IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 20 October 2023, accepted 13 November 2023, date of publication 16 November 2023,
date of current version 21 November 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3333680

STANDARDS

Performance Evaluation and Optimal Management of Mode 2 V2X Communications in 5G Networks

EDGAR E. GONZÁLEZ[1,2], **YANET ESTRADA**[1], **DAVID GARCIA-ROGER**[1], **AND JOSE F. MONSERRAT**[1], **(Senior Member, IEEE)**
[1]ITEAM Research Institute, Universitat Politècnica de València, 46022 Valencia, Spain
[2]Department of Engineering Sciences, Universidad Tecnológica Israel, Quito 170516, Ecuador

Corresponding author: Edgar E. González (edgonmal@doctor.upv.es)

This work was supported in part by the H2020 Marie Curie Program under Grant 955629 ITN-5VC-ITN-2020.

ABSTRACT New Radio (NR) Vehicle-to-Everything (V2X) communications, a subject of the Third Generation Partnership Project (3GPP) specifications for 5G networks, enable vehicle communications akin to Long Term Evolution (LTE). These communications can be implemented either centrally, by connecting to 5G nodes, or autonomously, by establishing sidelink through the PC5 interface. Particularly noteworthy is the latter connection mode, referred to as Mode 2, which is independent of cellular network coverage. Instead, communication is established using pre-configured parameters and a sensing mechanism for resource selection and allocation in time and frequency. This paper delineates the resource selection procedures for NR VV2X Mode 2 and evaluates their performance across various scenarios. The findings suggest superior performance of high numerologies compared to smaller subcarrier spacings. Even though the standard prescribes a random method for V2X resource selection, it was observed that the sensing procedures yield higher Packet Reception Ratio (PRR) levels. Moreover, factors such as a smaller sidelink channel size and an extended duration of the candidate resource sensing window were found to enhance the frequency diversification of resources, thereby improving PRR levels. A qualitative examination of key considerations for the performance evaluation of Radio Access Technologies (RAT) V2X communications is also provided, delving into aspects such as RAT interplay, resource utilization, interoperability, performance trade-offs, and Quality of Service (QoS) for optimal management of multi-RAT V2X scenarios.

INDEX TERMS 5G mobile communication, NR V2X, 3GPP, PC5, numerologies, mode 2, resource selection, multi-RAT.

I. INTRODUCTION

Throughout the various stages of 3GPP standards, enhancements are made to previous versions to improve the performance and functionality of mobile networks [1]. For example, improvements have been implemented in fourth-generation networks to enable them to offer advanced services and use new transmission techniques [2]. These enhancements include increasing uplink and downlink data rates, reducing equipment power consumption, improving spectral efficiency, and incorporating new mobile network-based services and applications.

On the other hand, 3GPP standards also focus on fifth-generation networks that can provide advanced services with potentially critical requirements [3]. This is due to new transmission mechanisms at the physical layer level that were not available in fourth-generation networks. These techniques include numerologies, frequency utilization in millimeter bands, improved modulation and coding schemes, and transmission and reception through multiple antennas, among other advances.

However, for 5G networks to work correctly with multiple services and applications, they must be backward compatible

The associate editor coordinating the review of this manuscript and approving it for publication was Tariq Umer.

with previous generations. Since fifth-generation networks are essentially an evolution of 4G networks, many services that have already been standardized for the latter can also be implemented in 5G networks. In addition, services that were previously limited by factors such as latency, bandwidth, network reliability, and throughput can now be supported by the enhanced networks. These issues are relevant globally, as essential services can be offered with one technology and advanced services can be incorporated as networks with enhanced capabilities are deployed. In some cases, due to channel conditions, congestion, interference, or lack of coverage, it is possible to switch between different mobile network technologies. This approach is known as multi-RAT and improves network efficiency by supporting multiple services and use cases [4].

Release 14 of the 3GPP standard defines a service that allows vehicles, whether connected to the cellular network or not, to send packets of information about themselves and their environment [5]. These packets include data from the vehicle's sensors, such as speed, braking, lane changes, etc., and external information collected from the environment by radars, Light Detection and Rangings (LiDARs), intelligent traffic lights, and other sources, including platforms or application servers. The way in which this information is sent is called V2X communication in the standard, and since it can be implemented in both LTE and 5G cellular networks, the term Cellular-based V2X (C-V2X) is commonly used.

The goal of V2X services and applications is to improve highway road safety and reduce environmental pollution by reducing fossil fuel consumption by vehicles. In other words, V2X communication increases vehicle connectivity, improving the efficiency and safety of vehicle control and traffic flow on the road. The term V2X encompasses connectivity between vehicles and any other element. Specifically, the standard defines the ability for vehicles to connect, Vehicle-to-Vehicle (V2V); to pedestrian-carried devices, Vehicle-to-Pedestrian (V2P); to V2X network infrastructures, Vehicle-to-Infrastructure (V2I); and to the cellular network, Vehicle-to-Network (V2N) [2]. Each type of connection uses different network interfaces and enables the implementation of specific use cases through vehicular communications.

3GPP Release 14 defines two modes of connection between vehicles, pedestrians, network infrastructure, and the cellular network [6]. One of these modes, known as Mode 3, enables network elements to connect via the Uu interface. It operates centrally, where the cellular network manages sensing procedures, resource allocation, and network congestion control. In contrast, Mode 4 is defined as a decentralized autonomous mode, allowing vehicles and network elements to independently manage resource utilization in terms of time and frequency. Mode 4 offers the advantage of not requiring cellular coverage, relying instead on specific procedures outlined in the standard for resource allocation and congestion control.

In situations where cellular coverage is unavailable, vehicles or network elements establish sidelink connections, utilizing the PC5 interface. This enables vehicles to exchange V2X messages over the cellular network through the Uu interface when it is available or to establish sidelink connections in coverage-limited scenarios. In our previous work, detailed in [4], we provided a comprehensive description and performance evaluation of LTE V2X Modes 4 and 3 under various conditions. While LTE V2X adequately supports essential vehicular communication services, it has limitations in meeting the potential requirements and Key Performance Indicators (KPIs) of advanced services [3].

Recently published literature related to 5G-V2X provides a detailed analysis of 5G-V2X technology features, focusing on the physical layer architecture, resource allocation and coexistence mechanisms between 5G NR V2X and LTE V2X [7], [8], [9]. In [10] an extension for NR network simulation models in the open-source ns-3 5G-LENA simulator [11] is proposed in order to support NR V2X capabilities. The authors analyzed the impact on the end-to-end network performance of different key parameters of the NR V2X system when using sensing-based resource selection in NR V2X mode 2. In [12] the extension of the ns-3 Lena simulator proposed in [10] is considered to study the impact of NR numerologies on end-to-end performance by considering non-sensing-based resource selection in addition to the sensing-based resource selection in NR V2X 2 mode. In [13] the open-source discrete event simulator LTEV2Vsim has been enhanced by including the 5G-V2X PHY and MAC layers and the impact of numerology and Modulation and Coding Scheme (MCS) in a highway scenario with high traffic density has been analyzed. In [14], the essential knowledge of 3GPP NR sidelink transmission is presented with a performance evaluation to determine the benefits of NR sidelink. In [15], the authors focus mainly on the impact of flexible NR numerology to analyze the improvements in reliability and timeliness of messages brought by the investigated NR features compared to the legacy C-V2X solution.

However, to the best of the authors' knowledge, few of these works are based on the evaluation of PRR performance considering different channel bandwidths and varying sidelink subchannel sizes. This is interesting because V2X packet sizes vary for different services [4]. Therefore, advanced use cases require sidelink subchannels composed of a larger number of resource blocks and mapped to a higher channel bandwidth to increase resource diversity in frequency and achieve similar performance with respect to less demanding V2X services. Furthermore, this research has analyzed that, although for NR mode 2, numerology $u = 0$, the size of the detection window can be reduced to 100 ms, no significant difference in the performance achieved is observed compared to using a window with a larger number of slots, as defined for LTE mode 4 with a detection window of 1100 ms. Nevertheless, it has been shown that a reduction in the sensing window does decrease the performance achieved when u = 1 and u = 2 numerologies are configured. Additionally, it has been shown that the use of high numerologies allows higher PRR levels to be achieved, as it increases the diversity of frequency resources that vehicles can select for their transmissions.

Therefore, this paper presents the evaluation results of NR V2X, which represents an evolution of LTE V2X to support new services and applications. As per the 3GPP specifications, some procedures, modes, and connection mechanisms bear similarities to LTE V2X. However, clear differences arise due to changes at the physical layer level defined for 5G networks. These differences must be adapted to cater specifically to the requirements of vehicle communication over the cellular network.

This document is organized as follows. Section II describes the transmission and communication modes defined for NR V2X. Section III details the physical layer aspects that 3GPP has defined for V2X communications in 5G NR, such as physical channels, numerologies, and resources in time and frequency. Section IV details the sensing, resource selection, and congestion control procedures. Section V presents the results obtained from simulations in different scenarios. Section VI explains the qualitative benefits of exploring the performance evaluation of multi-RAT V2X communications, covering RAT interplay, resource utilization, dynamic resource selection, interoperability, trade-offs, and QoS management for optimizing such systems. Finally, section VII draws the conclusions derived from this work.

II. NR V2X COMMUNICATION AND TRANSMISSION MODES

Similar to the definition for LTE V2X networks, NR V2X considers two modes of operation [3]. Mode 1 is a centralized mode that requires cellular network coverage. Thus, through the Uu interface, the V2X User Equipment (UE) can receive configurations from the network. As a centralized mode, the network knows the availability of resources and therefore two UEs will not share the same pool of V2X resources. A clear disadvantage of mode 1 is that the UE must be connected to a Next Generation Node B (gNB). In addition, because communication must be continuous over the Uu interface, communication latency increases, which is a negative aspect in certain use cases defined for Fifth Generation (5G) V2X.

