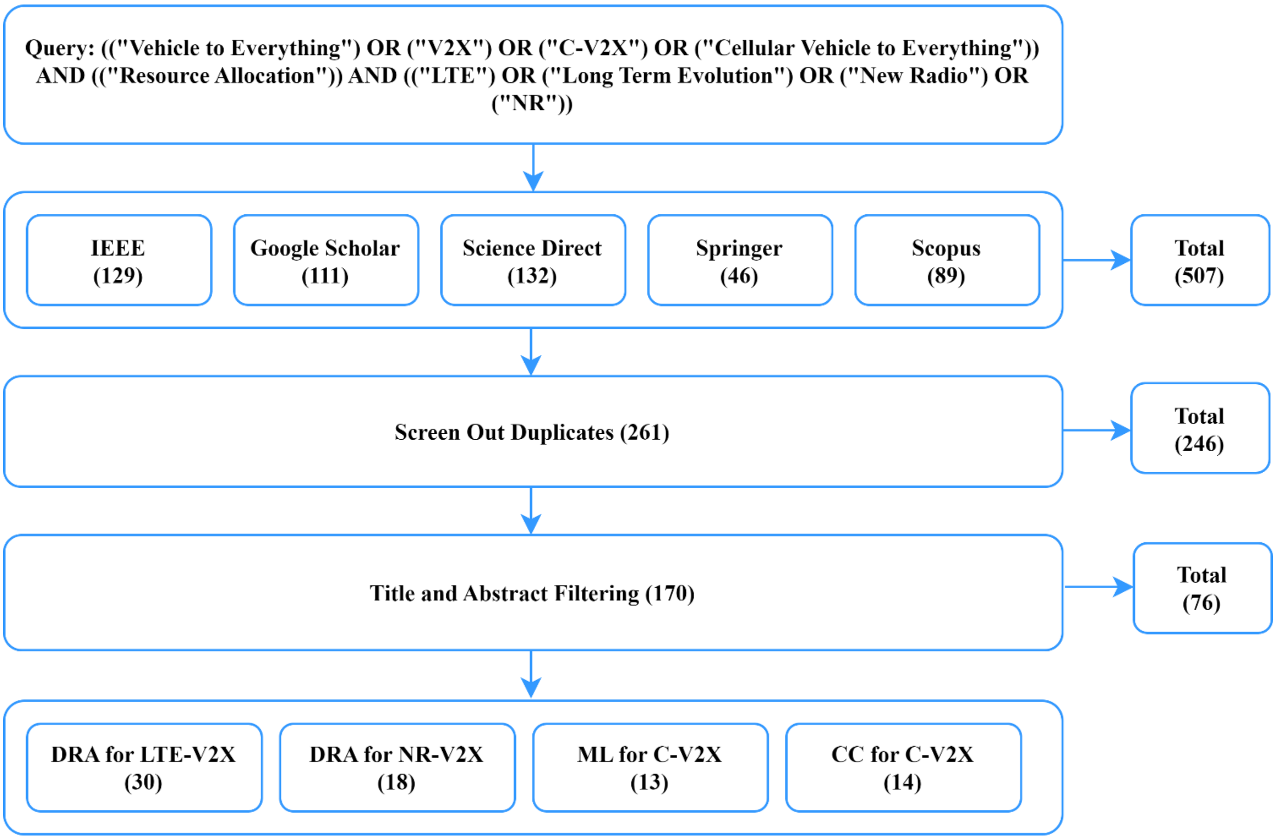

Figure 4. PRISMA flow chart screening process

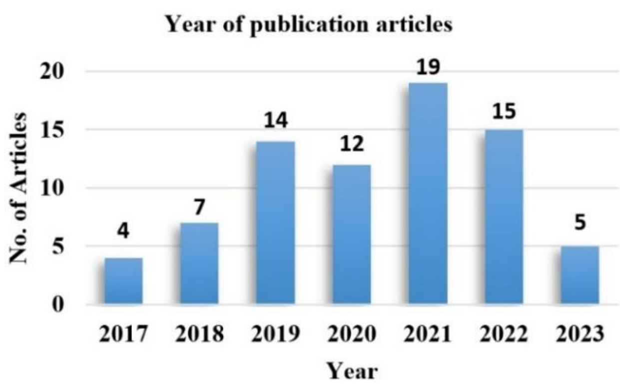

Figure 5. Publication articles per year

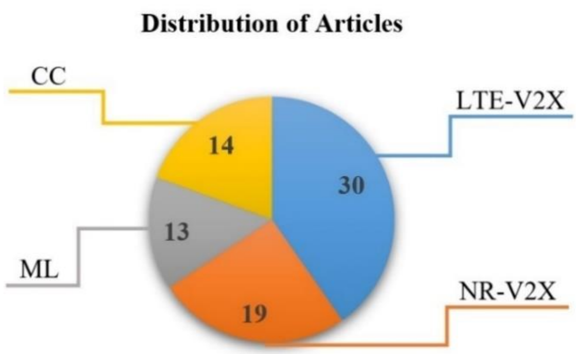

Figure 6. The articles distribution based on the SLR questions

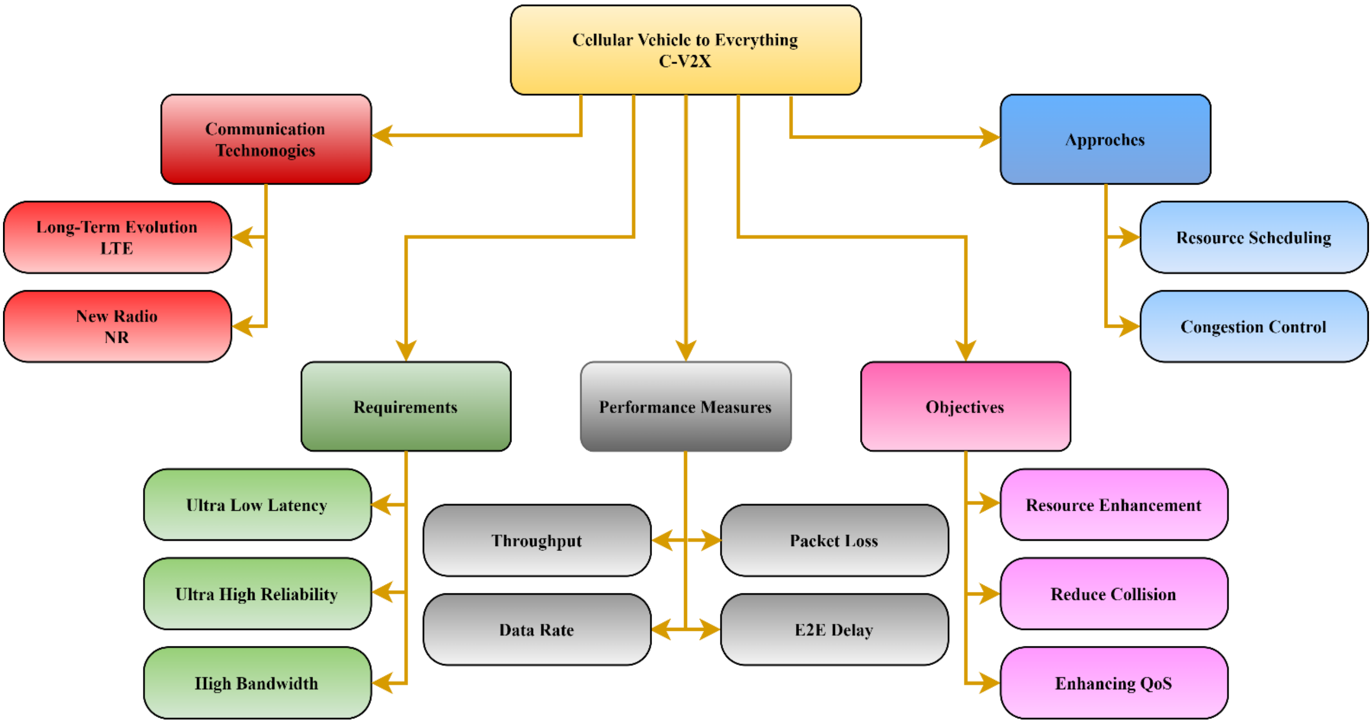

Figure 7. Taxonomy of C-V2X

4. DISCUSSION

The literature study identified various findings that were relevant to each one of the research questions, as will be presented in the following sub-section:

4.1 What is the DRA in LTE-V2X?

In this first subsection, we will discuss the fundamental concepts underlying the LTE-V2X resource configuration. In the second sub-section, study on resource allocation mode 4 LTE-V2X, is discussed in detail.

4.1.1 Resource configuration in LTE-V2X

LTE-V2X uses orthogonal frequency division multiplexing (OFDM) and single carrier frequency division multiple access (SC-FDMA) for its physical layer and medium access control (MAC) layer, respectively. For the most efficient use of the given bandwidth, such as a 10 MHz or 20 MHz channel, it is partitioned into many orthogonal resources throughout the time and frequency domains, as shown in Figure 8.

The signal is broken up into 10 ms frames within the time domain. Consequentially, each frame consists of 10 subframes, each lasting 1 ms, and each subframe comprises two TSs. Resource block pairs (RBP) define the signal in the frequency domain; it contains 12 subcarriers separated by 15 kHz and carries 14 OFDM symbols. A group of RBPs in the LTE-V2X subframe defines a subchannel, all subchannels within an eNB must maintain uniform subchannel sizes, which can be adjusted within the range of 4 to 50 RBPs [26].

When sending their data, individual vehicles have the option of using either one or multiple subchannels. A vehicle can have its cooperative awareness message (CAM) packet transmitted across a subchannel; it is the lowest resource unit that can be given to a vehicle. In C-V2X, the transport block (TB) is sent using a combination of 16-quadrature amplitude modulation (QAM) and quadrature phase-shift keying (QPSK) modulations. On the other hand, the sidelink control information (SCI) is transmitted only utilizing the last one. Both conventional cyclic prefix (CP) and turbo coding are utilized by LTE-V2X.

The data transport channel (TCH) and the SCI are carried by the PSSCH and PSCCH, respectively. The essential information required for the receiver to decode the message successfully is provided by the SCI, i.e., information regarding the Modulation and Coding Scheme (MCS), the Resource Reservation Interval (RRI), the priority of the message, and the resource blocks (RBs) that are occupied by the associated TB. The RRI calculates when the vehicle utilizes the reserved resources for the next transmission and reports the findings to the driver. Both PSSCH and PSCCH are multiplexed within the frequency domain, which means they are sent in the same sub-frame but make use of various frequency resources. This is accomplished through the process of frequency domain multiplexing.

Both the PSSCH and the PSCCH can be configured in two different ways as illustrated in Figure 9. The first configuration is known as "adjacent." It occurs when the PSCCH uses the first two RBs of the designated subchannel, and the PSSCH immediately follows. In the second one, which is called “non-adjacent.” PSSCH and PSCCH are not allocated consecutive RBs within the same subframe; the RB count in a given subchannel might vary [27]. In addition to this data, four DMRS symbols are transmitted within the OFDM subframe for use in channel estimation in conditions of high mobility.

