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Performance Evaluation of 3GPP Standards for C-V2X Communications

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To my parents,
to my sisters and brothers,
for all your support
along this journey.
Thank you for your love
and your light.
Thank you for believing in me.

Abstract

Fifth-generation mobile networks, commonly referred to as Fifth Generation (5G), are known for their robustness and surpassing their predecessors' performance. They enable significant improvements in Key Performance Indicators (KPIs) to support advanced use cases and services. These KPIs are classified into three fundamental scenarios: Enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low Latency Communications (uRLLC), and massive Machine Type Communications (mMTC). The eMBB scenario focuses on services that require high transmission and reception rates to improve the user experience. In contrast, uRLLC addresses situations that require strict low latency and high-reliability standards in the network. This need is particularly evident in real-time applications where prompt network response is essential. The mMTC scenario pertains to applications and services that require network support for massive device connectivity per square kilometer and enhanced energy efficiency. In particular, services and applications based on vehicular communications via the cellular network, referred to as Vehicle-to-everything (V2X) communications in the standard, are prominent. These services aim to enhance highway safety, optimize travel times, and reduce environmental pollution from fossil fuel consumption.

V2X communication refers to communication between vehicles and infrastructures. When using mobile network standards such as Long Term Evolution (LTE) or New Radio (NR), it is referred to as Cellular-based V2X (C-V2X). Vehicle-to-Vehicle (V2V) communication enables packet exchange between vehicles, while Vehicle-to-Infrastructure (V2I) facilitates exchange between vehicles and network infrastructures. Vehicle-to-Pedestrian (V2P) and Vehicle-to-Network (V2N) are two types of communication that enable the transfer of packets between vehicles and devices carried by pedestrians and the exchange of V2X traffic between vehicles and the network, respectively. These types of communication enable the implementation of various services, from basic functions to advanced applications with potential network requirements. The objective of this thesis is to evaluate the performance of C-V2X standards, specifically, the radio resource allocation procedures and mechanisms defined by Third Generation Partnership Project (3GPP) for LTE V2X and NR V2X. One hypothesis presented in this research suggests that while an LTE network can support basic V2X services, advanced services can only be implemented through a 5G NR network that integrates various access technologies, transmission/communication modes, and network interfaces.

To objectively evaluate these standards, particular attention has been paid to the decentralized modes defined for both LTE V2X and NR V2X. These modes allow vehicles to operate without relying on the cellular network's coverage. Instead, they use established mechanisms and procedures to select and use radio resources autonomously. The thesis addresses the need to evaluate the performance of decentralized modes under different reference parameters. This is done according to the standards guidelines to determine under which conditions maximum performance can be achieved. The evaluation will be based on the parameters defined in the Physical (PHY) and Media Access Control (MAC) layers for different use cases. It should be noted that while the standard sets specific parameters based on the fundamental characteristics of LTE and NR technologies, other parameters can be adjusted for different scenarios. These include numerologies, channel bandwidths, sidelink subchannel bandwidths, packet size, vehicle density, packet transmission frequency, sensing window size, and activation and deactivation of sensing mechanisms, among others.

This thesis provides a comprehensive review of the standard guidelines for V2X LTE and NR V2X communications, with a particular focus on the decentralized communication modes mentioned above. Following this, system-level simulations were conducted to configure V2X scenarios following 3GPP specifications. The results indicate that LTE mode 4 is sufficient for essential services that do not require high throughput, low latencies, or strict network reliability criteria. On the other hand, NR V2X mode 2 showed improved performance, allowing adaptation to advanced V2X services. High numerologies have been shown to contribute to better performance by providing greater resource diversity, reducing the probability that two vehicles use the same resources for their transmissions in the decentralized mode. In addition, it was found that in NR V2X, an adequate combination of numerologies, channel bandwidths, and sidelink subchannel sizes is crucial, depending on the V2X services to be implemented. Finally, the incorporation of multiple Radio Access Technology (RAT) (multi-RAT) was analyzed in order to support advanced services and improve interoperability through the use of LTE and NR-based access technologies, especially in scenarios with multiple Mobile Network Operators (MNOs), different connection interfaces and communication modes.

Resumen

Las redes móviles de quinta generación (5G) destacan por su robustez, superando las prestaciones ofrecidas por sus predecesoras. Dichas redes, comúnmente denominadas 5G, posibilitan mejoras significativas en los indicadores clave de rendimiento (KPIs en inglés) con el propósito de respaldar casos de uso y servicios avanzados. Estos KPIs se clasifican en tres escenarios fundamentales: Banda ancha móvil mejorada (eMBB en el estándar), comunicaciones utra fiables y de baja latencia (uRLLC) y comunicaciones masivas entre máquinas (mMTC). El escenario eMBB se orienta primordialmente hacia servicios que demandan elevadas tasas de transmisión y recepción para garantizar una experiencia de usuario mejorada. En contraste, uRLLC aborda situaciones que requieren estrictos estándares de baja latencia y alta confiabilidad en la red. Esta necesidad se manifiesta, por ejemplo, en aplicaciones de tiempo real donde la pronta respuesta de la red constituye un factor indispensable. En cuanto al escenario mMTC, se refiere a aplicaciones y servicios que solicitan el respaldo de la red para la conectividad masiva de dispositivos por kilómetro cuadrado, además de una eficiencia energética mejorada.

Entre los servicios y aplicaciones mencionados, destacan aquellos basados en comunicaciones vehiculares mediante la red celular, conocidos según el estándar como comunicaciones V2X. Estos servicios están diseñados con el objetivo de mejorar la seguridad vial en las carreteras, optimizar los tiempos de viaje y reducir la contaminación ambiental originada por el consumo de combustibles fósiles.

En términos generales, la comunicación V2X engloba el intercambio de paquetes entre vehículos y diversos elementos de la red. Cuando estas comunicaciones se efectúan mediante estándares basados en redes móviles, ya sea en LTE o NR, la interfaz radio de 5G, se denominan C-V2X. En este contexto, las comunicaciones Vehículo a Vehículo (V2V) posibilitan el intercambio de paquetes entre vehículos, mientras que las comunicaciones de Vehículos con Infraestructuras (V2I) facilitan el intercambio entre vehículos e infraestructuras de red. Por su parte, las comunicaciones de Vehículos con Peatones (V2P) comprenden la transferencia de paquetes entre vehículos y dispositivos portados por peatones, y las comunicaciones Vehículo a Red (V2N) permiten el intercambio de tráfico V2X entre vehículos y la red. Cada tipo de comunicación posibilita la implementación de diversos servicios, desde funciones básicas hasta aplicaciones avanzadas que exigen potenciales requerimientos por parte de la red.

Esta Tesis Doctoral tiene como objetivo principal llevar a cabo una evaluación del rendimiento de los estándares C-V2X, considerando los procedimientos y mecanismos de asignación de recursos radio definidos por el 3GPP, tanto para LTE V2X como NR V2X. Una de las hipótesis planteadas en esta investigación se fundamenta en la idea de que, si bien una red LTE puede respaldar servicios V2X básicos, es solo mediante una red 5G NR que se pueden aprovechar servicios avanzados, integrando diversas tecnologías de acceso, modos de transmisión/comunicación e interfaces de red.

Para llevar a cabo la evaluación de rendimiento de dichos estándares, se ha prestado especial atención a los modos descentralizados definidos tanto para LTE V2X como para NR V2X. Esta consideración se fundamenta en que, en tales modos, los vehículos no dependen de la cobertura de la red celular, sino que se establecen mecanismos y procedimientos para la selección y utilización autónoma de recursos radio. Dado que el estándar define una serie de parámetros en las capas física (PHY) y de control de acceso al medio (MAC) que pueden ser empleados en función de diversos casos de uso, la problemática abordada en esta tesis implica la necesidad de evaluar las prestaciones de los modos descentralizados bajo distintos parámetros de referencia, según las directrices del estándar, con el propósito de determinar en qué condiciones se puede alcanzar el rendimiento máximo. Es importante destacar que, si bien el estándar establece ciertos parámetros conforme a las características fundamentales de las tecnologías LTE y NR, existen otros parámetros que pueden ajustarse según diversos escenarios. Entre estos se incluyen diferentes numerologías, anchos de banda de canal, anchos de banda de los subcanales sidelink, tamaño de paquetes, densidad de vehículos, frecuencia de transmisión de paquetes, tamaño de las ventanas de sensado, así como la activación y desactivación de los mecanismos de sensado, entre otros.

En esta Tesis Doctoral, se llevó a cabo una revisión exhaustiva del estándar para comunicaciones V2X LTE y NR V2X, destacando particularmente los modos de comunicación descentralizados, como se mencionó anteriormente. Posteriormente, se realizó una campaña de simulaciones a nivel de sistema para configurar escenarios V2X conforme a las especificaciones del 3GPP. Los resultados obtenidos permitieron evidenciar que las prestaciones del modo 4 en LTE es adecuado para servicios básicos que no requieren un alto throughput, bajas latencias o estrictos criterios de fiabilidad en la red. En contraste, mediante el modo 2 de NR V2X, se observó un rendimiento mejorado, lo que permite la adaptación a servicios V2X avanzados. Asimismo, se demostró que altas numerologías contribuyen a un mejor comportamiento del sistema al proporcionar una mayor diversidad de recursos, reduciendo la probabilidad de que dos vehículos utilicen los mismos recursos para sus transmisiones en el modo descentralizado. Además, se comprobó que en NR V2X es crucial una combinación adecuada de numerologías, anchos de banda de canal y tamaño de los subcanales sideling, según los servicios V2X a implementar. Finalmente, Se analizó la incorporación de tecnologías de múltiples tecnologías de acceso radio (multi-RAT) con el fin de respaldar servicios avanzados y mejorar la interoperabilidad mediante el uso de tecnologías de acceso basadas en LTE y NR, especialmente en escenarios con múltiples operadores de red móvil (MNOs), distintas interfaces de conexión y modos de comunicación.

Resum

Les xarxes mòbils de cinquena generació (5G) destaquen per la seva robustesa, superant les característiques que ofereixen els seus predecessors. Aquestes xarxes, comunament anomenades 5G, permeten millores significatives en els indicadors de rendiment clau (KPI) per donar suport a casos i serveis d'ús avançats. Aquests KPI es classifiquen en tres escenaris fonamentals: banda ampla mòbil millorada (eMBB), comunicacions de baixa latència i fiabilitat (uRLLC) i comunicacions massives entre màquines (mMTC). L'escenari eMBB s'orienta principalment a serveis que exigeixen altes taxes de transmissió i recepció per garantir una millor experiència d'usuari. En canvi, uRLLC aborda situacions que requereixen estàndards estrictes de baixa latència i alta fiabilitat de la xarxa. Aquesta necessitat es manifesta, per exemple, en aplicacions en temps real on la resposta ràpida a la xarxa és un factor indispensable. Pel que fa a l'escenari mMTC, es refereix a aplicacions i serveis que sol·liciten suport de xarxa per a una connectivitat massiva de dispositius per quilòmetre quadrat, a més d'una millora de l'eficiència energètica. Entre els serveis i aplicacions esmentats destaquen els basats en comunicacions vehiculars a través de la xarxa cel · lular, coneguts segons la norma com a comunicacions V2X. Aquests serveis estan dissenyats amb l'objectiu de millorar la seguretat viària a les carreteres, optimitzar els temps de viatge i reduir la contaminació ambiental causada pel consum de combustibles fòssils.

En termes generals, la comunicació V2X engloba l'intercanvi de paquets entre vehicles i diversos elements de xarxa. Quan aquestes comunicacions es realitzen utilitzant estàndards basats en xarxes mòbils, ja sigui en Evolució a llarg termini (LTE) o Nova Ràdio (NR), s'anomenen C-V2X. En aquest context, les comunicacions Vehicle-to-Vehicle (V2V) permeten l'intercanvi de paquets entre vehicles, mentre que les comunicacions Vehicle-to-Infraestructura (V2I) faciliten l'intercanvi entre vehicles i infraestructures de xarxa. Per la seva banda, les comunicacions Vehicle-to-Pedestrian (V2P) inclouen la transferència de paquets entre vehicles i dispositius transportats per vianants, i les comunicacions Vehicle a Xarxa (V2N) permeten l'intercanvi de trànsit V2X entre vehicles i la xarxa. Cada tipus de comunicació permet la implementació de diversos serveis, des de funcions bàsiques fins a aplicacions avançades que requereixen possibles requisits de la xarxa. L'objectiu principal d'aquesta Tesi és dur a terme una avaluació del rendiment dels estàndards C-V2X, tenint en compte els procediments i mecanismes d'assignació de recursos de ràdio definits per 3GPP, tant per a LTE V2X com per a NR V2X. Una de les hipòtesis plante-

jades en aquesta investigació es basa en la idea que, tot i que una xarxa LTE pot suportar serveis bàsics V2X, és gràcies a una xarxa 5G NR que es poden aprofitar serveis avançats, integrant diverses tecnologies d'accés, modes de transmissió/comunicació i interfícies de xarxa.

Per dur a terme l'avaluació del rendiment d'aquests estàndards, s'ha prestat especial atenció als modes descentralitzats definits tant per a LTE V2X com per a NR V2X. Aquesta consideració es basa en el fet que, en aquests modes, els vehicles no depenen de la cobertura de la xarxa cel·lular, sinó que s'estableixen mecanismes i procediments per a la selecció i l'ús autònom dels recursos de ràdio. Atès que la norma defineix una sèrie de paràmetres en les capes de Control Físic (PHY) i Mitjà d'Accés (MAC) que es poden utilitzar en funció de diversos casos d'ús, el problema abordat en aquesta tesi implica la necessitat d'avaluar el rendiment dels modes descentralitzats sota diferents paràmetres de referència, segons les directrius estàndard, amb la finalitat de determinar en quines condicions es pot aconseguir el màxim rendiment. És important tenir en compte que, tot i que la norma estableix certs paràmetres segons les característiques fonamentals de les tecnologies LTE i NR, hi ha altres paràmetres que es poden ajustar segons diversos escenaris. Aquests inclouen diferents numerologies, amplades de banda del canal, amplades de banda del subcanal d'enllaç lateral, mida del paquet, densitat del vehicle, freqüència de transmissió de paquets, mida de finestres de detecció, així com activació i desactivació de mecanismes de detecció, entre d'altres.

En aquesta tesi, es va dur a terme una revisió exhaustiva de les directrius estàndard per a les comunicacions V2X LTE i NR V2X, destacant especialment els modes de comunicació descentralitzats, com s'ha esmentat anteriorment. Posteriorment, es va dur a terme una campanya de simulació a nivell de sistema per configurar escenaris V2X segons les especificacions del Projecte d'Associació de Tercera Generació (3GPP). Els resultats obtinguts van mostrar que el rendiment del mode 4 en LTE és adequat per a serveis bàsics que no requereixen un alt rendiment, latències baixes o criteris estrictes de fiabilitat de la xarxa. En canvi, es va observar un rendiment millorat mitjançant el mode 2 NR V2X, permetent l'adaptació a V2X avançats. serveis. A més, s'ha demostrat que les numerologies altes contribueixen a un millor rendiment proporcionant una major diversitat de recursos, reduint la probabilitat que dos vehicles utilitzin els mateixos recursos per a les seves transmissions en mode descentralitzat. A més, es va trobar que a NR V2X una combinació adequada de numerologies, amplades de banda del canal i mida dels subcanals SL és crucial, depenent dels serveis V2X a implementar. Finalment, es va analitzar la incorporació de múltiples tecnologies de tecnologies d'accés a la ràdio (multi-RAT) per donar suport a serveis avançats i millorar la interoperabilitat mitjançant l'ús de tecnologies d'accés basades en LTE i NR, especialment en escenaris amb múltiples operadors de xarxa mòbil (MNO), diferents interfícies de connexió i modes de comunicació.

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strength and my constant guide, for showing me the way and giving me Your kind hand at every moment of my life.

Emanuel

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Acronyms

3GPP	Third Generation Partnership Project
4G	Fourth Generation
5GAA	5G Automation Association
2G	Second Generation
5G	Fifth Generation
6G	Sixth Generation
5GC	5G Core Network
5GS	5G System
AGC	Automatic Gain Control
AMF	Access and Mobility Management Function
AS	Application Server
AF	Application Function
AI	Artificial Intelligence
BTP	Basic Transport Protocol
BWP	Bandwidth Part
BSA	Back-Situation Awareness
BSM	Basic Safety Message
BM-SC	Broadcast Multicast Service Centre
CAM	Cooperative Awareness Message
CCH	Control Channel
CP	Communication Profile
CM	Cooperative Maneuvering
CCA	Cooperative Collision Avoidance

ACRONYMS

CDF	Cumulative Distribution Function
C-ITS	Cooperative Intelligent Transportation Systems (ITS)
CTS	Catera Touring Sedan
C-V2X	Cellular-based V2X
CSR	Candidate Single-Subframe Resource
CSI-RS	Channel state information reference signal
CBR	Channel Busy Ratio
CR	Channel occupancy Ratio
D2D	Device-to-Device
DC	Dual Connectivity
DSRC	Dedicated Short Range Communication
DMRS	Demodulation Reference Signal
DRX	Discontinuous Reception
DSS	Dynamic Spectrum Sharing
DENM	Decentralized Environmental Notification Message
eMBB	Enhanced Mobile Broadband
eNB	evolved Node B
EPS	Evolved Packet System
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved Universal Terrestrial Radio Access
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
eV2X	enhanced V2X
E2E	end-to-end
EN-DC	E-UTRAN NR Dual Connectivity
FCC	Federal Communications Commission
FR	Frequency Range
GN	GeoNetworking
gNB	Next Generation Node B
HARQ	Hybrid Automatic Repeat Request
HSS	Home Subscriber Server

IEEE	Institute of Electrical and Electronic Engineers
IMT	International Mobile Telecommunications
IMT-2020	International Mobile Telecommunications (IMT) 2020
IoT	Internet of Things
IP	Internet Protocol
ITU	International Telecommunication Union
ITS	Intelligent Transportation Systems
IE	Information Element
KPI	Key Performance Indicator
LDPC	Low Density Parity Check
LTE	Long Term Evolution
LOS	Line-of-Sight
NLOSv	vehicle Non-Line-of-Sight
MAC	Media Access Control
MCS	Modulation and Coding Scheme
MBMS	Multimedia Broadcast Multicast Service
MIMO	Multiple-Input Multiple-Output
mMTC	massive Machine Type Communications
mmWave	Millimeter Wave
MNO	Mobile Network Operator
MR-DC	Multi-RAT Dual Connectivity
multi-RAT	multiple RAT
MN	Master Node
MRM	Multi-RAT Manager
ML	Machine Learning
NF	Network Function
ng-eNB	next generation evolved Node B (eNB)
NR	New Radio
NSA	Non-Standalone
NG-RAN	Next Generation - Radio Access Network
NLOS	Non-Line-of-Sight

NE-DC	NR-E-UTRA Dual Connectivity
NGEN-DC	NG-RAN E-UTRA-NR Dual Connectivity
OBU	On Board Unit
OFDM	Orthogonal Frequency Division Multiplexing
PD	Packet Duplication
PDCP	Packet Data Convergence Protocol
PDR	Packet Delivery Ratio
PRR	Packet Reception Rate
PHY	Physical
PLMN	Public Land Mobile Network
PSCCH	Physical Sidelink Control Channel
PSSCH	Physical Sidelink Shared Channel
PSBCH	Physical Sidelink Broadcast Channel
PSFCH	Physical Sidelink Feedback Channel
pps	packets per second
PT-RS	Phase-tracking reference signal
PDB	Packet Delay Budget
PSD	Power Spectral Density
PIR	Packet Inter-Reception
ProSe	Proximity Services
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RB	Resource Block
RLC	Radio link control
RAT	Radio Access Technology
RMa	Rural Macro-cell
RSU	Road Site Unit
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indicator
RSRQ	Reference Signal Received Quality

RC	Reselection Counter
RE	Resource Element
RRI	Resource Reselection Interval
RRC	Radio Resource Control
SAE	System Architecture Evolution
SL	Sidelink
SCH	Service Channel
SCS	Sub-Carrier Spacing
SCI	SL Control Information
SPS	Semi-Persistent Scheduling
S-PSS	Sidelink-Primary Synchronization Signal
S-SSS	Sidelink-Secondary Synchronization Signal
SN	Secondary Node
SMF	Session Management Function
TB	Transport Block
TCP	Transmission Control Protocol
TDD	Time Division Duplexing
TR	Technical Report
TS	Technical Specification
TTI	Transmission Time Interval
UE	User Equipment
UDP	User Datagram Protocol
uRLLC	Ultra-Reliable and Low Latency Communications
V2X	Vehicle-to-everything
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2V	Vehicle-to-Vehicle
vpm	vehicles per meter

Notation

This section describes the notation used in this Thesis.

u represents the numerology used for 5G NR. The numerology is a combination of different spacing between subcarriers and cyclic prefix.

n represents the slot used as a reference for radio resource sensing and selection procedures.

T_0 represents the number of slots that, together with $T_{proc,0}$, define the size and duration of the sensing window.

$T_{proc,0}$ represents the number of slots expected to launch the sensing procedures.

T_1 defines the slot in which the selection window starts.

T_2 defines the slot at which the selection window ends.

Chapter 1

Introduction

The evolution of mobile networks, from Second Generation (2G) to Fifth Generation (5G) systems, has led to the development of new services and applications aligned with the standards established for each generation of telephony. The initial 2G systems offered basic voice and low-capacity data services. The arrival of third-generation telephony standards allowed for increased network capacity and the implementation of new broadband services. Currently, fourth and fifth-generation networks are predominant and offer a wide range of services, from basic voice services and applications to those with strict requirements for bandwidth, low latency, high reliability, and support for massive user connectivity.