On the other hand, mode 2 is defined for NR V2X, which is a decentralized mode that does not require cellular network coverage. Thus, mode 2 allows V2X UEs to establish sidelink communication, known in the standard as Sidelink (SL). The communication interface used in this mode is PC5 and allows UEs to manage a process of sensing, selection, and re-selection of radio resources. In addition, the standard defines four sub-modes of operation for NR V2X SL mode 2: 2a, 2b, 2c, 2d. In mode 2a, which is like LTE V2X mode 4, the UEs autonomously select the resources to be used for V2X communication. In mode 2b, a V2X UE may assist other UEs in allocating resources for V2X transmissions. This assistance may be related to sending feedback information from other UEs to achieve efficient resource allocation. In 2c mode, UEs may use one or more pre-configured SL patterns in a resource pool. In 2d mode, a UE manages the allocation of SL resources for other UEs. That is, in 2d mode, a UE assumes a role similar to that of a gNB in mode 1 to allocate resources to other UEs. All simulations performed in this paper are based on the use of mode 2a.

In terms of transmission modes, unlike LTE V2X where only broadcast transmissions are supported, NR V2X defines three transmission modes between V2X UEs [3]: unicast, broadcast and groupcast. Broadcast communications send messages to all UEs in a given coverage area. Unicast communications are those that can be established directly between two UEs. Finally, groupcast communications allow messages to be sent or received only to a specific group of vehicles. Each transmission mode has particular use cases where its application is necessary. For example, groupcast communication is required in vehicle platoons where V2X messages are exchanged only between the members of the platoon. On the other hand, broadcast communications send V2X messages to all surrounding vehicles. For example, a V2X UE incorporated in an ambulance sends warning messages to surrounding vehicles so that they can take appropriate precautions. It is important to note that a V2X UE can have more than one transmission mode enabled. For instance, a UE corresponding to the lead vehicle of a platoon can use groupcast mode to communicate with platoon members, unicast mode to communicate with the lead vehicle of another platoon, and broadcast mode to send V2X messages to all surrounding vehicles.

III. NR V2X PHYSICAL LAYER

For NR V2X, the standard defines channels similar to those standardized for LTE V2X [16]: Physical Sidelink Broadcast Channel (PSBCH), Physical Sidelink Control Channel (PSCCH) and Physical Sidelink Shared Channel (PSSCH). However, the Physical Sidelink Feedback Channel (PSFCH) is added to support services that require the sending of feedback information from the receivers. Thus, NR V2X supports unicast and groupcast transmission modes and the broadcast transmission mode. Additionally, reference and synchronization signals are defined, mapped to specific REs and used for physical layer procedures: Demodulation Reference Signal (DMRS), Channel state information reference signal (CSI-RS), Phase-tracking reference signal (PT-RS), Sidelink-Primary Synchronization Signal (S-PSS), and Sidelink-Secondary Synchronization Signal (S-SSS).

The supported numerologies for NR V2X in FR1 are u = 0, u = 1, and u = 2, i.e., SCS of 15 kHz, 30 kHz, and 60 kHz, respectively. For FR2 only the numerology u = 2 is defined. It should be noted that, in general, numerologies up to 960 kHz, i.e., u = 6, are defined for NR. However, not all numerologies are supported in NR V2X. The simulation results shown in this paper are based on the configuration of different scenarios for FR1 numerologies.

The type of modulation that can be used depends on the channel used to transmit different types of information. For example, for PSSCH, Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (QAM), 64-QAM, or 256-QAM modulation can be used. On the other hand, only QPSK can be used for PSCCH and PSBCH [16].

The time and frequency resources that can be allocated for V2X communication are called resource pools. One or more resource pools can be assigned to a UE for sending and receiving V2X traffic in standalone or centralized mode. A resource pool is mapped in a Carrier Bandwidth, under a SL Bandwidth Parts (BWP) and a specific numerology. Only one SL BWP can be mapped in a carrier bandwidth for all UEs [3]. In terms of frequency, a resource pool consists of L contiguous subchannels mapped to a BWP. A subchannel in a slot consists of M contiguous Resource Blocks (RBs). The standard defines that for NR V2X, the number of RBs that make up a subchannel can be 10, 12, 15, 20, 25, 50, 75, or 100 [17]. Thus, the bandwidth corresponding to each subchannel depends on the numerology used. A subchannel is the smallest unit of frequency resources that can be allocated to SL rx or SL tx.

In time, a slot within the resource pool is the minimum unit that can be allocated for SL—NR V2X does not support mini-slots, unlike NR Uu. However, not all slots are available for SL, but are determined by Time Division Duplex (TDD) patterns and SL bitmaps [7]. The TDD patterns define the configuration of the slots as downlink, uplink or flexible. The SL bitmap specifies which of the slots defined as uplink in the TDD pattern can be used for SL. According to [10], any combination of TDD pattern and SL bitmap is valid. However, the standard defines that the length of the SL bitmap varies between 10, 11, 12, …160 [7].

As mentioned above, the minimum resource allocation for NR V2X is one subchannel in frequency and one slot in time. Thus, within each slot configured for SL, the PSCCH, PSSCH and PSFCH channels are multiplexed together with the corresponding reference and synchronization signals. The standard specifies in [18] two ways in which such channels and signals can be mapped into the 14 symbols corresponding to the use of the normal cyclic prefix [16]—the use of the extended cyclic prefix comprises 12 Orthogonal Frequency Division Multiplexing (OFDM) symbols and applies only to $u = 2$ numerology—, which consist of both time and frequency multiplexing—in LTE V2X only frequency resource multiplexing is supported. In addition, PSFCH channel multiplexing is optional, depending on whether HARQ-based procedures are used. Fig. 1 shows a representation of the time and frequency resources defined for SL. The first symbol in the slot is used for Automatic Gain Control (AGC). Next, 3 symbols are used for PSCCH. The number of consecutive RBs in which the PSCCH should be mapped are pre-configured and should be less than or equal to the number of RBs that conform a subchannel—according to the standard, the number of RBs for PSCCH can be 10, 12, 15, 20 or 25.

The PSSCH can be multiplexed in time and frequency in each slot available for SL. In frequency, the PSSCH can occupy the number of subchannels available for SL in the resource pool, depending on the type of traffic to be transmitted. On the other hand, the PSSCH can be multiplexed in time and frequency with the PSCCH, so that 1 OFDM symbol can contain both the PSCCH and the PSSCH. Since 7 to 14 symbols in a slot can be configured for SL, the PSSCH can occupy 5 to 12 consecutive symbols. This is because the PSCCH can occupy two or three symbols in the slot. A guard symbol remains after the last symbol contained in the PSSCH. Fig. 1 also shows the PSFCH multiplexed with the PSCCH and the PSSCH. The PSFCH occupies two OFDM symbols and a guard symbol is considered after it. In addition, DMRS PSSCHs located in the slot are mapped according to one of the patterns specified in [16].

IV. RESOURCE ALLOCATION IN NR V2X

In general, the resource allocation procedures defined in the standard are similar to the mechanisms specified for LTE V2X. However, the main differences lie in the physical layer changes defined for 5G NR networks described in the previous section. For example, the addition of the PSFCH channel allows V2X receivers to send feedback information to transmitters to improve the reliability of communications. This information can then be used to improve resource allocation procedures.

In NR V2X mode 1, as described above, a gNB is responsible for resource allocation. Thus, one or more sidelinks can be allocated depending on the type of V2X traffic or messages to be exchanged. It also takes into account whether the traffic is periodic or non-periodic, which is closely related to the types of V2X services or use cases to be implemented. Radio Resource Control (RRC) signaling can be used to define that UEs use sidelink grants immediately or when the gNB indicates that it is active. In addition, a gNB can specify the MCS to be used in the allocated grants. The V2X resource allocation criteria that a gNB can use can be based on feedback information sent by UEs. Since the resource allocation process is centralized, the network has global knowledge of the allocated resources and those available for allocation to other UEs.

NR V2X Mode 2 is currently of great interest because it is a mode in which resource allocation does not depend on a connection to a gNB, but the UEs perform resource selection autonomously. This ensures that V2X message exchange can take place in places where there is no cellular coverage. However, the challenge in this communication mode is that as an autonomous mode, two or more V2X UEs must perform certain sensing, selection, and resource reservation mechanisms in time and frequency. In addition, congestion control mechanisms must be implemented, which

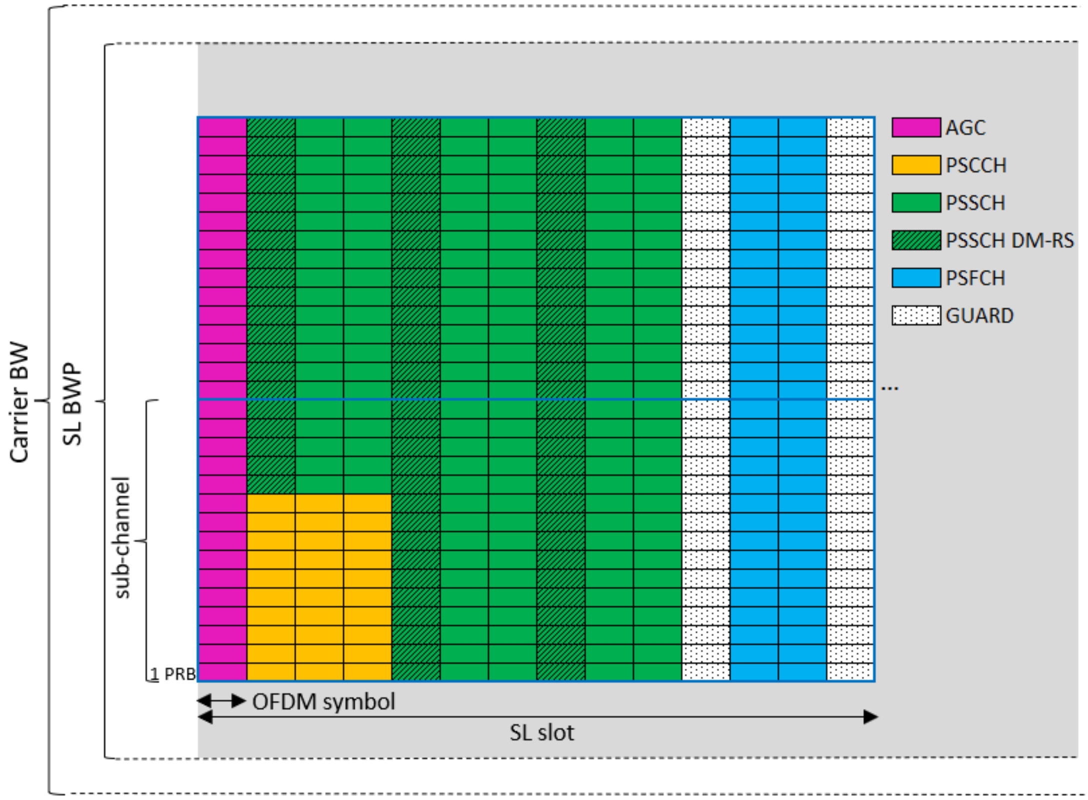

FIGURE 1. Example of sidelink slot structure in NR V2X.

is particularly necessary for scenarios with a high density of vehicles or, more generally, V2X UEs.