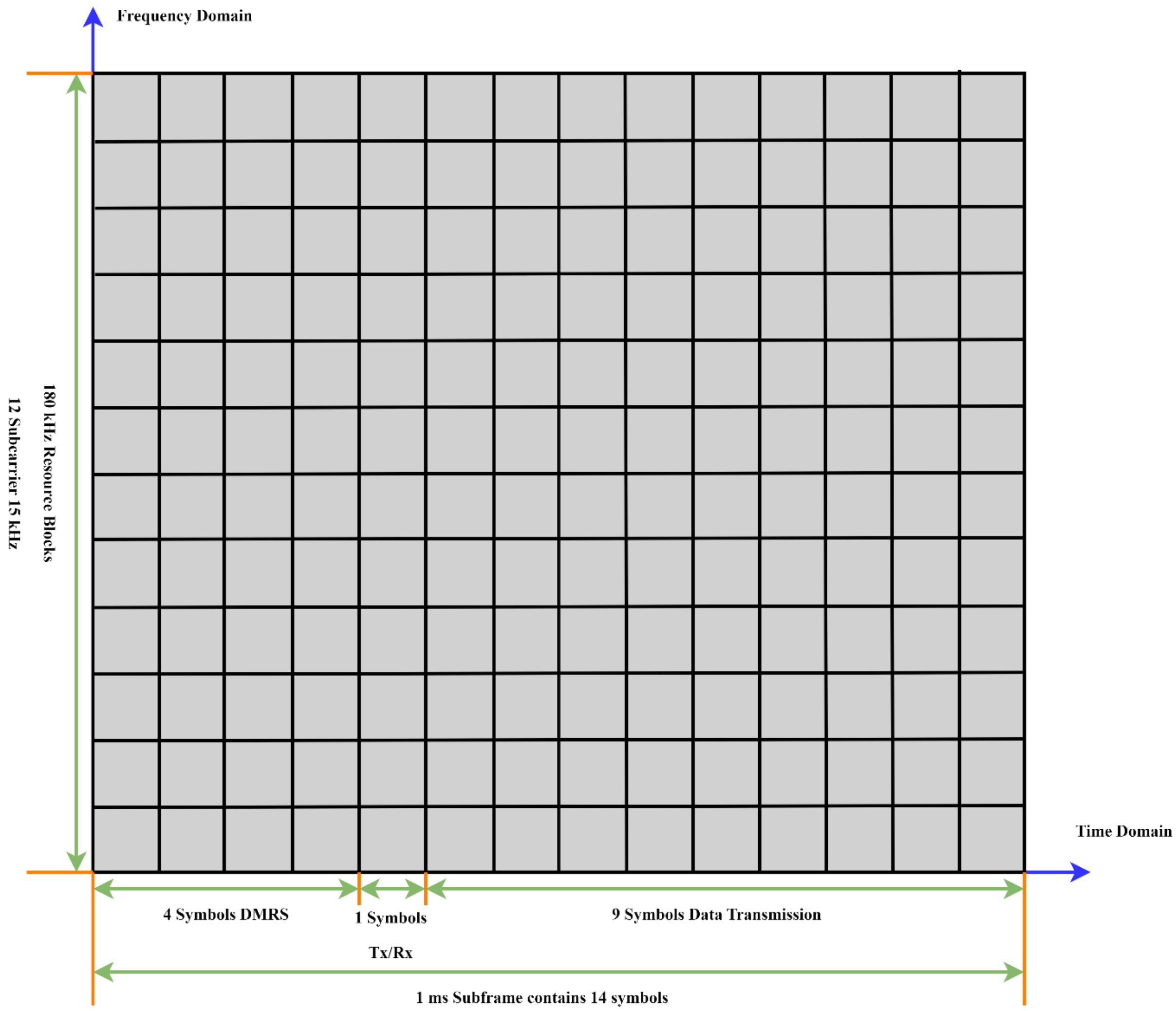

Figure 8. Resource configuration in time and frequency domain for LTE-V2X

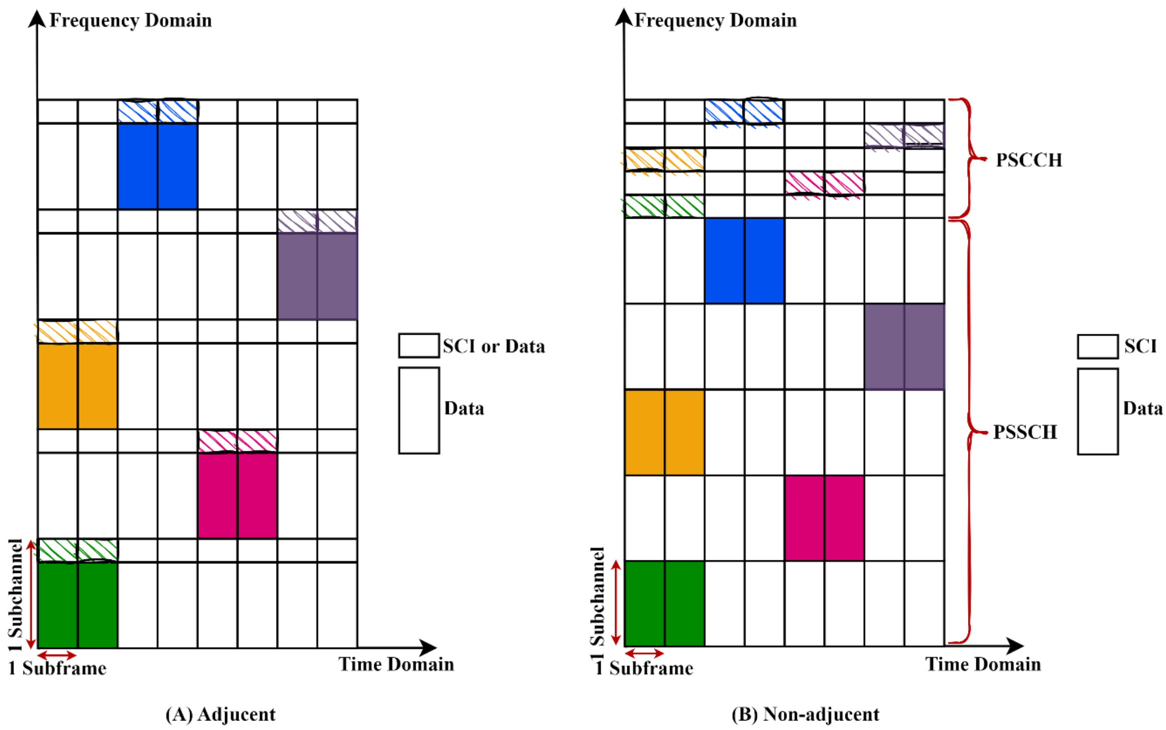

Figure 9. Adjacent (A) and nonadjacent (B) PSSCH and PSCCH

4.1.2 DRA mode 4 for LTE-V2X

Figure 10 represents two modes of resource allocation supported by LTE-V2X. These modes rely on the availability of the cellular network infrastructure. Mode 3, operating within cellular coverage, involves the eNB scheduling resources to the vehicles. Recognizing the need for critical safety services even when vehicles are beyond cellular network coverage, 3GPP introduced mode 4. In this mode, vehicles utilized the SB-SPS algorithm to autonomously select their resources, which includes detecting the channel before selecting resources from a list of candidate resources. The SB-SPS is described in greater detail in the study by the authors [28, 29].

The SB-SPS algorithm employs sensing in a pre-configured or configured resource prior to selecting a resource from a candidate resource. The fundamental tenets of this approach involve three primary stages, as delineated in the following manner, and visually shown in Figure 11.

Step 1: When any vehicle reserves and uses a single resource for transmitting a random number of messages one after another. The frequency at which Cooperative Awareness Messages (CAM) are transmitted determines the magnitude of this random number; it is also referred to as the reselection counter (RC). For a periodicity of 10 Hz, the RC is set to a value between [5-15], for a periodicity of 20 Hz, it is set to a value between [10-30], and for a periodicity of 50 Hz, it is set to a value between [25-75].

Step 2: The SCI field encompasses information pertaining to both the periodicity of the CAM as well as the RC value. As a result of having access to this information, the vehicle is able to determine which resources are available for use and which ones are now being used by other vehicles.

Step 3: The value of the RC is reduced by one after every CAM message that is sent out, as this value is kept track of. Upon depletion of the RC counter, a new resource needs to be selected. This selection is not always random; there is a probability (1-P) of keeping the current resource for subsequent transmissions. This probability is denoted by P.

Inside step 1 of the process, the allocation of candidate resources is performed by a vehicle inside a Selection Window (SW), which indicates a specific time interval that identified by [T + T1, T + T2], where T1 is the vehicle processing time that is used to detect and choose candidate resources for transmission within $1 \leq T1 \leq 4$ being the range of possible values for this parameter. The value of T2 is similarly chosen by the vehicle and must fall within the range of $20 \leq T2 \leq 100$ for it to be valid. Afterward, the vehicle requires 1 s during the SW to listen in to the channel for the next transmission. The SW is equal to 1000 subframes. The SW for the SB-SPS algorithm is presented graphically in Figure 12.

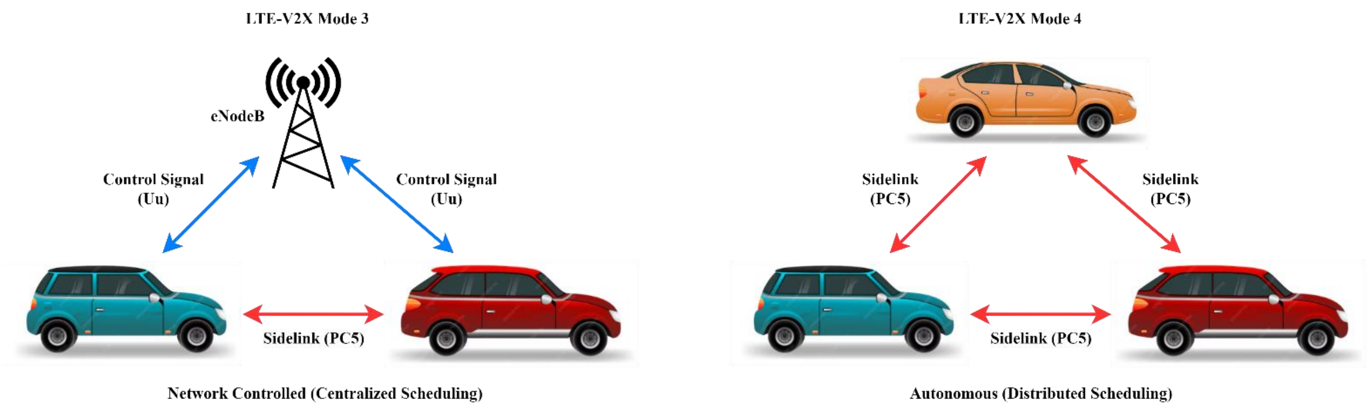

Figure 10. LTE resource allocation

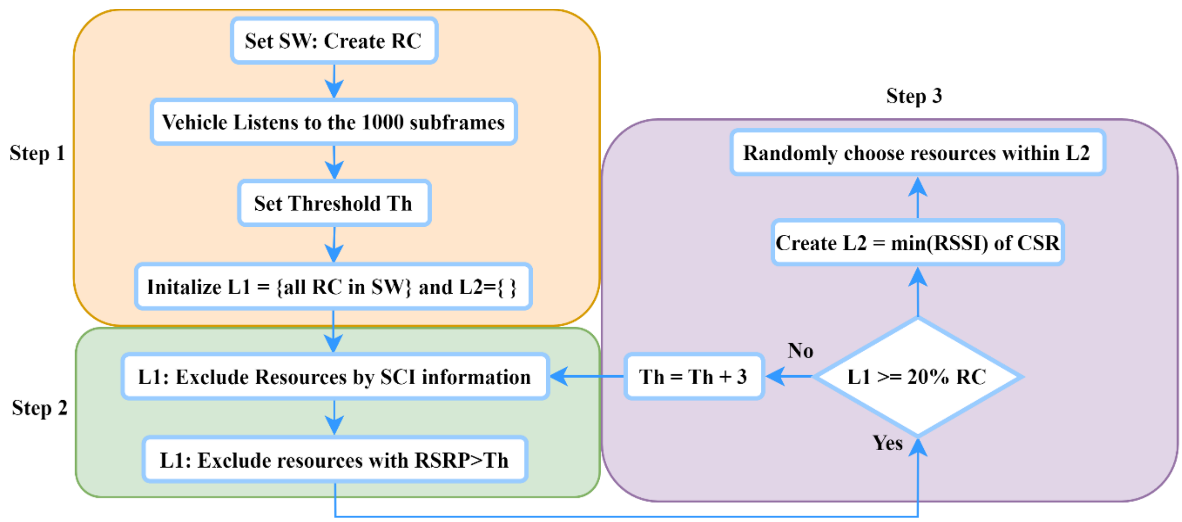

Figure 11. The SB-SPS algorithm flowchart for DRA LTE-V2X mode 4

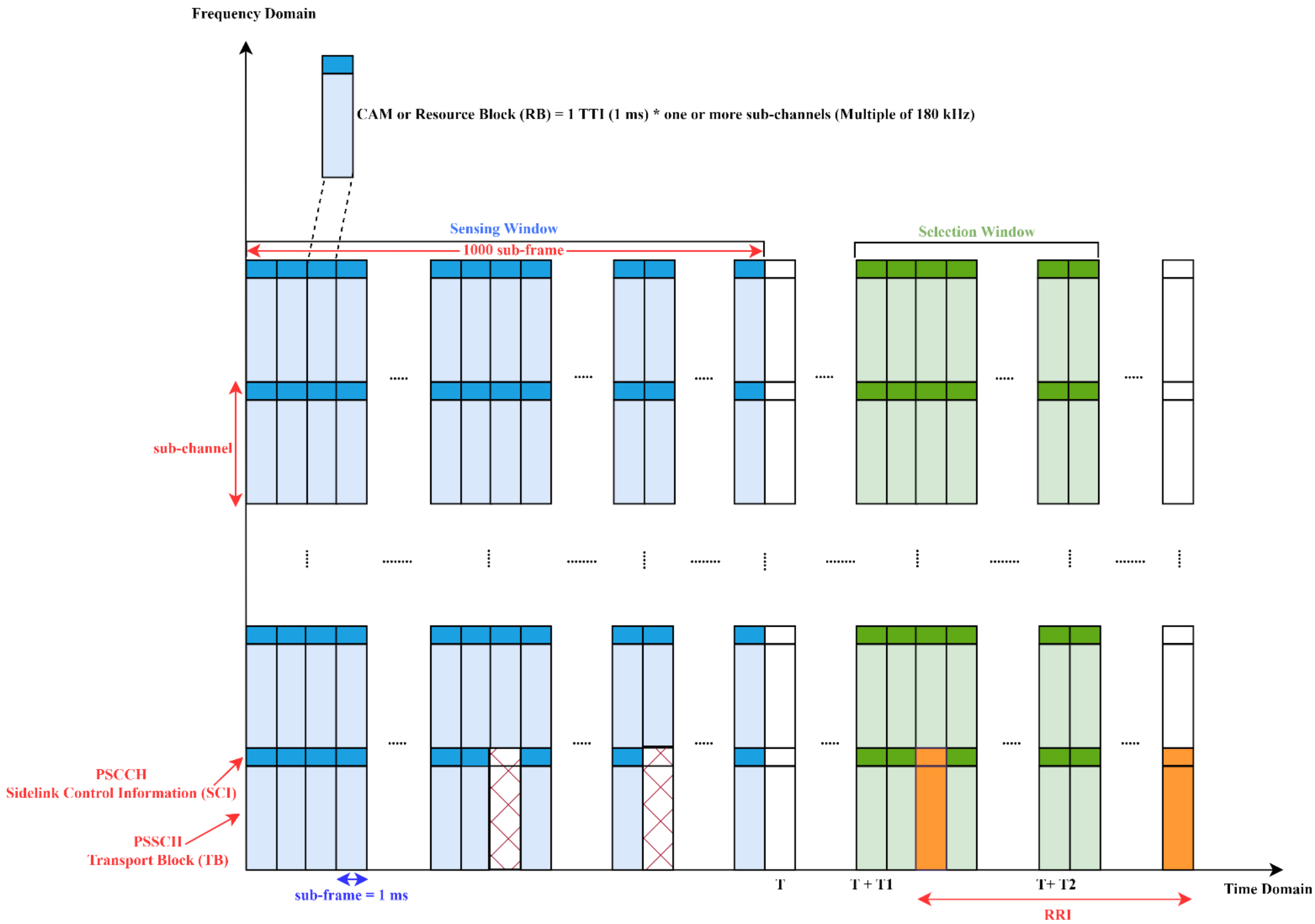

Figure 12. The SW of SB-SPS for LTE-V2X mode 4

Step 2 involves the vehicle creating a first list L1 that contains the resources that were previously selected during the SW, with the exception of those resources that a reference signal received power (RSRP) exceeding a predefined threshold. According to the information provided by the SCI, L1 does not take into account the resources that are being used by other vehicles for their subsequent transmissions. At least 20% of the total resources chosen in the first phase should be included on this list. However, if this is not the case, then step 2 is frequently repeated by raising the Th by 3 dB each time.

Finally, step 3 comprises the vehicle generating a list of resources called L2 that provides the minimum values for the received signal strength indication (RSSI). It is necessary that the amount of these resources corresponds to 20% of the total amount of the resources that have already been chosen in the very first step. Therefore, the vehicle will finalize its resource selection within the L2 list using a random number generator. The resource that is selected will then be saved by the vehicle for use in its subsequent transmissions using the RC parameter. Random selection eliminates the possibility of collisions occurring in the event that more than one vehicle chooses the same resource because their RSSI value is the lowest.

In LTE-V2X mode 4, resource distribution can be tailored based on the geographical positioning of zones. This means that one geographical region is capable of being divided into many zones. By employing a spatially based resource reuse strategy that operates on distance-based principles, various resource pools are distributed to zones that are geographically close to one another.

4.2 What are the existing state-of-the-art articles for DRA in LTE-V2X mode 4?

In this context, it is important to point out that mode 4 has been the subject of a significantly larger number of study articles published than mode 3. Due to its decentralized structure, mode 3 presents fewer challenges than mode 4. In contrast, mode 4 is susceptible to a new set of challenges, including collision, interference, and congestion management issues.

The research works associated with mode 4 can be divided into three groups. The first group seeks to evaluate how SB-SPS algorithm parameters affect performance. The second group illustrates modification in the SB-SPS algorithm to improve its performance. The third group presents novel alternatives schemes to the previously proposed SB-SPS algorithm and demonstrates that the performance of these proposed algorithms is superior to the previous method.

4.2.1 First group: Evaluating the performance effect of SB-SPS algorithm parameters

As indicated by the existing research literature, the article by Molina-Masegosa and Gozalvez [30] is the first study that presents an evaluation of the SB-SPS algorithm performance. In this article, the SB-SPS algorithm's is evaluated in an actual traffic situation in metropolitan scenarios in order to better understand its performance. Through the use of simulations, the authors show that considerable performance deterioration owing to packet collisions can occur in the SB-SPS algorithm.

In addition to this, Nabil et al. [31] demonstrated that the RRI has a substantial impact on the performance of the packet data rate. Based on their simulations, the authors conclude that with an increase in the RRI, it leads to a rise in the packet delivery ratio (PDR). This is because the probability of another vehicle utilizing the same resource has decreased. As a result, the PDR grows larger.