In particular, Third Generation Partnership Project (3GPP) standards have played a key role in developing services based on vehicular communications. Starting with Release 14, services based on vehicular communications have been defined to improve safety, efficiency, and intelligence in mobility, facilitate interaction between vehicles, infrastructures, and the environment to optimize driving and traffic management, and reduce environmental pollution from using fossil fuels. These services rely on communications between vehicles, pedestrians, network infrastructures, and other elements of the environment, utilizing different connection interfaces and resource selection mechanisms —the standard refers to the different modes of connection between vehicles and other network elements as V2X communications.

In subsequent Releases, 3GPP has offered support for advanced Vehicle-to-everything (V2X) services, integrating improvements derived from the standardization process of cellular networks. Therefore, the research conducted in this Thesis focuses on analyzing the 3GPP standards defined for vehicular communications based on cellular networks to evaluate their performance under different usage scenarios and configuration parameters. The variation in parameters and procedures established in technical standards can be explained by the diversity of implementation contexts. These parameters can be customized based on specific criteria, such as the deployment environment — urban or highway—, as well as considerations related to latency, performance, energy consumption, coverage, and network reliability that need to be achieved. This Thesis assesses the standards established by 3GPP for Long Term Evolution (LTE) V2X and New Radio (NR) V2X to determine the most appropriate configuration parameters to optimize performance in terms of network coverage and reliability. Parameter adaptation is achieved by modifying subchannel sizes and numerologies, sensing and resource selection window durations, and activating or deactivating specific procedures as the standard prescribes.

This chapter provides the reader with the general context under which this Thesis has been developed. It outlines the problem and hypothesis, the objectives, the methodology, the scientific publications derived from this research, and a description of the subsequent chapters composing this document. To that end, this chapter has been divided into the following sections:

- Section 1.1 identifies the main problem that motivates this Thesis and defines the research hypothesis.
- Section 1.2 defines the research objectives of this Thesis.
- Section 1.3 presents the methods used to achieve the objectives and verify the hypotheses proposed in this research.
- Section 1.4 lists the publications related to this Thesis, including journals and conference papers.
- Section 1.5 outlines the structure of the Thesis, summarizing the main contents of each chapter.

1.1 Problem and Thesis Scope

The 3GPP standards establish reference parameters to evaluate the performance of Cellular-based V2X (C-V2X) vehicular communications in various scenarios and use cases. These parameters are outlined in different Releases. Therefore, it is crucial to validate the performance of these technologies, considering various Radio Access Technology (RAT), communication modes, transmission modes, and communication interfaces. Furthermore, it is imperative to analyze and determine the performance of V2X technologies, considering the sensing and resource selection mechanisms defined by the standards. This evaluation provides critical information about the most appropriate configuration parameters for V2X services that use various communication technologies, whether LTE or NR-based.

The problem presented has motivated the definition of several hypotheses:

- Hypothesis 1: the precise definition of optimal configuration parameters for various V2X services involves their characterization in terms of potential requirements, such as coverage range and network reliability.
- Hypothesis 2: decentralized communication modes, such as mode 4 in LTE V2X and mode 2 in NR V2X, are crucial in environments without cellular network coverage.
- Hypothesis 3: NR V2X mode 2 provides superior performance compared to LTE V2X mode 4.
- Hypothesis 4: resource selection mechanisms based on the activation of sensing procedures achieve better performance in terms of Packet Reception Rate (PRR) than random resource selection.
- Hypothesis 5: higher numerologies offer superior performance due to a greater diversity of resources in terms of time and frequency, which User Equipments (UEs) can reserve for their transmissions.

1.2 Thesis Objectives

The main focus of this thesis is to validate the performance of different C-V2X technologies, addressing different interfaces, communication modes, and Physical (PHY) and Media Access Control (MAC) layer parameters according to the specifications established by the standard. The main objective is to analyze the performance of the decentralized modes defined for LTE V2X and NR V2X.

Sub-objectives derived from the general objective are:

- To characterize the potential requirements of different use cases defined for C-V2X communications and their interoperation with different communication modes, transmission modes, and RAT.
- To study the sensing and resource selection mechanisms established by the standard for C-V2X communications, focusing on decentralized modes.
- To research open-source simulation tools that enable system-level simulations in V2X communications, adhering to the guidelines established by the 3GPP.

- To perform simulations to evaluate LTE V2X mode 4 performance in various scenarios and configurations according to the specifications detailed in the standard.

- To perform NR V2X mode 2 simulations with different PHY and MAC layer parameters.

1.3 Methodology

After identifying the problem and objectives of this research, it is essential to develop a methodology that validates the proposed hypotheses. To achieve this, a detailed review of the existing literature in the field of vehicular communications, focused explicitly on C-V2X, was conducted. This review involved examining scientific publications and academic documents to understand the current state of knowledge in the area and to identify research gaps for the proposed study. The findings are presented in Chapter 2, which focuses on the State of the Art.

Furthermore, a systematic review was conducted on the information provided by 3GPP regarding LTE V2X and NR V2X communications. This was achieved by examining reports and technical specifications corresponding to Releases 14, 15, 16 and 17. This approach facilitated the understanding of the standard's aspects governing the sensing, selection, and allocation mechanisms of radio resources. Although there are similarities in the procedures defined for LTE V2X and NR V2X, specific procedures and parameters were identified, primarily related to the inherent characteristics of the PHY and MAC layers standardized in 4G and 5G networks.

Following this, a simulation campaign was executed utilizing system simulators that comply with the standard guidelines for both LTE V2X and NR V2X. Upon configuring various simulation scenarios, results were obtained to validate the performance of the decentralized communication modes defined for C-V2X, across diverse configuration parameters. Metrics such as PRR, Packet Delivery Ratio (PDR), transmitter-receiver distance, and throughput were analyzed to assess the performance of the different C-V2X technologies.

1.4 Thesis Publications

The work developed during this Thesis made the following publications possible.

Journals

[J1] **E. E. González**, Y. Estrada, D. Garcia-Roger and J. F. Monserrat, ”Performance Evaluation and Optimal Management of Mode 2 V2X Communications in 5G Networks,” in IEEE Access, vol. 11, pp. 128810-128825, 2023, doi: 10.1109/ACCESS.2023.3333680.

[J2] **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 (MDPI), vol. 14, 2022.

[J3] D. Garcia-Roger, **E. E. González**, D. Martín-Sacristán and J. F. Monserrat, ”V2X Support in 3GPP Specifications: From 4G to 5G and Beyond,” in IEEE Access, vol. 8, pp. 190946-190963, 2020, doi: 10.1109/ACCESS.2020.3028621.

Conferences

[C1] **E.E. González**, F. Morales and E. Lozano, ”Simulation of vehicular communications scenarios using the NS3 Millicar module,” 2023 18th Iberian Conference on Information Systems and Technologies (CISTI), Aveiro, Portugal, 2023, pp. 1-6, doi: 10.23919/CISTI58278.2023.10211664.

[C2] D. Garcia-Roger, **E. E. González** and J. F. Monserrat, ”Regional Multi-RAT Dual Connectivity Management for Reliable 5G V2X Communications,” 2022 Joint European Conference on Networks and Communications & 6G Summit (EuCNC/6G Summit), Grenoble, France, 2022, pp. 320-325.

[C3] **E.E. González**, F. D. Morales, R. Coral, and R. M. Toasa, “Fifth-generation networks and vehicle-to-everything communications,” in Information Technology and Systems, A. Rocha, C. Ferrás, P. C. López-López, and T. Guarda, Eds. Cham: Springer International Publishing, 2021, pp. 350–360.

1.5 Thesis Outline

The rest of this Thesis is organized into 6 additional chapters as follows:

Chapter 2 provides a comprehensive review of the state of the art about the present research work. In this context, it details the characteristics of standards for intelligent transportation systems, particularly those based on 3GPP and Institute of Electrical and Electronic Engineers (IEEE) network specifications. Furthermore, a comparison between V2X standards is carried out, highlighting the adoption process by various vehicle manufacturers worldwide. This review is complemented by analyzing relevant scientific publications on V2X communications, examining the main findings obtained through simulations. Finally, the set of tools used for conducting simulations in both LTE V2X and NR V2X contexts is described.

Chapter 3 provides a detailed analysis of the support that 3GPP offers to C-V2X communications. It thoroughly examines the key specifications and technical documents of 3GPP related to use cases, communication modes, transmission modes, and communication interfaces established in Releases 14, 15, 16, and 17 of 3GPP. An exhaustive analysis is conducted on the potential requirements of bandwidth, latency, V2X packet size, V2X packet transmission rates, reliability, and coverage for C-V2X use cases. Additionally, detailed representations of V2X communication architectures are provided following standard specifications for both LTE and NR.

Chapter 4 addresses aspects related to the physical layer and radio resource allocation according to the standards defined for LTE V2X. In this regard, comprehensive details of the relevant parameters that need to be configured for radio resources' sensing, selection, and reservation procedures for V2X transmissions are provided. Following this, a detailed description of the simulation tool used to evaluate the performance of LTE V2X modes 3 and 4 is presented. Subsequently, the simulation scenario and the reference parameters used to obtain results related to the variation of the PDR as a distance function are outlined. The analysis of these results considers various vehicle density configurations, packet transmission frequencies, and transmission power levels.

Chapter 5 provides a detailed analysis of the sensing, selection, and radio resource reservation mechanisms for NR-based V2X transmissions. These procedures differ from those established for LTE V2X, necessitating the definition of new parameters to configure in formulating simulation scenarios. Next, the simulation tool used to evaluate the performance of NR V2X's decentralized mode is described. Subsequently, the reference parameters considered for the simulations are detailed according to the specifications established by the standard. Following this, the results obtained regarding the variation of the PRR are presented, taking into account different distances between vehicles, numerologies, activation and deactivation of resource sensing procedures, vehicle density, size of Sidelink (SL) subchannels, and dimensions of the sensing window. Additionally, the results of the evaluation of NR V2X in Millimeter Wave (mmWave) communication scenarios are presented. Thus, it can be demonstrated that allocating a greater bandwidth enhances the achieved throughput. However, a decrease in performance is observed in situations involving high speeds and greater distances between vehicles, attributable to the utilization of high frequencies.

Chapter 6 describes the integration of multiple RAT (multi-RAT) technologies as a solution to ensure interoperability of V2X services in the context of different RAT, Mobile Network Operators (MNOs), interfaces, and communication modes. It thus presents Multi-RAT Dual Connectivity (MR-DC) architectures and usage scenarios that can be adapted to C-V2X communications.

Chapter 7 presents the conclusions drawn from this thesis and outlines potential future lines of research related to the evaluation of the performance of C-V2X technologies.

Chapter 2

State of the Art

The formulation of the objectives and hypotheses of this Thesis is grounded in a thorough review of the state of the art concerning communication standards, along with the corresponding guidelines and communication modes established by such standards. According to the examined information, Vehicle-to-everything (V2X) communications can be deployed using two radio technologies that are largely incompatible with each other: Institute of Electrical and Electronic Engineers (IEEE) 802.11 and Third Generation Partnership Project (3GPP) Cellular-based V2X (C-V2X). On one hand, IEEE defines the 802.11p and 802.11bd standards as options for implementing V2X services based on the protocol stack established for the 802.11 standard. On the other hand, 3GPP specifies standards for V2X communications based on protocols and aspects of the Physical (PHY) and Media Access Control (MAC) layers defined for Long Term Evolution (LTE) and New Radio (NR) cellular networks, known as C-V2X. Both technologies have specific characteristics that enable the implementation of various services, and currently, their adoption by companies in the automotive sector exhibits heterogeneity. However, due to its foundation in cellular networks, greater interest is observed in C-V2X technology.

This chapter presents an analysis of the state of the art within the field of study of this Thesis. To that end, this chapter has been divided into the following sections:

- Section 2.1 examines the standards for vehicular communications as defined by both the 3GPP and the IEEE.

- Section 2.2 focuses on establishing comparisons and assessing the reception different standards have received in the market. In addition, related work focused on evaluating the performance of these standards in various scenarios is discussed.

- Section 2.3 describes the functionalities and characteristics of the simulation tools used in this research.
- Section 2.4 draws the main conclusions of the chapter.

2.1 Standards for Intelligent Transport Systems

Intelligent Transportation Systems (ITS) are a collection of technological solutions designed to improve transportation systems' safety, fluidity, and efficiency. These diverse ITS technologies are primarily based on exchanging information between various components, involving communication links between vehicles, infrastructure, user devices, and the network. As a result, standards are being developed under the IEEE 802.11 and 3GPP networks to support these ITS initiatives.

2.1.1 IEEE Standards for V2X

Dedicated Short Range Communication (DSRC) and Cooperative ITS (C-ITS) are vehicular communication technologies built upon the IEEE 802.11p standard. While sharing features, these standards have operational variations, particularly at the physical layer. It's essential to note that these technologies are incompatible and cannot interoperate.

DSRC enables direct communications between vehicles and infrastructure without requiring connections through the cellular network. In other words, DSRC is a wireless technology that allows for Vehicle-to-Vehicle (V2V) and vehicle-to-infrastructure Vehicle-to-Infrastructure (V2I) communications. DSRC enables direct communications between vehicles and infrastructure without requiring connections through the cellular network. To achieve this, DSRC transmits messages between vehicles within a specific coverage area, commonly known as V2V communication. Additionally, DSRC expands its support to V2I communications, allowing interactions with roadside infrastructures referred to as Road Site Units (RSUs). DSRC is primarily based on the IEEE 802.11p standard, with its impact primarily observed in the PHY and MAC components of the lower protocol stack layers. These lower layers are adapted from earlier versions of the well-recognized Wi-Fi standard, IEEE 802.11. This adjustment is significant because DSRC communication differs from traditional

Wi-Fi, requiring modifications to satisfy new provisions for increased mobility, stronger security, reliable information, and extended communication range, among other factors.

The physical layer of DSRC utilizes Orthogonal Frequency Division Multiplexing (OFDM), a technology similar to the early versions of the IEEE 802.11 standard. DSRC allocates a 10 MHz bandwidth, which includes 48 subcarriers for data and an additional 4 pilot subcarriers. The Federal Communications Commission (FCC) has classified V2V communication equipment as class C devices with a maximum allowed power output of 20 dBm and a reach of up to 400 meters [1]. In the United States, the FCC has exclusively assigned the 5.9 GHz band for DSRC service operation, which spans a frequency range from 5.850 GHz to 5.925 GHz, thus constituting a bandwidth of 75 MHz. This allocation includes a 5 MHz guard channel located at the lower boundary of the band, in addition to six 10 MHz channels reserved for service, identified as Service Channel (SCH), and one 10 MHz channel allocated to control functions, referred to as Control Channel (CCH). It is worth noting that for DSRC V2V services, a single channel —specifically Channel 172— is used exclusively [2]. According to standard terminology, the message transmission and reception units found in vehicles are known as On Board Units (OBUs). Therefore, periodic monitoring of the control channel is necessary to detect any transmitted messages or check the availability of the service channel.

C-ITS frameworks have undergone standardization to enhance communication within the realm of transportation, encompassing interactions between vehicles, individuals, and infrastructure. Consequently, C-ITS has been subjected to comprehensive evaluation and received the endorsement of the European Parliament [1]. C-ITS systems, akin to their American DSRC counterparts, find their foundation in the IEEE 802.11 standard. In the protocol stack, the IEEE 802.11p standard corresponds to the PHY and MAC layers of this architecture and is known as ITS-G5.

Within the 5.9 GHz band, ITS-G5 is divided into four distinct sub-bands designated as ITS-G5A, ITS-G5B, ITS-G5C, and ITS-G5D in the standard. The European Telecommunications Standards Institute (ETSI) designates three of these sub-bands for ITS applications, specifically ITS-G5A, ITS-G5B, and ITS-G5D [3]. The ITS-G5A sub-band is characterized by three 10 MHz channels: SCH1, SCH2, and CCH. Here, SCH stands for Service Channels, and CCH refers to the Control Channel. For ITS-G5B and ITS-G5D, each encompasses two 10 MHz channels: SCH4 and SCH3 for ITS-G5B, and SCH5 and SCH6 for ITS-G5D. Notably, a comparison of channel allocation between ITS-G5 and DSRC reveals that the frequency range of the service channel SCH4 of ITS-G5B coincides with that of service channel 172 of DSRC, specifically falling within the range of 5855 to 5865 MHz [3].

In the realm of Cooperative C-ITS, which is similar to DSRC, the architecture easily supports the use of Transmission Control Protocol (TCP)/User Datagram Protocol (UDP) protocols for network and transport layers. However, C-ITS differentiates itself from DSRC by including support for two additional protocols in the network and transport layers: Basic Transport Protocol (BTP) and GeoNetworking (GN). The BTP protocol is a precisely tailored framework designed for end-to-end connections and establishing ad hoc networks within the ITS domain [4]. On the other hand, the GN protocol has a network layer protocol dedicated to managing packet routing in ad hoc networks. Notably, this protocol facilitates communication among ITS stations and oversees the dissemination of packets across defined geographic regions.

To enhance the performance of vehicular communication systems based on the IEEE 802.11p standard, the “IEEE Task Group 802.11bd” was established in March 2019 with the primary goal to develop the IEEE 802.11bd standard[5]. The expected requirements for the upcoming IEEE 802.11bd technology involve a two-fold improvement in performance at the MAC layer compared to 802.11p. This extension aims to support relative speeds of up to 500 km/h and double the communication range of 802.11p.

Interoperability between the 802.11bd technology and its predecessor demands significant modifications at the PHY and MAC layers, at least in a specific communication mode. Therefore, IEEE 802.11bd employs several techniques to guarantee seamless interoperability, including:

- Utilization of “Midambles”: Distinguished from conventional preamble signals, the introduction of “midambles” interlaces these signals amidst OFDM symbols transmitting data. This novel approach enhances the estimation of highly dynamic channel characteristics over time.

- Packet Retransmission Mechanisms: A mechanism has been devised to facilitate packets’ retransmission, thereby augmenting communication channels’ robustness and reliability.

- Introduction of Numerologies: The introduction of numerologies, denoting distinct sub-carrier spacing configurations, significantly enhances the efficiency of OFDM subcarrier utilization. This strategy concurrently increases the effective symbol duration concerning the comprehensive symbol duration, encompassing the cyclic prefix.

- Adoption of Low Density Parity Check (LDPC) Codes and Multiple-Input Multiple-Output (MIMO) Systems: The IEEE 802.11bd standard incorporates the utilization of LDPC codes and MIMO systems. These technological inclusions serve the dual purpose of elevating transmission reliability via spatial diversity and amplifying transmission rates through spatial multiplexing.

- Operation within Millimeter Wave (mmWave) Spectrum: IEEE 802.11bd extends its operation to encompass mmWave frequencies, specifically those exceeding the 60 GHz threshold. Although these higher frequencies offer abundant available spectrum, their utilization introduces unique challenges primarily associated with reduced coverage distances.

These significant upgrades, when combined, significantly improve the performance and adaptability of the IEEE 802.11bd standard, influencing the future of vehicular communication.

2.1.2 3GPP Standards for V2X

The 3GPP standards for V2X communications are those outlined in Release 14 and are detailed in Chapters 3 and 4. These standards have evolved to accommodate new features and meet the potential needs of V2X's emerging use cases and enhanced services. As previously stated, the centralized mode is supported for both LTE V2X and NR V2X services in the cellular network coverage areas. Additionally, the decentralized mode configuration supports scenarios where evolved Node B (eNB)/Next Generation Node B (gNB) coverage is not required, but vehicles autonomously manage radio resource sensing and selection.

2.2 Comparison and Reception of V2X Standards

Both LTE V2X and NR V2X offer improved performance in terms of lower communication latency, increased coverage ranges, and new connectivity modes, such as Vehicle-to-Network (V2N) communications. Furthermore, the latest features and Key Performance Indicators (KPIs) of 3GPP networks have given rise to new use cases that would be unlikely to be developed using IEEE 802.11p technologies. A comparison of the IEEE 802.11p standard —DSRC— and LTE C-V2X, in various scenarios, is available in [6]. The study findings indicate that mode 3 LTE V2X has the highest communication range —in meters— followed by mode 4 LTE V2X, with IEEE 802.11p having the lowest range. The reduced performance of mode 4, in contrast to mode 3, is due to the decentralized allocation of resources in mode 4 instead of centrally allocated resources in mode 3. Therefore, when many users require access to the V2X service, interference levels are higher in mode 4.

Concerning NR V2X technology, it is poised to serve as a complementary facet to LTE V2X. This addition engenders the potential for substantial enhancements in the capacity and performance of V2X services. These advancements are rooted in the assimilation of various new technologies and features.

Among the notable inclusions are:

- Scalable OFDM Numerologies: Incorporating scalable OFDM numerologies is set to optimize the system's adaptability to diverse scenarios and channel conditions.
- Augmented Bandwidth: Enabling access to a broader bandwidth increases transmission rates, substantially elevating the data throughput.
- Advanced Channel Coding Techniques, LDPC/Polar: The introduction of advanced channel coding techniques, such as LDPC and polar codes, bolsters error correction capabilities, pivotal for reliable and error-resistant data transmission.
- Low-Latency Slot Structures: Implementing slot structures engineered for low-latency communications is a paramount feature. This configuration substantially reduces communication latency, particularly in time-sensitive applications.
- Integration of Massive MIMO: The inclusion of MIMO technology promises notable improvements in spatial diversity and the potential for achieving higher data rates through spatial multiplexing.

Regarding these improvements, a comparative evaluation presented in [7] underscores that V2X 3GPP technologies consistently outperform IEEE 802.11bd systems across various performance metrics. Notable advantages include reduced latencies, enhanced transmission rates, and extended coverage ranges.