Specifically, in NR V2X mode 2, two resource allocation schemes can be used: dynamic and semi-persistent. In the dynamic scheme, resources are selected for the transmission of one Transport Block (TB), while the semi-persistent scheme can select and reserve resources for the transmission or retransmission of multiple consecutive TBs [7]. Unlike LTE V2X, NR V2X defines two levels of information sent via SL Control Informations (SCIs). The first stage of the SCI, sent through the PSCCH, contains information necessary for the sensing process and allows knowing the resources reserved —maximum 3 reserved resources as per [19]— by other UEs to perform their transmissions. On the other hand, the receivers utilize the second stage of the SCI, which is sent via PSSCH, to decode the V2X packets. Note that V2X receivers can only receive the first SCI level and use this information for sensing operations, but not the second SCI level, because these V2X messages were not addressed to this receiver —this occurs in use cases with unicast or groupcast transmissions.

When a V2X UE needs to perform transmissions, a resource selection trigger is activated in slot n. This slot is used as a reference because the resource sensing, selection, and reservation procedures are performed around this time.

A. SENSING PROCEDURES

When the resource selection trigger is enabled, UEs must select resources based on the measurements made in a sensing window in the slots between $[n - T_0, n - T_{proc,0}]$, as shown in Fig. 2.

T_0 is a parameter that is specified by RRC signaling in a number of slots but must be set to times of 100 ms or 1100 ms [7]. Since the number of slots varies depending on the numerology used, then it should be noted that if the same number of slots is maintained in higher numerologies, then the sensing window time is reduced. On the other hand, if the same sensing time is maintained in higher numerologies, then the sensing window contains a larger number of slots where corresponding measurements must be performed.

$T_{proc,0}$ is a time required to complete the sensing process, e.g., to complete the SCI first stage decoding processes and reference signal measurements. $T_{proc,0}$ is equal to 1 slot for $u = 0$ and $u = 1$ numerologies, and 2 or 4 slots for $u = 2$ numerology. Similar to the T_0 parameter, the time left to complete the sensing process varies depending on the numerology used. For example, for the $u = 0$ numerology this time is 1 ms.

In the sensing window, Reference Signal Received Power (RSRP) measurements are performed on the reference signals mapped on the PSCCH and PSSCH channels for which the first SCI stage has been successfully received. In this

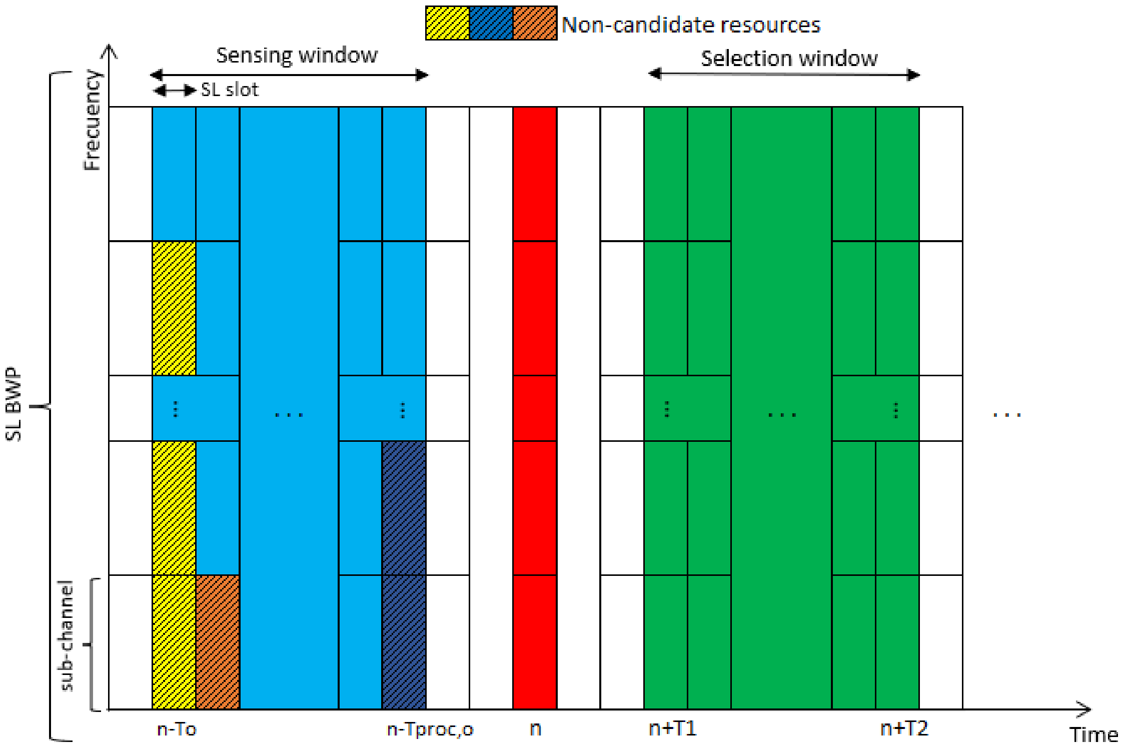

FIGURE 2. Time and frequency resource mapping in NR V2X.

way, the UE senses the sidelink resources that are already occupied or reserved by other UEs and that should be discarded in the resource selection phase to perform its transmissions. Resources that are not reserved by other UEs, or where RSRP measurements are below a threshold, become candidate resources for V2X transmissions. In some cases, it is important to note that a UE may be transmitting V2X packets and therefore unable to detect the resources that other UEs have reserved. Thus, it must also define mechanisms to exclude these resources as candidates for V2X transmissions.

B. RESOURCE SELECTION PROCEDURES

According to Fig. 2, the selection window occupies the interval $[n + T_1, n + T_2]$. T_1 is the processing time to be considered by a UE to identify candidate resources for its V2X transmissions. T_1 must be less than or equal to 3, 5, 9 slots for the numerologies $u = 0$, $u = 1$ and $u = 2$ respectively [7]. On the other hand, T_2 is a time that must be less than or equal to the Packet Delay Budget (PDB), i.e. the maximum time in which a TB must be transmitted. T_2 is a parameter to be configured in the UE depending on the specific application. The minimum value of T_2 is configured according to the numerology used. Thus, the minimum value of T_2 is obtained for the numerology $u = 0$, where T_2 must be equal to 1 slot, i.e., 1 ms.

After defining the duration of the selection window, the UE must select the resources to perform its V2X transmissions from those defined as candidate resources in the sensing window, considering the following criteria:

- Resources that have been defined in the sensing window as selected or reserved for transmission by other UEs and whose RSRP levels are above a threshold should be excluded. This means that certain resources that have already been reserved by other UEs for their transmissions can be selected if the measured power levels are sufficiently low.
- It will be checked that the set of selected resources is larger than a certain percentage of the total V2X resources in the selection window. This percentage is configured by RRC signaling and can be 20%, 34%, or 50% depending on the type of V2X traffic, i.e., the priority it has according to the implemented use case. If the number of selected resources does not meet this percentage, the RSRP threshold is increased by 3 dB until the required minimum number of resources is reached. In this case, even if a UE has reserved certain resources below a certain RSRP threshold, another UE that needs to transmit V2X traffic with a higher priority may need a higher percentage of resources. Thus, the UE with higher transmission priorities can select the already reserved resources because the power threshold of the resources it can select is higher.
- Before the UEs can transmit on the resources selected in the previous steps, it must re-evaluate to confirm that the resources are still available. If the minimum percentage

of available resources is no longer available, the resource reservation process must be repeated in a new selection window based on measurements made in an updated sensing window.

- The UE then randomly selects the reserved resources and may transmit V2X traffic in either dynamic or semi-persistent mode. In addition, such transmissions may include blind re-transmissions for broadcast transmissions or HARQ re-transmissions in case of use with unicast or groupcast transmissions. The number of resources that the UE can select for its transmissions, configured by RRC signaling, varies between 1 and 32.
- If the UE uses semi-persistent mode transmissions, there is a possibility that it will use the same resources to transmit the following TBs —in dynamic mode, they are selected each time a new TB is to be sent. This is done using mechanisms similar to those defined for LTE V2X [4]. Thus, a Reselection Counter (RC) is selected each time it is needed to select new resources for V2X transmissions. The RC is randomly selected from a defined interval depending on the resource reservation period and decremented each time the UE transmits a TB —or its re-transmissions. When the RC decreases to zero, it evaluates with a probability of $(1 - P)$ whether to select new resources, otherwise, it continues using the same resources selected in the previous selection process. Each UE can set a P value between 0 and 0.8. If the Channel occupancy Ratio (CR) reaches zero and it is necessary to reselect resources, the UEs send this information through the first stage of the SCI to inform other UEs that they no longer have those resources reserved.
- To prevent a UE from using the same resources indefinitely, the standard defines a maximum of $10 * RC$ times it can occupy them [10]. For example, if the RC is defined as 5, then a maximum of 50 times the same resources can be used to transmit V2X traffic.