However, Molina-Masegosa et al. [32] showed that increasing in reselection probability P can enhance the overall system of the SB-SPS scheme, especially once vehicles are transmitting data frequently (at 10 packets per second in this case). This may be understood when considering the fact that the decrease in the resource reservations is a result of the increase in P, which in turn makes the sensing environment more stable. Simulations, on the other hand, indicate that a decrease in PDR is possible if there is an increase in P when the channel load increases. The decrease in communication range is a direct result of the increased channel load. Due to high vehicle mobility, selecting resources for a long duration increases the chance of encountering other vehicles. These vehicles were previously outside the sensing awareness range and thus not regarded during the initial resource selection process. The SB-SPS algorithm does not take into consideration vehicles that come within a range of the selected resource after the resource has been selected. As a direct consequence, this vehicle is going to be subject to packet collisions, this might lead to a decline in the efficiency and effectiveness of the SB-SPS algorithm, impacting its ability to adequately manage resource allocation and network performance. Furthermore, the study shows that utilizing a low RSSI threshold in step 2 of SB-SPS combined with high-power transmission leads to improved overall system performance.

Simulations have been used to evaluate the performance of the SB-SPS algorithm, which forms the basis of the aforementioned research papers. On the other hand, Gonzalez-Martin et al. [28] made use of analytical models for the goal of their investigation. The authors selected Packet Delivery Ratio (PDR) as a performance metric. This work simulates four common types of errors that could impact the transmissions quality. These errors stem from the fact that the SL interface PC5 operates in a half-duplex (HD) mode, collision issues, and propagation conditions. Another objective of the project is to compare the results obtained from analytical models with those produced by the simulator built on the Veins platform. The study's findings suggest that analytical models can effectively model the mode 4 performance.

McCarthy et al. [33] presented an implementation of through the utilization of an open-source simulator offers an invaluable opportunity to delve into the intricacies of vehicular communication protocols. This implementation has been validated to ensure its accuracy, Enabling the utilization of V2X communications performance by the vehicular networking community. An in-depth analysis of the restrictions of the SB-SPS scheme when it comes to supporting aperiodic application traffic features has been provided, specifically for the European Telecommunications Standards Institute (ETSI) CAM standard as well as the 3GPP application model. Assessment of performance enhancement methods, including parameterization within the SB-SPS mechanism and dedicated aperiodic scheduling techniques, has been conducted as possible solutions for future C-V2X. It has been highlighted that the variability degree in the packet inter-arrival time period significantly impacts the efficacy of these schemes.

In addition to the above, Eckermann et al. [34] created and evaluated an open-source C-V2X mode 4 simulator that was implemented in NS-3. The authors investigated the simulator performance using the PRR and PIR standards. Even in the most catastrophic situations, the simulation findings reveal that the C-V2X mode 4 is highly scalable even in realistic scenarios, with the performance exceeding 3GPP Release 14 standards. In addition, an analysis of the effect of the resource reselection probability and resource reservation period analysis was conducted.

The performance of the LTE-V2X mode 4 algorithm was discussed by Bazzi et al. [29]. The results of three different simulations, each of which takes into account the effects of the PHY and MAC layers independently, are presented. According to the findings, changing any of the characteristics does not seem to make much of a difference in scenarios, but when congestion arises, it may become significant. It has been notified that the optimal number somewhat fluctuates by vehicle density, and thus lowering the percentage of the resources transmitted to the MAC layer from the current value of 20% by the requirements can yield a minimal benefit. Furthermore, some performance enhancements at the PHY layer can be made by adjusting the sensing period, which is currently set to 1 s; Nevertheless, this necessitates a reevaluation of how the channel is sensed, as merely reducing it might be counterproductive, especially considering that only certain nodes may be transmitting at 1 Hz.; and in order to achieve a balance between a reduced update latency and a greater packet reception probability, the keep probability can be modified at the MAC layer. As outlined in the specifications, setting specific quantities for the maximum and minimum number of beacon durations before reallocation is deemed appropriate. The variability of keep probability shows up to be adequate for maintaining system performance.

Using the sensing-based resource allocation approach developed in C-V2X mode 4, Romeo et al. [35] investigated the performance of Decentralized Environmental Notification Message (DENMs) delivery via the PC5 interface under various load scenarios. mode 4's most important characteristics for an adequate configuration have been determined. The results indicate that short-term sensing is superior to long-term sensing because it offers precise channel measurements, and that reducing the SW to fit delay constraints alone is inconvenient until further countermeasures are used as well. Cutting back on resources by selecting the appropriate one to send might be useful in such a scenario. Overall, the study makes a substantial contribution to our knowledge of NR-V2X requirements and C-V2X mode 4's sufficient configuration for handling asynchronous traffic, which is crucial in many cutting-edge vehicle applications.

Chourasia et al. [36] examined how the general system performance in PC5 interface-based C-V2X networks was affected by a variety of different configurations of the RC and pKeep parameters used by the SB-SPS algorithm. According to the findings of the study, a new version of the SPS system, which has been given the name TA-SPS and modifies these parameters in accordance with the existing traffic density, is recommended. Compared to traditional SB-SPS, the utilization of TA-SPS results in a 4% increase in PDR for time-varying traffic cases. This is an improvement over the traditional SB-SPS. RC and pKeep each have a vast range of possible combinations; hence, these parameters must be configured appropriately to meet the performance requirements of ITS systems. Bartoletti et al. [37] examined the influence of CAM packet generation; it investigated scenarios where the interval Tg deviates from the allocation period Tb. Specifically, it considered situations where Tg is either longer or shorter than Tb. The research focused on determining the impact of these factors on overall performance, with a primary emphasis on the Packet Reception Ratio (PRR). Simulation findings indicate that the optimal value of Tb varies based on circumstances, but an overall optimal value is 0.1 s. Additionally, the study demonstrates that mode 4's general performance declines as the CAM packet production interval surpasses the allocation period.

Recent research conducted by Yin and Hwang [38] evaluated the performance of the traditional SB-SPS mechanism in LTE-V2V mode 4. However, they identified limitations in the fixed and unified reselection probability Pk for each VUE. To overcome these limitations, the article proposed an enhanced SB-SPS mechanism that incorporates channel-sensing information to dynamically adjust Pk based on real-time CSI. The proposed algorithm divides Pk into multiple ranges to account for different user scenarios. To validate its effectiveness, simulations were conducted for three scenarios: highways with varying densities, high-speed highways, and congested urban areas. Comparative analysis revealed that the proposed algorithm outperformed the conventional approach in terms of PRR, Zhang et al. [39] investigated the SB-SPS process specified in the standard. Initially, they mathematically described the scheduling methodology and employed PPR as a measure of reliability. To further enhance understanding, the authors leveraged the semi-persistent characteristics of the scheduling to establish a reliability equation with CBR as a variable. Through simulations, they demonstrated the successful representation of the scheduling's reliability by the theoretical curve. Their analyses and simulations led to the conclusion that the reliability of SB-SPS in LTE-V2X exhibits a quadratic function relationship with the CBR. This finding provides valuable insights into the reliability characteristics of SB-SPS and paves the way for future research in this area.

In summary, the primary limitation of the first group's research is the absence of an examination into the effect of the SB-SPS algorithm on the restricted requirements of V2X applications. This includes aspects like the reliability and latency of safety messages under varying channel conditions. Given that DRA mode 4 is considered a foundational mode, addressing these issues would provide valuable insights, this feature needs to be investigated in greater depth. After demonstrating that the SB-SPS algorithm may be susceptible to significant performance issues, it became evident that mode 4 functioning required further enhancements. Therefore, the second group is concerned with the modification of the SB-SPS algorithm for enhancing mode 4 performance.

4.2.2 Second group: Modifying the SB-SPS algorithm to enhance performance

Prior research has identified collision as one of the primary performance issues, as it has a significant influence on overall performance. In the SB-SPS algorithm, if multiple vehicles select the same radio channel during resource selection, a packet collision can occur. While the random selection in the SB-SPS's last step helps mitigate resource collisions among vehicles, it is not adequate to fully address the issue of the packet collisions probability significantly.

Therefore, Bonjourn et al. [40] presented a novel approach in order to prevent collision issues within the SB-SPS algorithm. It intends to reduce the probability of transmission collisions and enhance the reliability of DRA mode 4 communications. In reality, the overlap in the reselection window may cause a resource collision among vehicles. To overcome this issue, they introduced a CLR technique. In this technique, the counter values are transmitted with each packet transfer. The vehicles are then made aware of upcoming concurrent reselections. Consequently, the algorithm prevents vehicles from reselecting resources, which could lead to resource collisions in the reselection window.

Moreover, Jeon and Kim [41] developed a novel technique for reserving resources to prevent packet collisions. In order to improve the SB-SPS algorithm, a new reservation system was implemented. In this technique, vehicles communicate the reserved resource information utilizing a time-frequency coordinate. This resource is reserved well in advance of its actual use, necessitating several announcements to improve the accuracy of this reservation. Through simulations, the authors demonstrated that this approach outperforms the conventional SB-SPS scheme in terms of both latency and reliability. However, the presented technique may exacerbate the problem of resource overload resulting from the necessary notifications regarding the allocated resource.

He et al. [42] proposed a short-term sensing and reservation scheme, STS-RS. It is utilized and configured immediately prior to the resource selection step. In contrast to the standard SB-SPS algorithm, where any transmitting vehicle can initiate this process during the initial resource in the SW. Vehicle then performs the STS measurements at a predetermined back-off time. Consequently, the outcome of this STS process determines the selection of the right resource. The simulation findings demonstrate that decreasing the likelihood of packet collisions can improve transmission reliability. During resource selection in SB-SPS, vehicles choose channels based on the average power (linear average) sensed across all subchannels within the SW. Nonetheless, Abanto-Leon et al. [43] suggested a novel approach of nonlinear power averaging where the major observations are given higher importance by exponential weighting. This strategy is implemented in steps 2 and 3 in the SB-SPS algorithm. Through simulations, the authors show that their method has a positive influence on PRR performance and improves the reliability of vehicular networks in mode 4.

In the same regard, it is very important to point out that incorrect resource selection may result in packet loss over consecutive transmissions of packets during the resource reserve time. Bazzi et al. [44] characterized this problem as a WBS and attempted to determine its occurrence probability. To circumvent this issue, they propose a modification to the conventional SB-SPS procedure that restricts the maximum length of time of any incorrectly reserved resource. They proposed that each vehicle maintain an additional parameter that specifies the maximum length of time of the resource reserve period. Through findings corroborated within simulations, the authors demonstrated that their proposal outperforms the conventional SB-SPS algorithm.

Molina-Masegosa and Gozalvez [45] drew attention to an additional significant feature associated with the change in packet size. In actuality, V2V communication messages consist of a 300-byte packet followed by four 190-byte packets. Consider that the transmission of 300-byte boxes requires only two subchannels, whereas 190-byte boxes require only one subchannel. In this instance, only one of the two subchannels designated for transmitting packets of 300-bytes, that was reserved throughout RC, would be utilized to send the 190-bytes packet. To address this issue, the authors suggest reserving resources via the RC exclusively for packets of 190-byte, which are the most common. In contrast, with a 300-byte packet, the SB-SPS only utilizes the appropriate resource selection, however this resource is not reserved within the RC. In terms of PDR, the suggested SB-SPS outperforms the standard SB-SPS algorithm. Here, we notice that the authors omit aperiodic traffic application scenarios, such as the DENM.

Sabeeh and Wesolowski [46] published a paper on the AM and AMCD algorithms for reselection of resources. The authors created both techniques to enhance SB-SPS resource reselection in order to address the resource collision issue for distributed resource reselection. They hypothesized that when more than two vehicles in the consciousness region select the same resources, or the channel load exceeds highest threshold, the resource collision problem arises. They compared the performance between both algorithms in a freeway scenario with five distinct zones of vehicle density. In comparison to the AM method, the suggested AMCD algorithm achieves a greater improvement in the PRR and an outstanding collision ratio, as demonstrated by the simulation results.

In addition, Dayal et al. [47] proposed an adaptive SB-SPS protocol known as SPS ++ to improve the performance of on-road safety applications in DRA. Specifically, SPS ++ enables every vehicle to dynamically adjust RRIs according to the availability of channel resources and select appropriate transmission opportunities for timely BSM transmissions at adjusted RRIs, while taking into account various traffic applications. Experiments revealed that the SPS ++ protocol improves road safety performance in all C-V2X test scenarios.

4.2.3 Third group: New alternative methods to mode 4 to improve the SB-SPS algorithm

The third and final group is dedicated to literature proposing new alternative methods for DRA-V2X. These new solutions are considered as incremental improvements on the SB-SPS algorithm.

Sabeeh et al. [48] presented an ERRA approach as a new method. This ERRA algorithm attempts to improve mode 4's reliability by resolving packet collisions and improving PRR. The primary aspect of the proposed algorithm is that every vehicle specifies the positions of all received packets using a random counter, so that each vehicle may forecast the available resources during the subsequent resource selection. Thus, the vehicle is independent of the sensing process. Simulations are used to validate the ERRA method, and the authors demonstrate that it is vastly superior to the conventional SB-SPS technique. The same authors then developed E-ERRA, a new variant of the ERRA algorithm [49]. Its main objective is to resolve the lost reserved resources issue. This issue may arise while vehicles with pre-allocated resources have recently entered or exited the broadcast range prior to reselection. The methods provide alternative resources that the vehicle will utilize if this problem occurs. Through simulations, the authors demonstrate that the algorithm can reduce the collisions rate and boosts the PRR. Similarly, Yang et al. [50], developed a novel method called PRESS. By using the overall RC information, before broadcasting, vehicle must initially predict the channel status for upcoming transmissions prior transmitting. Utilizing the CAM periodicity signals, The PRESS algorithm is capable of estimating the future resource usage status at the time of resource utilization. As a result, a vehicle may select the resources that are least utilized. Simulations show that the proposed algorithm outperforms the SB-SPS method in PRR.

For reducing the probability of collisions, Zhao et al. [51] have presented a novel autonomous cluster-based resource selection technique that breaks the pool of resources into orthogonal resource sets. The vehicles are clustered according to their method of operation. Then, based on the sensing, every single Cluster Head (CH) selects a resource set with minimal collision. They demonstrate that this strategy delivers superior PRR performance in comparison to the legacy SB-SPS algorithm. However, this research is limited by the fact that collision problems may result due to the CH selection technique of resource set.

Another motivational approach to DRA is proposed by Molina-Masegosa et al. [52] with aiming of mitigating the hidden node issue. The authors proposed a novel resource allocation mechanism with the goal of minimizing packet collisions. In this system, vehicle resource selection is dependent on the order of neighboring vehicles and their location. Analytical and simulation evaluations demonstrate that the proposed method outperforms the conventional SB-SPS algorithm. The performance of the suggested DRA scheme could be decreased if the vehicles' position, upon which it is based, is inaccurate.

Nevertheless, Sahin and Boban [53] investigated resource allocation for vehicles in delimited out-of-coverage areas (DOCA). Imagine a DOCA as a tunnel with no signal from cell towers (Base Stations). However, cell towers at the tunnel entrances can communicate with vehicles just before entering or exiting. This technique for DRA attempts to increase vehicular communication reliability. Therefore, the authors recommend that the BS continue to manage DRA for vehicles entering the tunnel based on predicted vehicle positions and conditions of propagation.

Moreover, Heo et al. [54] presented a novel hybrid DSRC and autonomous C-V2X approach for enhancing the reliability of the IoV networking. The suggested H-V2X scheme makes use of the derived equations of the collision probability to manage the SB-SPS period and adaptively support DRA, allowing C-V2X mode 4 users to maintain a reliable network and efficiently utilize the DSRC communication. C-V2X mode 4 scheduling was given a higher priority than DSRC scheduling due to the fact that it utilizes a more reliable licensed frequency channel that enables a greater transmission range and is much better suited for CAM traffic. In terms of PDR, the H-V2X protocol outperforms previous technologies in the area of interest with the highest traffic density.