The global landscape of V2X standards exhibits a nuanced tapestry of adoption. It reveals an intricate web of choices made by different regions and countries, and certain manufacturers even incorporate multiple standards into their vehicle models. Notably, the 3GPP V2X standards command a substantial and growing global interest, outpacing their IEEE counterparts. These preferences can be attributed to two primary factors. First, IEEE 802.11p-based standards face the challenge of large-scale implementation due to their incompatibility with counterparts developed in different regions. As a result, some automakers have embraced the American standard —DSRC— while others favor the European standard —C-ITS. This divergence has created fragmentation and hindered broader adoption.

By contrast, the ascendancy of 3GPP V2X technologies stems from several factors. Their co-evolution with LTE and NR standards is a notable benefit. This enables economical implementation by capitalizing on pre-existing infrastructures for mobile telecommunications, thus realizing economies of scale. Additionally, the formation of the 5G Automation Association (5GAA) [8] in 2016 vastly accelerated the drive towards 3GPP-based V2X standards. This prominent organization, which includes more than 115 prominent companies from the technology, automotive, and telecommunications sectors, is dedicated to advancing and standardizing C-V2X technologies. Notably, prominent industry leaders, including AUDI, BMW, Nokia, and Qualcomm, actively participate in the association's initiatives, solidifying the significance of V2X technologies based on 3GPP.

Integrating different V2X communication technologies in the automotive industry displays a notable level of heterogeneity. In 2019, prominent automakers such as Toyota and General Motors have selectively integrated IEEE 802.11p technology into certain vehicle models. In contrast, Geely and Ford have already implemented C-V2X technology in some of their vehicles. Certain automakers have begun integrating hybrid technology, implementing diverse V2X communication technologies across their vehicle models. A relevant example is General Motors, which has adopted IEEE 802.11p technology for its Cadillac Catera Touring Sedan (CTS) model while pursuing collaborative initiatives with business partners to introduce C-V2X technology in the Chinese market. This complex integration of technologies illuminates the intricate terrain of V2X communication technology implementation within the automotive sector.

C-V2X standards have gained significant momentum, penetrating various regions globally and being utilized across numerous industries. The journey towards widespread adoption has covered a wide range of progress, from standard formalization to independent field testing and initial deployments. Geographically, C-V2X implementations have appeared in North America, Europe, China, Korea, Japan, and Australia. Qualcomm is a leading player in the technology evolution and is regarded as the world's primary manufacturer of C-V2X chipsets. The pioneering chipset, introduced by Qualcomm in 2017, played a crucial role in evaluating V2X standards in recent releases [9]. Additionally, significant progress has been made in realizing the potential of hybrid networks. Autotalks, a prominent player in the V2X communications device sector, providing for both on-board and roadside units, has released a revolutionary product: the first ever Dual-Mode V2X chipset. This innovative chipset smoothly incorporates both DSRC and C-V2X technologies, allowing for easy switching between the two modes [10].

Based on market research reports, the forecasts indicate a positive outlook for the worldwide adoption of V2X standards. The emergence of V2X is projected to grow substantially, with the market expected to exceed 37.48 billion by 2030 [11]. This growth trend of V2X standards suggests a promising future for the technology. It is a transition period in the telecommunications industry as LTE is expected to start its gradual decline, leading to a downward trend that will end at the end of 2025. This shift reflects the increase of Fifth Generation (5G), estimated to cover up to 65% of the global population and control 45% of the world's mobile data traffic in the same year [12]. The aforementioned seismic shifts in telecommunications are set to trigger substantial growth in the global automotive V2X industry. By 2028, this sector is expected to reach the impressive milestone of becoming a 12 billion market, as projected by Markets and Markets [13].

Several studies have been conducted on the assessment of vehicular communication standards. These studies analyze technologies based on the 802.11 and 3GPP standards. During the literature review, there is great interest in using Dual Connectivity (DC) technologies to meet the requirements of new applications and services. In response, an evaluation of DC performance within LTE networks, incorporating mmWave schemes, was carried out in [14]. The simulations conducted in this article show that DC enhances throughput and significantly decreases end-to-end delay. Additionally, [15] evaluates DC architectures in the context of both LTE and 5G nodes. Thus, the simulation includes an LTE base station as the primary node and a 5G base station as the secondary node, which is also referred to as 5G Non-Standalone (NSA) networks. The simulation results show that DC transmissions significantly increase the power consumption of the devices compared to the differences in transmission in a single connection. In addition, this study introduces a novel radio resource allocation system that minimizes communication latency. Low network latency is a crucial requirement in vehicular communication systems due to the need to process significant amounts of information, which could be transmitted to an edge cloud or in critical applications.

In the research conducted by [16], a new approach is proposed to meet the requirements of the 5G networks concerning the Ultra-Reliable and Low Latency Communications (uRLLC) usage scenario. This technique is a high-layer solution known as Packet Duplication (PD), which optimizes the utilization of radio resources when combined with DC architectures. Thus, in scenarios that require high network reliability, low latency, and support for highly mobile users, implementing PD in a DC architecture enhances communication robustness. This enables reliable transmission of packets with minimal delays.

Other proposals demonstrating promising results for vehicular communications involve using multiple Radio Access Technology (RAT). In [17], an evaluation of the use of multi-RAT architectures for V2X communications is being carried out. In this case, V2X packets are transmitted to the network using the LTE Uu interfaces, while direct links are established using the PC5 interface, bypassing the cellular network. Additionally, to meet the reliability needs of certain services, a multi-RAT system is suggested whereby data packets are redundantly sent via both the PC5 and LTE Uu interfaces. The performance of the various technologies depends on the particular scenario in which they are utilized, as indicated by the findings. Furthermore, the proposed multi-RAT system substantially enhances Quality of Service (QoS). In the study conducted by [18] an evaluation of multi-RAT schemes in vehicular communication is carried out. Consider LTE V2X and 802.11p networks in this case. The results demonstrate that employing only the 802.11p network yields satisfactory network performance in terms of latency. The communication's throughput and Packet Delivery Ratio (PDR) are compromised. On the other hand, simulating a multi-RAT architecture —802.11p and LTE— results in increased latency but significantly improved throughput and PDR. Different connection modes can be utilized depending on the usage scenario as the requirements for services and use cases in vehicular communications differ. According to [19], implementing multi-RAT technologies can enhance vehicular communication reliability for cooperative automated control purposes. The research reveals that 802.11p and LTE technologies demonstrate promising potential. They extend transmission ranges thanks to their increased resilience against channel congestion. Thus, good results were obtained in high-density V2X service conditions with strict network reliability requirements.

The initial specifications for V2X were based on LTE networks, which are unreliable or flexible enough to meet the latency, throughput, and reliability demands of new vehicular communication services, particularly those regarding automated driving. For example, [20] shows that the existing C-V2X systems, which rely on LTE networks, are inadequate to meet the quality of service requirements associated with the information exchange of vehicle platoons. Therefore, multiple RAT are combined in parallel to meet various requirements. [21] introduces the term Communication Profile (CP), which is defined as the combination of a specific RAT and a communication mode. The paper proposes two primary types of CPs based on data flow: cellular and direct. The cellular profile pertains to links where information flow must occur through the cellular network via a base station. In contrast, data packets are transmitted directly between vehicles in the direct profile. Moreover, the direct Cellular Profile can be carried out with or without assistance from the cellular network. In assisted mode, the network controls the allocation of radio resources, unlike unassisted mode, where resources are assigned through a MAC layer protocol. In all scenarios, adding several profiles to enhance transmission rates or incorporate redundancy into communication channels is possible, thereby improving their reliability.

In the realm of vehicular communications, several generic documents and overviews relating to the integration of 5G technology have been published. Preliminary research indicates that, to begin with, 5G NR should function as an NSA network alongside LTE. As stated in [22], it is crucial to define the physical layer Sidelink (SL) procedures, protocol structure, and synchronization mechanisms using both Uu and PC5 interfaces. In the study conducted by [23, 24], the PC5 interface was used to evaluate the decentralized transmission mode, where the User Equipments (UEs) manage radio resource allocation unlike in the centralized mode. This mode is crucial in 5G NR networks, enabling connections in areas without base station coverage. Testing these mechanisms for both LTE and NR networks is important. The benefits of integrating V2X communication services on 5G networks —5G V2X— are explored in [21]. Unlike LTE networks with fixed Transmission Time Intervals (TTIs) of 1 ms, scalable TTIs can be achieved on 5G V2X through numerologies, resulting in expected TTIs below 1 ms —500 us. This reduces the latency caused by the air interface in essential vehicle communications. Similarly, [25] studies the impact of the numerologies defined for 5G NR to meet the requirements of the new V2X services. The results show significant improvements in both message delay and transmission by utilizing lower TTIs and higher Sub-Carrier Spacing (SCS) compared to LTE-based solutions.

2.3 Simulation Tools

To simulate and assess the performance of C-V2X vehicular communication standards, there exist various open-source and non-open-source tools based on C++. However, some of these simulators have limitations as they are not open-source and can only simulate at the link level instead of the system level. The main features of the simulators used in this research to analyze the performance of both LTE V2X and NR V2X are described below.

2.3.1 OpenCV2X

This open-source tool complies with the 3GPP C-V2X —Release 14— mode 4 standard. It is based on an expanded edition of the SimuLTE OMNeT++ simulator, simplifying LTE network simulations [26]. This implementation is available in two distinct variants. The first variant integrates with the Artery framework, delivering comprehensive ITS-G5 standardization across the entire communication stack. Conversely, the second variant interfaces exclusively with Veins. Details on the model implementation and its validation are available at [27].

The OpenCV2X architecture models the entire stack of layers, ranging from the physical to the application layers. The utilization of the Artery or Veins frameworks can be defined in the higher layers. Consequently, Veins can operate jointly with the road traffic simulator SUMO. In the lower layers, OpenCV2X modifies the already established models in the simuLTE simulator, thereby enabling the simulation of C-V2X communications. Specifically, changes are implemented at the PHY and MAC layer levels from the previously established Device-to-Device (D2D) communication classes to meet the 3GPP standards for LTE V2X specifications. At the PHY layer level, integration of the WINNER+ B1 channel, as stipulated by 3GPP for V2X communication, is a salient feature. Furthermore, the SL communication capability is established. At the MAC layer level, crucial operational procedures such as scheduling, sensing, and resource selection are meticulously enabled, ensuring adherence to the standards delineated in the 3GPP framework.

Additionally, the simulator underwent validation through analytical models proposed by [28], confirming the obtained results' accuracy.

In this Thesis, simulations of LTE V2X mode 4 were conducted using openCV2X. The simulation parameters were configured according to the standard specifications. The simulations employed various parameters following the standard, including vehicle density, speed, packet transmission frequency, and power. A highway scenario was used to examine the performance of this mode under different conditions.

2.3.2 Millicar

This tool, designed for use in the ns-3 simulation framework, provides a reliable platform for emulating mmWave V2V networks [29]. A comprehensive explanation of the module's features and functions is available in a dedicated document on [30]. Notably, this module integrates the latest 3GPP Channel Model and offers several key attributes. The software offers assistance for the advanced 3GPP channel model, specially created for V2X networks that function above the 6 GHz frequency spectrum. The PHY and MAC classes are custom-built to meet 3GPP framework requirements and are designed to match the NR frame structure as stated in 3GPP standards. The software also provides full-stack simulation capabilities. The system stands out for its capacity to coordinate full-stack operations, incorporating functions from the Radio link control (RLC) and Packet Data Convergence Protocol (PDCP) layers. This all-inclusive strategy is enabled by the seamless integration with the LTE module within the ns-3 environment.

Millicar has updated its PHY and MAC layers to align with the standard guidelines for vehicular communications. The PHY layer includes modules for

SL management, error modeling, interference, NR frame structure, and beam alignment. The modules at the MAC layer include medium access management, resource allocation, and link adaptation. Next, connections are established with upper layers, allowing the reuse of available modules in ns-3.

As part of this Thesis, the Millicar tool was used to evaluate the performance characteristics of mode 2 in the challenging context of mmWave communications. Consequently, various scenarios were configured to examine the performance metrics of both throughput and Packet Reception Rate (PRR).

2.3.3 5G LENA V2X

In this research, the tool used to perform NR V2X simulations is an extension of the NR 5G-LENA open source network simulator [31]. 5G-LENA is an advanced network simulation tool created to emulate NR technology. Its significant advantage is the GPLv2 licensing and seamless integration as a pluggable module within the ns-3 framework. As a natural progression, it also takes over from its predecessor, the LTE/Evolved Packet Core (EPC) Network Simulator, LENA. The development of 5G-LENA began by integrating the mmWave module and then expanding to include crucial PHY and MAC functionalities that align with NR Release 15's specifications.

The integration of NR V2X capabilities required adjustments across all layers of the protocol stack, including PHY, MAC, and higher layers. A significant change was the addition of SL functionality, allowing for direct vehicle-to-vehicle communication. This is a crucial adaptation for NR V2X communications, distinguishing it from conventional cellular communications in the 5G LENA simulator. Concretely, the introduced modifications encompass the capacity to establish NR V2X communications in mode 2 strictly adhering to the parameters delineated within the standard. This encompasses the flexibility to employ various numerologies, advanced modulation schemes, and broadcast transmission methods. A comprehensive description of this field can be found in [32].

This Thesis uses this extension to perform comprehensive simulations of NR V2X mode 2. These simulations involved various scenarios, such as numerology variations, bandwidth adjustments, SL channel dimensions, resource sensing activation, and deactivation, and other parameters stipulated in the standard.

2.4 Conclusions

This chapter has presented the state of the art relevant to the research topic addressed in this Thesis. It has provided information on the standards for

V2X communications and the simulation tools that evaluate their performance. Services based on vehicular communications —V2X— have been developed to improve road safety and reduce fossil fuel consumption. These services can be provided through communications based on IEEE and 3GPP standards. There is a growing interest in V2X services based on 3GPP networks. This is because they are based on the evolution and improvements developed mainly at the PHY and MAC layers, corresponding to LTE and NR networks. One of the advantages of V2X communications based on the cellular network, known as C-V2X, is the potential to establish communication with other vehicles, pedestrians, or infrastructure. Additionally, the connection to the cellular network itself is a benefit. Consequently, the mobile network can facilitate managing and allocating radio resources for V2X communications. Nevertheless, in the absence of cellular network coverage in all locations, an autonomous mode has been defined in which V2X UEs are capable of independently managing the sensing and resource selection processes through the application of the mechanisms established in the standard. Given that the standardization process for V2X services commenced with Release 14, which utilized LTE networks, these services can be considered fundamental in that they do not require the fulfillment of rigorous potential requirements from the network. However, as the new standards for 5G NR have been developed, the V2X services that can be offered are more advanced and have more stringent requirements in terms of bandwidth, latency, reliability, coverage, and other factors. The information presented in this chapter provides a rationale for evaluating the performance of C-V2X standards in the context of different procedures, parameters, and mechanisms defined for V2X communications.

This Thesis focuses mainly on the assessment of the C-V2X standards for decentralized modes, designated as mode 4 in LTE V2X and mode 2 in NR V2X. In order to achieve this objective, simulation tools that comply with the standard specifications have been selected to perform system-level simulations in various scenarios.

Chapter 3

V2X Support in 3GPP Specifications

Given that the present research work focuses specifically on the evaluation of the performance of Cellular-based Vehicle-to-everything (V2X) (C-V2X) standards, this chapter delineates the characteristics established by the Third Generation Partnership Project (3GPP) for both Long Term Evolution (LTE) V2X and New Radio (NR) V2X. Thus, the information presented herein is predicated upon a review of specifications and technical reports released by the 3GPP across various Releases. It should be noted that the initial C-V2X standards were based on Releases 12 and 13 of the 3GPP, wherein communication modes for services termed Proximity Services (ProSe) were already defined. From these specifications, standards for LTE V2X were delineated, followed subsequently by NR V2X, wherein specific use cases, potential requirements, communication interfaces, communication modes, and transmission modes are specified. Consequently, this chapter describes the aspects established in Releases 14, 15, 16, and 17, which are pertinent to LTE V2X and NR V2X, serving as a reference for the simulations whose results are presented in subsequent chapters. The chapter is structured as follows:

- Section 3.1 provides an overview of the standards defined for C-V2X communications, which are contained in 3GPP Releases 14, 15, 16, and 17.

- Section 3.2 describes the use cases defined by 3GPP for C-V2X. In addition, it details potential requirements for different LTE V2X and NR V2X-based services.

- Section 3.3 examines and analyzes the transmission and communication modes defined for C-V2X communications. Consequently, V2X architectures based on LTE V2X and NR V2X are represented by the respective connection interfaces and transmission modes.
- Section 3.4 draws the main conclusions of the chapter.

3.1 Overview of 3GPP V2X Standards

For 3GPP, V2X is a comprehensive concept that includes numerous enhancements, such as improvements in radio access, protocols, and the core network, to facilitate vehicular communications. This includes:

- Vehicle-to-Vehicle (V2V) communication, which occurs directly between User Equipments (UEs) in vehicles;
- Vehicle-to-Pedestrian (V2P) communication, which involves communication between a vehicle and the UE of a pedestrian;
- Vehicle-to-Infrastructure (V2I) communication connects a vehicle with fixed road infrastructure, such as a Road Site Unit (RSU), providing connectivity for V2X applications with other UEs;
- Vehicle-to-Network (V2N) communication involves wide area communication over the cellular network between vehicles and various cellular network entities, supporting V2X traffic operations.

In the context of 3GPP standards, Release 14 [33] was a crucial milestone, as it introduced enhancements for Fourth Generation (4G) technology in V2X communications. The focus of Release 14 was to improve support for V2V communication within the Evolved Packet System (EPS). The EPS constitutes the 3GPP's 4G innovation that merges LTE —a radio communication interface that endows high-speed and low-latency mobile broadband— with the System Architecture Evolution (SAE). SAE is an architecture based on Internet Protocol (IP) data services that is non-hierarchical and designed to dissociate control and user plane traffic. Evolved Packet Core (EPC) is the central element of SAE. This focused endeavor aims to address the use cases of the automotive industry, rendering it a vital and prioritized matter within the 3GPP standards.

Release 15 [34] marks the start of standardization for Fifth Generation (5G), illustrating the first phase —5G Phase 1— of the 5G System (5GS) and delineating its architecture and capabilities. Release 15 operationalizes the service-based approach for the 5G Core Network (5GC), subsequently providing for data connection across NR and LTE access technologies, and traits to enhance mobility, Quality of Service (QoS), traffic management, and network slicing from an architectural standpoint.

Release 16 [35], which was developed by 3GPP as the second phase of their 5G project, represents a significant expansion of 5G specifications. From March 2017 to June 2020, this phase encompasses two important dimensions. Firstly, it involves further refinement of the 5G architecture. Secondly, it introduces support for new specialized service functionalities with a particular emphasis on selected use cases deemed crucial for industry verticals, including V2X. Release 16 outlines the 5G's role in facilitating advanced V2X services and providing support for vehicle QoS. Additionally, it addresses the coexistence of NR and LTE Sidelink (SL) communication. Notably, through the Uu interface, a Next Generation Node B (gNB) can manage and oversee the LTE SL. Furthermore, LTE can configure the NR SL, as described in Technical Specification (TS) 23.287 [36]. This enables the concurrent utilization of multiple 3GPP Radio Access Technology (RAT), facilitating direct SL transmissions, both NR-based and Evolved Universal Terrestrial Radio Access (E-UTRA) based.

Release 17 [37] focuses primarily on enhancing the specifications established in Release 16. These enhancements are designed to encompass features applicable to the three usage scenarios outlined in the International Mobile Telecommunications (IMT) 2020 (IMT-2020) project [38], namely Enhanced Mobile Broadband (eMBB), Ultra-Reliable and Low Latency Communications (uRLLC), and massive Machine Type Communications (mMTC). Concerning V2X communications, Release 17 introduces enhancements in the domains of SL, NR Positioning, and NR Broadcast/Multicast. In the context of V2X, Release 17 explores advanced developments in SL communications, aiming to implement V2X in public safety applications and accommodate new requirements and use cases. Additionally, it considers the potential utilization of SL communications in commercial applications. In this regard, investigating the effectiveness of SL-based relaying becomes crucial to expanding device coverage and enhancing power efficiency. These improvements enable the deployment of SL communications in areas lacking coverage through a multi-hop approach. Consequently, the assessment of SL-based relaying technologies, standardized in Release 16, is being evaluated for potential incorporation into NR architectures. Furthermore, Release 17 addresses other significant requirements to optimize network reliability and reduce latency, particularly in the context of new scenarios relevant to uRLLC.

Tables 3.1 and 3.2 offer a complete collection of the newest TS and TR generated by each release of 3GPP, with a concentrated emphasis on V2X communications.

Table 3.1: Versions of 3GPP Technical Specifications on V2X.

Ref.	*Tech.*	*Topic*
TS 22.185	LTE	Requirements for V2X services
TS 22.186	5G	Requirements for eV2X scenarios
TS 23.285	3G, LTE	Architecture enhancements for V2X services
TS 23.286	LTE	Application layer architecture support for V2X services
TS 23.287	5G	5GS support for V2X services
TS 24.385	LTE	Management objects for V2X services
TS 24.386	LTE	UE to V2X control function protocol
TS 24.486	LTE, 5G	VAE layer protocol
TS 24.587	5G	V2X services in 5GS
TS 24.588	5G	V2X services in 5GS; UE policies
TS 29.388	LTE	V2X Control Function to HSS Server (V4)
TS 29.389	LTE	Inter-V2X Control Function signalling aspects (V6)
TS 29.486	LTE, 5G	VAE service
TS 33.185	LTE, 5G	Security aspect for LTE support of V2X services
TS 33.536	LTE, 5G	Security aspects of 3GPP support for advanced V2X services

3.2 C-V2X Use Cases

Vehicular communications encompass a range of services and use cases, each with unique requirements. Enhancing these services involves considering the evolution of mobile communication systems. It is noteworthy that not all services share identical potential demands. For instance, certain services rely on minimal latency for efficient operation, while others prioritize high network reliability, particularly low packet loss. Some services require the network to meet stringent latency, reliability, and bandwidth criteria. Consequently, there exists a direct correlation between the diverse service requirements and the Key Performance Indicators (KPIs) provided by the network. Incorporating relevant KPIs is instrumental in ensuring that the network delivers optimal service quality tailored to the specific needs of each service. The International Telecommunication Union (ITU) has delineated mobile network performance indicators for three usage scenarios, namely eMBB, uRLLC, and mMTC, as part of the IMT-2020 project [38].