Fig. 3 shows a flowchart corresponding to the resource sensing, reservation, and re-selection processes defined for NR V2X.

C. CONGESTION CONTROL

As in LTE V2X, NR V2X defines the congestion control mechanisms to be followed by UEs using two metrics: Channel Busy Ratio (CBR) and CR. The CBR is based on Received Signal Strength Indicator (RSSI) measurements in a window of 100 slots —it is also possible to configure a measurement window of $100 * 2^u$ slots [7], i.e., depending on the numerology used— corresponding to all UEs occupying resources in that time and frequency slot. If a pre-configured RSSI threshold is exceeded, a given sub-channel is defined as busy. On the other hand, the CR estimates the occupancy generated by a UE using resources for V2X transmissions. The CR is calculated as the ratio of sub-channels selected or reserved by the UE for V2X traffic transmission. This calculation is performed in a fixed window of 1000 slots. However, the window can also be configured according to the numerology, in which case the measurement must be performed in $1000 * 2^u$ slots [7]. For example, for the numerology u = 1, the window is 2000 slots, i.e., it has a duration of 1 second.

The standard does not establish a specific algorithm for congestion control, but it can be implemented based precisely on the CBR and CR parameters calculated. Thus, based on the CBR calculation, CR limit values are configured to reduce congestion. If the CR exceeds the defined limit, then the UE can reduce congestion by increasing the MCS, limiting the number of subchannels used, reducing the number of retransmissions, or decreasing the transmission power.

D. PARTIAL SENSING

The whole sensing process mentioned above leads to an increase in the power consumption of the devices. This can be a problem in applications where the devices carry batteries and therefore need to reduce power consumption —e.g., in V2P communication, the device is carried by a pedestrian or embedded in a bicycle. Therefore, to minimize the complexity of the sensing procedures, the standard for NR V2X —similar to LTE-V2X— defines that resource selection can be random or partial. The random selection of V2X resources is based on the UE randomly selecting resources based on pre-configured resource pools. Thus, this selection process does not require any sensing measurements, making the process less complex. On the other hand, partial sensing consists of the UE sensing only a certain number of slots defined in the sensing window. The number of slots to be sensed is preconfigured and can be adapted to periodic or aperiodic traffic.

In addition, the standard defines another alternative to minimize the power consumption of the UEs, known as SL Discontinuous Reception (DRX) [20]. Thus, in the active DRX state, the UE performs the usual acquisition and decoding procedures of the PSCCH, PSSCH, etc. In the inactive DRX state, the UE performs only the reception and decoding of the PSCCH and RSRP measurements according to the sensing procedure. The SL DRX is supported in NR V2X for unicast, groupcast and broadcast transmission modes. In addition, a UE receiver can assist a UE transmitter in assigning an appropriate SL DRX configuration to the type of V2X traffic.

V. RESULTS

The 5G LENA simulator and the branch developed for Mode 2 vehicular communications with NR V2X were chosen as simulation tools [21]. In [10], the developers of this branch describe the main features and functionalities of the simulator according to the 3GPP standard. To install this simulator, it is first necessary to install the ns3 simulator. Then we will continue with the installation of the 5G LENA simulator together with the branch for V2X communication. Since the simulator is strictly based on the 3GPP technical reports

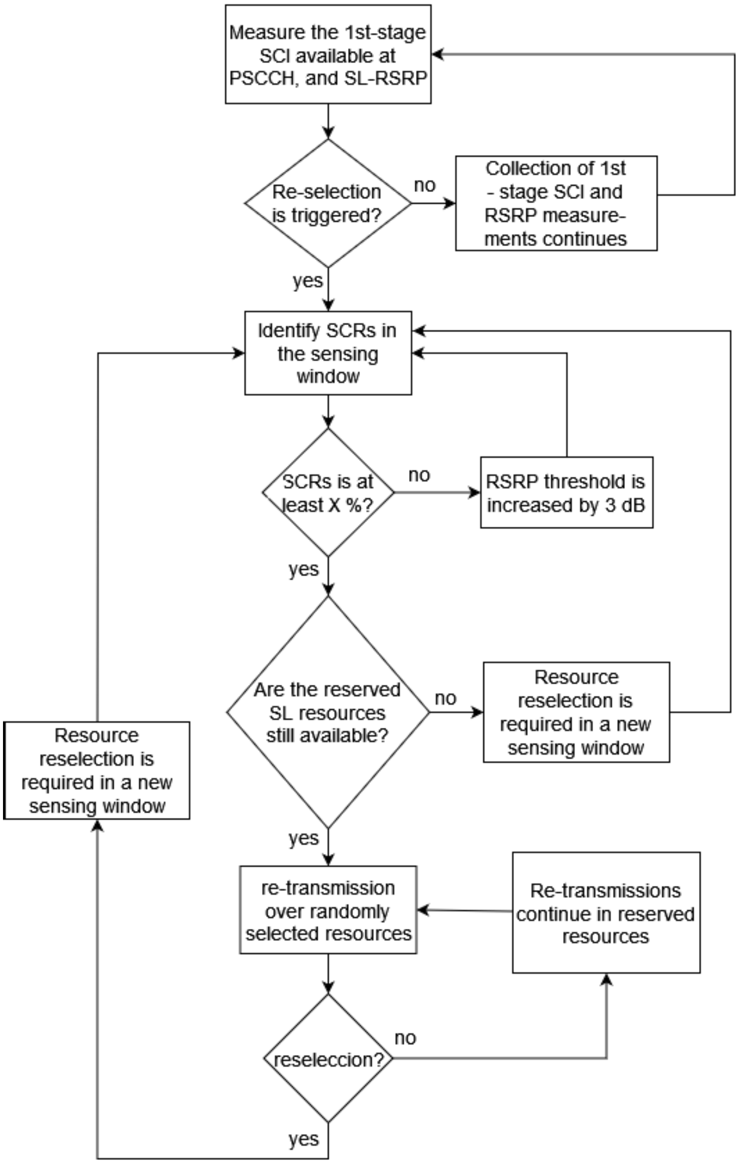

FIGURE 3. Procedures for sensing and resource selection in NR V2X.

and specifications, it has a code base that can be used to modify and generate simulation scenarios to obtain metrics to evaluate the performance of NR V2X Mode 2.

Key features supported by the branch for V2X communications include:

- Radio Frame: as specified in the 3GPP standard [16], the simulator is configured with a radio frame length of 10 ms. Each frame contains 10 subframes of 1 ms, and the number of slots per subframe varies depending on the numerology used. The numerologies supported by the simulator are u=0, u=1, u=2, u=3, and u=4. These numerologies should be selected according to the operating band, i.e., sub 6 GHz or mmWave.
- Bandwidth parts: more than one bandwidth part can be configured for sidelink, but only one will be active at a time.
- Duplex Mode: the supported duplex mode is TDD. A TDD pattern can include slots defined for Downlink, Uplink, or Flexibles.
- Resource Pool: for sidelink, a configuration of resources in time and frequency is defined according to the standard specifications. Only the slots preconfigured as uplink and defined as sidelink by the bitmap can be used for V2X traffic transmission. In the sidelink slots, the channels for V2X communication are mapped to the corresponding symbols. The corresponding calculation of the number of available RBs in a subchannel size is performed in frequency, depending on the numerology.
- Support for QPSK, 16-QAM, 64-QAM, and 256-QAM modulation. The modulation is not adaptive but remains fixed during all transmissions.

TABLE 1. Reference parameters for simulations.

Parameter	Configured parameter	Units
Channel model	Highway	-
Number of lanes	3	-
Lane width	4	m
Vehicles per lane	30	-
Distance between vehicles	20, 78	m
Vehicles speed	140	km/h
Carrier frequency	5.89	GHz
Bandwidth	40	MHz
Transmission power	23	dBm
Numerology	0,1,2	-
Lane width	4	m
Sensing window, T_0	100	ms
Sub-Channel size	20, 50	RBs
Resources to reserve, max.	3	-
Probability of keeping the same resources	0	%
Maximum number of PSSCH transmissions (including retransmissions)	5	-
Resource reservation period	100	ms
T_1	2	slots
T_2	33	slots
RSRP for sidelink measurements	-128	dBm
MCS	14 (64-QAM 3/4)	-

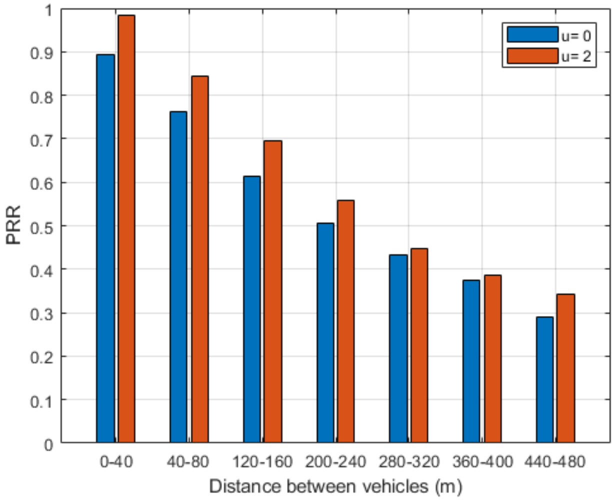

FIGURE 4. Average PRR for different ranges of separation between vehicles, with sensing procedures activated.

- Resource location can be configured randomly or using the sensing techniques described in previous sections.
- The channel coding is Low Density Parity Check (LDPC) and the modulation is OFDM.
- The output metrics are PRR, Packet Inter-Reception (PIR), and throughput.

The baseline scenario set up for the simulations is shown in Table 1. All simulations were generated for a Highway scenario whose reference parameters correspond to the 3GPP guidelines [22]. The remaining parameters are considered according to the 3GPP standard for NR V2X.