Recently, Ha et al. [55] presented the SS and DP-ASTS schemes to enhance PDR performance for DENM and CAM communications. The PDR performance of the DP-ASTS method was enhanced by getting the SD value restricted by the necessary number of data symbols to include the payload of DENM or CAM. Simulation findings indicate that the DP-ASTS strategy may significantly increase PDR performance for both traffic types compared to the current random resource selection scheme for DENM traffic. In the same context, Yin and Hwang [56] proposed a separate resource pool specifically dedicated to CAM and DENM messages for C-V2X transmission. A key aspect of their proposal is the dynamic adjustment of the DENM load, which closely aligns with real-world scenarios. By dynamically adjusting the number of allocated resources for DENM based on the message count, this mechanism ensures that important aperiodic emergency data can have dedicated resources with minimal interference. Additionally, it prevents excessive resource allocation to aperiodic messages, thereby avoiding congestion and preserving resources for periodic messages. Through comprehensive simulations, the researchers concluded that their proposed separate resource pool method effectively enhances the PRR and transmission range of aperiodic messages. Importantly, it achieves these improvements while maintaining a satisfactory PRR for periodic messages. The performance of their proposed method surpassed that of the conventional scheme, further validating the effectiveness and advantages of their approach.

In addition, Asano and Fujii [57] suggested two techniques that, without the need for further information, helped LTE-V2X mode 4 function better. By utilizing the fact that Prsvp reaches 0 when the resource is reselected, the suggested methods can lower the number of packet collisions. Using three RRI patterns, the authors assessed the efficacy of the suggested techniques. In the long run, the suggested PA approach was quite effective and efficiently utilized the resources that were released. The suggested OA technique was quite successful in the short range and did not involve an overlapping SW. Because of the way the two systems interacted, the combination of the PA and OA procedures performed better than the conventional scheme in every range. Moreover, there was no verified decline in performance. Making efficient use of the data in Prsvp, which is utilized in the SB-SPS scheme. While many approaches have been researched to use more information to improve the DRA problem's performance, these approaches necessitate standard-breaking extensions. On the other hand, this study makes use of Prsvp, which is a standard for improving performance without sacrificing compatibility. This method's biggest benefit is that it can be implemented without changing current standards. The two approaches to using Prsvp that the authors suggest are the PA and OA, together with their fusion method, which consistently performs better than each of them by itself. The suggested approach has no drawbacks but might not have a major impact because it is meant to be compatible with current standards.

To conclude this subsection which is related to DRA schemes in LTE-V2X. Although mode 4 has attracted the interest of a significant number of researchers over the past several years, some of these works are assessing the performance effect of SB-SPS mechanism parameters as in the first group, such as in the study by Zhang et al. [39], where the authors present a mathematical model and simulations to increase the reliability curve. Whereas the second group is dedicated to refining the SB-SPS algorithm to bolster its performance, exploring innovative adjustments and optimizations to optimize resource allocation and network efficiency, Dayal et al. [47] extend the SB-SPS in order to accommodate an adaptive RRI, referred as SPS ++, this modification outperform the standard scheme. Moreover, in the third group which propose new alternative methods to mode 4 to improve the SB-SPS algorithm, as in the study by Asano and Fujii [57], the work introduce two reselection methods to improve the system performance.

However, there is still a need for additional research into various areas pertaining to the management of interference and collision avoidance. As mode 4 is considered the cornerstone of C-V2X due to its ability to function without cellular networks, innovative approaches are crucial for its continued development. Figure 13 depicts the distribution of state-of-the-art DRA in LTE-V2X according to the three groups. For the benefit of readers, we provide a summary in Table 7 of the current state-of-the-art regarding the primary ideas for DRA approaches in mode 4.

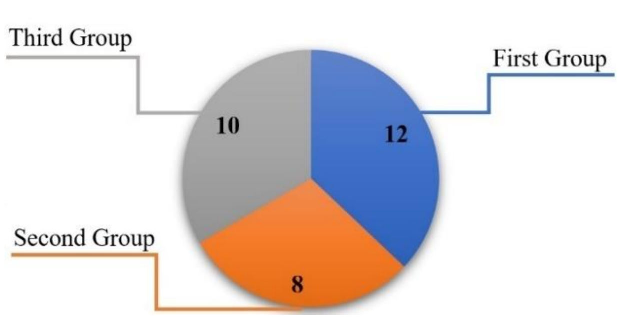

Figure 13. State-of-the-art of DRA in LTE-V2X

4.3 What is the DRA in NR-V2X?

In this subsection, we will first begin by discussing some of the more fundamental concepts associated with NR-V2X resource allocation. Secondly, we provide a comprehensive discussion on the resource allocation mode 2 utilized by NR-V2X. Last but not least, we will discuss the current state-of-the-art regarding DRA-relevant research studies.

4.3.1 Resource configuration in NR-V2X

In 3GPP specifications Release 16 [18, 58], NR-V2X services and applications shared the same standard physical infrastructure for system resources such as storage, bandwidth, and computing. This was made possible through the use of 3GPP's standard physical infrastructure specification. According to the link shown [59], a SL physical channel is responsible for carrying information that has been created at a higher layer.

In NR-V2X, regardless of the numerology employed, the 10 ms radio frame and 1 ms subframe are identical to those in LTE-V2X [22], as illustrated in Figure 14. In the frequency domain, a physical resource block (PRB) is comprised of 12 successive subcarriers, whereas every TS is comprised of 14 OFDM symbols. Whereas the resource elements (REs) are the most basic and minimal representation of resources, specified in both the time and frequency domains. The RE is characterized by a single OFDM symbol for the time domain and a single subcarrier within the frequency domain. The TS length is dependent on the numerology value and satisfies the condition *TS=1/2n*, where *n* is the numerology sequence. For instance, the TS value for numerology 0 is 1 ms, while the value for numerology 1 is 0.5 ms. Table 8 tabulates the main parameters associated with each numerology in NR-V2.

Multiplexing various numerologies is an additional level of NR frame structure flexibility. Numerology multiplexing may accommodate the various applications need. As an illustration, driving safety applications with ultra-low latency needs can utilize a short TS. Nonetheless, infotainment applications need ultra-high throughput, that may be achieved within a long TS.

As illustrated in Figures 15 and 16, the numerology multiplexing of NR-V2X can be accomplished using either the time-division multiplexing (TDM), the frequency-division multiplexing (FDM), or a combination of the FDM and TDM techniques [60]. The bandwidth part method (BWP) enables FDM-based numerology multiplexing. A feature introduced in

3GPP Release 15, this has been recently incorporated into the NR-V2X SL tandard. This addition aims to support UE with limitations in processing power, preventing them from supporting wide bandwidths [22]. The BWP is a chunk of PRBs on a specific channel, configured for numerology include in 1) symbol duration, 2) CP length, and 3) SCS.

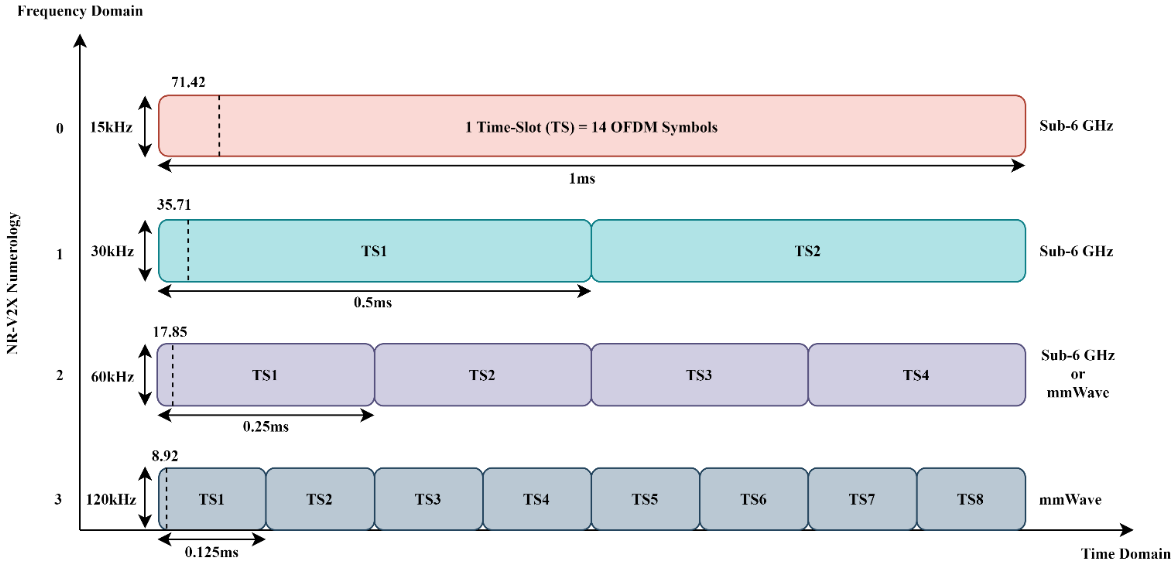

Figure 14. The frame structure of NR-V2X numerology

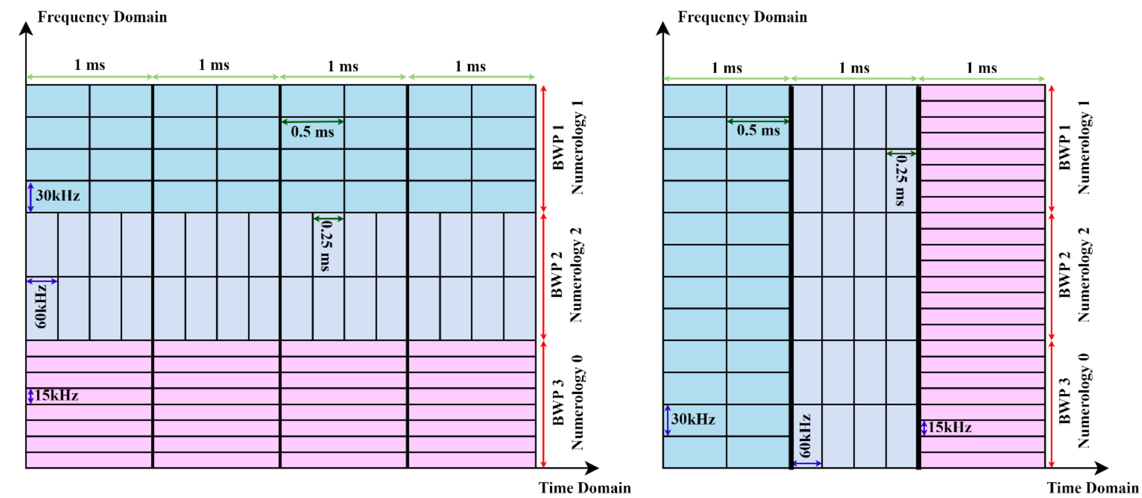

Figure 15. TDM and FDM numerology multiplexing

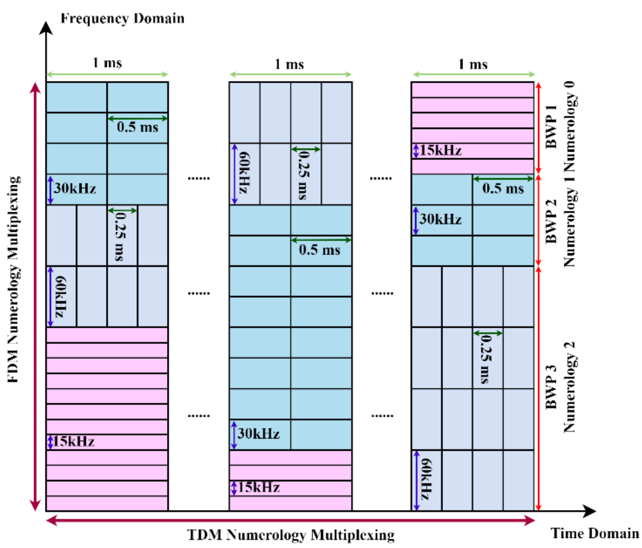

Figure 16. Mixing the FDM and TDM numerology multiplexing

Table 7. State-of-the-art of DRA schemes in LTE-V2X mode 4

Reference	Objective	Performance Metric	Traffic Application	Simulation Scenario	Simulation Tool	Findings and Limitations
[30]	SB-SPS algorithm evolution.	PDR	Periodic	Urban scenario	NS-3	High packet collision occurs in the SB-SPS algorithm.
[31]	Examine the effect of RRI on the SB-SPS algorithm performance.	PDR	Periodic	Highway scenario	NS-3	The PDR rises as the RRI increases.
[32]	Impact of *P* and RSRI on the performance of the SB-SPS algorithm.	PDR	Periodic	Highway scenario	OMNeT++	*P* affects SB-SPS algorithm performance depending on channel load, and RSRP to increase mode 4 performance.
[28]	Analytical evaluation of the SB-SPS algorithm performance.	PDR	Periodic	Highway scenario	MATLAB	Analytical models adequately depict the performance of C-V2X mode 4.
[33]	Examine the restrictions of SB-SPS algorithm in aperiodic traffic.	PDR	Aperiodic	Highway scenario	OMNeT++	The SB-SPS system performance degrades for aperiodic traffic.
[34]	Analyzed an open-source mode 4 simulators utilizing PRR and PIR performance criteria.	PRR, PIR	Periodic	Urban and Highway scenario	NS-3	Even in worst-case circumstances, C-V2X mode 4 scales.
[29]	Analyzed SB-SPS algorithm parameters and system performance.	PRR, UD	Periodic	Urban and Highway scenario	MATLAB	Changes to certain settings have no noticeable impact, while others, when selected carefully, may significantly improve service quality, and another set of parameters permits balancing reliability and update latency.
[35]	Examined DENM delivery performance via the PC5 interface using mode 4's sensing-based resource allocation mechanism under varied load situations.	PRR	Periodic	Highway scenario	MATLAB	Short-term sensing outperforms long-term sensing because it provides more precise channel measurements and lowering the SW to fit delay restrictions is inconvenient without

						additional countermeasures.
[36]	Examined how SB-SPS algorithm *pKeep* and RC parameters affect system performance in PC5-based C-V2X networks.	PDR	Periodic	Highway scenario	OMNeT++	Incorporating TA-SPS results in a 4% increase in PDR.
[37]	Examine the effect of aperiodic CAM packet creation on mode 4's overall performance.	PRR	Aperiodic	Highway scenario	MATLAB	Performance deteriorates when there is an imbalance between CAM packet generation and allocation.
[38]	Proposal of a separate resource pool for C-V2X CAM/DENM with dynamic aperiodic data transmission.	PRR	Periodic, aperiodic	Highway scenario	Not Detailed	The proposed method outperformance the conventional scheme.
[39]	Provided a theoretical representation of the scheduling reliability for LTE-V2X mode 4.	PRR	Periodic	Not Detailed	Not Detailed	The theoretical curve can successfully represent the reliability of the scheduling.
[40]	A proposal for a novel CLR mechanism.	BLER	Periodic	Not detailed	MATLAB	Reduce the probability of collision issues.
[41]	A proposal for a new reservation system to lessen the collisions probability.	PRR	Periodic	Urban scenario	OMNeT++	Superior performance regarding reliability and latency.
[42]	A proposal for a novel STS-RS scheme pre-resource selection.	PDR	Periodic, aperiodic	Highway scenario	MATLAB	Decrease the packet collision problems.
[43]	SB-SPS algorithm employs a novel non-linear power averaging approach.	PRR	Periodic	Urban and Highway scenario	MATLAB	An increase in PRR performance.
[44]	Improve the SB-SPS algorithm using a new approach that sidesteps the WBS issue.	PRR	Periodic	Highway scenario	MATLAB	The suggested approach is superior to the SB-SPS algorithm.
[45]	New approach for reserving resources that considers the varying packet sizes of transmitted messages.	PDR	Periodic	Highway scenario	Not Detailed	Superior PDR performance compared to the conventional SB-SPS.