In the field of Intelligent Transportation Systems (ITS), services are categorized into what are commonly referred to as Day 1, Day 2, and Day 3 services, as outlined by CAR2CAR [39]. Day 1 services encompass fundamental functionalities associated with Awareness Driving. Within this category, the V2X service facilitates the exchange of critical information on vehicle position, speed, driving direction, and similar parameters. Moving to Day 2 services, these are labeled Sensing Driving, where vehicles utilize sensors to gather environmental

Table 3.2: Versions of 3GPP Technical Reports on V2X

Ref.	*Tech.*	*Topic*
TR 22.885	LTE	LTE support for V2X services
TR 22.886	5G	3GPP support for 5G V2X services
TR 23.764	LTE, 5G	Application layer support for V2X services
TR 23.776	LTE, 5G	3GPP support of advanced V2X services
TR 23.785	3G, LTE	LTE support for V2X services
TR 23.786	LTE, 5G	EPS and 5GS support for advanced V2X services
TR 23.795	APP	Application layer support for V2X services
TR 26.985	5G	V2X; Media handling and interaction
TR 33.836	5G	Security in 3GPP support for advanced V2X services
TR 33.885	LTE	Security in 3GPP support for V2X services
TR 36.785	LTE	V2V services based on LTE SL; UE radio Tx/Rx
TR 36.786	LTE	V2X services based on LTE; UE radio Tx/Rx
TR 36.787	LTE	V2X new band combinations
TR 36.788	LTE	V2X UE radio Tx/Rx
TR 36.885	LTE	LTE-based V2X services
TR 37.885	LTE, 5G	Evaluating new V2X use cases for LTE and NR
TR 37.985	LTE, 5G	RAN aspects for V2X based on LTE and NR
TR 38.885	5G	Study on NR Vehicle-to-Everything (V2X)
TR 38.886	LTE, 5G	V2X Services based on NR

data and subsequently share this information with other vehicles. This sharing mechanism alerts other vehicles about potential hazards, such as situations involving vulnerable road users or navigating intersections. Day 3 services, on the other hand, refer to Cooperative Driving scenarios. These advanced services involve the exchange of information regarding planned maneuvers and trajectories. This type of communication enables road users to engage in intelligent interactions, even in complex traffic situations. It is crucial to note that Day 3 services require a high level of network performance in terms of low latency and dependable network reliability to operate effectively.

Release 14 outlines the main application areas that are initially expected to derive benefits from LTE V2X, as specified in TS 22.185 [40] (Figure 3.1, highlighted in wheat):

- Enhancing Road Safety by reducing traffic accidents is the network's primary goal, which follows strict reliability and latency requirements. Road safety services in LTE V2X leverage shorter messages that vehicles periodically broadcast to nearby vehicles in a specific local geographical region.

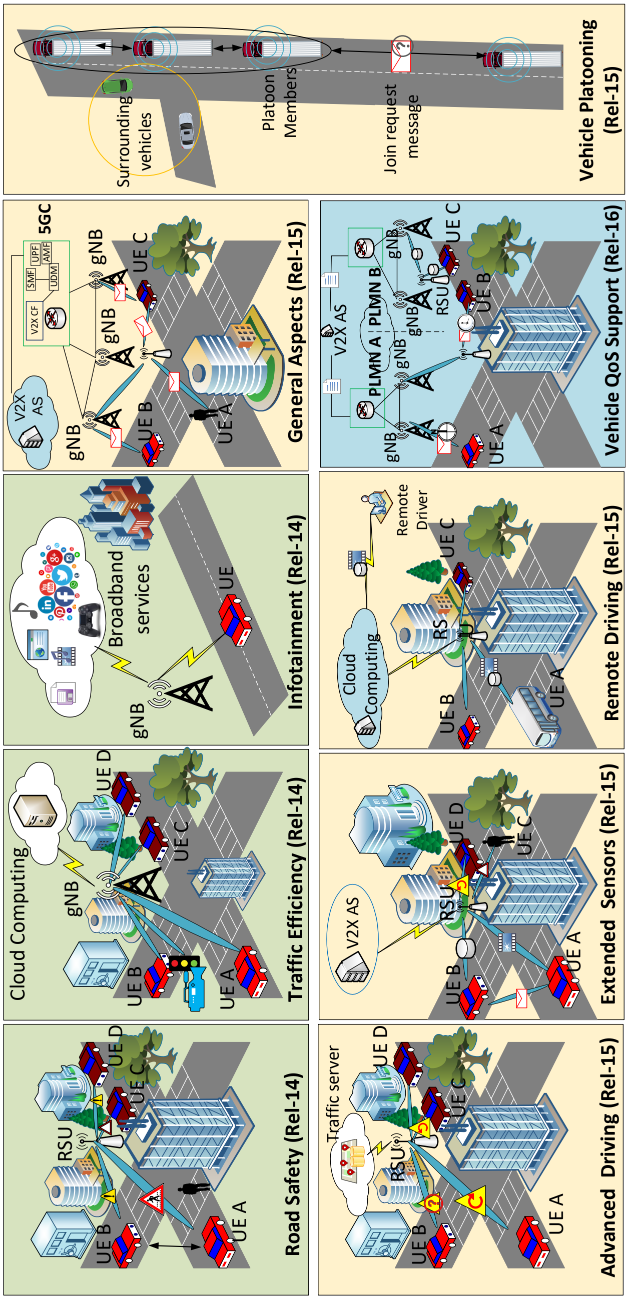

Figure 3.1: Summary of V2X service categories targeted by 3GPP Rel-14, Rel-15, and Rel-16 specifications.

- Traffic Efficiency, which pertains to the enhancement of route planning, exemplified by applications like vehicle platooning, achieved through alleviating traffic congestion. This approach presupposes that vehicles gather sensor-generated data and relay it to remote management servers responsible for devising optimal routes. In the network context, a relaxation of the stringency associated with reliability and latency requirements exists. Nevertheless, it remains imperative to manage and mitigate both packet loss and delay effectively under high-speed conditions.

- Infotainment, a category encompassing both traditional and emerging Internet services designed to enhance the overall travel experience of passengers —including conventional web browsing, data sharing, downloading, and social networking— is notably the most adaptable concerning network limitations.

In the context of Release 14 V2X communication, also known as LTE-V2X, fundamental safety services are addressed from a data transport perspective. This technology facilitates the transmission of messages commonly referred to as Cooperative Awareness Message (CAM) or Basic Safety Message (BSM), as well as Decentralized Environmental Notification Message (DENM). CAMs/BSMs are generated regularly and disseminate essential vehicle information, encompassing details such as the vehicle's heading, speed, and geographic coordinates. In contrast, DENMs are activated by specific events, including sudden braking, imminent collisions, or traffic congestion, and their content may vary based on the nature of the triggering event. Connected vehicle applications relying on V2X communication depend on network support to meet the QoS requirements for transmitting such messages. The essential criteria for these applications, outlined in TS 22.185 [40], are presented in Table 3.3. The specified range is based on allocating a 5-second response time to the driver, serving as a prudent safety margin. It is important to note that the maximum vehicle speed of 500 km/h applies to V2V communication; this value is reduced to 250 km/h when the communication involves V2P or V2I scenarios. Lastly, the most stringent latency requirement is intended for communications in exceptionally critical situations, such as pre-crash sensing warning messages.

Within the context of the 3GPP Technical Report (TR) 22.885, a component of Release 14, several use cases specify the prospective requirements that a network must meet to ensure the effective operation of associated services. These use cases have been formulated focusing on vehicular communication executed over LTE networks, resulting in the exclusivity of the provision of fundamental V2X services. As shown in Table 3.4, this TR presents a variety of use cases for LTE V2X. The requirements for latency, message packet size, and speed support depend on the specific use case being considered. It is im-

Table 3.3: QoS requisites for V2X message transfers.

Parameter	*Requisite*
Range	>braking distance (e.g., 140 m at 140 km/h)
Vehicle Speed	up to 500 km/h
Latency (general case)	<100 ms
Latency (stringent case)	<20 ms
Periodicity	10-50 messages/s

Table 3.4: Potential requirements for LTE V2X [41]. The units for packet transmission are packets per second.

Use case	*Latency (ms)*	*Packet size (Bytes)*	*Packet transmission rate - max.(pps)*
Forward Collision Warning	100	50-300	10
Emergency Vehicle Warning	100	50-1200	10
Emergency Stop	100	1200	10
Queue Warning	100	1200	-
Automated Parking System	100	50-400	-
Pre-crash Sensing Warning	20	50-300	-
V2N Traffic Flow Optimization	1000	50-300	1
Road Safety Services	100	300	10

portant to note the varying demands of each use case. Latency is crucial within the realm of V2X services. Any delays encountered during message transmission or reception can impede the optimal performance of the services and, in extreme cases, lead to counterproductive outcomes. The size of the packets intended for transmission is intrinsically related to the type of message being transmitted, whether it is for V2V, V2I, V2P, or V2N services. Furthermore, the network must provide a reliable connection for vehicles traveling at high speeds.

Additional LTE V2X use cases include providing road safety services, disseminating speed warnings in curved road sections, and issuing collision warnings to pedestrians or cyclists.

Expanding upon the preceding accomplishments, the Release 15 initiative serves as an amplification of 3GPP's endorsement of enhanced V2X (eV2X), encompassing four distinct categories of increasingly sophisticated low-latency communication scenarios —Figure 3.1, highlighted with green background. This expansion is explicitly driven by the focus on accommodating NR V2X, as documented in the specifications outlined in TS 22.186 [42]:

- Vehicle Platoon refers to the coordinated operation of a group of vehicles and effective management, including removing or adding vehicles when necessary. The leading vehicle periodically transmits data to the other vehicles within the platoon to control the collective operations of the vehicles. Platoon management algorithms enable multiple vehicles to accelerate or decelerate simultaneously, significantly decreasing the necessary reaction distance to levels below human driver standards. As a result, inter-vehicle spacing is reduced, increasing road capacity and fuel efficiency. Thus, transportation infrastructure and energy consumption benefit favorably from this technology.

- Advanced Driving is intended to facilitate the deployment of semi-automated and fully autonomous driving systems. This service requires a collaborative information-sharing framework between vehicles and road infrastructure elements, such as RSUs. These elements exchange data from their local sensors and driving intentions with nearby vehicles. Therefore, vehicles use this information to coordinate their movements and adjust their paths to increase safety and improve both Cooperative Collision Avoidance (CCA) and road operational efficiency.

- The concept of Extended Sensors pertains to the capacity of a vehicle to share either unprocessed or processed data, including real-time video streams, with various entities within the road environment. These entities encompass other vehicles, RSUs, pedestrians' UEs, and a V2X AS. This collaborative data sharing enhances the vehicle's perception of the broader road environment, surpassing the limitations of local sensors and expanding its situational awareness significantly.

- Remote Driving allows a remote operator, whether a human driver located far away or a V2X application, to take charge of a vehicle located at a remote site. This capability enables distance driving and offers flexibility in vehicle control. The term refers to the capacity to steer vehicles remotely during exploration expeditions, search and rescue missions, or military operations. This capability holds importance for various applications, such as public transportation and environments with elevated risks. When travel routes demonstrate predictability, the 3GPP finds a cloud-based platform offering back-end services and computational resources an enticing option for effectively implementing this use case category.

- General Aspects represents a comprehensive category as an overarching framework for supporting eV2X scenarios. This category addresses elements shared across all services, encompassing interoperability and communication-related prerequisites.

Table 3.5: Potential requirements for NR V2X [43].

Use case group	*Max. Latency (ms)*	*Packet size (Bytes)*	*Relia-bility* (%)	*Data Rate (Mbps)*	*Min.* Range *(meters)*
Vehicle Platooning	10-500	50-6000	90-99.99	50-65	80-350
Advanced Driving	3-100	300-12000	90-99.999	10-50	360-500
Extended Sensors	3-100	1600	90-99.999	10-1000	50-1000
Remote Driving	5	-	99.999	UL: 25 DL: 1	-

Table 3.5 presents an overview of the primary requirements set for NR V2X use cases. These requirements vary depending on the specific use case. For example, in the case of Remote Driving, the network must guarantee a maximum latency of less than 5 ms. Conversely, services related to Extended Sensors may require a greater bandwidth for transferring video data. The network must maintain a reliability level of over 90% in all scenarios.

In the context of Vehicle Platooning and Advanced Driving applications, exchanging up to 50 V2X messages per second is necessary. This requirement assumes heightened significance because, as evidenced by simulation outcomes presented later, an escalation in packet transmission frequency leads to an elevated occurrence of packet loss attributed to congestion and interference. This, in turn, inevitably diminishes the network's reliability concerning a specified coverage distance.

Several use cases, as listed in Table 3.4 and Table 3.5, demonstrate potential associations with environmentally sustainable transportation solutions. Specific LTE V2X use cases, such as the Automated Parking System and V2N Traffic Flow Optimization, aim to reduce a vehicle's time on the road, leading to decreased greenhouse gas emissions and reduced energy consumption, especially for battery-powered vehicles. Additionally, these use cases help reduce tire wear and alleviate traffic congestion.

Moreover, transmitting vehicle-related information to road traffic management platforms can play a crucial role in bypassing traffic congestion and providing suggestions for alternate routes that lead to decreased travel time. To achieve this, a constant update of this information is imperative, and it can serve as a basis for creating traffic forecast algorithms, which can facilitate proactive event anticipation.

In the realm of 5G V2X, Advanced Driving Services enable vehicles, user devices, and infrastructure to collaborate on communication management to ensure smooth vehicle flow on the road. For example, at intersections, two vehicles can coordinate traffic priority effectively, eliminating the need for either vehicle to come to a complete stop and then restart. When referring to Vehicle Platooning, either autonomous or semi-autonomous, studies indicate that it is possible to decrease fuel consumption and gas emissions by precisely synchronizing vehicle spacing and speed. Effective communication among the platoon and surrounding vehicles is crucial to accomplish this. Communication means include unicast, groupcast, and broadcast.

3.3 C-V2X Communications y Transmission Modes

In order to advance new services and applications available through the LTE platform, the 3GPP has implemented updated standards for vehicular communications. The initial specifications for C-V2X were developed during Release 14, completed in Q4 2016, and cited in [44]. The V2V communications in this standard are based on Device-to-Device (D2D) communications that were previously established as part of ProSe in Release 12 and Release 13. The D2D interface, called PC5, has specifically been reused for V2V, V2I, and V2P communications. Currently, 3GPP has developed two vehicular communication technologies under LTE V2X and NR V2X standards.

The technical specifications of 3GPP consist of four types of vehicular communications, namely V2V, V2P, V2I, and V2N, that are detailed in [41]. Intelligent transportation services are the main objective of these four categories of vehicular communications, which aim to enhance road safety, optimize traffic management, and mitigate environmental pollution, among other similar goals. It should be noted that, unlike technologies based on the Institute of Electrical and Electronic Engineers (IEEE) 802.11p standard, C-V2X technologies incorporate the potential of V2P and V2N connections, which enables the creation of new use cases. Furthermore, these communication types allow for integrating new internetworking mechanisms via the Multi-RAT Dual Connectivity (MR-DC) approach and cross-border and cross-Mobile Network Operator (MNO) communications. Additionally, hybrid communication interfaces can be implemented to improve communication redundancy.

Concerning communication modes, LTE V2X introduces two separate modes for V2X communications, named mode 3 and mode 4, as specified in [45]. Modes 3 and 4 essentially expand on the foundational principles of D2D modes 1 and 2 that were standardized in Release 12. Mode 3, referred to as managed mode, is similar to mode 1 for D2D communications, wherein the UE requests network resources for V2X services from evolved Node B (eNB). This means that for UE-to-eNB communication, the LTE-Uu interface is used, while the PC5 interface is used for V2V, as shown in Figure 3.2. Similarly, mode 4, similar to mode 2 for D2D communications, is called the unmanaged mode and operates autonomously, requiring no communication from the UEs to the network. In this mode, communication occurs autonomously and utilizes the PC5 interface, commonly known as SL.

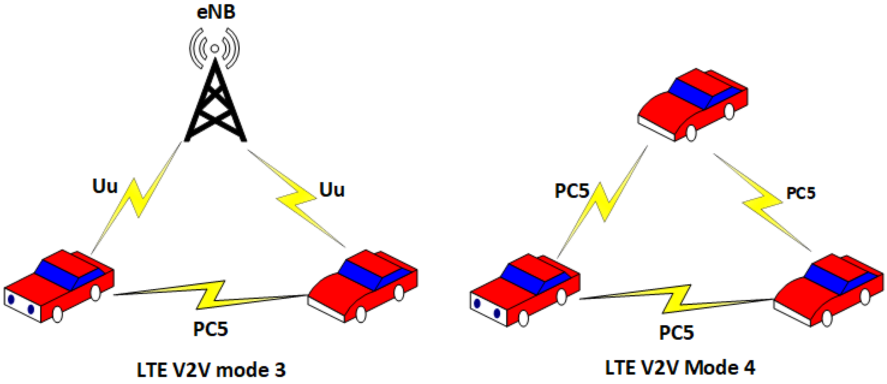

Figure 3.2: LTE V2X modes.

The 3GPP Release 14 specifications concerning C-V2X function as the fundamental framework for the advancement of the new NR-based technology. The first stage, referred to as V2X Phase 1, was completed successfully in March 2017. Phase 2 V2X was subsequently introduced in 3GPP Release 15. This phase includes multiple enhancements targeted at 4G LTE networks to prepare for the arrival of 5G NR. The improvements introduced for the V2X service involve carrier aggregation, latency reduction, increased transmission rates, and other elements. Furthermore, improvements have been made to enhance direct communication over the PC5 interface, including transmission diversity and higher-order modulations such as 64-Quadrature Amplitude Modulation (QAM).

Figure 3.3 presents several connectivity scenarios involving V2X LTE over the EPC network. The architecture outlined in TS 23.285 [46] serves as a foundation, enabling the exchange of information among vehicles, RSUs, and UEs regarding their surroundings, either among themselves or with a V2X AS. It facilitates a standardized framework for V2X communication. Before Release 16, the 3GPP V2X standard has shown the potential to provide significant help for the advancement of ITS applications. This facilitates the offer of messaging and various services via LTE/EPC.

As illustrated in Figure 3.2, Rel-14 delineates a single cellular technology comprising two different V2X communication modes that function over:

- PC5 interface, which connects UEs directly.
- LTE Uu interface, which usually connects UE to an LTE eNB.

A UE can independently participate in transmitting and receiving operations using these communication modes. It is important to note that before the update introduced in Rel-16, the foundational principles governing the standardized V2X communication modes stayed constant and unchanged. Furthermore, when formulating design assumptions for these two modes, 3GPP thoroughly considered crucial factors such as transmission frequencies, priority mechanisms, and KPIs mandated by the ITS sector. These KPIs include parameters such as latency, reliability, message size, and communication range.

TS 24.386 [47] outlines the architecture for inter-Public Land Mobile Network (PLMN) interactions and roaming scenarios. It deploys protocols over the V4 interface to set up authorization procedures between the V2X Control Function and the Home Subscriber Server (HSS), as well as over the V6 interface linking V2X Control Functions operating within different PLMNs. The main goal of these authorization procedures is to ascertain whether a UE has the requisite authorization to operate as either a Vehicle UE or a Pedestrian UE in the V2X setting. The HSS assumes a crucial role in communicating information regarding the particular PLMNss in which PC5-based communications are sanctioned for the UE in question. If multiple PLMNs are involved, the V2X Control Function in the home PLMN can request authorization details about a specific UE from the V2X Control Function in the visited PLMN. The V2X Control Function in the visited PLMN conveys the UE's permissions, such as the ability to communicate through PC5-based or Multimedia Broadcast Multicast Service (MBMS) channels. These channels are facilitated via the M1 interface, which connects an eNB to the EPC.

It is imperative to note that MBMS operations involve the involvement of the Broadcast Multicast Service Centre (BM-SC) entity, which manages QoS, broadcasts announcements for multicast sessions and performs similar functions, in addition to depending on the presence of an MBMS-Gateway.