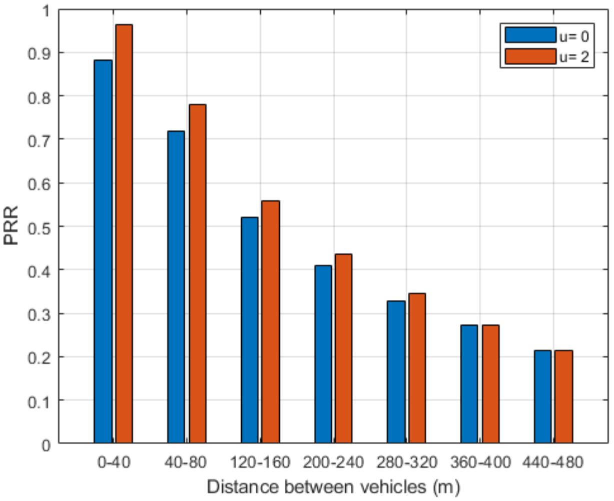

FIGURE 5. Average PRR for different distances between vehicles without activating sensing procedures.

First, we were interested in obtaining the results of the PRR variation as a function of the distance between a transmitting and receiving vehicle. In this simulation, 30 vehicles per lane are considered, for 90 vehicles transmitting and receiving V2X packets between each other. Fig. 4 shows the variation of the PRR as a function of the distance between the sender and receiver. The PRR value corresponds to the average value of packets received for a given range of distances. In this simulation, resource allocation is enabled using the resource discovery and selection procedures described in the previous sections. The curves shown in Fig. 4 indicate a better performance of numerology 2 compared to the use of numerology 0. However, for distances above 120 meters, the PRR is below 80%, which is a low value for V2X applications that require strict potential requirements to function properly.

Fig. 5 shows the results obtained when the sensing procedures defined by 3GPP are disabled. Therefore, the resource selection is performed in a random manner. The results obtained show that the PRR obtained is lower when the resource selection is not performed by such sensing procedures. In addition, the trend that the performance is higher when working with 60 kHz numerology is maintained.

In this way, we can highlight the importance of activating the sensing procedures to achieve a higher rate of correctly received packets in communications. In other words, by applying a set of rules and procedures that transmitters follow when selecting available resources, the probability of vehicles selecting the same resources for their transmissions is minimized. However, the cost of resource selection by sensing involves computational costs that must be incorporated into the chipsets, as well as an increase in battery consumption. The latter can be a sensitive factor in certain V2X scenarios, such as devices carried by a pedestrian —V2P communication— or devices integrated into a bicycle to send and receive warnings to avoid accidents and generally improve road safety. In other cases, such as V2N, V2V, or V2I communications, the energy consumption of the devices is not a limiting factor, so the activation of sensing procedures would provide significant benefits to achieve higher performance. In addition, these procedures can be enabled or disabled depending on the potential requirements of the specific V2X services to be implemented, as described in [4]. Thus, services have specific KPIs of reliability, latency, throughput, packet size, coverage area, etc.

Fig. 6 shows the Cumulative Distribution Function (CDF) for the average PRR obtained for the numerologies u = 0, u = 1 and u = 2. These results have been obtained without activating the resource selection mechanisms defined by 3GPP, i.e., a random resource selection is used. The results obtained in Fig. 6 confirm the hypothesis that high numerologies offer better PRR performance. However, it is observed that the CDF curves for PRR have a point of intersection. The reason is due to the resources in time and frequency resulting from the use of one or the other numerology. In these simulations, 40 MHz of bandwidth has been allocated. Since the size of each subchannel for the sidelink has been defined as 50 RBs, we have 4 subchannels for u = 0 numerology, 2 subchannels for u = 1 numerology, and 1 subchannel for u = 3 numerology. Therefore, in u = 0 numerology, there is a greater diversity of frequency resources that vehicles can select for their V2X transmissions. However, it must be considered that, since the selection of the resources is random, a vehicle may select the same resources that another vehicle has already selected for its transmissions, causing an interference that affects the packets not to be received correctly. On the other hand, when the number of resources is increased, although there is much less diversity of resources in the frequency that vehicles can use for their transmissions, the duration of the resource selection window is reduced in time. This is because the resource selection window is defined by the number of slots between T1 and T2, so increasing the numerology reduces the time because the slots have a shorter duration. In our simulations, 32 slots were configured for the selection window, so the window duration is $32/2^u$ ms. Thus, the duration of the selection window is 32 ms, 16 ms, and 8 ms for numerologies u = 0, u = 1, and u = 2, respectively. Since the resource reservation period is fixed —100 ms in our simulations—, at high numerologies there is less probability that users will select the same resources for their transmissions, so the PRR is higher.

Fig. 7 shows the CDF of the PRR for the same 3 numerologies of Fig. 6, but in this case when the available resource sensing techniques are enabled. Fig. 7 shows that the PRR is higher when the sensing techniques specified in the 3GPP standards are used. For example, the probability that the PRR is less than or equal to 0.7, for numerology u = 2 is 60% when the sensing procedures are not activated. On the other hand, when the sensing procedures are active, the probability decreases to about 30%. In addition, the trend that the average performance is better at higher numerologies is maintained. The explanation for the crossover between the numerology curves is similar to the one mentioned for the case when the sensing procedures are active. In this case, the time and frequency resources selected by the vehicles for their transmissions are also affected because, as explained in the previous sections, the RSRP threshold is increased when the minimum percentage of candidate resources for V2X transmissions is not available. This directly affects the use of one or more resources already selected by other vehicles for their transmissions. Thus, in these simulations we can see the importance of high numerologies for increasing PRR levels. In general, the u = 0 numerology is the best for direct comparison with LTE, since the time-frequency resources are the same. However, although there are some similarities in the sensing and resource selection procedures, there are some differences that mean that the performance achieved is not exactly the same. For example, basic services that do not have strict latency, network reliability, and throughput requirements can be provided with low numerologies. On the other hand, for services with potentially higher requirements, the use of high numerologies can provide better network performance. In this way, even the transition from NR V2X to LTE V2X services under multi-RAT operating conditions can be considered. As explained above, although only one bandwidth part can be defined with one numerology within a carrier frequency, other bandwidth parts with different numerologies can be assigned and activated depending on a specific scenario or use case. It should also be noted that under the same numerology, the standard also provides the flexibility to vary the size of the sidelink bandwidth, the size of the subchannels, the length of the sensing and selection windows, among others.

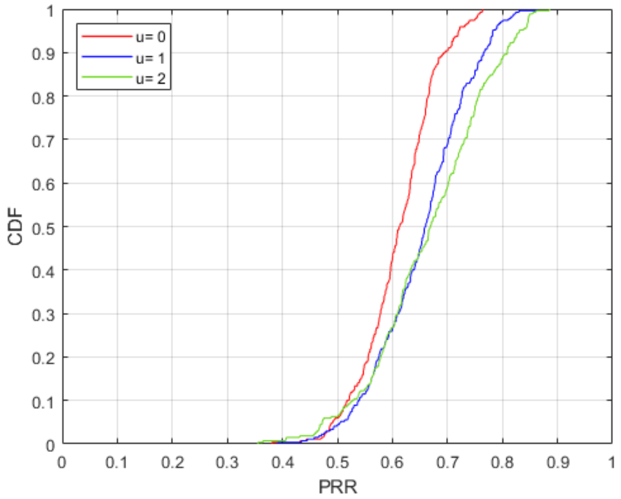

FIGURE 6. CDF of the PRR for different numerologies without activated sensing procedures. The maximum distance between the transmitter and receiver is 200 m.

Our next experiment consists of varying the distance between vehicles from 78 to 20 meters. In this scenario, the vehicles are physically closer to each other, so the interference they cause in communication is greater. Fig. 8 compares the results obtained for numerology 2. As expected,

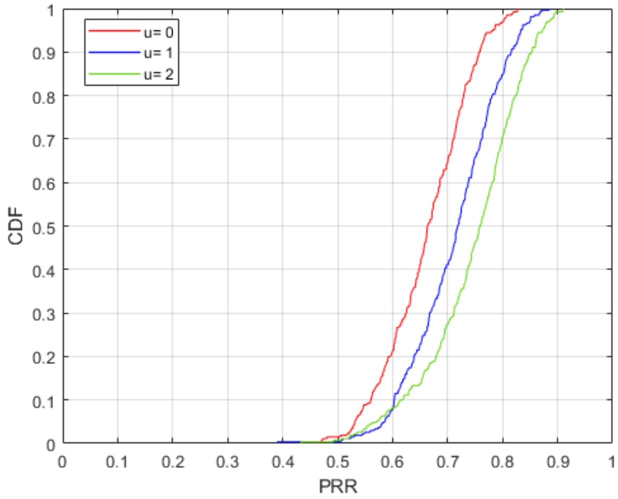

FIGURE 7. CDF of the PRR for different numerologies by activating the sensing procedures. The maximum distance between transmitter and receiver is 200 m.

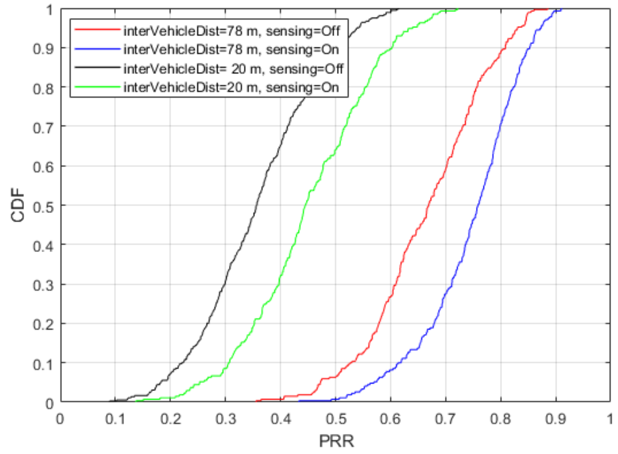

FIGURE 8. Variation of the PRR CDF for different inter-vehicle distances taking into account the activation and deactivation of resource sensing.

the performance is lower as the distance between vehicles decreases, i.e., as the vehicle density increases. The results in Fig. 8 also show higher performance when resource sensing is enabled.