[46]	Developed AM and AMCD algorithms to enhance SB-SPS resource reselection to address resource collision for autonomous resource selection.	PRR	Periodic	Highway scenario	MATLAB	The AMCD algorithm outperforms AM in PRR and Collision Ratio.
[47]	SPS++, an adaptive SB-SPS, improves on-road safety in decentralized V2X networks.	PDR	Periodic	Highway scenario	NS-3	In all C-V2X situations, SPS++ exceeded standard SB-SPS in on-road safety.
[48]	To improve mode 4's reliability, the ERRA algorithm is proposed.	PRR	Periodic	Urban scenario	MATLAB	ERRA outperforms the SB-SPS algorithm.
[49]	E-ERRA is an extension of ERRA to tackle the lost reserved resource issue.	PRR	Periodic	Highway scenario	MATLAB	E-ERRA decreases the collisions and enhances the PRR.
[50]	PRESS algorithm for mode 4 sensing and resource selection.	PRR	Periodic	Highway scenario	MATLAB	PRESS algorithm is more efficient than the traditional SB-SPS algorithm.
[51]	Orthogonal resource sets for autonomous resource selection.	PRR	Periodic, aperiodic	Urban and Highway scenario	Not detailed	The PRR performance was significantly enhanced.
[52]	Autonomous resource selection based on vehicle location and route order.	PDR	Periodic	Highway scenario	OMNeT++	Increased efficiency in C-V2X mode 4 communication.
[53]	Proposal of a DOCA-specific algorithm for resource allocation	Multi KPI	Periodic	Highway scenario	MATLAB	Increased the reliability of DOCA's V2V communication.
[54]	A hybrid C-V2X mode 4 and DSRC method is proposed to improve IoV networking reliability and performance.	PDR	Periodic	Not detailed	MATLAB	Improved the PDR based on traffic density range compared to previous technologies.
[55]	Proposed SS and DP-ASTS schemes to improve DENM and CAM communication.	PDR	Periodic, aperiodic	Not detailed	MATLAB	DP-ASTS can increase DENM and CAM performance in terms of PDR.
[56]	Presented the performance of the	PRR	Periodic	Urban and Highway scenario	MATLAB	The proposed algorithm superior to the

	conventional SB-SPS algorithm for the LTE-V2V mode 4.					conventional algorithm and enhance the performance of each scenario.
[57]	Proposed two techniques to increase LTE V2X mode 4 performance without extra information to prevent packet collisions.	PRR	Periodic	Highway scenario	OMNeT++	The proposed techniques can boost PRR without extra information.

Table 8. Supported numerologies in NR-V2X SL

Numerology	Slots/sub-Frame	Symbol Length (μs)	Slot Duration (ms)	SCS (kHz)	Symbol	CP	Frequency Range	Maximum Carrier Bandwidth (MHz)
0	1	71.42	1	15	14	Normal	sub-6 GHz	50
1	2	35.71	0.5	30	14	Normal	sub-6 GHz	100
2	4	17.85	0.25	60	14 12	Normal Extend	Any	200
3	8	8.92	0.125	120	14	Normal	mmWave	400

4.3.2 DRA mode 2 for NR-V2X

NR-V2X offers dual resource allocation modes similar to LTE-V2X. Mode 1 is used while the vehicle is in the cellular coverage range, whereas mode 2 is used when the vehicle is out of the cellular coverage range. 3GPP has explored how NR-V2X modes 1 and 2 can share the same resources. It is reported that both modes may utilize their own discrete resource pools, or they may share a single resource pool, which is considered more efficient for using the radio resources. Unfortunately, this could lead to collisions involving vehicles that are within various modes. In order to bypass this issue, mode 1 vehicles use the SCI field to let mode 2 vehicles know how much bandwidth will be made available for mode 2 future transmissions.

In mode 2, vehicles become autonomous regarding the resources they require. Resources utilized within mode 2 are selected from the SL resources, which are either pre-configured in the vehicles or specified by the gNB. However, to address these new use cases of NR-V2X, 3GPP has improved the SB-SPS algorithm used in mode 4 of LTE-V2X communication by proposing several potential solutions [9]. NR-V2X offers greater flexibility in communication compared to LTE-V2X. LTE-V2X is primarily designed for applications where traffic is predictable and messages have a fixed size. NR-V2X, however, can accommodate various traffic types with potentially different message sizes, to enhance safety services. In NR-V2X, the 3GPP provides a novel way for channel sensing that is referred to as short-term sensing, which is analogous to the Listen-Before-Talk (LBT) mechanism [61]. The 3GPP recommends adapting the sensing and resource selection procedures to cater to dynamic traffic applications, ensuring flexibility and efficiency in communication protocols. In fact, the SB-SPS algorithm is the proposed resource allocation algorithm for mode 2 in NR-V2X, and it has already been standardized in former technology. The sensing and selection processes are now one of the outstanding issues that receive the most attention in mode 2. For this reason, the 3GPP has proposed two different channel sensing mechanisms, as follows.

- *Long-Term Sensing:* in mode 4, vehicles rely on a continuous sensing process to identify available resources. This long-term approach helps prevent collisions by ensuring vehicles don't transmit on channels already in use by other devices (UEs).
- *Short-Term Sensing:* which involves checking channel availability just before transmission, is more suitable for handling unpredictable traffic patterns (aperiodic traffic). This approach can be combined with long-term sensing for additional collision prevention in these scenarios.

Various discussions suggest that in mode 4, long-term sensing for resource selection becomes less relevant for aperiodic traffic applications. This is because the unpredictable nature of aperiodic traffic makes relying solely on past channel conditions unreliable. For periodic traffic applications, NR-V2X mode 2 can use the same long-term sensing process as LTE-V2X mode 4, however, for aperiodic traffic applications, short-term sensing based on LBT is essential. Conversely, periodic traffic applications rely on short-term sensing through decoding the SCI and measuring the SL is sufficient. The SCI is particularly utilized for predicting the occupancy state of channel resources. Nevertheless, in aperiodic messages it could be challenging for SCI to decode in order to prevent potential resource conflicts. In such cases, resource selection may use the power measurement to serve it as a reference point. Furthermore, the integration of these two sensing procedures is also considered an alternative method. In this situation, long-term sensing may be utilized for identifying and excluding the occupied resources, as well as creating a list of potential transmission resources in the SL resource of the SW. Subsequently, short-term sensing operates in the SW utilizing the information that was obtained from the long-term sensing technique.

Note that such solutions must be evaluated in accordance with realistic scenarios. Consequently, the optimal sensing approach should be chosen solely on the basis of validated experimental tests. In light of the new definition of mode 2 in NR-V2X, a significant amount of study is necessary to examine more operational aspects of this mode.

4.4 What are the existing state-of-the-art articles for DRA in NR-V2X Mode 2?

Due to the recent completion of the 3GPP's standardization of the NR-V2X technology, there are not many published research papers that investigate the DRA in NR-V2X. In this part of the article, we will discuss the most recent research studies that have been conducted on this topic. In this section, we shed light on the contributions that have shown interest in mode 2 as distributed scheduling.

The research works related to mode 2 can be classified into two distinct categories or groups. The primary objective of the first group is to evaluate the impact of SB-SPS settings on mode 2 performance. In contrast, the second group proposes novel alternatives for the SB-SPS algorithm and demonstrating the efficacy of these suggested algorithms is superior to the original technique.

4.4.1 First group: Assessing the effect of SB-SPS parameters on mode 2 performance.

This group introduced recent research efforts that evaluate the performance of the SB-SPS mechanism for DRA in NR-V2X. Among these studies, we identify [62], in which Ali et al. investigated the effect of the SB-SPS algorithm's key parameters upon the total system performance. In this study, the authors consider many factors, including the MCS levels, the maximum quantity of per-reservation resources, NR flexible numerologies, and SW resource. Furthermore, Romeo et al. [63] emphasized DENM transmission reliability in the autonomous mode. The DENM, which is an aperiodic message in nature, is broadcast from a vehicle to warn other vehicles of potential roadway hazards. In this regard, authors are particularly concerned about a situation in which both periodic and aperiodic messages are broadcast and share certain resources within the scenario. They explore the primary parameter's impact of the SB-SPS algorithm on the delivery ratio of DENM, as well as the impact of the aperiodic generation of DENM on the periodic CAM transmission reliability. In fact, they investigate the short-term sensing efficiency within 100 ms period for transferring the DENM. They also demonstrate the combination of short-term sensing with frequent iterations of DENM is advantageous to DENM delivery rate. Whereas the CAM message reliability is impacted when the scenario's DENM message load increases.

In the same relation, Romeo et al. [64] studied the performance of sporadic traffic coexisting with periodic traffic application over mode 2. The combination of NR numerology and short-term sensing provides a preliminary demonstration of the benefits of the newly defined mode 2 in 3GPP Release 16. First, multiple DENM repeats are viewed as a simple method for enhancing transmission reliability. Then, a reservation system for multiple DENM copies is provided and combined with the pre-emption technique for traffic prioritizing in mode 2. With two DENM copies already in place, the proposal strikes a fair balance between DENM dependability and its influence on CAMs. In addition, the reservation comes at the price of carrying little or no extra signaling in the SCI.

Recent research has also examined the influence of flexible NR numerologies on the performance of DRA [65, 66]; this is an additional significant issue to consider. Ali et al. [65] investigated the influence of NR numerology on sensing as well as the SB-SPS algorithm SWs. When all resource sizes of the SW are identical for all numerologies, the authors show that a larger SCS improves the basic safety service performance and increases reliability. additionally, Campolo et al. [66] investigated how SCS impacts the reliability of CAM transmitted using DRA. Their study considers several circumstances with varying values of MCS levels, channel densities, and CAM message periodicities. They demonstrate that the SCS increasing enhances CAM transmission reliability and improves the PRR. In contrast, this procedure decreases the UD, which is the time interval between two consecutive decoding CAM message receptions. Their failure to examine channel delay spreading and vehicle speed as significant characteristics is the flaw in their study. As established in Flores De Valgas et al. [67], these two factors have a clear influence on the total system performance owing for the ISI and ICI difficulties caused primarily by the multipath fading and doppler shift issues, respectively. Moreover, Todisco et al. [68] evaluated the performance of DRA, with a specific concentrated on the new features presented in NR-V2X, includes the flexible numerologies and other modifications to resource selection techniques, covering various settings and processes for sensing and characterizing candidate resources.

Campolo et al. [69] evaluated the performance of autonomous resource allocation algorithms for NR-V2X under various density settings and traffic production patterns. Results validate findings in the literature indicating that retransmissions are less effective as load increases. This trend, however, does not apply to dynamic scheduling, as it is always advantageous. When considering an aperiodic traffic generation pattern, it has been observed that the SB-SPS algorithm may still offer advantages over dynamic scheduling. With considerable aperiodicity and high channel occupancy during packet creation, a dynamic allocation might be advantageous if retransmissions are required.

Cao et al. [70] have analyzed the SB-SPS parameters used for BSM scheduling with an AoI approach. The authors examined the performance of packet delivery based on given RRI values under varying vehicle densities, demonstrating the relationship between RRI values and the AoI measure. In terms of RRI values, they subsequently examined the predicted PAoI with or without packet collision. The generated analytical model was further validated using a Monte Carlo simulator. Based on a particular vehicle density, the ideal RRI value, which minimizes the estimated PAoI can be determined.

Shen and Wei [71] explored the upgrades to the DRA feedback channel for NR-V2X. The authors describe the physical layer structure for SL and the distributed mode processes of NR-V2X. In order to aid the UE in estimating the collision ratio, an analytical approach for assessing the collision ratio based on its sensing results is provided. Computing the Markov Chain steady states that formulate the SB-SPS algorithm sensing technique yields the detection ratio. They offer an initial discussion on the modifications to NR-V2X DRA that leverage the feedback channel in order to boost reliability and satisfy advanced needs. A receiver grant-based resource allocation is suggested to enhance the reliability of the DRA in NR-V2X. The authors have compared the suggested Rx Reserve solution to the Rx Reserve approach, whereby the receiver reserves resources via the feedback channel. They examine the collision situations of both the Rx Grant and Rx Reserve in depth and provide the corresponding analytical models. Through simulation results, they demonstrate that the suggested Rx grant-based resource allocation enhances network stability by decreasing the hidden node issues. In addition, they show that the analytical models also assist UEs with an accurate calculation of the SL transmission collision ratio.

Yan and Harri [72] demonstrate that a 64QAM corresponds to the optimal modulation and coding rate for NR-V2X SL broadcast communication, which represents a significant deviation from previously accepted values. Authors present heterogeneous types of transmit densities and characteristics in their methodology, representing more realistic transmission patterns anticipated for NR-V2X application services. They demonstrate that packets requiring fewer V2X physical resources enable a more efficient spectral under NR stringent subchannel numerology.

Recently, Campolo et al. [73] evaluated the performance of vehicles equipped with FD transceivers that exchange data through SL. Particularly, the authors have revised the SB-SPS algorithm of the DRA by allowing an FD-enabled vehicle to initiate a resource reselection the moment that a collision is detected during transmission. The objective of such an approach is to avoid retaining potentially compromised resources and suffering recurring losses. This approach does not require resource allocation modifications or any extra signaling. Simulation findings demonstrate that the approach is superior to the conventional SB-SPS algorithm imposed by HD VUEs. Intriguingly, these advantages are extremely sensitive to the detection of the threshold setting, which influences the findings differently depending on the traffic density setting. More recently, Lee et al. [74], classified the resources determined to be collision-free inside the SW to avoid the extra-window collision. Compared to the standard SB-SPS, the enhancement achieves a non-negligible reduction in the total packet collisions and consecutive collision events for various combinations of packet transmission periods among vehicles.

4.4.2 Second group: New alternative methods to mode 2 to improve the SB-SPS algorithm.

Recent studies have proposed an alternative algorithm to enhance the DRA for NR-V2X. Starting with Yoon and Kim [75], they presented a stochastic reservation method for aperiodic traffic applications in an effort to improve the current SB-SPS algorithm. The central concept of their approach involves predicting the timing of the next transmission for the subsequent packet to conserve resources for the transmission. This forecast is generated through analyzing the intervals between the last packets. Through simulations, the authors show that the suggested approach yields high PRR values. The majority of previously described ideas do not account for crowded environments, where resource allocation becomes more challenging because of the likelihood of interference issues. Nevertheless, Yi et al. [76] focused on the congestion at intersections. The authors introduced a novel SB-SPS approach for optimally allocating resources to vehicles by leveraging the RSUs sensing information. In their proposal, a RSU broadcasts CSI to vehicles at regular intervals. Using this information, it produces the Sidelink-Received Signal Strength Indicator (S-RSSI) and RSRP maps and broadcasts them to vehicles so that they can choose radio resources more autonomously. This proposed approach allows for the avoidance of collision issues, thereby outperforming the conventional SB-SPS algorithm provided for mode 2.