As previously stated, LTE V2X has established two communication modes: mode 3 and mode 4. Similarly, NR V2X has delineated two transmission modes, specifically referred to as mode 1 and mode 2. Within mode 1, which closely parallels the LTE V2X mode 3, the gNB is responsible for resource allocation to UEs. On the contrary, SL mode 2, resembling the LTE V2X mode 4, gives UEs the ability to establish communication links beyond the boundaries of gNB coverage. Additionally, the standard introduces four sub-modes, namely

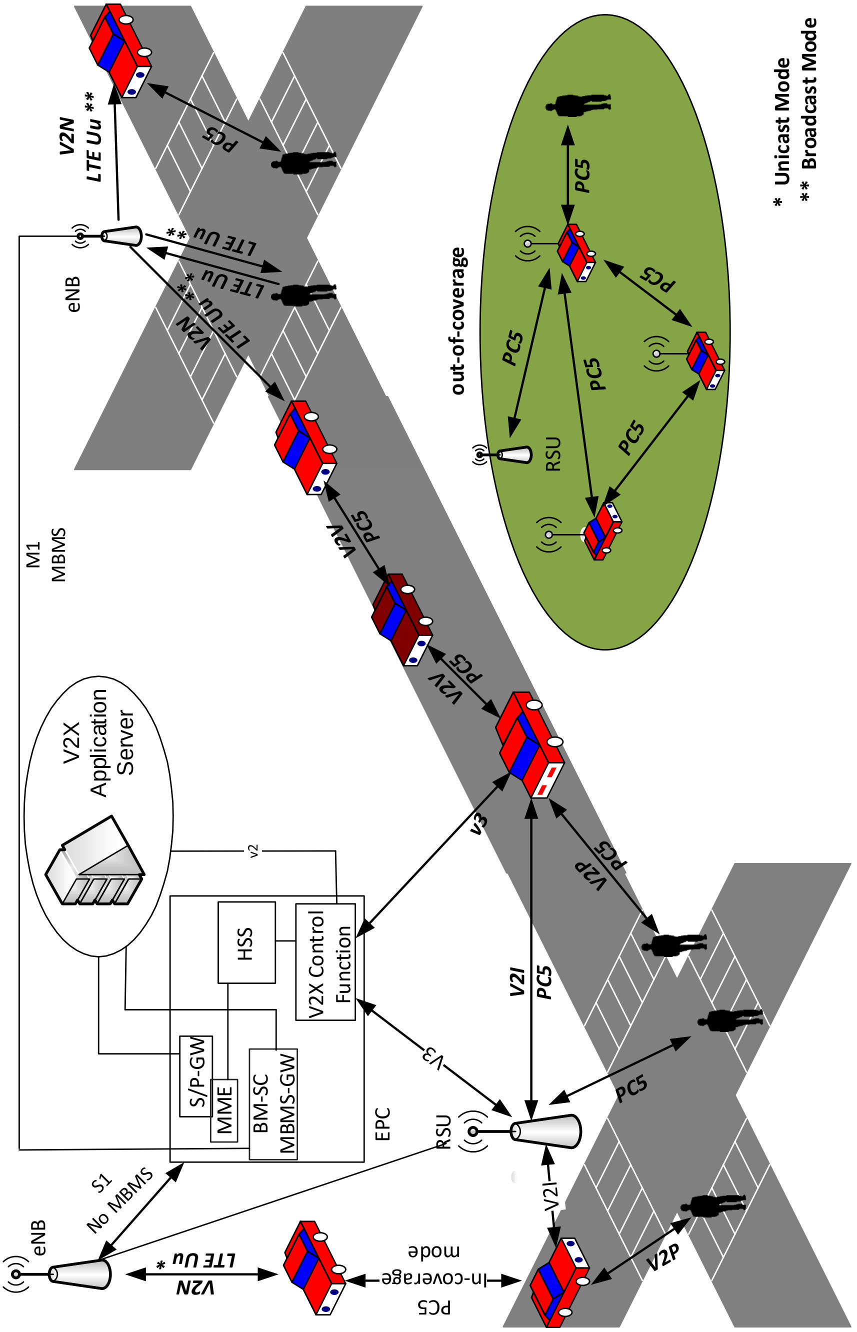

Figure 3.3: Overview of pre-Release 16 V2X Architecture over EPC.

mode 2a, mode 2b, mode 2c, and mode 2d, which are elaborated in [48]. In mode 2a, UE will autonomously select the resources to be used, while in mode 2b, a UE can assist other UEs in the process of resource selection for transmission. Mode 2c differentiates between operations conducted outside the network coverage area —out-of-coverage operation— and within the coverage area —in-coverage operation. For out-of-coverage operation, mode 2c comprises the pre-configuration of one or multiple transmission patterns, each mapped to a specific resource pool. Conversely, the operational mode within the coverage area presupposes that the gNB delineates the positioning of one or multiple transmission patterns. In mode 2d, a UE assumes a proactive role in allocating resources for other UEs.

In the context of NR V2X, message transmission modes between UEs comprise of unicast, groupcast, and broadcast. Figure 3.4 depicts the unicast mode in which a UE communicates exclusively with another designated UE. In groupcast mode, a UE can transmit messages to one or multiple UEs in its proximity. An illustrative example of this mode of communication is a lead vehicle sending messages to members of a vehicular platoon. Conversely, within the broadcast mode, a UE disseminates messages to all nearby vehicles within the transmission coverage area. It is important to note that within NR V2X, user equipment can effectively support the three modes of information transmission, as shown in Figure 3.4. In real-world situations, a leading vehicle can simultaneously facilitate groupcast transmission to platoon members and engage in unicast communication with a nearby vehicle outside the platoon.

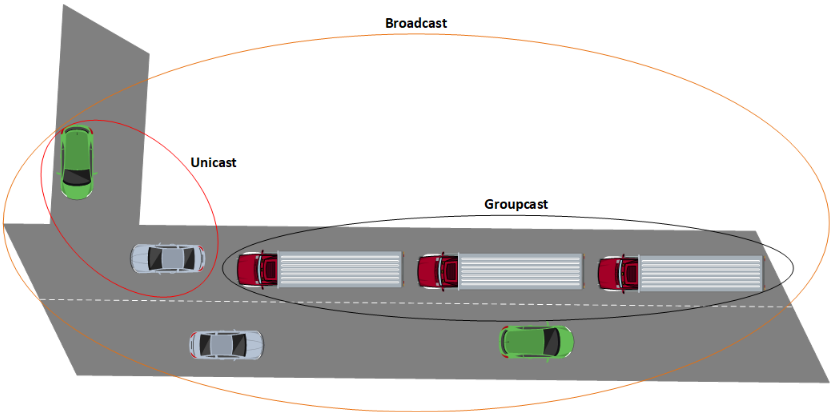

Figure 3.4: NR V2X transmission modes.

Figure 3.5 displays the different connectivity scenarios and illustrates how NR-based V2X scenarios align with the architectural framework in TS 23.287, including reference points and Network Function (NF), among other elements. Importantly, the architecture revolves around 5GC, with specific NFss essential to V2X communication highlighted in green for clarity. The uplink, downlink, and SL modes for communication scenarios, facilitated by 5G NR V2X interfaces, are highlighted using red arrows. It is important to note that within the context of 5G, there is no designated LTE V2X Control Function. However, this entity may be required in situations that involve interworking with 5G nodes that provide LTE connectivity — next generation eNB (ng-eNB)— or when cross RAT scheduling is necessary. Figure 3.5 presents a standard method for handling groupcast mode addresses, as demonstrated in a common use case with truck platooning. This is a departure from the earlier strategy, pre-Release 16, where unicast and groupcast addressing were Media Access Control (MAC)-handled and relied on the specific implementation. In Release 16, detailed provisions are set forth for communication utilizing both variants of PC5 interfaces, namely NR PC5 and LTE PC5. These specifications encompass support for roaming scenarios and inter-PLMN operations. The PC5 reference point can be effectively employed whether a device is within the coverage area of NR or E-UTRA or situated outside such coverage areas.

3.4 Conclusions

This chapter has presented information related to the 3GPP support for V2X services. Consequently, the principal specifications and technical reports delineated in Releases 14, 15, 16, and 17 have been subjected to examination. About the standard, it provides a set of specifications for V2X services based on LTE and NR and supports several services and use cases with varying potential requirements. V2X services defined for LTE can be considered basic services where the requirements for latency, packet size, V2X packet transmission periodicity, etc. can be met, given the inherent limitations of this technology. Nevertheless, the 3GPP specifications for 5G include significant improvements at the Physical (PHY), MAC, and higher layers, which permit the adaptation of this more robust network to advanced V2X services that demand potential requirements. It is important to note that the potential requirements for each use case may vary depending on the specific type of service to be implemented. Consequently, different configuration parameters can be set, resulting in different network performance. For example, use cases related to advanced driving require the imposition of rigorous network latency and reliability requirements for the service to function optimally.

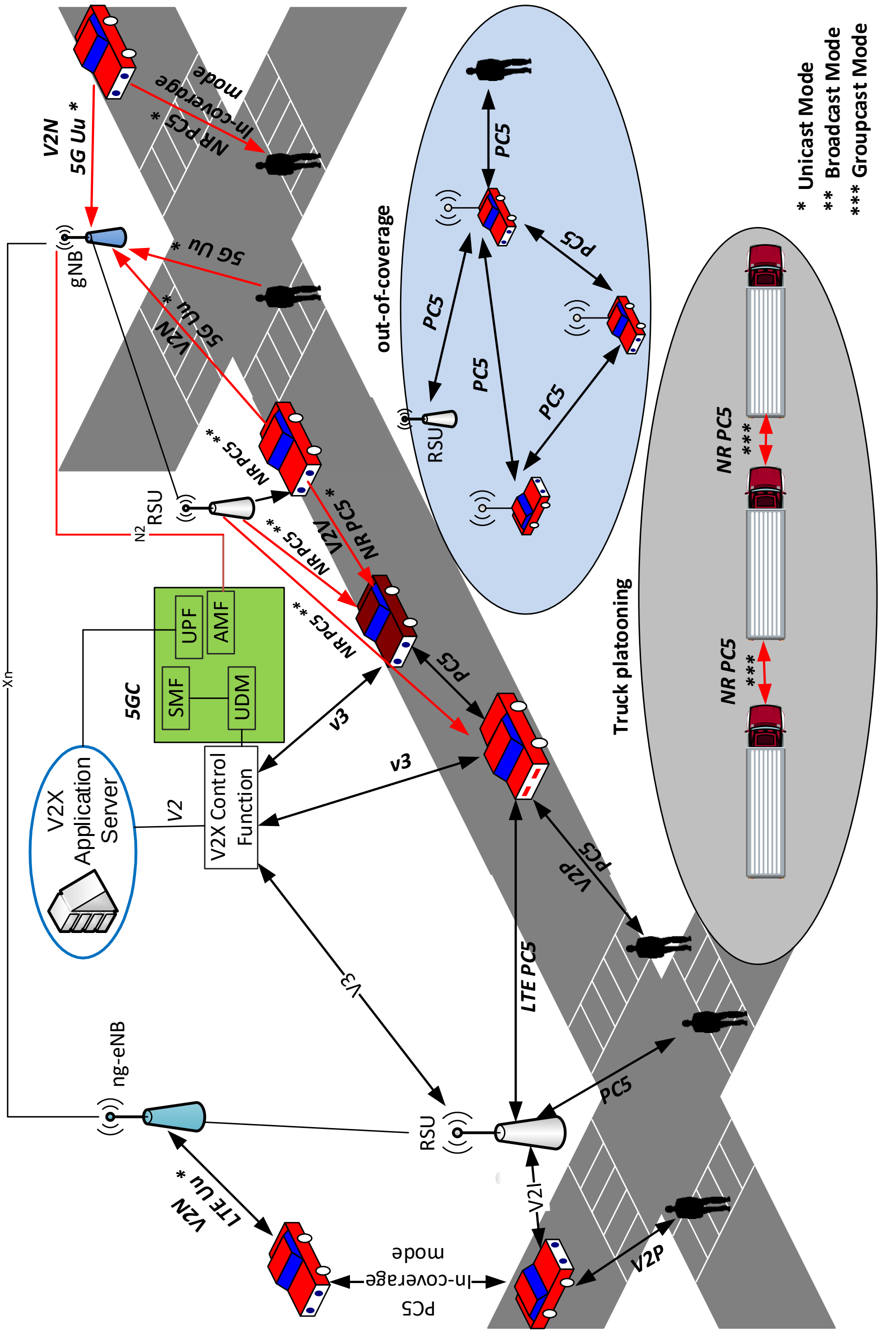

Figure 3.5: Release 16 5G NR V2X Architecture.

Regarding communication and transmission modes, these have been designed to adapt to various use cases and V2X scenarios. Support is provided for establishing communications in services that require data transmission to road safety platforms, servers for cloud-based applications, the Internet of Things (IoT), and other similar systems. Furthermore, the SL interface facilitates the connection between V2X devices without cellular network coverage. Transmission modes are selected according to the specific V2X service to be implemented. For instance, in the context of LTE V2X, only the broadcast transmission mode is supported. In contrast, for NR V2X, multicast and broadcast modes have been additionally defined, thus enabling the implementation of new V2X services based on these transmission modes.

Finally, adopting of 5G technologies for services presents several significant challenges. The challenges associated with the massive deployment of 5G networks in urban and rural environments are primarily related to the need for operators to make considerable investments in order to ensure the proper operation of NR V2X-based services. Furthermore, vehicles must be equipped with devices compatible with these technologies, and the deployment of V2X infrastructures, such as RSUs, may be required in certain scenarios. For instance, a vehicle that currently incorporates an LTE V2X unit to support advanced NR V2X-based services may require a more substantial upgrade, such as a firmware update or adjustments to configuration parameters, in order to fully support the new technology. It is, therefore, necessary to replace the unit with one that supports the new frequencies and procedures defined for NR V2X. Consequently, it is anticipated that manufacturers marketing new vehicle models are expected already to include the updated C-V2X technology. Nevertheless, for vehicles that have already been released with previous versions of V2X technologies, it may be necessary to install a new C-V2X device in order to guarantee compatibility and optimal operation with NR V2X networks.

Chapter 4

LTE V2X Physical Layer, Resource Allocation, and Performance Evaluation

Following a review of the standards delineated for Cellular-based Vehicle-to-everything (V2X) (C-V2X) across various Third Generation Partnership Project (3GPP) Releases, it is imperative to assess the performance of Long Term Evolution (LTE) V2X following the procedures and parameters specified in the standard. Firstly, this chapter outlines the sensing and resource selection mechanisms established by 3GPP for LTE V2X communications. It provides a detailed description of the Physical (PHY) and Media Access Control (MAC) layers, which are essential for selecting resources in terms of time and frequency that vehicles must use to transmit V2X packets. Subsequently, the results of the performance evaluation of LTE V2X modes 3 and 4, conducted under the established standards, are presented. Simulation scenarios were designed to examine the variability of the Packet Delivery Ratio (PDR) under various conditions, such as inter-vehicle distances, vehicle densities on the road, travel speeds, V2X packet transmission rates, and transmission powers.

This chapter is structured into the following sections:

- Section 4.1 provides a detailed discussion of the physical layer and radio resource location aspects defined in Release 14 for LTE V2X.

- Section 4.2 details the simulator's characteristics, as well as the reference parameters and scenarios considered for LTE V2X simulations.

- Section 4.3 presents the results of the LTE V2X mode 4 simulation for different scenarios.
- Section 4.4 discusses the tool used for LTE V2X mode 3 performance evaluation and presents the results obtained.
- Section 4.5 draws the main conclusions of the chapter.

4.1 Physical Layer and Resource Allocation Aspects of LTE V2X

4.1.1 LTE V2X Physical Layer

Resource allocation for V2X communications in the LTE framework involves two distinct communication modes: mode 3 and mode 4. Mode 3 requires cellular network coverage and uses the Uu interface. On the other hand, mode 4 enables User Equipments (UEs) to independently manage resources in both time and frequency domains to establish communications. In this context, the fundamental unit for allocating resources in the frequency domain is the Resource Block (RB), which measures 180 kHz. Meanwhile, the temporal domain utilizes the subframe as its elementary unit, lasting 1 millisecond in LTE. These RBs can be configured using channel bandwidths of 10 and 20 MHz. Furthermore, subchannels are introduced, which signifies a grouping of n RBs within a single subframe. These subframes serve as the medium for transmitting both data and control information in the realm of V2X communications. The standard defines a range of possible subchannel sizes, as explained in [45, 49]: 4, 5, 6, 8, 9, 10, 12, 15, 15, 16, 18, 20, 25, 30, 48, or 50 RBs. On the other hand, it is defined that up to 1, 3, 5, 10, 15, or 20 Sidelink (SL) subchannels can be assigned.

More specifically, data is conveyed by Transport Blocks (TBs), while control information is sent by SL Control Information (SCI) messages, as described in [45]. These SCIs are broadcasted using Physical Sidelink Shared Channel (PSSCH) for TBs and Physical Sidelink Control Channel (PSCCH) for SCIs [50]. The SCI messages contain essential information like the Modulation and Coding Scheme (MCS) utilized in the TBs, the initial and retransmission frequency resource allocation, resource reservation, retransmission index, and other vital details. Therefore, it is obligatory to transmit a TB with its corresponding SCI within the same subframe [50]. In the LTE V2X standard, two subchannelization schemes have been defined: the adjacent PSCCH + PSSCH scheme and the nonadjacent PSCCH + PSSCH scheme. Figure 4.1 illustrates both schemes. In the first scheme, SCIs are transmitted in adjacent

RBs alongside their corresponding TBs, occupying two RBs in the frequency domain. The number of RBs allocated to TBs depends on the type of message being transmitted, such as Cooperative Awareness Message (CAM) messages. In the second subchannelization scheme, separate resource pools transmit SCIs and TBs. Both schemes assume that each TB mapped within a subframe includes its associated SCI. Additionally, it is possible to transmit multiple sets of TBs and their corresponding SCIs within a single subframe.

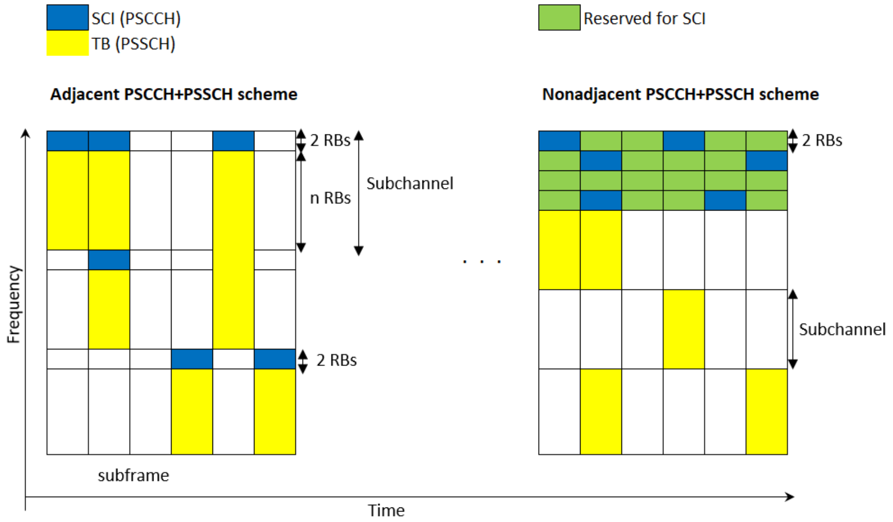

Figure 4.1: Adjacent and noadjacent PSCCH+PSSCH channelization.

Further physical layer parameters, as outlined in the standard [51], include the selection of modulation schemes for TBs and SCI information. TBs can be transmitted using either Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (QAM) or 64-QAM. SCI messages, however, can only be transmitted by using QPSK modulation. The standard specifies a maximum transmit power level of 23 dBm and a receiver sensitivity threshold of -90.4 dBm.

4.1.2 Resource Allocation in LTE V2X

When employing mode 4 for Vehicle-to-Vehicle (V2V) communications in vehicles, the utilization of Semi-Persistent Scheduling (SPS) is necessary [45, 52]. According to [51, 53, 54], SPS enables vehicles to reserve channels by following standardized procedures. These procedures guarantee that vehicles conduct time and frequency sensing and reserve available resources using a technique that decreases the likelihood of multiple vehicles selecting the same resources. As illustrated in Figure 4.2, the SPS sensing and resource reservation procedures rely on a sensing and selection window. During the sensing window, a vehicle chooses a set of Candidate Single-Subframe Resources (CSRs), which will undergo filtering and be utilized during the selection window to transmit V2V packets —i.e., specific n SCIs+TBs. To carry out the resource selection process using SPS, the following four steps are required:

- **Step 1:** During the dedicated Sensing Window, which spans 1000 milliseconds, equivalent to 1000 subframes or precisely one second —as shown in Figure 4.2—, vehicles diligently detect and assess CSRs. Each vehicle conducts an exhaustive process in this interval to identify and evaluate available CSRs. An exception is made for CSRs explicitly reserved for use by neighboring vehicles, as indicated by SCI. The efficient operation of vehicular communication systems relies on the complex resource detection and evaluation process.

- **Step 2:** During this phase, CSRs that have an average Reference Signal Received Power (RSRP) above a specific predefined threshold are systematically excluded from further consideration. This value threshold is determined by the upper-level network protocols, considering packet priority and the associated V2V service category. It is worth noting that this filter intentionally excludes common CSRs) that neighboring vehicles may have already reserved or actively used, maximizing the management of frequency resources in vehicular communication systems.

- **Step 3:** It is crucial to verify that at least 20% of the initial set of sensed CSRs have undergone filtration in the preceding step. If this condition is not met, a proportional adjustment is implemented to the threshold value that governs the average RSRP. This results in a 3 dB increase. This refinement process, Step 3, is repeatedly executed until the criteria of ensuring at least a 20% availability of CSRs is met.

- **Step 4:** In the final step of the selection process, a 20% subset of the CSRs that underwent filtration in step 3, and thus exhibit the lowest average Received Signal Strength Indicator (RSSI) across all RBs, is chosen. Subsequently, a CSR is randomly designated for use in the first transmission.

In addition, the following issues should be considered when selecting resources using SPS in mode 4 LTE V2X:

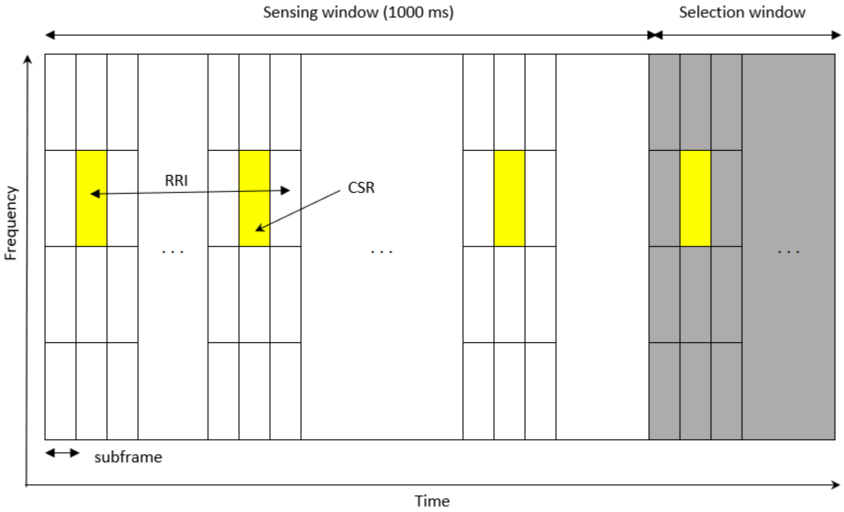

Figure 4.2: Semi-Persistent scheduling for LTE V2X mode 4.