In the next simulation, the density of vehicles on the road was changed. Thus, ten vehicles per lane were configured, leaving a total of 30 vehicles each sending and receiving V2X packets. The results shown in Fig. 9 indicate that the PRR increases when the vehicle density is lower. This is because with a smaller number of vehicles configured on the road, the interference they generate at the time of resource selection in time and frequency is less. In these cases, vehicles are less likely to need to increase the PRR threshold to reach the minimum percentage of candidate resources for V2X transmissions. As mentioned in the previous sections, if vehicles do not have the minimum percentage of candidate resources to perform their transmissions, then the RSRP threshold must be increased. This results in using the same resources that have already been selected by other vehicles for their transmissions.

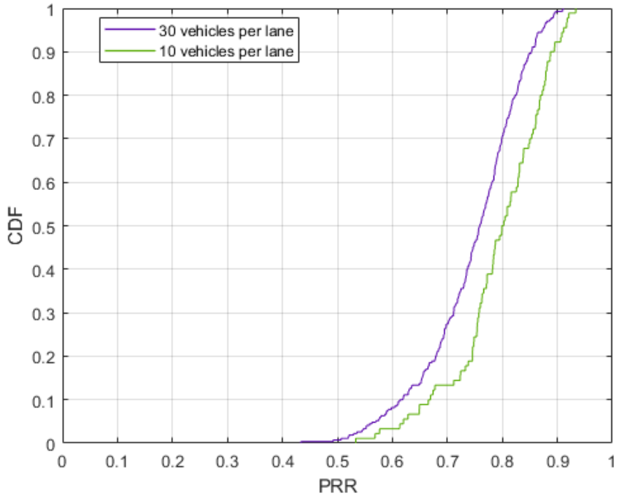

FIGURE 9. Variation of PRR for different vehicle densities and u = 2 numerology.

Fig. 10 shows the variation of the PRR CDF for numerologies u = 0 and u = 2 when the size of the subchannels defined for sidelink is varied. In this case, the effect of reducing the size of the sidelink subchannels from 50 RBs to 20 RBs, as specified in the standard, is compared. For both numerologies, it is observed that the performance is higher when the size of the subchannels is reduced. This is due to the fact that reducing the size of the sidelink subchannels increases the diversity of available frequency resources that vehicles can select for their V2X transmissions. Thus, for 50 RBs of subchannel size, we get 4 subchannels for u = 0 numerology and 1 subchannel for u = 2 numerology. When the subchannel size decreases to 20 RBs, the number of sidelink subchannels increases to 11 subchannels for u = 0 numerology and 2 subchannels for u = 2 numerology. This increase in the number of available subchannels directly influences that there is a lower probability of vehicles using the same resources in frequency. That is, the minimum percentage of candidate resources is more likely to be met without requiring an increase in RSRP, thus minimizing interference. In addition, higher numerologies offer better performance due to a shorter selection window in time. However, as shown in Fig. 11, a lower number may perform better when the subchannel size is smaller. It should also be noted that the size and number of subchannels that transmitters should select should be related to the size of the V2X packets. For example, larger V2X packets require either larger subchannels or more subchannels to be selected in one or more slots.

The variation in subchannels size also has an impact when considering the activation or deactivation of resource sensing. Fig. 12 compares the performance of the numerology under

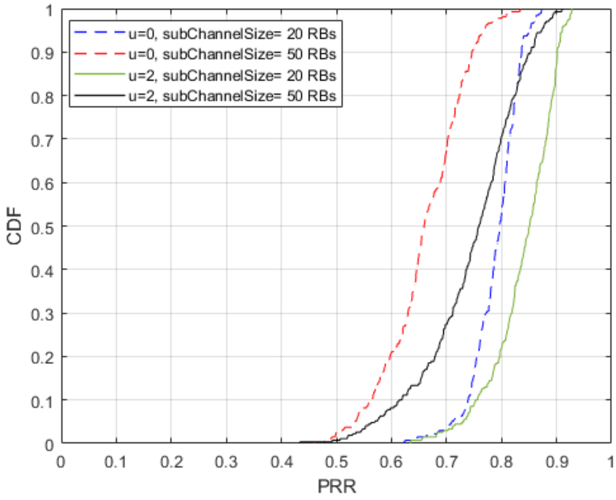

FIGURE 10. PRR CDF for different numerologies and sidelink subchannel sizes.

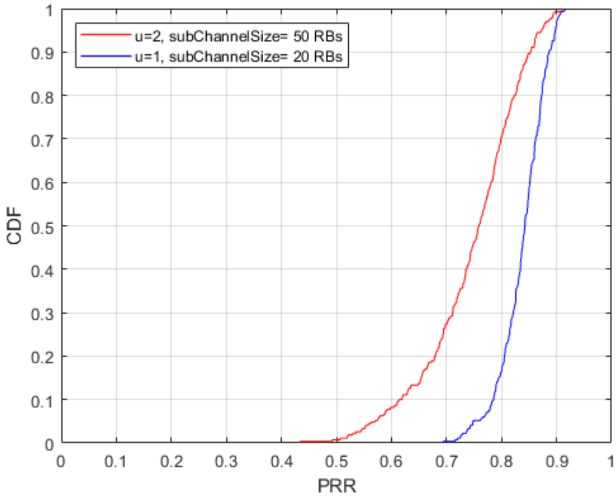

FIGURE 11. Increased PRR when decreasing numerology and sidelink subchannel size.

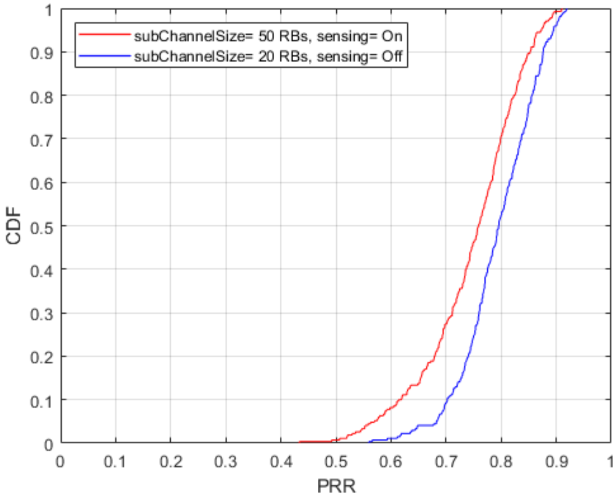

FIGURE 12. Increased PRR under the same numerology with resource sensing disabled and smaller sidelink subchannels.

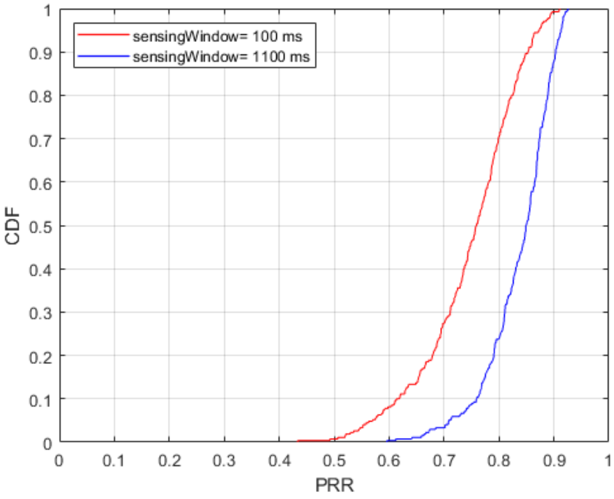

FIGURE 13. Influence on PRR of increasing the resource sensing window.

active and deactivated sensing conditions, for channel sizes of 50 RBs and 20 RBs. The simulation results indicate that for the same numerology, and with the resource sensing option disabled, better performance can be achieved when the subchannel size is smaller than when resource sensing is enabled. Such configurations may be useful in scenarios where V2X devices require lower power consumption. Although the performance is higher —under the same operating conditions— when sensing is enabled, this results in higher power consumption of the devices due to all the resource measurement, candidate resource determination, and congestion control procedures.

The length of the sampling window also affects the performance obtained for PRR. Fig. 13 shows the results obtained by increasing the length of the sensing window from 100 ms to 1100 ms —according to the standard— for $u = 2$ numerology. By increasing the length of the sensing window, more information is available from the sidelink resources available for V2X transmissions. In this way, vehicles discard the resources already reserved by other vehicles for their transmissions or retransmissions, thus improving the PRR. However, the increase in sensing time has a direct impact on the energy consumption of the devices and their complexity. Therefore, a larger sensing window may be recommended in scenarios where devices are not resource-constrained or battery-consumption constrained. Note that the sensing window is defined in time, so at higher numerologies the sensing is done in a larger number of time slots.

The results of the simulations performed allow to understand that, in general, the best performance is obtained with high numerologies and with the activation of the sensing and resource selection procedures. However, it was found that the performance can vary depending on the parameters configured according to the specifications of the standard. For example, the size of the sidelink subchannels —as specified by the standard— can be 10, 12, 15, 20, 25, 50, 75, or 100 RBs. In our simulations, we only calculated the PRR for specific scenarios with 20 and 50 RBs, but there are other variations that can be considered. In addition, it should be noted that for a given channel bandwidth, not all subchannel sizes can be configured. For example, for a 40 MHz bandwidth and a sidelink subchannel size of 100 RBs, 2 subchannels are obtained for u = 0 numerology, 1 subchannel for u = 1 numerology, and no subchannel for u = 2 numerology. This is obviously because the size of the subchannels is defined in number of RBs and there is a maximum channel bandwidth that must not be exceeded. According to the standard, it is also possible to define channel bandwidths of 10 MHz per BWP, so that in order to guarantee at least one sidelink subchannel, the size of these subchannels must be a maximum of 50, 20 and 12 RBs for numerologies 0, 1 and 2, respectively.