Saad et al. [77] presented the e-SPS approach to supplement the DRA in NR-V2X to allocate resources for aperiodic CAMs; the simulation findings indicate that the re-evaluation procedure established in the e-SPS facilitates the scheduling of resources for aperiodic traffic applications. In addition, all vehicles are treated as agents, and the structure of the SW and other SB-SPS characteristics are modified continuously based on the outcomes of machine learning. This facilitates conflict-free assignment of resources for aperiodic message delivery and eliminates resource contention. The performance statistics demonstrate that the overall networks improve in terms of PDR. additionally, Zang and Shikh-Bahaei [78] presented an alternative MAC layer protocol, namely FDPS, to improve the performance in terms of latency, collision period, and PDR. This protocol is compatible with the existing NR eV2X standard. FD technology enables collision detection, and the collision resolution process has been meticulously devised. FDPS has improved the performance and viability of future NR eV2X VANETs, as determined by analytical and simulation evaluations of its functionality. Djaidja et al. [79], presented an enhanced version of the SB-SPS algorithm to combat resource selection jamming assaults in C-V2X. First, a feedback mechanism was developed to notify vehicles when they failed to transmit their packets. Next, fuzzy logic was utilized to implement an optimal defense policy against packet-dropping attacks, which comprised of dynamically adjusting the RC value as a significant metric in the semi persistent schemes. Even with a large number of attackers, the simulation results demonstrate that the technique may greatly minimize the effectiveness of such attacks. In terms of PRR, the technique outperforms the SB-SPS scheme by limiting the number of valid collisions.

Choi et al. [80] presented a modified sensing algorithm for PSCCH detection in 5G-NR systems. PSCCH detection is crucial for transmitting UE to reserve a resource and for the receiving UE to identify the resource for data reception. The proposed algorithm offers significant advantages by reducing the average number of SCI decoding's to only half. This reduction in decoding requirements alleviates the hardware burden, as it eliminates the need for detection on all sub-channels throughout the slot period. As a result, the proposed algorithm proves to be a viable and efficient option for implementing SL functionality in the 5G-NR system. With its reduced hardware complexity and comparable performance, this modified sensing algorithm presents a promising solution for enabling efficient PSCCH detection in 5G-NR systems.

The DRA for NR-V2X subsection could be summarized by providing a comparative performance analysis between the most recent studies for each group. In the first group which is Assessing the impact of SB-SPS parameters on mode 2 performance, Lee et al. [74] proposed a RSSI based scoring assistance scheme to reduce the packet and consecutive collisions in the system. Whereas the second group consists of researches that introduce an alternative method to improve the mode 2 performance such as in the study by Choi et al. [80], presents an algorithm for detecting the PSCCH efficiency to decrease the SCI decoding time and enhance the SL communication. Even though the efforts of the academic researchers to improve the performance of DRA in NR-V2X yet this technology still has a lack of performance in high vehicle densities and aperiodic traffic applications. Figure 17 illustrates the two groups' state-of-the-art of DRA in NR-V2X.

In Table 9, we have compiled a summary of the most recent and advanced schemes used for DRA within the NR-V2X communication system.

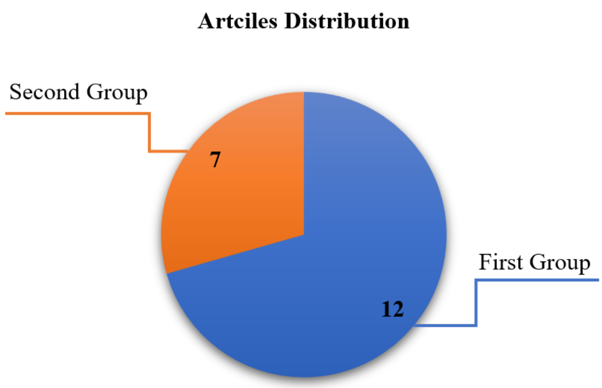

Figure 17. State-of-the-art of DRA in NR-V2X

4.5 What are the ML algorithms that improve the DRA in C-V2X?

Massive volumes of data will be created, processed, and communicated via vehicular networks, despite the fact that vehicles are anticipated to utilize numerous facilities, such as enhanced onboard sensors consisting of cameras, radar, storage facilities, and high-performance computing. Machine learning (ML) algorithms are expected to be excellent tools for analyzing such as a massive amount of data and making data-driven decisions for improving the vehicular networks [81]. For more information on ML, see the studies [82, 83].

Nonetheless, for automotive networks where the network architecture and channel quality may be continuously changing, the typical optimization technique may need to be redone each time a little change occurs, incurring a substantial amount of overhead [84]. While an ML approach could be an alternative to popular optimization approaches, research into the application of ML in vehicular networks is currently in its infancy [81]. In the existing researches [85-97], ML has been used to improve resource allocation, users' association and virtual resource management for V2V communications based on the dynamic features.

Ye and Li [85] proposed a deep reinforcement learning (RL) based power allocation and distributed channel method for C-V2V communications. The authors focused on resource allocation for V2V connections based on the limitations of V2V link latency and the lowest interference impact on V2I links, under the premise that orthogonal resources are provided in advance for V2I links. Figure 18 depicts the framework of RL as it applies to V2V connections. Each V2V connection is represented by an agent, and the agent in turn interacts with the environment. The environment's state is specified by a collection of parameters, such as the current traffic load, the remaining time until latency limits are met, the interference level on neighboring channels, and the channels that were chosen by neighbors during the previous TS.

At time epoch t, every V2V connection, acts like an agent to observe the current state st ϵ S based on its policy π and execute an action A, where S and A are the set of all states and the set of all possible actions, respectively. Following the activity, the agent receives a reward rt that is determined by the V2V latency. Consequently, the optimal strategy for decision-making is determined by deep learning.

The training data is created and stored by an environment simulator. Initially, during the training phase, the produced data is used to progressively improve the strategy applied in every V2V connection for power selection and spectrum. Then, during the testing phase, activities in V2V connections are selected based on the enhanced policy. The authors expanded this work to provide a comprehensive scenario [86]. According to Ye et al. [86], every vehicle is modeled like an agent, the number of received messages and the distance between vehicles that have broadcast are also taken into account when calculating its state. Then, all the vehicles enhance their sub-channel selection rules and broadcast messages by using a learning method.

Utilizing the IEEE 802.11p standard for DSRC, Pressas et al. [88] examine the contention of MAC for V2V broadcast communication. In a situation with not more than 50 vehicles, IEEE 802.11p may provide superior performance to LTE-V2V with respect to greater PDR and reduced latency. Nevertheless, as the number of vehicles on the road increases, the existing need is no longer sufficient to handle the increasing amount of traffic. In order to overcome the scalability challenge associated with vehicle density, Pressas et al. [88] proposed an ML-based method to enable efficient data packet exchanges for stringent reliability criteria by determining the appropriate contention window. Each vehicle, which is a separate learning agent, uses learning to determine the CW size. The input from each packet transfer, whether successful or unsuccessful, is used to determine the CW size. In the study of Ye and Li [85], the two-stage RL is predicted to produce immediate performance gains beginning with the first transmission. Initially, the policy is enhanced with the data provided by a simulator. During the testing phase, actions are selected according to the pre-trained policy while the policy continues to evolve. The simulation was used by Pressas et al. [88] to test the performance of the suggested ML. The results demonstrate that the proposed ML strategy offers greater system throughput and reliable packet delivery.

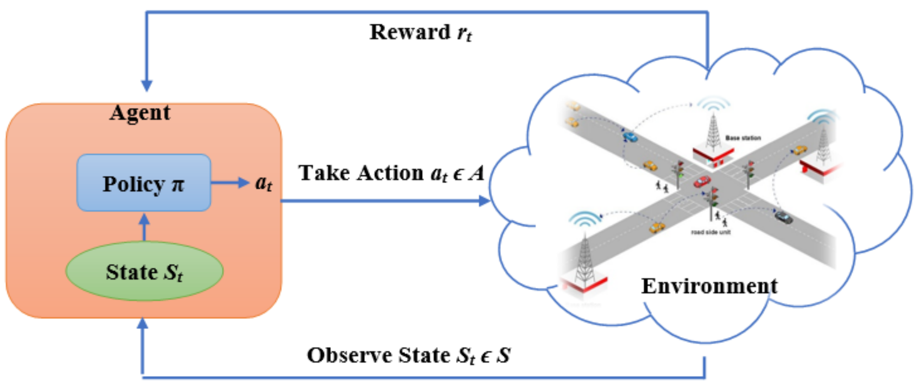

Figure 18. The structure of RL for V2V links [7]

Table 9. State-of-the-art of DRA schemes in NR-V2X mode 2

Reference	Objective	Performance Metric	Traffic Application	Simulation Scenario	Simulation Tool	Findings and Limitations
[62]	Investigate how adjusting the primary SB-SPS algorithm parameters affects the performance of the whole system.	PIR, PRR	Periodic	Urban and Highway scenario	NS-3	The performance of SB-SPS algorithm enhances with several parameters and trad-off others.
[63]	Examine the effect of autonomous mode 2 on the aperiodic DENM messages transmission.	PRR	Aperiodic	Not detailed	MATLAB	Short-term sensing boosts DENM delivery.
[64]	Investigated NR-V2X autonomous mode performance with sporadic and periodic traffic.	PRR	Periodic, aperiodic	Highway scenario	MATLAB	Achieved a fair trade-off between DENM reliability and CAM impact for two DENM copies.
[65]	Examine the effect of NR numerologies on mode 2 performance.	PIR, CDF	Periodic	Highway scenario	NS-3	High SCS is advantageous for mode 2's basic safety service.
[66]	Assessed SB-SPS performance in C-V2X mode 4 with NR flexible numerology.	PRR	Periodic	Highway scenario	MATLAB	Increased SCS and shorter TTI duration boost PRR and lower UD.
[67]	Study the NR numerology changes affect BLER performance.	BLER	Not detailed	Highway scenario	Not detailed	The ICI and ISI effects trade off system performance as SCS increases.
[68]	Analyzed SL Mode by focusing on the new features in NR-V2X compared to earlier 3GPP versions.	PRR	Periodic, aperiodic	Highway scenario	MATLAB	The flexible NR numerology and resource selection mechanism allow for diverse sensing and candidate resource identification processes.
[69]	Examined NR-V2X autonomous resource allocation techniques under varied density levels and traffic generation patterns.	PRR	Aperiodic	Highway scenario	MATLAB	When traffic generation is aperiodic, SB-SPS can still outperform dynamic scheduling.
[70]	An AoI-based analysis of the SB-SPS parameters used for BSM scheduling.	PRR	Periodic	Highway scenario	MATLAB	Based on vehicle densities, SB-SPS's optimal RRI values can reduce the vehicular network's expected PAoI.
[71]	Discussed the NR-V2X DRA enhancements with the feedback channel.	PRR	Periodic	Highway scenario	MATLAB	The suggested Rx Grant-based resource allocation increases reliability by decreasing hidden node issues.
[72]	Assessing MCS's influence on V2X broadcast communication using numerous NR-V2X service parameters.	PRR	Periodic	Highway scenario	NS-3	Packets with less V2X physical resources or greater MCS have superior spectrum efficiency with NR strict subchannel numerology.
[73]	Using FD to detect collisions and trigger resource reselection more consciously to improve autonomous mode 2.	PRR	Periodic	Highway scenario	MATLAB	The proposed SL V2X improves reliability and timeliness over mode 2.
[74]	Proposed a resource scoring method and an RSSI-based scoring assistance scheme.	Not detaile	Periodic	Not detailed	MATLAB	The enhancement achieves non-negligible reduction in the total packet collisions and consecutive collision events for various combinations of packet

						transmission periods among vehicles.
[75]	New stochastic reservation approach for aperiodic traffic.	PRR	Aperiodic	Highway scenario	MATLAB	Superior performance as measured by PRR.
[76]	A unique SB-SPS technique is proposed for the congested intersection region.	BLER	Periodic	Urban scenario	MATLAB	Decrease the collision probability.
[77]	Proposed e-SPS to supplement NR-V2X mode 2 for aperiodic CAM resource scheduling.	PDR	Aperiodic	Not detailed	NS-3	e-SPS outperforms others.
[78]	suggested FDPS, a new MAC layer protocol compatible with NR eV2X, to improve latency, collision duration, and PDR.	PDR	Periodic	Not detailed	MATLAB	FDPS improved future NR eV2X VANET performance and feasibility.
[79]	Develop a feedback-based attack detection technique and an optimum evasion policy using a fuzzy inference system which dynamically adapts resource reservation time.	PRR	Periodic	Not detailed	MATLAB	The suggested approach considerably reduces packet-dropping attacks and improves network PRR.
[80]	Introduced a method to detect the PSCCH efficiently.	BLER	Periodic	Not detailed	Not detailed	The proposed method presents a good performance and can be used for SL 5G-NR.

Li et al. [87] employ ML to create the user association algorithm for load balancing in heterogeneous vehicular communications. Considering the spatial-temporal properties of data flow produced by vehicle networks, a two-step association technique is presented. Subsequently, BS makes judgments about affiliation based on previous association patterns. In addition, as a learning agent, BS continues to update the association findings and accumulate feedback information adaptively. While the proposed algorithm is distributedly executed by each BS, it is demonstrated that both regular traffic association patterns and real-time feedback aid the system in adapting to network changes over time. Moreover, Liang et al. [89] created a distributed resource-sharing method based on multi-agent RL for vehicular networks using multiple V2V connections that reuse the V2I line spectrum. When paired with DQN and experience replay, a fingerprint-based technique was used to overcome the nonstationary concerns of independent Q-learning for multi-agent RL issues. The suggested RL-based technique for multiple agents is comprised of a distributed implementation stage and a centralized training stage. Despite the fact that each V2V transmitter makes decisions locally, the authors show that the proposed resource-sharing method is effective at fostering collaboration across V2V connections to enhance the performance of the system-level.

Saad et al. [90] recently proposed a multi agent collaborative DRL-based system. Here, a single DQN is trained for each zone, which is preset with resources that comprise the resource pool. The vehicles in the same pool share a function that provides a reward. This strategy encourages vehicles to cooperate rather than compete when picking transmission resources. The suggested strategy is contrasted with C-V2X for the random allocation of resources. Even in a crowded vehicle environment, the findings indicate that the suggested approach outperforms. On the other hand, Zang and Shikh-Bahaei [91] have presented a flexible FD DRL-based architecture for 5G VANETs. VUEs use both the benefits of FD technological capabilities and DRL. In contrast to the SB-SPS method, AFD-DRL addresses acknowledgment and collision issues, allowing VUEs to promptly terminate broadcasting and reselect resources. Due to the absence of blind re-broadcasting in FD-DRL, the broadcast storm issue has also been resolved. The findings demonstrated that the suggested AFD-DRL approach is superior to the SB-SPS algorithm.

In addition, the framework is characterized as a contextual multi-armed bandit (MAB) presented by Kim et al. [92], which is based on RL. The authors have offered a comprehensive algorithmic approach that includes: (i) quantification indicators of the driver's behaviors for a vehicle risk accident; (ii) a contextual MAB algorithm that is adaptive to the driver's behavior for the selection of the optimal TBS for SL-SCH in NR-V2X mode 2; and (iii) the ability of the algorithm to operate autonomously at the vehicle without the requirement for any support from a centralized entity. The simulation revealed that the suggested technique is capable of locating the optimal TBS. This resulted in a normalized throughput performance and a more reliable BLER for a vehicle existing in a dangerous environment. Gu et al. [93] present a multiagent DRL-SPS method to assist vehicles in reducing packet collisions through the selection of suitable radio resources. In addition, a multi-head attention system is used for boosting training efficiency by enabling all vehicles to selectively focus on observations and actions of the other vehicles within the scenario. Notably, the DRL-SPS algorithm matches the features of LTE-V2X mode 4 by selecting the resources without requiring global information. The findings from the simulation indicate that the DRL-SPS algorithm outperforms alternative decentralized techniques and demonstrates its durability and scalability in a dynamic vehicular network. Miao et al. [94] introduced an energy-efficient resource allocation strategy for V2V communication based on DDQN. Simulation results demonstrate that the suggested multi-agent DRL system surpasses the random selection strategy. The greater the V2V success probability, the shorter the latency since a packet is only deemed successful if it reaches its destination within the allotted time.