- The length of the message to be transmitted determines the number of subchannels of a CSR that a vehicle must reserve.

- The selection window's duration relies on V2X communication latency requirements and has a maximum term of 100 milliseconds, equivalent to 10 packets per second (pps). In addition, it is possible to have selection windows lasting 50 ms and 20 ms for 20 pps and 50 pps, respectively, as stated in [52].

- The vehicle can continue transmitting continuously after a certain number of packets. This number relies on the value of a Reselection Counter (RC) that decreases based on the transmission time of consecutive packets and is identified as Resource Reselection Interval (RRI). The RC is randomly selected and can range from [5,15] for 10 packets per second, [10, 30] for 20 packets per second, and [25, 75] for 50 packets per second.

- Each time the RC reaches 0, the process of selecting and reserving resources must be repeated. The probability of retaining the previously selected resources ranges from 0 to 0.8.

Figure 4.3 illustrates the key considerations involved in LTE V2X resource sensing, selection, and re-transmission procedures.

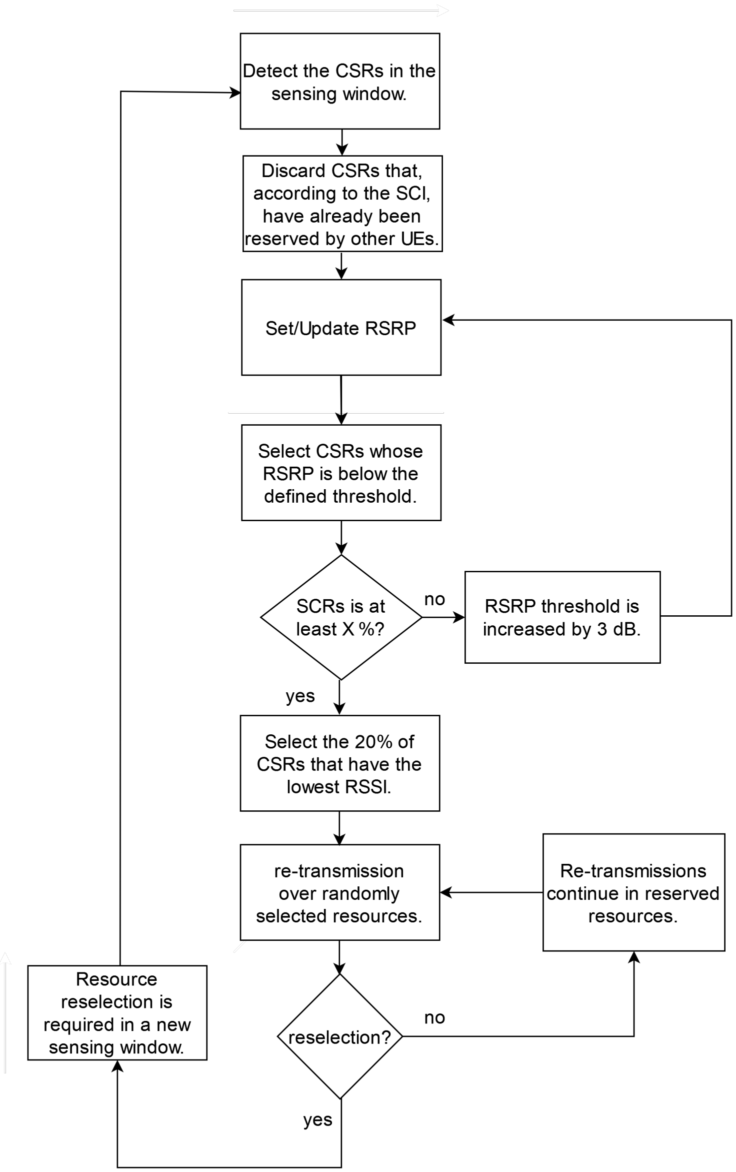

Figure 4.3: Procedures for sensing and resource selection in LTE V2X.

4.2 Simulation Tool and Preliminary Configurations

Most of the existing academic papers focus on the study of LTE mode 4, due to its decentralized nature, eliminating the need for cellular network coverage. Accordingly, the works of [49, 53–55] offer insights derived from evaluating resource allocation and congestion control mechanisms aligned with 3GPP specifications. In a divergent vein, the work by [56] presents a simulator tailored for LTE V2X mode 4, characterized by its open accessibility and adherence to standard specifications. This simulator serves as a central tool for evaluating the decentralized mode in the context of this research. Conversely, evaluating the centralized mode requires using an analytical model constructed through MATLAB [28]. Using both simulation tools facilitates the derivation of the PDR as a function of various parameters such as distance, vehicle densities, packet sizes, and packet transmission rates per second.

This study aims at simulating the use of LTE V2X mode 4, which was chosen due to its autonomous capabilities in scenarios lacking cellular network coverage. To achieve this goal, a highway scenario was developed based on the guidelines outlined in [57]. Consequently, the scenario includes a two-way highway with three lanes in both directions, as shown in Figure 4.4. The highway extends for 2 kilometers, each lane measuring 4 meters wide. Various vehicle densities were configured to reflect fast —0.06 vehicles per meter (vpm)— and slow —0.12 vpm— highway scenarios to consider diverse operational conditions.

Table 4.1 lists additional PHY and MAC layer parameters used in the simulations.

The open-source tool openCV2X [56] is used to perform LTE-V2V mode 4 simulations. This tool, based on the discrete event simulator OMNeT++ [58], derives its functionality from the simuLTE framework [59], as described in Section 2.3. The simuLTE framework facilitates complex system-level performance evaluation of LTE and LTE-Advanced networks.

Furthermore, openCV2X requires additional add-ons for optimal functionality:

- INET [60]: is an open-source framework for OMNeT++ that offers libraries for wired and wireless networks.

- VEINS [61]: is an open-source framework that generates simulations of vehicular networks.

- SUMO [62]: is an open-source road traffic simulator.

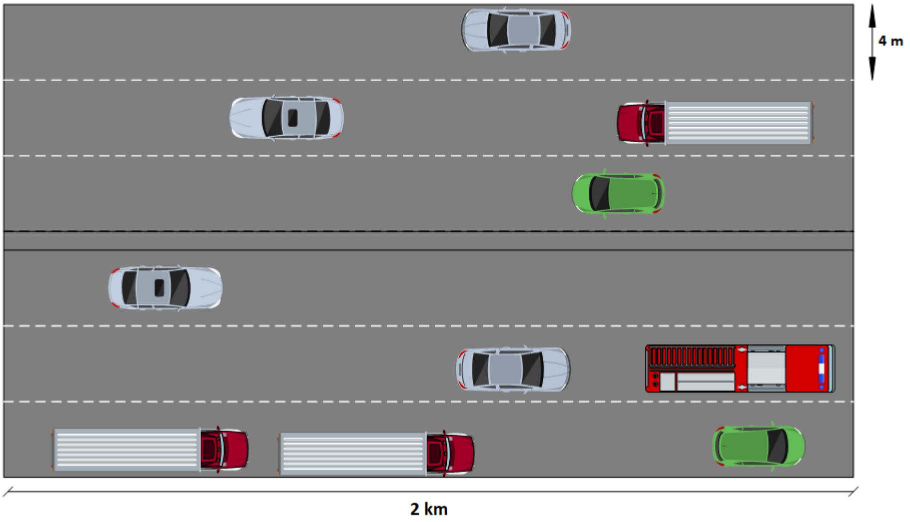

Figure 4.4: Highway conditions considered for simulating LTE V2X mode 4.

Table 4.1: Reference parameters for LTE V2X mode 4 simulations.

Parameter	*Value*
Carrier frequency	5.9 GHz [57]
Channel bandwidth	10 MHz [57]
Packet size	190 Bytes [57]
PSCCH, PSSCH	Adjacent
Simulation time	12 s
Vehicle density	0.06, 0.12 vpm
Sensing window	1000 ms
ProbResourceKeep	0.4
SubChannel size	14
Num. SubChannels	2
RSRP threshold	−128 dBm
RSSI threshold	−92 dBm

During the preliminary stage of the OpenCV2X experiment, vehicles are placed on the road with a predetermined density. To ensure scenario stabilization, a temporal span of 500 seconds is given at the start of the simulation before inter-vehicle communication is initiated. Subsequently, simulation periods of

12 seconds are utilized, encompassing a range of parameters, such as diverse packet transmission rates, vehicular density on the roadway, and transmission power levels.

Figure 4.5 illustrates a comprehensive flowchart outlining the primary steps to obtain the research outcomes. To prevent simultaneous transmission of initial messages by all vehicles, the first packet includes a configurable delay ranging from 0 to 1000 ms. Following this, the transmission and receipt of alert messages by vehicles are governed by the resource selection and congestion control processes specified for mode 4. The multicast transmission mode is employed to disseminate CAM packets, each consisting of 190 bytes, featuring diverse transmission frequencies.

The number of RBs needed for transmitting each packet depends on both MCS and packet size. Defining the required RBs for packet transmission is done through the TB, along with two additional RBs needed for conveying the SCI, which are the adjacent PSCCH/PSSCH. The calculation of PSSCH-RSRP involves multiplying the Power Spectral Density (PSD) of the RBs by the bandwidth of each Resource Element (RE). The resulting value represents the average power across all REs, assuming a uniform power distribution. In computing the RSSI, it is crucial to include power noise and interference for each RB to ensure accurate measurement. Hence, RSSI is calculated by adding the power received per RB, multiplied by the total number of transmitted RBs.

Dealing with reception failures of SCIs is a critical consideration in the simulations performed. In situations where the SCI is not received accurately, it is necessary to discard the associated TBs linked to that SCI. The reason is the inability to correctly decode TBs, resulting in a lack of essential SL information.

After running numerous simulations in different scenarios, the collected data is processed using Python libraries.

4.3 Mode 4 LTE V2X Performance Evaluation Results

OMNeT++ provides results recorded in vector (.vec) and scalar (.sca) files. Data analysis and visualization are easy using the Jupyter Notebook, which operates within the Anaconda package management system.

Figure 4.6 presents the PDR curves for different packet transmission rates at varying distances. The experimental setup involves a road density of 0.06 vpm using openCV2X, resulting in around 130 vehicles on the two-kilometer stretch of the highway. This scenario aligns with the conditions previously

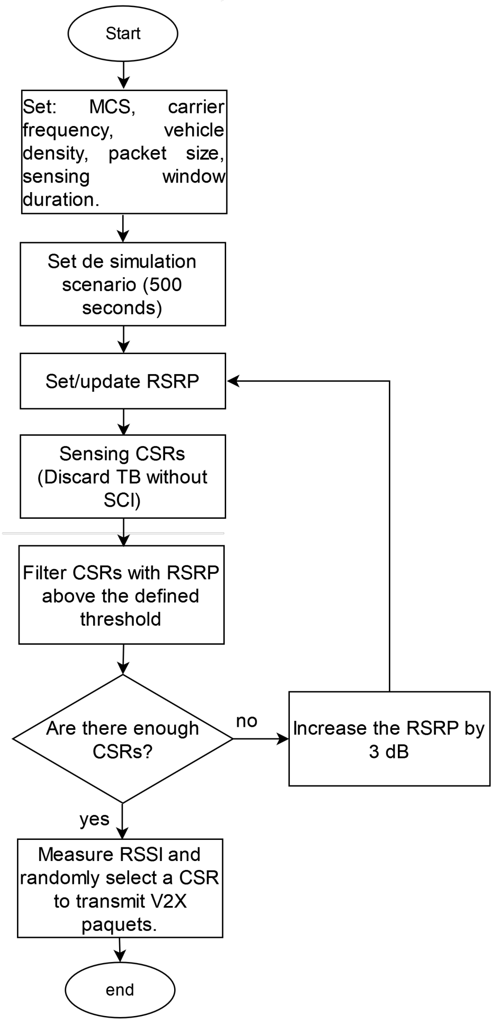

Figure 4.5: Main procedures followed by the openCV2X simulator.

outlined for a high-speed highway. The average speed of the vehicles traversing the road is 140 km/h.

The findings from the data illustrated in Figure 4.6 demonstrate that increasing V2V packet transmission rates results in a decrease in the distance at which a satisfactory PDR can be achieved. In particular, when the packet transmission rate is 5 pps, the maximum distance to ensure 80% PDR cannot be greater than 250 meters. Enhancing the transmission rate causes a substantial decrease in coverage conditions.

It is important to note that varying services require distinct packet transmission rates based on possible network requirements. Certain services require a higher packet transmission rate for advanced use situations, with relatively low latency and high network dependability. The decline in PDR with an increase in V2X packet transmission rates results from the increased number of resources that UEs must reserve in the selection window for their transmissions. This increases the likelihood that other vehicles have already reserved an SL subchannel. It is important to note that the LTE V2X mode 4 resource sensing and selection algorithm identifies SL subchannels that have been reserved by other UEs as ineligible for V2X transmissions. Suppose a vehicle does not reach the minimum percentage of eligible resources. In that case, enhancing the RSRP by 3 dB is feasible, which may cause two UEs to use identical resources for their transmissions, causing interference.

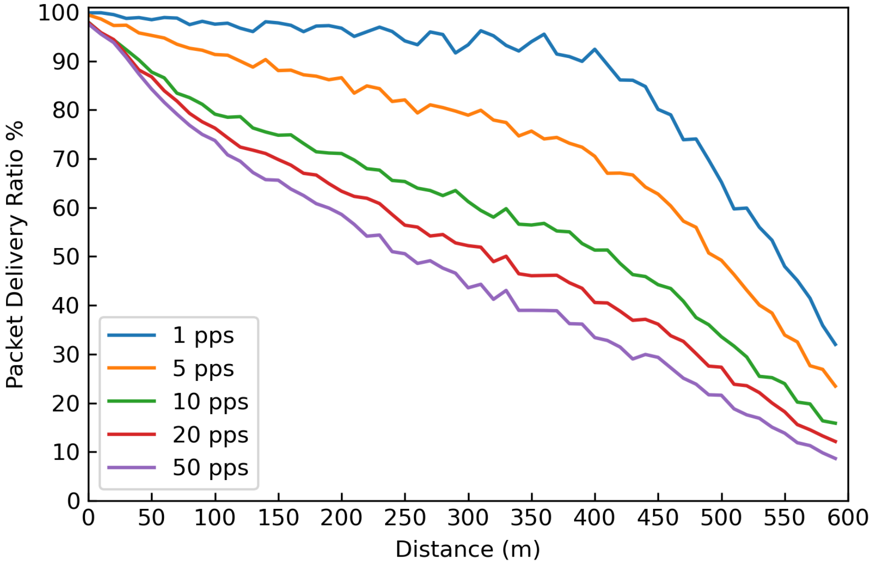

Figure 4.6: PDR variation as a function of distance between vehicles and under different packet transmission rates.

Another factor contributing to traffic congestion and the probability that V2X resources have been resources reserved by other vehicles is certainly the increasing density of vehicles on the road. In this context, when a resource pool designed for V2X transmissions has a specific number of SL subchannels, it raises the probability that multiple UEs will choose the same CSR for their transmissions. To examine the performance of PDR in congested freeway conditions, a scenario was created with a vehicle density on the highway set at 0.12 vpm and an average speed of 70 km/h. Figure 4.7 displays the fluctuation of PDR regarding propagation distance under different packet transmission and road vehicle density rates. In this case, it is evident that channel congestion increases as the number of vehicles on the road increases, causing a decrease in PDR. As a result, it is more likely that multiple vehicles reserve the same resources in both time and frequency domains, which interferes with the proper reception of the SCIs associated with each V2V message.

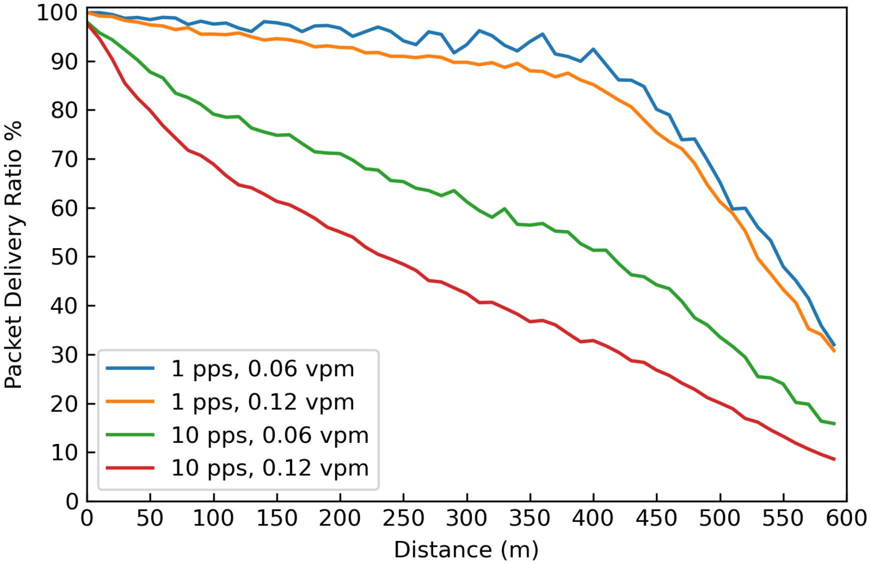

Figure 4.7: Variation of PDR based on distance, packet transmission rates, and road vehicle densities.

In Figure 4.8, an examination of the impact of transmit power on PDR for various propagation distances is conducted. This analysis centers on a fast highway scenario with a fixed transmission rate of 1 packet per second (pps). The findings confirm that a reduction in transmit power, specifically from 23 dBm to 20 dBm, yields comparable PDR levels for distances less than 300 meters. However, extended distances result in elevated packet losses. Reducing transmit power can significantly benefit by reducing interference caused by simultaneous resource selection for V2X transmissions by two or more vehicles. However, transmission at lower power levels will decrease range due to the intrinsic characteristics of signal propagation.

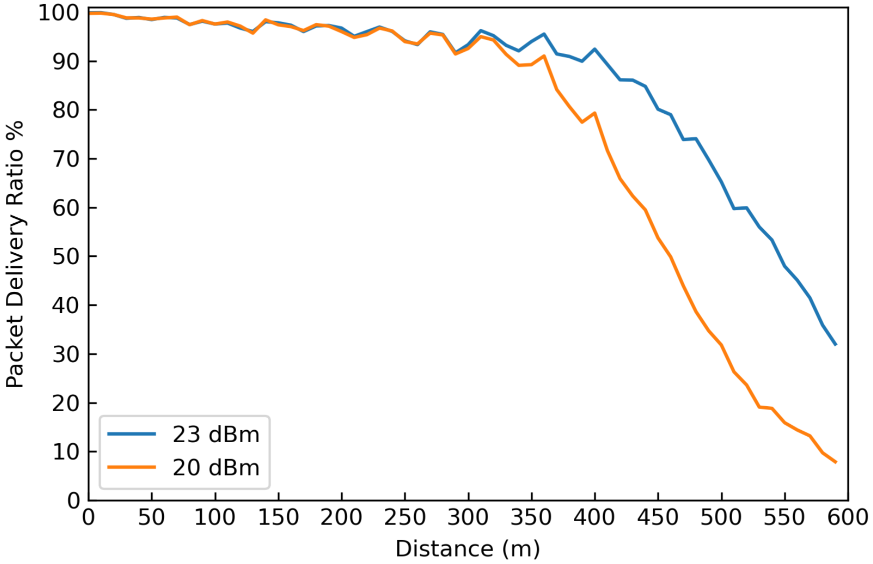

Figure 4.8: variation of PDR concerning propagation distance across distinct transmit power levels.

4.4 Mode 3 LTE V2X Performance Evaluation Results

In contrast to LTE mode 4, the standard does not have a defined resource allocation mechanism within mode 3. As a result, there is a possibility of formulating different mechanisms to alleviate channel congestion and mitigate packet loss, especially in environments characterized by a high density of vehicles on the road. To perform simulations in mode 3, an analytical model described in [28] is used. This model, called DIRAC —aDaptive spatIal Reuse of rAdio resourCes—, is implemented using MATLAB and facilitates the configuration of scenarios like those considered in mode 4. DIRAC uses vehicle locations to create a dynamic configuration, ensuring equal interference levels for all vehicles. This model also reduces the signaling overhead in centralized modes.

The model uses reference parameters identical to those listed in Table 4.1. Figure 4.9 shows PDR fluctuation with distance at different packet transmission rates in mode 3, with a vehicle density of 0.06 vpm. Similarly to mode 4, an increase in packet transmission rate reduces the distance range for a given PDR. Across all instances, mode 3 outperforms mode 4. More specifically, when transmitting packets at rates of 10 and 20 packets per second, the PDR remains above 95% consistently. However, when transmitting packets at a rate of 50 pps, the same PDR level can only be sustained up to a coverage range of 200 meters.