In addition, 5G NR specifies that only one bandwidth with specific numerology will be available to all V2X UEs on a carrier frequency. However, each UE within a BWP may be allocated different resource pools, in which different pre-configurations may be established [3]. Such configurations may include variations in the number of RBs per subchannel, the number of retransmissions, and the MCS. For example, for the simulations shown in Fig. 11, a reduction in the number of RBs per subchannel implies a greater diversity of resources in frequency and is beneficial for obtaining better PRR levels. However, depending on the size of the V2X packets, it may be necessary for the same UE to select more than one sidelink subchannel, so the alternative is to use, if possible, a higher MCS to transmit the same V2X traffic without consuming more resources in frequency. It should be emphasized that a high MCS should only be used in scenarios with low interference or congestion, otherwise, it will be counterproductive.

Both Mode 4 and Mode 2, defined for LTE and NR, respectively, are based on decentralized modes where resource allocation does not depend on cellular network coverage, but is performed by autonomous sensing, reservation and resource selection procedures in time and frequency. Thus, there are some similarities in the resource selection mechanisms defined by 3GPP in Mode 4 —Release 14— and Mode 2 —Release 16. The main differences between these procedures are related to the new physical layer aspects defined for 5G NR.

In order to estimate the performance of LTE Mode 4 and compare it with NR Mode 2, the parameters specified by the standard for both modes were adjusted in the simulator we used. It is worth noting that some physical layer parameters are basically the same. However, other parameters are different because of the possibility of configuring higher numerologies or larger channel bandwidths in NR. For example, in mode 4, only 12 subcarrier resource blocks of 15 kHz can be used. In mode 2, on the other hand, the resource blocks can consist of 12 subcarriers of 15 kHz, 30 kHz and 60 kHz, corresponding to numerologies u = 0, u = 1 and u = 2, respectively. Thus, the u = 0 numerology is the one that coincides with the frequency size of the resource blocks used in LTE mode 4. On the other hand, in LTE, the channel bandwidth normally used for V2X communication is 10 MHz. However, in NR V2X, bandwidths up to 50 MHz can be defined for u = 0 numerology [23]. Other differences relate to the size of the sidelink subchannels defined for Mode 2 and Mode 4. For mode 4, the standard defines that the size of the subchannels varies from 4 to 50 RBs [4]. On the other hand, for mode 2, the size of sidelink subchannels can vary from 10 to 100 RBs.

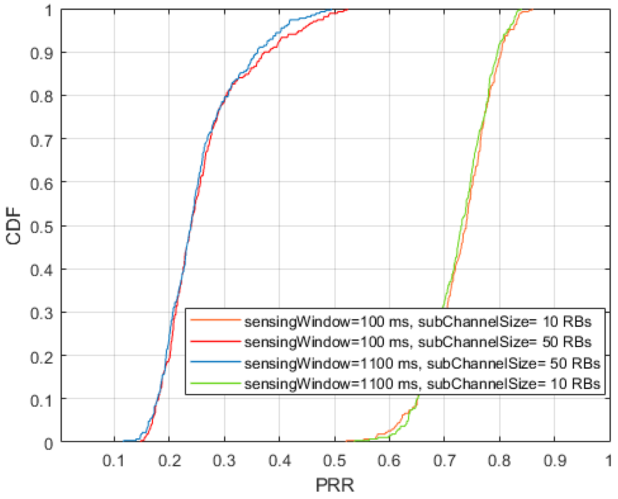

FIGURE 14. **Performance achieved with a bandwidth of 10 MHz, for numerology u = 0, when varying the duration of the sensing window and the size of the sidelink subchannels.**

Fig. 14 compares the performance achieved with u = 0 numerology utilizing a 10 MHz channel bandwidth and variation of the sensing window from 1100 ms —this value is close to the value defined for mode 4 V2X, i.e. 1000 ms— to 100 ms. Fig. 14 shows that the variation of the sensing window does not have an influence on the performance achieved in the u = 0 numerology. However, as shown in the previous results, a decrease in the size of the sidelink subchannels improves the performance because a greater diversity of resources in frequency is generated.

For a bandwidth of 10 MHz, when the subchannel size is 10 RBs, in the u = 0 numerology, up to 5 sidelink subchannels are obtained. However, when the bandwidth is increased to 50 MHz —as defined by the standard for NR—, up to 27 sidelink subchannels are obtained. Fig. 15 shows that this increase in frequency resources improves performance because there is a greater diversity of subchannels that vehicles can select for their transmissions.

For certain V2X applications or services that require larger packet transmission sizes, the sidelink subchannels must also be enlarged. Therefore, to boost the size of sidelink

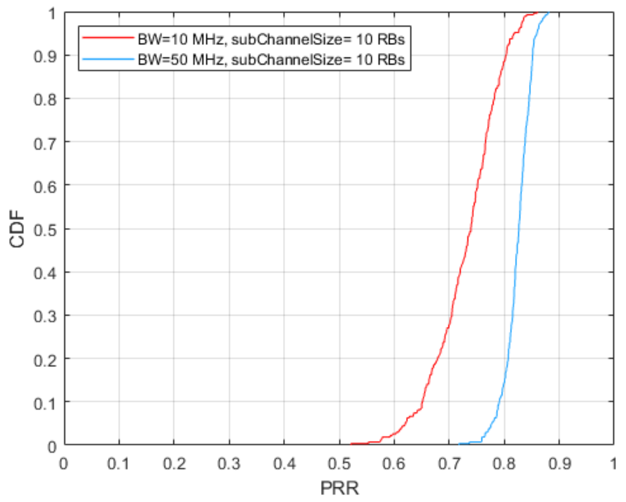

FIGURE 15. Performance achieved when increasing the bandwidth from 10 MHz to 50 MHz, under u = 0 numerology and sidelink subchannels of 10 RBs.

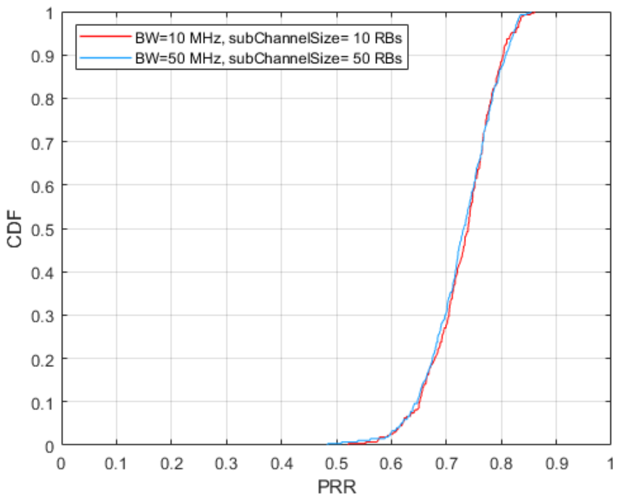

FIGURE 16. Performance achieved by using a u = 0 numerology, combining 10 MHz bandwidth and subchannels with 10 RBs, compared to utilizing 50 MHz bandwidth and subchannels with 50 RBs.

subchannels without decreasing performance, one possible solution is to increase the channel bandwidth. Fig. 16 shows that configuring a 10 MHz bandwidth and subchannel size of 10 RBs under u = 0 numerology results in similar performance compared to a 50 MHz bandwidth and sidelink subchannel size of 50 RBs. With both configurations, there are up to 5 subchannels per slot, resulting in comparable performance.

VI. MULTI-RAT V2X AND FUTURE RESEARCHES

Adopting V2X communications through multiple RATs (multi-RAT) has the potential to unlock numerous benefits and create a strong foundation for the future of transportation systems. Enabling multi-RAT V2X, such as NR and LTE, enhances the reliability and robustness of V2X systems. In situations where one RAT may face coverage limitations or congestion, the ability to seamlessly switch to an alternative RAT ensures continuous connectivity and communication between vehicles and their surrounding environment. This promotes safer driving conditions and enables critical V2X applications, such as collision avoidance and real-time traffic management, to operate effectively. In addition, multi-RAT V2X facilitates improved resource utilization. By utilizing multiple communication technologies, the available spectrum resources can be efficiently allocated, reducing congestion and maximizing system capacity. This leads to enhanced overall performance, increased data transmission rates, and lower latency in V2X applications. Moreover, the flexibility offered by multi-RAT V2X allows for dynamic resource selection based on the specific requirements of different V2X use cases, optimizing the allocation of resources and ensuring efficient utilization across diverse applications and traffic conditions. Note also that multi-RAT is a way to support interoperability and future-proofing current V2X systems. As current cellular network technologies evolve and new generations emerge, like the Sixth Generation (6G), having the ability to integrate multiple RATs ensures compatibility with legacy systems and facilitates a smooth transition to future technologies. This flexibility allows for the coexistence of different communication protocols and standards, enabling backward compatibility, alleviating costs, and ensuring that V2X systems can adapt and scale as technology progresses.

Specifically, to assess multi-RAT V2X performance evaluation, applying principles akin to those articulated in this paper holds significant relevance. Analyzing the interplay between NR V2X and other RATs is essential to determine how NR V2X would operate alongside other communication technologies like LTE. Hence the interactions between different RATs need to be studied to understand how seamless RAT switching may occur when the vehicles encounter coverage limitations or congestion. This would involve investigating the handover procedures and the handover latency between NR and LTE to ensure continuous connectivity and minimal disruption during RAT transitions. Also, with multiple communication technologies being used, it is crucial to optimize the allocation of spectrum resources to maximize system capacity and minimize interference. Advanced resource allocation algorithms, such as Dynamic Spectrum Sharing (DSS) may be used, thus enabling concurrent utilization of LTE and 5G cellular wireless technologies within a identical frequency range, dynamically allocating bandwidth according to user needs. This can be employed to efficiently distribute available resources among NR and LTE V2X systems; this also would require a careful assessment of spectrum-sharing mechanisms, coexistence protocols, and interference management techniques to enhance overall performance and data transmission rates.