Recently, Wang and Wang [95] Implemented the Q-learning principle into the contention-based resource allocation strategy in distributed media access control when there is insufficient connection information available. The suggested technique introduces a novel approach to collision avoidance using Q-learning. It features a unique bidirectional backoff reward model within the Q-learning framework. Heo and Kim [96] Demonstrated that a model based on deep learning can accurately forecast the timing of when each detected nearby vehicle will be incorporated into a CPM message. It allows for the anticipation of the timing of the next CPM transmission and facilitates the allocation of resources for it. The simulation experiment of the proposed upgrade demonstrated a significant reduction in wasted resources and packet collisions compared to the utilization of the conventional SPS.

More recently, Hegde et al. [97] introduced a new method to enhance the efficiency of a 5G-NR V2X communication network by utilizing artificial intelligence techniques for radio resource allocation. The network was modeled as a multi-agent networked Markov Decision Process (MDP), and actor-critic schedulers, specifically IAC or SEAC, were employed to adaptively adjust resource allocation parameters. This adjustment was based on V2X data traffic patterns and aimed to reduce radio resource collisions. The simulation results indicate that schedulers based on artificial intelligence outperform schedulers based on rules, specifically in scenarios with irregular traffic patterns and varying data quantities. Under conditions of high traffic congestion, the SEAC version demonstrated a transmission success ratio ranging from 70% to 80%. Compared to the SB-SPS, the AI versions IAC and SEAC have a 15-25% higher likelihood of reception for the aperiodic data flow model.

In ML, the type of data (labeled or unlabeled) may be a crucial factor in determining the learning approach to use, and the quality of the data that has a significant effect on the success of learning. However, the lack of relevant actual datasets for vehicular networks has been identified as one of the greatest obstacles to the implementation of ML [98]. In contrast to learning methods that require pre-obtained datasets, The RL algorithms can be applied in absent of any former understanding of the environment or pre-existing datasets, as observed through the aforementioned experiments. It demonstrated that the online RL method may converge to a solution by repeatedly receiving feedback from the dynamic vehicular network environment.

As a result, the vehicle network performance may deteriorate due to an increase in communication overheads and the computational difficulty of analyzing a large amount of data; hence, a distributed learning technique is considered in the aforementioned research.

Table 10 provides a concise summary of ML-based algorithmic features that are found in the research literature.

4.6 What is the impact of CC on DRA in C-V2X?

Decentralized congestion control (DCC) has long been seen as an important part of V2X for dealing with congested environments, and it has been widely studied on top of IEEE 802.11p [99, 100]. According to the link shown [101], ETSI has put forth a system for C-V2X, wherein the transmitting of a packet across PC5 may be limited based on its precedence and two calculated characteristics: the channel occupancy ratio (CR) as well as the channel busy ratio (CBR). In 5G-V2X [102], the CR is measuring the vehicle transmission channel occupancy and is referred to number of subchannels used by the vehicle over the course of 1000 subframes (1000 slots or 2µ 1000 slots), which may include both current and future subframes. Whereas the CBR refers to the proportion of a subchannel that has been used for data transmission in the last 100 subframes (100 slots or 2µ 100 slots [102]) with an average RSSI greater than the threshold, and it serves as an approximation of the overall occupied channel (the 3GPP Releases 14 and 16 are specified ranges of these values).

For CR and CBR computations, NR-V2X establishes a time interval of 1 or 2 ms, which is shorter than the 4 ms interval for LTE-V2X. This finer time resolution allows for better tracking of load changes resulting from aperiodic traffic applications [58]. The 3GPP does not specify a particular DCC method in both Releases 14 and 16, but instead outlines the countermeasures and metrics as described above. Yet, specific methods are not standardized in the United States, and the same applies to C-V2X at the upper SAE levels, with a variation of J2945/1 under development [103].

Due to the significance of reliability in vehicular networks and results of several studies suggesting that SL C-V2X may be vulnerable to interference in dense scenarios, congestion control is regarded by the vehicular network community as one of the most important aspects of C-V2X [104], and it has already been extensively discussed in a number of studies [105-118].

Table 11 provides a summary that is specific to this issue due to its distinctive importance. While several of the listed articles provide innovative concepts or enhancements to the design specification, the primary emphasis of this section is on the functionality of DCC mechanisms in the SL C-V2X. Mansouri et al. [105] analyze the impact of the DCC mechanism under the assumption that when congestion is present, it leads to packet loss at the application level. In this strategy, a conflict is observed between the sensing technique and DCC, resulting in a deterioration that is significantly worse than in the absence of control. Additionally, Toghi et al. [106, 107] alternatively propose congestion control mechanisms based on American standards developed with DSRC in mind and issued by SAE. The algorithms that affect both the transmission power and the production of packets demonstrate that the adjustment of the interval of packet generation is more successful than range control in ensuring high PRR and minimal IPG. A similar conclusion is reached by Bazzi et al. [108], who examining the effect of variations in packet generation rate, range, or MCS in the absence of a specific reference to particular DCC schemes. The findings indicate that controlling packet generation rate is the sole truly effective method for improving PRR, albeit at the expense of IPG. Shimizu et al. [109] compare the LTE-V2X mode 4 performance to IEEE 802.11p with SAE congestion control. The modification of the transmission power and message intervals are also examined by Kang et al. [110], excluding the

DCC metrics, the adjustment of the message duration based on the predicted interference likelihood becomes essential for optimizing communication reliability and efficiency in vehicular networks, while dynamically adapting transmission power to maximize the expected PRR based on surrounding neighborhood awareness., as measured by S-RSSI data. Furthermore, Yoon and Kim [111] recommend modifying the rate control function such that it responds to the congestion in a comfortable way, as a result, the power control is capable of making a more substantial contribution to the overall congestion control. This rebalancing of control components has been demonstrated to enhance IPG performance. Kang et al. [112] and Haider and Hwang [113] also present power control algorithms, demonstrating that a reduction in transmission power in crowded conditions results in some improvement.

Saifuddin et al. [114] take into account the coexistence of event-driven and periodic communications. The results indicate that transmission power regulation of periodic messages could be very beneficial for event-driven messages with a higher priority. Choi and Kim [115] augment SAE DCC with a QoS mechanism for the same purpose of performance differentiation. Two classes of QoS are studied, one prioritizes range protection at the cost of reduced update rate, while the other prioritizes information update rate at the expense of decreased range. The packet transmission rate and transmission power are altered accordingly for each class. According to Naik et al. [116], congestion control is discussed in terms of HARQ. In particular, the authors recommend issuing retransmissions in an adaptive manner, noting that while they may enhance dependability under lightly congested conditions, they may increase collisions under densely congested conditions.

Table 10. State-of-the-art of DRA schemes for ML in C-V2X

Reference	Objective	Performance Metric	Traffic Application	Simulation Scenario	Simulation Tool	Findings and Limitations
[85]	Deep reinforcement learning-based DRA method for V2V communications is presented.	Not detailed	Not detailed	Not detailed	Not detailed	Each agent may learn to meet V2V limitations while decreasing V2I interference.
[86]	Deep reinforcement learning-based DRA algorithm for V2V communications is proposed.	Not detailed	Not detailed	Not detailed	Not detailed	The agent may meet V2V limitations while reducing V2I interference.
[88]	Proposed a contention-based MAC technique for V2V broadcast transmissions that uses Q-Learning to continually interact with the network to find the best contention window.	PDR	Periodic	Urban scenario	OMNeT++	As network traffic rises, boost performance relative to IEEE 802.11p while maintaining acceptable transmission delay.
[87]	Propose ORLA for load balancing in heterogeneous BS vehicular networks.	CDF	Periodic	Urban scenario	MATLAB	ORLA load-balances better than other common association approaches.
[89]	Developed a multi-agent RL-based distributed resource sharing method for vehicular networks with numerous V2V connections employing V2I spectrum.	Not detailed	Periodic	Urban scenario	Not detailed	The resource sharing strategy improves system performance by promoting collaboration among V2V connections.
[90]	Proposed multi-agent collaborative DRL scheme to decrease resource contention.	PDR	Aperiodic	Urban scenario	Not detailed	The suggested method functions well even in dense vehicle environments.
[91]	Utilizing DRL algorithm and FD technology adaptively to improve NR-V2X networks.	Not detailed	Periodic	Not detailed	OMNeT++	AFD-DRL outperforms SB-SPS algorithm.
[92]	The proposed framework is built on RL, which is represented as an MAB in a specific setting.	BLER	Periodic	Not detailed	Not detailed	An adequate TBS was located using the suggested technique.
[93]	Propose a multiagent RL-SPS method to assist vehicles choose radio resources to reduce packet collisions.	PRR	Periodic	Not detailed	OMNeT++	RL-SPS beats decentralized alternatives and shows its scalability and robustness in a dynamic vehicular network.
[94]	Proposes DRL and a model is trained with the using of the DDQN.	Not detailed	Periodic	Urban scenario	Not detailed	The suggested model beats the comparable method in energy efficiency and latency performance.

[95]	Presented a novel approach for improving the per- formance of a 5G-NR V2X communication network using AI techniques for radio resource allocation.	PRC	Periodic, Aperiodic	Urban scenario	OMNeT++ and Artery-C	The AI-based schedulers out-perform rule based SB-SPS, particularly under aperiodic traffic conditions with variable data sizes (type)
[96]	Proposes a novel QCA scheme characterized by a Q-learning-based bidirectional backoff in the intelligent MAC to achieve fair communication with improved QoS performances of the dynamic distributed vehicular networks.	PDR	Not detailed	Not detailed	NS-2	QCA can achieve fair communication efficiently and robustly, with advantages of superior Jain's fairness index, relatively high packet delivery ratio, and low time delay.
[97]	Proposes a deep learning-based scheme that predicts when the sensed vehicles will qualify to be included in the CPM.	PRR	Aperiodic	Urban scenario	Not detailed	The number of wasted resources and packet collisions can be greatly reduced compared to using standard SPS.

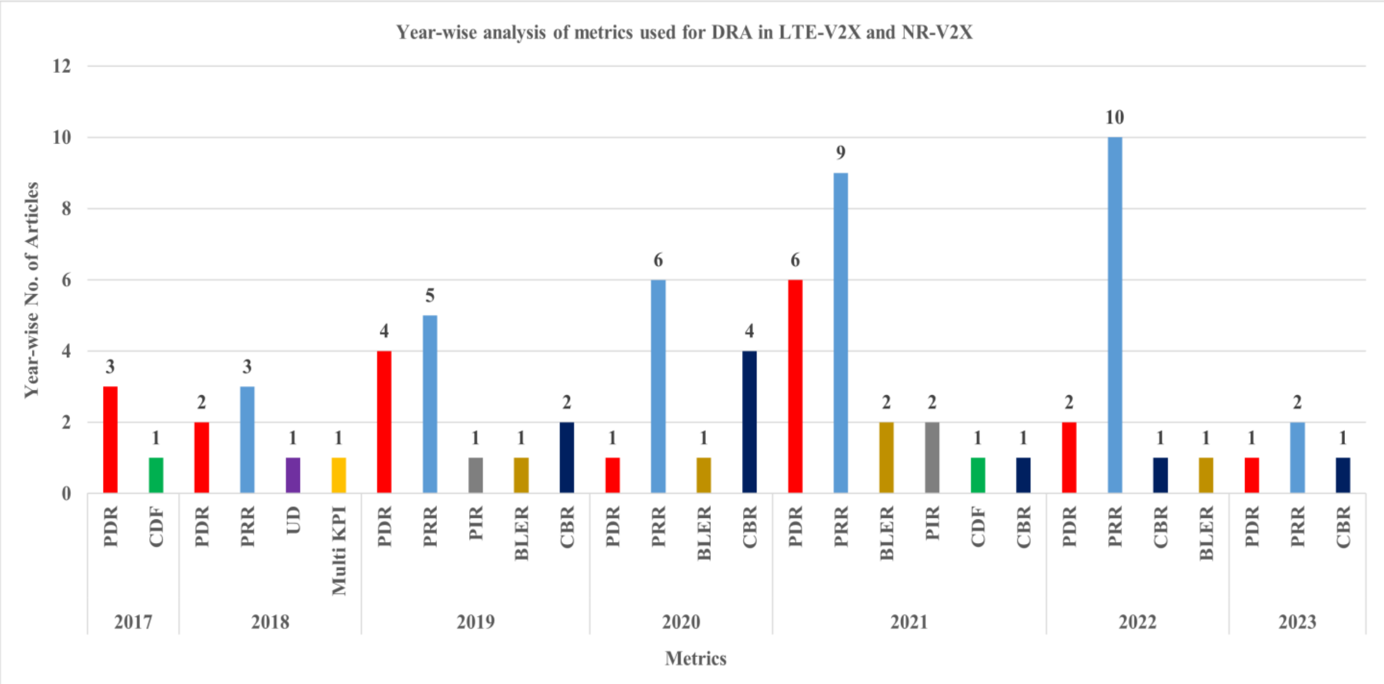

Figure 19. Year-wise analysis of metrics used for DRA in LTE-V2X and NR-V2X

Recently, McCarthy and O'Driscoll [117] provided a comprehensive quantitative analysis of the current congestion control standards in C-V2X and NR-V2X. The RRI DCC protocol, which consists of three standard-compliant variations and is fully compatible with the SB-SPS procedures for both technologies, is then presented. The authors have demonstrated that RRI DCC provides significantly improved performance in the light of PDR while maintaining the same mean neighbor awareness and IPG compared to current conventional techniques. More recently, Tian et al. [118], introduces an optimized DCC scheme employing a hybrid strategy, blending Transmission Rate Control (TRC) and Transmission Power Control (TPC) methods for developing an efficient and resilient CC solution. This Hybrid Power-Rate DCC (HPR-DCC) scheme dynamically assigns transmission power and rate based on congestion levels, enhancing the performance and effectively distributing available bandwidth.

4.7 Which metrics, simulation tools, and parameters are considered for DRA of LTE-V2X and NR-V2X?

4.7.1 Performance metrices

The contributions that were found in the studied body of SLR focused mostly on link layer metrics, more specifically PRR. The PRR is defined as the average fraction of correctly decoded TBs with respect to the total number of transmitted TBs. Nonetheless, they do not even come close to capturing how the DRA operates in relation to the C-V2X application, the PRR is evaluated as:

$$PRR = \frac{\sum_{j=1}^{N} X_i^j}{\sum_{j=1}^{N} Y_i^j} \tag{1}$$

where, X_i^j indicates the number of vehicles in the i-th range that received the j-th packet successfully, Y_i^j is the number of vehicles in the i-th range and N denotes as the number of generated packets. As a result, the evaluation of performance measures that are unique to applications is strongly recommended, as shown in Figure 19.

4.7.2 Simulation tools

A significant amount of effort has been put into the creation of simulation systems for the assessment of DRA in LTE-V2X and NR-V2X, with a particular emphasis on mode 4 and mode 2. However, in the majority of instances, the implementations are confidential and are not made available to the public. This tendency makes it difficult to easily reproduce findings and make relevant comparisons. Open-source implementations of a handful of the proposed solutions have also been made publicly available. The first one is called the LTEV2Vsim [119], which is a simulator that was created in MATLAB. It is intended to facilitate investigations into SL resource allocation in LTE-V2X for both modes. The WiLabV2Xsim [120] is the second simulator, and it is likewise implemented in MATLAB. The primary emphasis of this simulator is on the efficiency with which NR-V2X SL resource allocation. The simulator that was provided in reference number [121], which focused on the D2D framework. Another simulator that focuses on mode 4 is presented by Rouil et al. [122]. This simulator is a modified and extended version of SimuLTE that is contained in OMNeT++. It is executed in two different versions: the first version integrates with the Artery8 framework that provides complete ITS-G5 standardization throughout the overall communication stack, and the second version integrates with Veins. Both versions are available for use. Figure 20 illustrates the simulation software tools for the articles previously discussed.