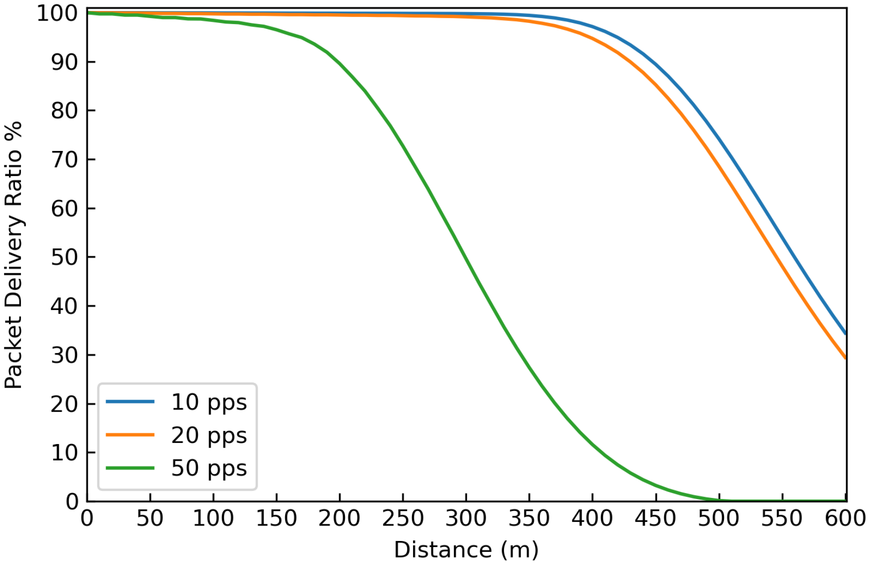

Figure 4.9: PDR variation versus distance for different V2V packet transmission rates in LTE V2X mode 3.

Figure 4.10 shows the fluctuations in PDR as vehicle densities on the road vary. Slower scenarios have a greater impact on PDR than fast highway scenarios due to increased vehicular density. However, even in high-density scenarios, PDR remains above 80% for distances below 100 meters at a packet transmission rate of 50 pps.

Simulations for LTE modes 3 and 4 consistently demonstrate the possibility of achieving a PDR over 90% but only within limited distances.

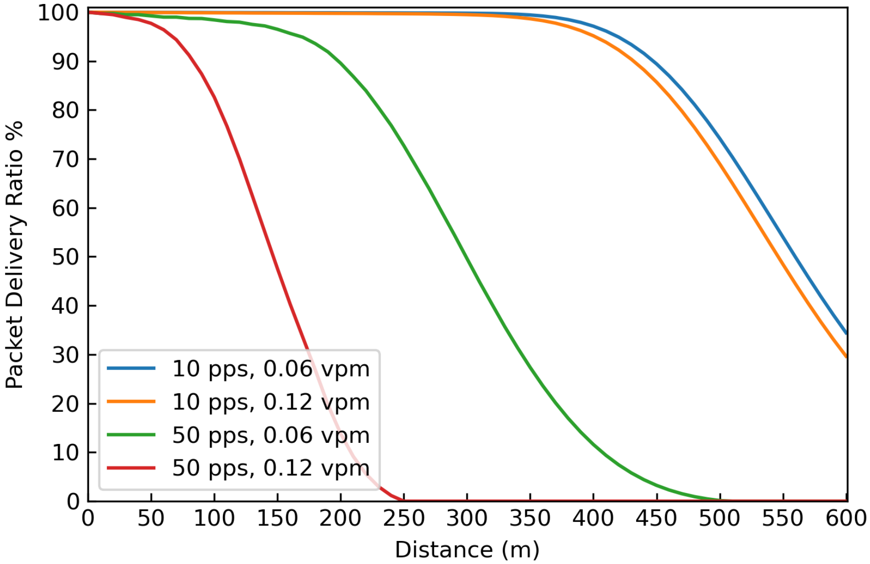

Figure 4.10: PDR variation as a function of propagation distance for different packet rates and vehicle densities in LTE V2X mode 3.

Table 3.5 summarizes relevant data, underscoring the need for diverse use cases requiring various coverage ranges for optimal functionality. Notably, scenarios requiring extended sensor coverage could necessitate distances up to 1 km. Meeting the required network reliability threshold of 90% to 99.999% remains challenging, regardless of whether centralized or non-centralized LTE modes are employed. The situation worsens with increased packet transmission frequencies, higher vehicular density on roads, and reduced transmission power.

4.5 Conclusions

This chapter has provided a detailed description of the aspects of the PHY and MAC layers that correspond to LTE V2X. Furthermore, the performance evaluation results of modes 3 and 4 in various scenarios are presented.

The sensing and resource selection mechanisms of LTE V2X mode 4 allow V2X UEs to manage radio resources autonomously, thus obviating the need for cellular network coverage. This is of great importance, as not all locations have cellular network availability, which means that a V2X service can continue to operate under such conditions. The specific procedures that 3GPP defines for the sensing and selection of resources in LTE V2X require that a set of resources be sensed by V2X UEs, which they may then consider as candidates for their transmissions. Suppose the minimum percentage of candidate resources is not met. In that case, an increase in RSRP levels is allowed until the minimum percentage of resources is available under the priority of the V2X traffic.

The simulated scenarios have enabled the verification that, in mode 4, an increase in the V2X packet transmission rate has a direct impact on the PDR obtained. For instance, at a reference distance of 300 meters and a vehicular density of 0.06 vpm, the PDR experiences a decrease of 50 percentage points when the transmission periodicity of the packet increases from 1 pps to 50 pps. Therefore, for services that require higher periodicity in the transmission of packets, it is imperative to acknowledge that the PDR declines in direct proportion to the distance from the transmission of the signal. Another pertinent consideration is that as the density of vehicles on the road increases, the probability that UEs reach the minimum percentage of candidate resources for their transmissions is low. This increases RSRP levels, thereby causing a higher degree of interference in communications, affecting the PDR. This indicates that LTE V2X mode 4 can function with an acceptable level of performance for basic services that do not necessitate a high packet transmission rate or strict coverage requirements. Nevertheless, in advanced use cases, LTE V2X may not offer optimal performance in terms of PDR under conditions of high density of V2X UEs and high periodicity of V2X packets.

The simulations have shown that mode 3 performs better than mode 4. This is attributed to the centralized execution of the sensing and resource allocation processes from an eNB node in mode 3, which can significantly improve PDR compared to the decentralized mode. Nevertheless, analogous to mode 4, PDR tends to diminish with increasing distance between the transmitter and receiver or with higher densities of V2X UEs. This is a crucial factor to be considered in scenarios where high network reliability and coverage are paramount. According to the simulations conducted, for a packet transmission rate of 10 pps and with the objective of achieving a PDR exceeding 80%, mode 4 is capable of maintaining this threshold only for distances less than 100 meters and 50 meters at vehicle densities of 0.06 vpm and 0.12 vpm, respectively. Conversely, in mode 3, due to its centralized resource management, a PDR above 80% can be sustained for distances up to 500 meters and 490 meters for vehicle densities of 0.06 vpm and 0.12 vpm, respectively. For instance, at a specific distance of 300 meters and a vehicle density of 0.06 vpm, mode 3 demonstrates up to a 40 percentage points improvement in PDR compared to mode 4. Table 4.2 provides a summary of these parameters.

Table 4.2: Comparative analysis of LTE V2X modes 3 and 4 across various performance benchmarks.

LTE V2X	PDR= 80%		Range= 300 m	
	0.06 vpm	0.12 vpm	0.06 vpm	0.12 vpm
Mode 3	500 m	490 m	PDR= 99.9%	PDR= 50%
Mode 4	100 m	50 m	PDR= 60%	PDR= 40%

Although a centralized approach may be more efficient in managing resource allocation for V2X communications, it may result in higher latencies due to the passage of resource allocation requests through a common node responsible for monitoring resource usage in both the time and frequency domains. This increased latency could present a limitation for advanced use cases. Consequently, utilizing a centralized mode can be advantageous in scenarios where cellular network infrastructure is unavailable or when the potential requirements of a V2X service are related to low latency, scalability, or autonomous operation. The practical implications of the findings of this chapter for implementations in real-world scenarios depend on the type of application or specific use cases. For instance, cellular network coverage is typically available in dense urban environments, suggesting that the optimal configuration may be mode 3. Additionally, vehicle speeds are relatively low in this scenario, and a high vehicle density is expected, so mode 4 will not provide optimal performance. Conversely, in rural environments, the recommended mode of operation may be mode 4 to ensure communications in scenarios without coverage. In particular, mode 4 on highways can be important in guaranteeing low latencies and high reliability, derived from implementing sensing and resource selection mechanisms that are managed autonomously.

Chapter 5

NR V2X Physical Layer, Resource Allocation, and Performance Evaluation

Similar to Long Term Evolution (LTE) Vehicle-to-everything (V2X), New Radio (NR) V2X establishes two modes of packet transmission for V2X: centralized and decentralized. In centralized mode, a V2X User Equipment (UE) located within the coverage area of a Next Generation Node B (gNB) node connects to the network through the Uu interface. In this scenario, the network assumes responsibility for resource allocation procedures and congestion control. Generally, the Packet Reception Rate (PRR) in centralized mode is higher compared to decentralized mode. This is because the network has continuous knowledge of the Sidelink (SL) subchannels in use, which avoids simultaneous allocation of such resources to other UEs for transmission. However, it is important to note that effective cellular network coverage is required in the centralized mode, referred to as mode 1 in NR V2X. In contrast, in the decentralized mode, or mode 2 of NR V2X, a V2X UE does not need to establish a connection with a gNB node to receive information about the radio resources to use for its transmissions. Instead, these procedures are autonomously managed among the V2X UEs that require transmitting V2X packets. This Thesis focuses on the evaluation of the mode 2 performance of NR V2X, taking into consideration the sensing and resource selection mechanisms outlined by Third Generation Partnership Project (3GPP). The exclusive evaluation of the decentralized NR V2X mode is justified by the particular interest in this mode, as it does not require cellular coverage. This feature is especially relevant in the current context, where 5G NR networks, unlike LTE V2X networks, are in an initial deployment phase in several countries worldwide, including numerous developing countries. In such circumstances, the implementation of a centralized mode would be impractical due to the limited infrastructure and incomplete coverage of 5G networks. Therefore, the focus on the decentralized mode of NR V2X allows the advantages of advanced vehicular communications to be leveraged without relying on full cellular network coverage, thus facilitating faster and more efficient deployment in various regions. The complementarity of decentralized operation in 5G C-V2X and centralized operation in 4G C-V2X could allow for low latency services to be delivered by the 5G network, thus further encouraging the focus of the evaluation on 5G mode 2 operation.

Firstly, an exhaustive account of the Physical (PHY) aspects is provided, along with a delineation of the sensing and resource selection procedures specified for NR V2X. Subsequently, the narrative elucidates the simulation tool utilized, the reference parameters derived from the 3GPP specifications, and the outcomes gleaned from a series of simulations conducted across various scenarios. The evaluation of the results focuses on the variation of the PRR as a function of factors such as the distance between vehicles, numerologies, channel bandwidths, SL subchannels lengths, vehicle densities, sensing window lengths, and considering the activation/deactivation of resource sensing procedures. Finally, an evaluation of NR V2X performance in Millimeter Wave (mmWave) bands was carried out. To this end, simulation scenarios were designed, and the parameters were defined according to the specifications established by the standard. One of the inherent advantages of mmWave bands lies in the ability to significantly increase the channel bandwidth, which translates into the expectation of achieving higher transmission rates and reduced communication latency due to higher numerologies. However, in the context of mmWave bands, it is important to remember that operating at high frequencies tends to decrease communication performance as the distance between the transmitter and receiver increases.

The chapter is structured as follows:

- Section 5.1 describes the physical layer and radio resource location aspects of both Release 15 and Release 16 for NR V2X.

- Section 5.2 provides a detailed description of the simulator utilized and the reference parameters defined for the NR V2X decentralized mode simulations.

- Section 5.3 presents the results obtained from the simulation of NR V2X mode 2 under different scenarios.

- Section 5.4 provides a comparative analysis of the performance of decentralized LTE V2X and NR V2X modes across various configuration parameters.
- Section 5.5 presents the results of the evaluation of NR V2X performance in mmWave bands.
- Section 5.6 draws the main conclusions of the chapter.

5.1 Physical Layer and Resource Allocation Aspects of NR V2X

5.1.1 NR V2X Physical Layer

Similarly to the categorization of LTE V2X networks, the NR V2X framework, as described in 3GPP Technical Specification (TS) 38.885 [63], defines two different modes of operation. Mode 1 involves a centralized operational paradigm that requires cellular network coverage to be available. In this setup, the UE connects with the network via the Uu interface, enabling the reception of operational configurations. It is worth noting that in this centralized approach, the network is aware of available resources. This ensures that multiple UEs do not compete for access to the same pool of V2X resources. However, mode 1 has a significant drawback, requiring the UE to be connected to a gNB. Additionally, the sustained communication requirement over the Uu interface in this mode causes an increase in communication latency, which is particularly disadvantageous in certain use cases defined for NR V2X networks.

Conversely, in the context of NR V2X communication, mode 2 represents a decentralized operational paradigm that operates independently of cellular network coverage. In this mode, designated as mode 2, V2X UEs units can establish SL communications. The PC5 interface enables UEs to manage a sensing, selection, and re-selection process of radio resources. The standard also outlines four sub-modes of operation for NR V2X SL Mode 2: 2a, 2b, 2c, and 2d. In Mode 2a, resembling LTE V2X mode 4, UEs independently select resources for V2X communication. In Mode 2b, a UE may aid in resource allocation for V2X transmissions by transmitting feedback information from other UEs to improve efficiency. In Mode 2c, UEs have the option to use preconfigured SL patterns from a designated pool of resources. In Mode 2d, a UE assumes the responsibility of managing the allocation of SL resources for other UEs, similar to a gNB in Mode 1, by organizing the distribution of resources to other UEs.

It is important to note that the NR V2X standard, as specified in 3GPP TS 38.885 [63], has a more flexible layout that includes three unique transmission modes for UEs. This contrasts with LTE V2X, which only allows broadcast transmissions. Three communication modes are available: unicast, broadcast, and groupcast. These modes are tailored to particular communication scenarios and requirements. Broadcast communications distribute messages to all V2X UEs located in a designated coverage area, ensuring that information spreads widely. On the other hand, unicast communications enable direct point-to-point communication between two individual V2X UEs and provide a more private and targeted exchange of information. Finally, groupcast communications transmit messages only to a specific selection of vehicles, restricting the number of recipients to a predetermined subset of V2X UEs.

Each transmission mode serves specific use cases where its application is essential. For example, groupcast communication is indispensable in scenarios like vehicle platoons, where V2X messages are exclusively exchanged among platoon members. In contrast, broadcast communications are vital in situations that require timely warnings or information to be sent to all nearby vehicles. For example, a UE integrated into an ambulance can use broadcast mode to send important warning messages to nearby vehicles, allowing them to take appropriate safety measures. It is essential to note that a UE can support multiple transmission modes simultaneously, allowing for greater flexibility in various communication situations. For instance, the leading vehicle of a platoon can use groupcast mode to communicate solely with members of the platoon, unicast mode to communicate with the leading vehicle in another platoon directly, and broadcast mode to transmit V2X messages to all nearby vehicles, thus optimizing communication based on each situation's specific needs.

In the context of NR V2X communication, the established standard prescribes the allocation of channels that bear a resemblance to those standardized for LTE V2X, as documented in [64]. These channels encompass the Physical Sidelink Broadcast Channel (PSBCH), the Physical Sidelink Control Channel (PSCCH), and the Physical Sidelink Shared Channel (PSSCH). It is noteworthy, however, that NR V2X introduces an additional channel, the Physical Sidelink Feedback Channel (PSFCH), specifically tailored to accommodate services that require transmitting feedback information from the recipients. Consequently, NR V2X is equipped to support a spectrum of transmission modes, including unicast, groupcast, and broadcast modes. Furthermore, the standard defines a set of reference and synchronization signals that are meticulously mapped to designated Resource Elements (REs) and are integral to various physical layer procedures. These signals include the Demodulation Reference Signal (DMRS), the Channel state information reference signal (CSI-RS), the Phase-tracking reference signal (PT-RS), as well as the Sidelink-Primary Synchronization Signal (S-PSS) and the Sidelink-Secondary Synchronization Signal (S-SSS).

The supported numerologies for NR V2X communications in Frequency Range (FR) 1 include the values u=0, u=1, and u=2, corresponding to Sub-Carrier Spacing (SCS) options of 15 kHz, 30 kHz, and 60 kHz, respectively. On the other hand, within the limits of FR 2, numerologies u=2 and u=3 are explicitly defined. Notably, within the broader context of the NR specifications, numerologies up to 960 kHz —i.e., u=6— are defined. However, it must be emphasized that not all these numerologies are supported in the context of NR V2X communications.

The modulation scheme selection depends on the channel used to transmit several types of information. For instance, for the PSSCH, available modulation options include Quadrature Phase Shift Keying (QPSK), 16-Quadrature Amplitude Modulation (QAM), 64-QAM, or 256-QAM. For PSCCH and PSBCH, the only allowable modulation scheme as stated in 3GPP specifications is QPSK [64].

The time and frequency resources assigned to V2X communication are known as resource pools. In standalone or centralized mode, these pools can be assigned to one or more UEs to transmit and receive V2X traffic. Each resource pool aligns with a carrier bandwidth and is mapped within a SL Bandwidth Part (BWP) using a specific numerology. It is noteworthy that, within a specific bandwidth of the carrier, only one SL BWP can be mapped to serve all UEs, as outlined in the 3GPP specifications [63].

Concerning frequency, a resource pool consists of L contiguous subchannels mapped to a BWP. Each subchannel, located within a time slot, comprises M contiguous Resource Blocks (RBs). The 3GPP NR V2X standard stipulates that a subchannel can contain 10, 12, 15, 20, 25, 50, 75, or 100 RBs, as detailed in [65]. As a result of numerology selection, the bandwidth assigned to each subchannel varies. It should be noted that a subchannel is the smallest unit of spectrum resources that can be allocated for SL reception or SL transmission purposes.

In the time domain, a slot is the smallest unit for SL communication in the resource pool of NR V2X. Notably, unlike NR Uu, NR V2X does not support mini-slots. Furthermore, it is imperative to recognize that not all slots are accessible for SL usage, as their availability is decided by Time Division Duplexing (TDD) patterns and SL bitmaps [66].

TDD patterns regulate the slot configuration, categorizing them as downlink, uplink, or flexible. Meanwhile, the SL bitmap specifies which of the slots labeled as uplink in the TDD pattern can be utilized for SL communication. According to [67], any legitimate TDD pattern, and SL bitmap pairing is viable. However, according to the standard, the SL bitmap length may vary between 10 to 160 as described in [66].

As previously stated, the minimum allocation of resources for NR V2X is one frequency subchannel and one time slot. Therefore, within each slot configured for SL, the PSCCH, PSSCH, and PSFCH are multiplexed along with the corresponding reference and synchronization signals. The standard outlines two methods for mapping channels and signals into 14 symbols that correspond to the use of the normal cyclic prefix, as explained in [64] —the use of the extended cyclic prefix consists of 12 Orthogonal Frequency Division Multiplexing (OFDM) symbols and only applies to u=2 numerology. These methods involve both time and frequency multiplexing —in LTE V2X only frequency resource multiplexing is supported. In addition, the optional multiplexing of PSFCH channels depends on whether Hybrid Automatic Repeat Request (HARQ)-based procedures are utilized.

Figure 5.1 illustrates the time and frequency resources specified for SL. The initial symbol in the slot serves for Automatic Gain Control (AGC), while the following 3 symbols are allocated for PSCCH. According to standards, the RBs for PSCCH can be 10, 12, 15, 20, or 25. The mapping of PSCCH into consecutive RBs should also be pre-configured and limited to the number of RBs that form a subchannel.

The PSSCH can be multiplexed in time and frequency in every slot designated for SL. Moreover, PSSCH can be multiplexed with PSCCH in time and frequency. Regarding frequency, the PSSCH can be assigned the number of subchannels accessible to SL in the resource pool, which depends on the type of data that must be transmitted. This enables 1 OFDM symbol to accommodate both PSSCH and PSCCH. Since 7 to 14 symbols can be configured for a slot in SL, the PSSCH can occupy 5 to 12 consecutive symbols. This is because the PSCCH can occupy two or three symbols in the same slot. A guard symbol remains after the last symbol contained in PSSCH. Additionally, Figure 5.1 depicts the multiplexing of PSFCH with PSCCH and PSSCH. The PSFCH utilizes two OFDM symbols, and a guard symbol is considered after that. Furthermore, DMRS is also available. PSSCH in the slot are mapped based on one of the patterns specified in [64].

5.1.2 Resource Allocation in NR V2X

The established standard's resource allocation protocols broadly align with those prescribed for LTE V2X systems. Still, principal disparities arise in the physical layer modifications unique to Fifth Generation (5G) NR networks —as detailed in the preceding section. An example is the PSFCH, which provides V2X receivers with the ability to provide feedback to transmitting entities,

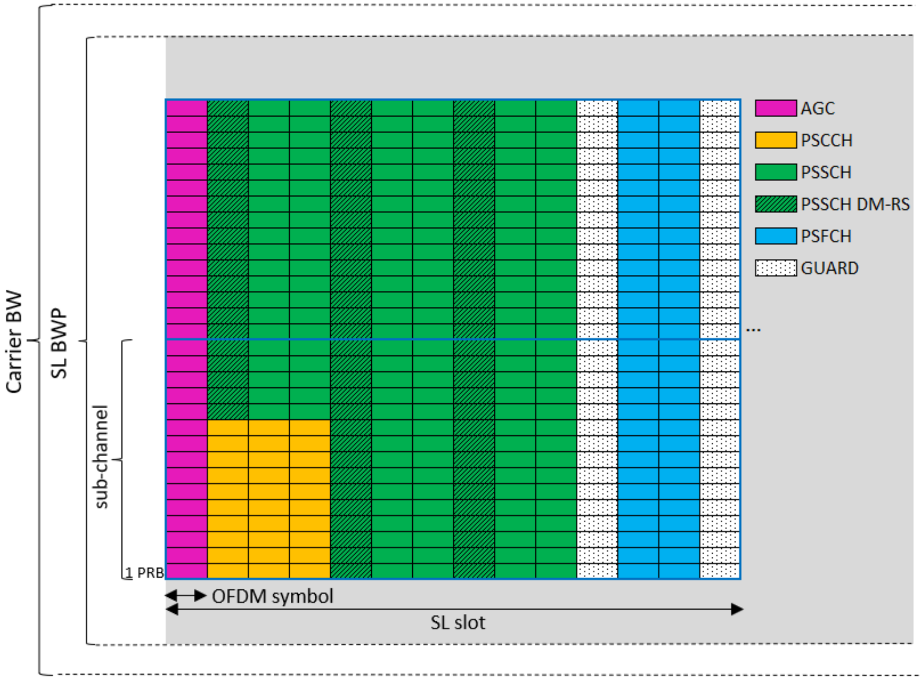

Figure 5.1: Example of sidelink slot structure in NR V2X.

thus enhancing communication robustness. The resulting feedback can refine the overall resource allocation protocols.