In parallel, multi-RAT V2X systems would benefit from dynamic resource selection, allowing for adaptive allocation of resources based on specific V2X use cases and traffic conditions. In fact, we are on the brink where intelligent algorithms and machine learning techniques can be utilized to predict resource requirements and make real-time resource allocation decisions. The availability of recent datasets such as [24] makes researching this approach feasible, where the goal would be to optimize the allocation of resources across diverse applications and traffic scenarios, ensuring efficient utilization and minimizing resource wastage. Additionally, ensuring the seamless integration of NR V2X with existing and future communication technologies is critical for long-term system viability. This involves adhering to standardized communication protocols, ensuring common frequency bands, and enabling cross-technology communication interfaces. Therefore interoperability testing and compliance with V2X communication standards become key factors in achieving a smooth coexistence among RATs.

Trade-off of performance aspects would be also important, for example, balancing the sidelink sub-channel size on interference reduction, which will require extensive simulations and performance evaluations, considering different traffic scenarios and mobility patterns, to determine the optimal configuration for resource size and allocation. Last but not least, maintaining a high level of QoS in multi-RAT V2X scenarios is essential for critical V2X applications, such as collision avoidance and every aspect related to real-time traffic management. In fact, robust QoS management mechanisms taking advantage of multi-RAT will need to be in place to prioritize and allocate resources to time-sensitive V2X messages, ensuring low latency and reliable communications.

VII. CONCLUSION

This paper has evaluated the performance of NR V2X Mode 2, according to the 3GPP specifications. For this purpose, different simulation scenarios have been configured using the V2X branch provided by 5G LENA. The results show that the highest PRR performance is obtained when higher numerologies are used. This is due to the relationship that exists in the number of resources in time and frequency, depending on the spacing between subcarriers. Thus, when the numerology is higher, fewer resources are available in frequency, but since the resource selection window is defined as a function of the number of slots, it is smaller in time. Therefore, the simulations performed show that there is a lower probability that the transmitters select the same resources, so there is less interference and a better rate of correctly received packets.

With respect to the sensing techniques defined by 3GPP, the results obtained show that PRR performance improves when these techniques are enabled. However, since using the sensing techniques involves a series of measurements and data processing, random mode resource selection may be necessary when power-constrained transmitters.

Since the standard defines the possibility of varying the size of the sidelink channels, it is concluded that the performance of the PRR increases when the size of the sidelink channels is reduced. The reason is that in this way there is a greater diversity of resources in frequency, so the interference that occurs when vehicles select candidate resources is reduced. It should be noted that reducing the size of the sidelink subchannels implies that less information can be sent in this bandwidth; this depends on the size of the V2X messages defined for a service and can be compensated, if possible, by increasing the MCS. Finally, increasing the sensing window improves the information available to the transmitters about the candidate resources, thus improving the PRR.

REFERENCES

[1] (2023). *3rd Generation Partnership Project (3GPP)*. Accessed: Jul. 4, 2023. [Online]. Available: https://www.3gpp.org/

[2] *Study on LTE Support for Vehicle-to-Everything (V2X) Services*, document TR 22.885, V14.0.0, 3GPP, Dec. 2015.

[3] *Study on NR Vehicle-to-Everything (V2X)*, document TR 38.885, V16.0.0, 3GPP, Mar. 2019.

[4] E. E. González, D. Garcia-Roger, and J. F. Monserrat, "LTE/NR V2X communication modes and future requirements of intelligent transportation systems based on MR-DC architectures," *Sustainability*, vol. 14, no. 7, p. 3879, Mar. 2022.

[5] *Vehicle-to-Everything (V2X) Services Based on LTE; User Equipment (UE) Radio Transmission and Reception*, document TR 36.786, V14.0.0, 3GPP, Mar. 2017.

[6] *Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation*, document TS 38.211, V14.15.0, 3GPP, Jul. 2020.

[7] M. H. C. Garcia, A. Molina-Galan, M. Boban, J. Gozalvez, B. Coll-Perales, T. Sahin, and A. Kousaridas, "A tutorial on 5G NR V2X communications," *IEEE Commun. Surveys Tuts.*, vol. 23, no. 3, pp. 1972–2026, 3rd Quart., 2021.

[8] K. Sehla, T. M. T. Nguyen, G. Pujolle, and P. B. Velloso, "Resource allocation modes in C-V2X: From LTE-V2X to 5G-V2X," *IEEE Internet Things J.*, vol. 9, no. 11, pp. 8291–8314, Jun. 2022.

[9] C. Ghodhbane, M. Kassab, S. Maaloul, H. Aniss, and M. Berbineau, "A study of LTE-V2X mode 4 performances in a multiapplication context," *IEEE Access*, vol. 10, pp. 63579–63591, 2022.

[10] Z. Ali, S. Lagén, L. Giupponi, and R. Rouil, "3GPP NR V2X mode 2: Overview, models and system-level evaluation," *IEEE Access*, vol. 9, pp. 89554–89579, 2021.

[11] N. Patriciello, S. Lagen, B. Bojovic, and L. Giupponi, "An E2E simulator for 5G NR networks," *Simul. Model. Pract. Theory*, vol. 96, Nov. 2019, Art. no. 101933.

[12] Z. Ali, S. Lagen, and L. Giupponi, "On the impact of numerology in NR V2X mode 2 with sensing and random resource selection," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Nov. 2021, pp. 151–157.

[13] V. Todisco, S. Bartoletti, C. Campolo, A. Molinaro, A. O. Berthet, and A. Bazzi, "Performance analysis of sidelink 5G-V2X mode 2 through an open-source simulator," *IEEE Access*, vol. 9, pp. 145648–145661, 2021.

[14] S.-Y. Lien, D.-J. Deng, C.-C. Lin, H.-L. Tsai, T. Chen, C. Guo, and S.-M. Cheng, "3GPP NR sidelink transmissions toward 5G V2X," *IEEE Access*, vol. 8, pp. 35368–35382, 2020.

[15] C. Campolo, A. Molinaro, F. Romeo, A. Bazzi, and A. O. Berthet, "5G NR V2X: On the impact of a flexible numerology on the autonomous sidelink mode," in *Proc. IEEE 2nd 5G World Forum (5GWF)*, Sep. 2019, pp. 102–107.

[16] *NR; Physical Channels and Modulation*, document TR 38.211, V17.4.0, 3GPP, Jan. 2023.

[17] *NR; Services Provided by the Physical Layer*, document TR 38.202, V17.3.0, 3GPP, Jan. 2023.

[18] *NR; Services Provided by the Physical Layer*, document TR 37.985, V17.1.1, 3GPP, Apr. 2022.

[19] *NR; Radio Resource Control (RRC); Protocol Specification*, document TS 38.331 V17.3.0, 3GPP, Jan. 2023.

[20] *NR; Medium Access Control (MAC) Protocol Specification*, document TS 38.321, V17.3.0, 3GPP, Jan. 2023.

[21] (2023). *5G LENA—NR V2X Release V0.1*. Accessed: May 19, 2023. [Online]. Available: https://5g-lena.cttc.es/blog/16/

[22] *Study on Evaluation Methodology of New Vehicle-to-Everything (V2X) Use Cases for LTE and NR*, document TR 37.885, V15.3.0, 3GPP, Jun. 2019.

[23] *NR; User Equipment (UE) Radio Transmission and Reception; Part 1: Range 1 Standalone*, document TS 38.101, V18.2.0, 3GPP, Jun. 2023.

[24] R. Hernangómez, P. Geuer, A. Palaios, D. Schäufele, C. Watermann, K. Taleb-Bouhemadi, M. Parvini, A. Krause, S. Partani, C. Vielhaus, and M. Kasparick, "Berlin V2X: A machine learning dataset from multiple vehicles and radio access technologies," in *Proc. IEEE 97th Vehicular Technol. Conf.*, 2023, pp. 1–5.

EDGAR E. GONZÁLEZ received the M.S. degree in communication technologies, systems and networks from Universitat Politécnica de Valéncia, Spain, in 2018, where he is currently pursuing the Ph.D. degree, with a focus on internetworking mechanisms for V2X services through a multi-RAT approach. Since April 2019, he has been a full-time Teacher/Researcher with Universidad Tecnológica Israel, Quito, Ecuador.

YANET ESTRADA received the M.Sc. degree in telecommunications engineering from Universidad Nacional de Cuyo, Argentina, in 2018. She is currently pursuing the Ph.D. degree with the iTEAM Research Institute, Universitat Politécnica de Valéncia, Valencia, Spain. She is also an Early Stage Researcher with the ITN-5VC European Project. Her current research interests include optimizing and improving the reliability of 5G V2X/cellular interoperability for the case of autonomous driving.

DAVID GARCIA-ROGER received the Ph.D. degree in telecommunications from Universitat Politécnica de Valéncia (UPV), Spain, in 2007. He has been a Researcher with ITEAM, UPV, since 2012, and an Adjunct Professor with Universitat de Valéncia, since 2020. He has participated as a Researcher in European Projects ALPHA, METIS-II, and 5G-CARMEN. He has published about 40 papers. His research interests include the evaluation of 5G candidate technologies and vehicular communication systems.

JOSE F. MONSERRAT (Senior Member, IEEE) received the M.Sc. (Hons.) and Ph.D. degrees in telecommunications engineering from Universitat Politécnica de Valéncia (UPV), Spain, in 2003 and 2007, respectively. He is currently a Full Professor with UPV. He holds six patents and has published more than 50 journal articles. He was a recipient of the First Regional Prize of Engineering Studies, in 2003, for his outstanding student record, also receiving the Best Thesis Prize from UPV, in 2008. In 2009, he was awarded the Best Young Researcher Prize in Valencia. In 2016, he received the Merit Medal from the Spanish Royal Academy of Engineering in the Young Researcher Category.

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