4.8 What are the challenges, open issues and promising future directions for DRA in C-V2X?

The preceding sections have demonstrated The SLR of DRA in LTE-V2X and NR-V2X, ML and CC standard in vehicular networks. This subsection outlines the most intriguing conclusion drawn from the SLR. It consists of two parts: the first one demonstrates the challenges associated with the DRA in C-V2X, and the second one presents the interesting open issues and promising future directions that must be investigated further in future research.

4.8.1 Challenges

According to the mentioned issues that have already been reviewed in the state-of-the-art for mode 4 in LTE-V2X and mode 2 in NR-V2X on DRA algorithms, our review of the literature has revealed various challenges in terms of the SB-SPS algorithm in relation to the collision issue, as it is one of the most stringent problems in the DRA, along with resource-efficient allocation.

In reality, the DRA relies on channel sensing for resource selection operation. However, faulty sensing could lead to selecting a resource that is currently being utilized by another vehicle, resulting in packet collisions. Incorrect sensing occurs when two vehicles fail to identify each other, resulting that one of these vehicles selecting resources currently in use by another vehicle. Furthermore, in a densely populated environment with fast-moving vehicles, the probability of packet collisions could increase. This occurs because the SB-SPS algorithm does not take into account other vehicles utilizing the very same resource that are not within the vehicle's sensing range when it makes its resource selection. We call attention to this issue because, while numerous concepts in the literature target addressing the collision issue,

further endeavor is required in future research to thoroughly investigate this challenging aspect.

In addition, we underscore another challenging issue, namely the efficiency of resource allocation to fulfill QoS demands of different V2X applications. There are still insufficient studies examining the influence of DRA schemes on the requirements of various C-V2X applications. We emphasize advanced cooperative driving for an instance of the time-sensitive NR-V2X application within ultrareliable low-latency communications (URLLCs), necessitating exceedingly minimal latency. Furthermore, NR-V2X infotainment applications, for example, video streaming, are also indicated as one of the challenges.

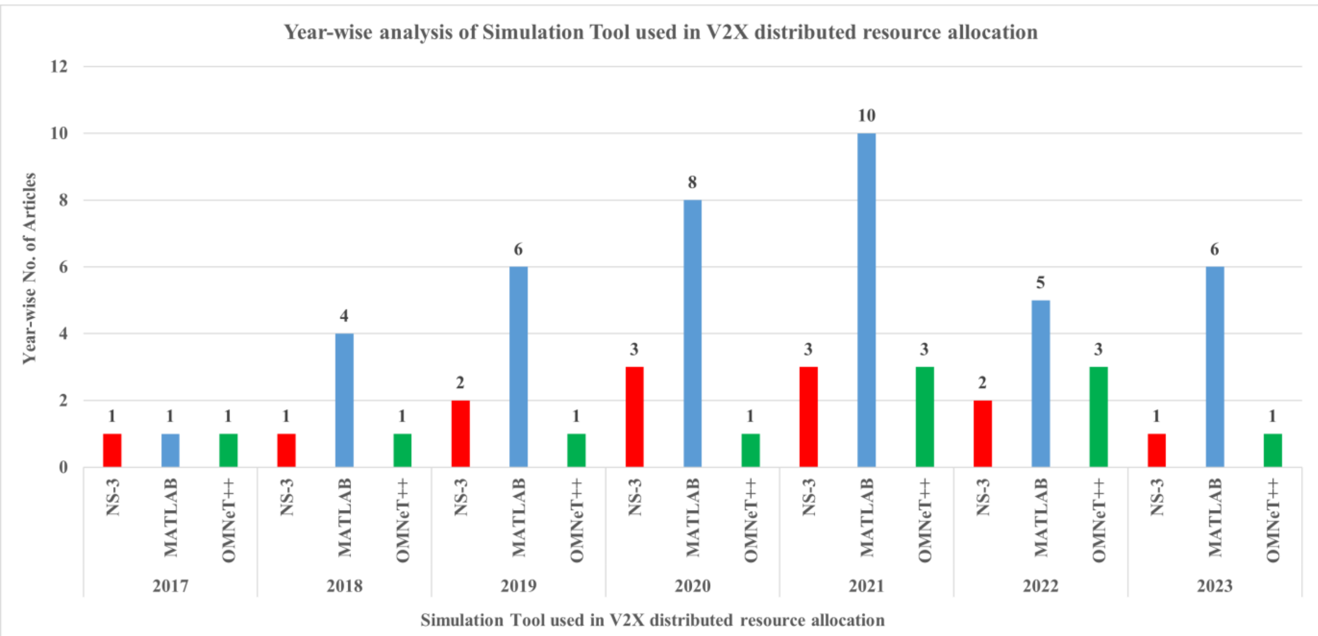

Figure 20. Analysis of simulation tools used for DRA in LTE-V2X and NR-V2X by year

Table 11. State-of-the-art of proposed schemes that enhanced the CC in DRA

Reference	Objective	Performance Metric	Traffic Application	Simulation Scenario	Simulation Tool	Findings and Limitations
[105]	Focus on LTE-V2X mode 4 DRA and DCC method interactions.	CBR	Periodic	Highway Scenario	NS-3	Counterproductive interactions that degrade performance and mitigation techniques are provided.
[106]	In VANETs, explore the congestion control algorithm's settling time, stability, and reliability.	CBR	Periodic	Highway Scenario	Not detailed	Congestion management improved communication reliability and latency.
[107]	Proposed a combined DCC-enabled structure and analyzed DCC range control and transmission rate components.	PDR	Periodic	Highway Scenario	Not detailed	Rate control affects performance more than range control.
[108]	Channel congestion control addresses IEEE 802.11p and SL LTE-V2X.	PDR	Periodic	Highway Scenario	MATLAB	IEEE 802.11p effectively trades congestions for range power, MCS, or delay.
[109]	Analyzed the performance of LTE-V2X mode 4 and DSRC in highway situations with varied vehicle densities utilizing SAE congestion control techniques.	CBR	Periodic	Highway Scenario	NS-3	LTE-V2X may reduce sequential packet loss with a packet retransmission and wider bandwidth.
[110]	ATOMIC approach for C-V2X mode 4, where each vehicle uses neighbor information and real-time channel sensing to decrease channel congestion for enhanced reliability and delay.	PRR	Periodic	Urban and Highway Scenario	MATLAB	The algorithm improves traditional mode 4 in both scenarios.
[111]	Modify the rate control function for responding to congestion more slowly so that power control may actively control congestion.	CBR	Periodic	Highway Scenario	MATLAB	Get better congestion control dynamics, when distance and information update frequency are traded off as congestion occurs.
[112]	Suggests an adaptive power control algorithm to handle transmission power under different vehicle density.	PRR	Periodic	Highway Scenario	MATLAB	The suggested algorithm improves mode 4 PRR.
[113]	An SB-SPS-based A-TPC algorithm is proposed for CAM transmission power control.	PRR	Periodic	Urban and Highway Scenario	MATLAB	The suggested approach outperforms current TPC algorithms for traffic situations with high vehicle density, but it becomes significant in congestion.
[114]	Examine comparable congestion control for C-V2X, focusing on transmit power control.	PRR	Periodic	Urban Scenario	NS-3	Event-driven messages benefit from periodic message transmission power control.
[115]	Demonstrates congestion control that lets V2X safety applications pick a QoS class that prioritizes their QoS need.	CBR	Periodic	Highway Scenario	MATLAB	Regardless of V2X application options, the congestion control scheme may lower channel consumption uniformly.
[116]	Propose and analyze C2RC based on channel congestion, which lets vehicles autonomously determine whether to utilize packet re-transmissions without	CBR	Periodic	Highway Scenario	NS-3	C-V2X-capable vehicles perform better in lightly loaded circumstances without loss of performance in denser scenarios.

	cellular infrastructure.					
[117]	RRI DCC is a novel technique that quantitatively evaluates ETSI & 3GPP DCC and packet dropping procedures for LTE-V2X and NR-V2X.	CBR	Periodic	Not detailed	Omnet++	All approaches outperform ETSI and 3GPP standards.
[118]	Presents DCC scheme that utilizes a hybrid approach to create a more effective and robust congestion control solution.	PRR, CBR	Periodic	Highway Scenario	Not detailed	The proposed scheme effectively controls the maximum CBR compared to the original DCC approach.

4.8.2 Open issues and promising future directions

Resource allocation is a crucial aspect of a C-V2X communication system. Although this topic has been extensively examined, there is still potential for more research in this field. Specifically for the DRA, which is regarded as more challenging. In the discussion that follows, we identify a number of unresolved research issues that have not yet been addressed in the literature and will necessitate further exploration in the future.

(1) *Physical Layer Structure*: Several modifications have already been made to the physical layer structure of C-V2X communications. As previously noted, 3GPP has investigated a flexible frame structure for Release 16 of NR-V2X [59]. To lessen the Doppler effect, C-V2X communications need shorter TTI and greater SCS. Scalable SCS, as outlined in the study by Ali et al. [62], may be used for expanding V2X use cases. Although a broader SCS can better manage Doppler shift and frequency offset, inter-symbol interference will be significant. Extended CP may be utilized to reduce inter-symbol interference; however, this affects the OFDM's efficiency. Consequently, more research is necessary to overcome the problem of inter-symbol interference in scalable SCS in Release 16 of NR-V2X. In addition, a unified frame structure with an adequate number of DMRS symbols is necessary to handle the problem of extremely dynamic vehicle communications.

(2) *NOMA based techniques*: It is envisioned that vehicular communications based on 5G technology can deliver diverse C-V2X services and facilitate vast connections. However, NOMA-based resource allocation is difficult owing to a great deal of interference generated on the receiver side. As described by Trabelsi et al. [123], information may be shared between the receiver and transmitter to cancel subsequent interference. Nonetheless, the flow of information imposes a substantial communication burden. Therefore, future research should attempt to tackle the interference cancellation problem without significantly increasing communication costs.

(3) *Power Consumption:* In Release 17, 3GPP intends to implement a novel version of mode 2 that may minimize the power consumption of UEs [71]. DRA mode 2 relies on channel sensing throughout a SW. This channel sensing technique necessitates a receiving UE to sample all the received signals for decoding the PSCCH and the PSSCH, which wastes a significant amount of energy. 3GPP aims to substitute the original channel sensing technique with partial techniques as well as randomized resource allocation algorithms. This shift holds the potential to significantly reduce total power consumption for UEs. Nevertheless, we point out that it is more intriguing to compare the efficiency of newly presented approaches to that of the conventional DRA mode 2, which may be seen as a promising avenue for future research direction.

(4) *Scheduling UE*: Mode 2(d), a sub-mode of mode 2, has been explored by Shen and Wei [71] as part of the standardization process for 3GPP Release 16 NR-V2X SL transmissions. In mode 2(d), a UE known as a scheduling UE has the ability to schedule resources for the transmission of SL data between the other two UEs. Due to time constraints within the normative processes, this sub-mode will not be part of Release 16 when it is finally Released. It is anticipated that this sub-mode will be supported as part of future updates to V2X in order to maintain vehicle platooning.

(5) *Machine-Learning-Based DRA*: The prevalence of ML in cellular networks has increased, particularly in the areas of power management, routing protocol, channel access mechanism, and other related areas. When it comes to the NR-V2X, a large number of vehicles may demand resource allocation that is both efficient and reliable in order to resource pool reserving in the frequency-time domain. Moreover, environmental factors such as vehicles density on the road, the shifting of location from a highway to an urban, the multi-use scenario, and the speed of vehicles may also impact the resource pool. The learning algorithm may use these conditions as inputs for the intelligent algorithm that satisfies the QoS requirements for throughput reliability and latency in future communications. The ML can also be applied to the C-V2X applications for enhancing vehicles requirements such as navigation, security, or safety, as mentioned by Tong et al. [124]. Additionally, it may be used to anticipate the available resource or time that vehicles are in or out of the cellular coverage area as well as forecast channel conditions in order to optimize the transmission number while meeting QoS standards. Thus, ML requires additional research in the light of C-V2X communications.

(6) *Congestion Control:* Numerous studies have demonstrated the relatively minor impact of power changes and advocated concentrating primarily on packet creation rate. This criterion seems to be vulnerable to exceptions when high-priority communications are examined, as illustrated by Saifuddin et al. [114]. In addition, only a handful of studies have investigated the performance of ETSI DCC within the C-V2X, which may result in different findings than those found with the SAE solution.

(7) *In-Band Full-Duplex*: As we go towards the development of 6G, there is a proposal to utilize self-interference cancellation technology, which allows for simultaneous transmission and reception. This capability can be utilized not just to augment the quantity of received messages, but primarily to enable simultaneous sensing with collision detection [125].

(8) *Security and Access Control Mechanism:* With the increasing deployment of C-V2X technologies, ensuring

secure and authorized network access is essential. Future DRA advancements will integrate dynamic access control mechanisms, enabling vehicles and infrastructure to manage access permissions based on authentication and authorization protocols. This integration enhances network security and optimizes resource allocation, prioritizing access for safety-critical applications and authorized users. Collaborative access control schemes leveraging V2V communication will likely emerge to efficiently manage access and mitigate potential security threats. By integrating access control into DRA, future C-V2X networks can ensure robust and secure communication while effectively meeting the diverse needs of vehicular applications.

(9) *Interference Management:* Increasing density of vehicles in urban environments, managing interference becomes critical for optimizing communication reliability and efficiency. Integrating interference management with DRA promises to enhance network performance by dynamically adapting resource allocation to minimize interference. Future research will likely focus on developing advanced interference mitigation algorithms, leveraging ML and collaborative schemes to achieve seamless and robust communication in dynamic vehicular environments. This convergence represents a compelling direction for addressing interference challenges and maximizing the potential of C-V2X networks.

5. CONCLUSION

One of the most important enablers of the IoV concept in ITS is the C-V2X. The DRA in C-V2X significantly impacts the efficiency of V2X communications. In this article, we started by explaining the resource allocation configuration in C-V2X for both LTE and NR technologies focusing on DRA and then provided A comprehensive state-of-the-art of DRA for these technologies. Even though, there are many existing research works from 2017 onwards that related to mode 4 and mode 2 of LTE and NR, respectively, as a DRA were presented. However, mode 4 still presents additional critical issues related to resource collisions and interference. Furthermore, mode 2 requires additional investigation on DRA to meet the QoS requirements and system accomplishments. We also demonstrated the impact of ML and CC on DRA by addressing the problems, policies, and algorithms that were implemented for improving the DRA system efficiency. We also pointed out the primary performance metrics and simulation tools used in the related work. In addition, based on several readings of the studies presented in this review article, we have identified a number of research challenges and limitations related to DRA in C-V2X i.e., faulty sensing, collision likelihood, and resource-efficient allocation that still need attention. Ultimately, we have outlined the challenges, identified open issues, and highlighted promising future directions for research in this field. We have proposed potential solutions leveraging new emerging technologies such as physical layer structure, NOMA based techniques, power consumption, scheduling UE, congestion control, machine-learning-based, and in-band full-duplex in terms of DRA in C-V2X.

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