In NR V2X mode 1, the gNB has the responsibility for resource allocation. The allocation of SL hinges on various factors, such as the nature of V2X traffic or messages designated for exchange. The allocation process also considers the periodicity or non-periodicity of the traffic, which is closely tied to the V2X services or use cases intended for implementation.

The use of SL grants by UEs can be determined through Radio Resource Control (RRC) signaling, providing flexibility for immediate or responsive implementation based on gNB activity indicators. Additionally, gNBs have the ability to specify the Modulation and Coding Scheme (MCS) to be used within the allocated resources. Crucially, the standard dictating the allocation of resources for V2X, which can be utilized by a gNB, is based on feedback provided by UEs. The resource allocation process is centralized, giving the network a thorough understanding of the allocated resources and those available for assigning to other UEs.

NR V2X mode 2 has received significant attention due to its unique feature of decoupling resource allocation from a gNB connection. This mode enables UEs to independently select resources, facilitating V2X message exchanges in areas without cellular coverage. Nevertheless, mode 2 also presents its own set of challenges. Two or more V2X UEs must carry out precise sensing, selection, and resource reservation procedures in both time and frequency domains to function autonomously. Moreover, it is essential to implement effective congestion control mechanisms to alleviate high-density vehicle situations or congestion caused by numerous V2X UEs. These mechanisms ensure efficient and reliable communication in V2X environments.

Within NR V2X mode 2, two resource allocation schemes are prominent: dynamic and semi-persistent. The dynamic scheme allocates resources for a single Transport Block (TB) transmission, while the semi-persistent scheme selects and reserves resources for transmitting or re-transmitting multiple consecutive TBs. This duality enhances resource management flexibility and accommodates diverse communication requirements [66]. Unlike LTE V2X, NR V2X features a more advanced information exchange method utilizing SL Control Information (SCI). The SCI is transmitted in two stages, where the first stage is disseminated via the PSCCH. This initial stage provides the necessary information for the sensing process, enabling UE to determine the resources reserved for other UEs' transmissions. According to the [68] specification, a maximum of three reserved resources is allowed. In contrast, V2X receivers depend on the second stage of SCI that is transmitted through the PSSCH for decoding V2X packets. It is crucial to note that V2X receivers can only receive and use the first level of SCI, which is used exclusively for sensing operations. The second level of SCI is not accessible to them since V2X messages, particularly in instances of unicast or groupcast transmissions, are not designed for this receiver.

When a V2X UE initiates transmission, it triggers resource selection in slot n. This designated time slot serves as a reference point for performing resource sensing, selection, and reservation procedures, performed in proximity to slot n. This coordinated approach assists the UE efficiently manage and secure necessary resources for its transmission requirements.

Sensing Procedures

Once the resource selection trigger is activated, UEs must initiate resource selection based on measurements taken within a designated sensing window. This period encompasses slots falling within the interval denoted as $[n-T_0, n-T_{proc,0}]$, as depicted in Figure 5.2.

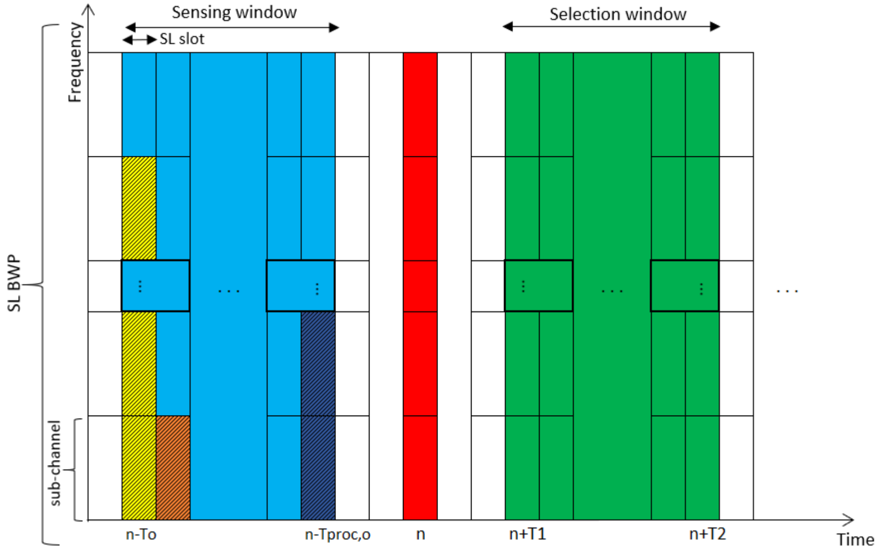

Figure 5.2: Time and frequency resource mapping in NR V2X.

The parameter T_0, as defined by RRC signaling, is a numerical value expressed in a specific number of slots. However, it is crucial to configure T_0 to align with either 100 ms or 1100 ms intervals, as explained in [66]. It is important to note that the precise number of slots is contingent upon the chosen numerology. Preserving the same slot count in higher numerologies leads to reduced duration of the sensing window. On the other hand, maintaining the same sensing time in higher numerologies requires increasing the number of slots in the sensing window, consequently necessitating a proportional increase in corresponding measurements.

The parameter $T_{proc,0}$ represents the duration required to execute the sensing process, which involves tasks like decoding the SCI and measuring reference signals in the initial stage. For u=0 and u=1 numerologies, $T_{proc,0}$ corresponds to a duration of one slot, while for u=2 numerology, it corresponds to 2 or 4 slots. Similarly to the T_0 parameter, the time allocated to complete the sensing process depends on the numerology used. For instance, in the case of u=0 numerology, this temporal interval amounts to 1 millisecond.

During the designated sensing window, Reference Signal Received Power (RSRP) measurements are conducted on reference signals related to the PSCCH and PSSCH. These measurements are performed specifically on channels that have received the initial stage of the SCI. This approach allows the UE to determine whether SL resources are occupied or reserved by other UEs. Resources that are already claimed by other UEs, as indicated by RSRP measurements above a specific threshold, are excluded during the resource selection phase because they cannot be used for V2X transmissions. Conversely, resources not reserved or exhibit RSRP measurements below a specific threshold are considered candidate resources for V2X transmissions. It is essential to note that in certain scenarios, a UE may itself be engaged in transmitting V2X packets, rendering it unable to detect resources reserved by other UEs. Consequently, mechanisms must be devised to exclude such occupied resources from consideration as candidates for V2X transmissions.

Resource Selection Procedures

As illustrated in Figure 5.2, the selection window spans the temporal interval $[n + T_1, n + T_2]$. The parameter T_1 represents the duration that a UE must account for in order to identify potential resources for its V2X transmissions. It is imperative that T_1 adheres to the following constraints: it must be less than or equal to 3 slots for numerology u=0, 5 slots for numerology u=1, and 9 slots for numerology u=2, as specified in [66].

Conversely, T_2 signifies a temporal value that should not exceed the Packet Delay Budget (PDB), which is the maximum time allocated for transmitting a TB. The configuration of T_2 depends on the specific application and is subject to customization at the UE level. The minimum permissible value of T_2 is determined based on the selected numerology. In the case of numerology u=0, the minimum T_2 value equates to 1 slot, corresponding to a duration of 1 millisecond. Upon establishing the duration of the selection window, the UE is tasked with the crucial resource selection process for its V2X transmissions. This selection process is governed by a set of criteria, which are as follows:

- Resources designated for transmission by other UEs that exhibit RSRP levels exceeding a specific threshold should be excluded from consideration. Nevertheless, certain resources, even if allocated to other UEs for transmission, may still be chosen by the current UE if the measured power levels fall below the specified threshold. This suggests that the measured power levels at these resources are sufficiently low to qualify them as viable candidates for selection, regardless of previous reservations made by other UEs.

- The selection process also involves verifying that the set of chosen resources constitutes a portion greater than or equal to a specific percentage of the total available V2X resources within the selection window. This percentage is determined through configuration using RRC signaling. It may be set at 20%, 34%, or 50%, contingent on the nature of the V2X traffic and its associated priority within the implemented use case. In cases where the number of selected resources falls short of meeting the prescribed percentage threshold, an incremental approach is employed to adjust the RSRP threshold. Specifically, the RSRP threshold is increased by 3 dB increments until the minimum requisite number of resources is achieved. This adjustment accommodates situations where a UE has previously reserved resources that fall below a certain RSRP threshold. In such instances, another UE with a higher transmission priority may necessitate a greater percentage of resources. Consequently, UEs with higher transmission priorities have the flexibility to select resources that have already been reserved, given that the power threshold for the resources they can choose is higher, enabling them to meet their transmission needs effectively.

- Before transmission begins on selected resources, UEs must conduct a re-evaluation process to confirm continued resource availability —These re-evaluation mechanisms were introduced in 3GPP Release 17. If the minimum required percentage of available resources is not met, the resource reservation process must restart. This updated process occurs in a new selection window and uses measurements collected in an updated sensing window. If the previously chosen resources are no longer feasible, UEs must adapt by selecting new resources to guarantee the successful execution of their transmissions.

- Subsequently, the UE chooses the reserved resources randomly, and it has the flexibility to transmit V2X traffic using dynamic or semi-persistent modes. These transmissions may encompass a range of approaches, including blind re-transmissions for broadcast transmissions or HARQ re-transmissions in the case of unicast or groupcast transmissions. The specific quantity of resources that the UE can select for its transmissions is subject to configuration through RRC signaling and may vary within the range of 1 to 32 resources.

- Semi-persistent mode transmissions allow the same resources to transmit consecutive TBs. This differs from dynamic mode, where resources are selected anew for each new TB. In the semi-persistent mode, a Reselection Counter (RC) manages the selection of resources for V2X transmissions. The RC is randomly chosen from a set interval whose length depends on the resource reservation period and is decremented every time the UE initiates a transmission of a TB or its associated re-transmissions. When the RC reaches a value of zero, the UE evaluates whether to select fresh resources with a probability of $(1 - P)$. If the outcome is positive, new resources are chosen. Otherwise, the UE continues to use the same resources selected in the previous resource allocation process. Each UE can choose a value for P between 0 and 0.8, which allows control of the probability of selecting new resources when the RC expires. When the RC reaches zero, and resource re-selection is necessary, the UEs transmit this information through the initial stage of the SCI to notify other UEs that they no longer have access to the previously allocated resources. This guarantees efficient resource management and allocation within the V2X communication system.

- To prevent a UE from continuously using the same set of resources indefinitely, the standard specifies a limit of $10 * RC$ times that the UE can occupy those resources, as discussed in [67]. For instance, if the RC is defined as 5, the UE can utilize the same resources for transmitting V2X traffic for a maximum of 50 times. This limitation guarantees equitable resource distribution and efficient utilization within the V2X communication system, preventing any individual UE from dominating the shared resources for an extended period.

The diagram depicted in Figure 5.3 shows a comprehensive flowchart that illustrates the sequential processes that are integral to resource discovery, reservation, and re-selection in the context of NR V2X) communication.

Congestion Control

Following the LTE V2X framework, NR V2X establishes methods for managing congestion in UEs through two primary metrics: Channel Busy Ratio (CBR) and Channel occupancy Ratio (CR). The CBR metric relies on measurements of Received Signal Strength Indicator (RSSI) during a designated 100-slot window, with the potential to adjust to a measurement window of $100 * 2^u$ slots depending on chosen numerology [66]. This time and frequency slot window includes all UEs that use resources. The associated subchannel is labeled as occupied if the RSSI goes beyond a predetermined threshold. The CR metric measures the occupancy produced by a UE involved in V2X transmissions. It calculates the ratio of subchannels chosen or booked by the UE for V2X traffic transmission. This calculation takes place in a fixed window of 1000 slots and offers the option to configure the window duration based on numerology. The measurement is necessary in $1000 * 2^u$ slots [66]. For example, in numerology u=1, the window extends to 2000 slots, corresponding to a duration of one second.

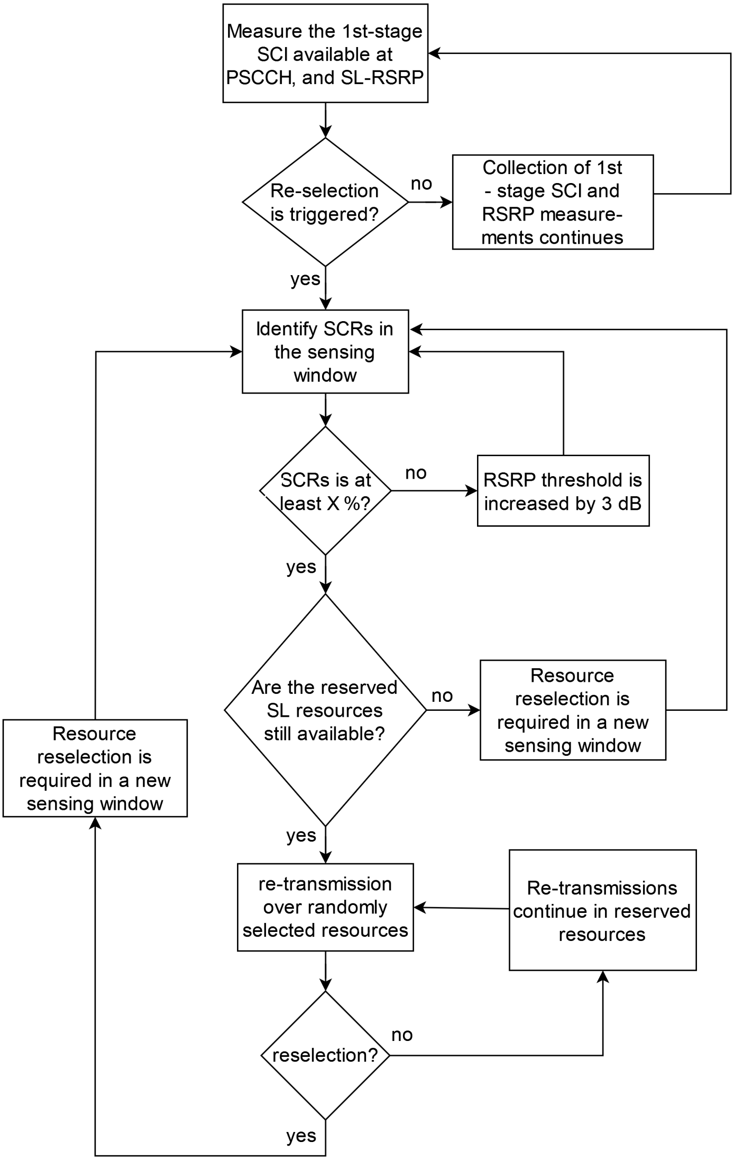

Figure 5.3: Procedures for sensing and resource selection in NR V2X.

The standard does not require a specific congestion control algorithm. Rather, it allows implementation based on the calculated CBR and CR parameters. Therefore, by utilizing the CBR calculation, threshold values for CR are set to reduce congestion. If the CR exceeds the specified limit, the UE can reduce congestion by adjusting various parameters. This involves improving the MCS, limiting the number of used subchannels, reducing re-transmissions, or lowering transmission power.

5.1.3 Advancements in Release 17 for NR V2X

Some enhancements have been incorporated in 3GPP Release 17 in order to support advanced services over NR V2X. In addition to the resource re-selection selection mechanisms described in the previous section, Release 17 includes enhancements aimed at reduced power consumption, improved reliability, and low latency.

The above sensing techniques contribute to increased device power consumption, a particularly relevant concern in applications where devices are battery-powered. For example, power efficiency is crucial in Vehicle-to-Pedestrian (V2P) communication scenarios where devices are either integrated into bicycles or carried by pedestrians. To address this, the NR V2X standard, aligned with LTE V2X, specifies that resource selection can use a random or partial approach [69]. When using random resource selection, UE autonomously selects resources from pre-configured resource pools, eliminating the need for sensing measurements. This method greatly simplifies the selection process. Conversely, partial sensing involves the UE evaluating only a predetermined number of slots within the sensing window. The quantity of slots to be sensed is pre-configured and can be adapted to accommodate periodic or aperiodic traffic patterns.

The standard presents an alternate approach to reduce the power consumption of UEs, referred to as SL Discontinuous Reception (DRX) [69]. During active DRX state, UEs execute the customary acquisition and decoding procedures for the PSCCH, PSSCH, among others. During the UE's inactive DRX state, it selectively receives and decodes the PSCCH and performs RSRP measurements according to the prescribed sensing procedure. This SL DRX functionality is applicable in NR V2X for unicast, groupcast, and broadcast transmission modes. Furthermore, a UE receiver can assist a UE transmitter in determining an appropriate SL DRX configuration tailored to the specific characteristics of the V2X traffic.

Alternative solutions introduced by Release 17 for V2X necessitate enhancements at the application layer to accommodate advanced services with stringent requirements. Furthermore, specific frequency bands have been delineated to facilitate the concurrent utilization of Uu and PC5 interfaces within LTE V2X and NR V2X networks. This integration is imperative for the deployment of V2X services in multi-RAT environments, enabling operations across diverse communication interfaces, transmission modes, and radio access technologies, as detailed in Chapter 6.

5.2 5G LENA and Benchmarks for Simulations

The simulation tools chosen for this study comprise the 5G LENA simulator, with a particular branch tailored for mode 2 vehicular communications exploiting NR V2X [70]. In [67], the branch developers specify the fundamental features and functionalities of the simulator, coordinating with the 3GPP standard. The first step in deploying this simulator requires the installation of the ns3 simulator. Subsequently, the installation process expands to integrating the 5G LENA simulator, which includes the specialized branch for V2X communication. Since the simulator strictly adheres to the technical reports and specifications of the 3GPP, it has a versatile code base. This code base serves as a flexible basis for creating different simulation scenarios. The primary objective of these scenarios is to derive essential metrics necessary for evaluating the performance of NR V2X mode 2.

The branch developed to enable V2X communication capabilities in the 5G LENA simulator includes several outstanding features, including:

- Radio Frame: The radio frame of the simulator adheres to the 3GPP standard [64], with a length of 10 ms divided into 10 subframes of 1 ms each. The number of slots per subframe varies depending on the employed numerology. This simulation tool supports several numerologies, including u=0, u=1, u=2, u=3, and u=4.

- Bandwidth parts: A bandwidth part is a contiguous set of RBs under the same numerology and carrier frequency. In NR V2X, multiple bandwidth parts can be configured for SL, but only one can be active at any given time.

- Duplex mode: The supported duplex mode is TDD. A TDD pattern can include slots defined for downlink, uplink, or flexible configurations.

- Resource Pool: A specified configuration of resources in time and frequency is defined for SL, following standard specifications. Only slots preconfigured as uplink and identified as SL by the bitmap are available for V2X traffic transmission. Within these SL slots, channels designated for V2X communication are mapped to the corresponding symbols. The number of RBs available in a subchannel is calculated in the frequency domain based on the numerology.

- Modulation: Support is included for QPSK, 16-QAM, 64-QAM, and 256-QAM modulation. It is crucial to note that the modulation scheme is not adaptive; it remains fixed for all transmissions.
- The configuration of resource location can be accomplished either randomly or by employing the sensing techniques detailed in Section 5.1.
- The employed channel coding is Low Density Parity Check (LDPC), and the modulation technique is OFDM.
- The output metrics include PRR, Packet Inter-Reception (PIR), and Throughput.

The simulation setup is shown in Table 5.1. To ensure consistency, all simulations for this study were designed specifically for a highway scenario and adhered to the reference parameters outlined in the 3GPP guidelines [71]. Additionally, the remaining parameters were meticulously configured to comply with the 3GPP standard for NR V2X.

5.3 NR V2X Mode 2 Performance Evaluation

The primary objective of the investigation was to elucidate the variations in PRR as a function of the spatial separation between transmitting and receiving vehicle units. In this computational simulation, the model includes 30 vehicles per lane, resulting in a total of 90 vehicles actively engaged in transmitting and receiving V2X packets. The graphical representation in Figure 5.4 shows in detail the discernible changes in PRR with respect to inter-vehicle distance. The PRR values presented in Figure 5.4 indicate the average packet reception within specific distance intervals. Notably, the simulation incorporates resource allocation by implementing resource discovery and selection procedures as described in the preceding sections. The depicted curves in Figure 5.4 underscore the superior performance of numerology u=2 compared to numerology u=0. Nevertheless, it is noteworthy that, beyond a distance of 120 meters, the PRR precipitously descends below the threshold of 80%, a level deemed insufficient for the seamless functioning of V2X applications that necessitate stringent performance standards.

Figure 5.5 illustrates the consequences of deactivating the sensing procedures prescribed by 3GPP. As a result, resource selection occurs randomly.

Table 5.1: Reference parameters for the simulation of NR V2X mode 2.

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	%
Max. PSSCH re-transmissions	5	-
Resource reservation period	100	ms
T_1	2	slots
T_2	33	slots
RSRP for SL measurements	-128	dBm
MCS	14 (64-QAM 3/4)	-

The results demonstrate a decrease in the PRR when resource selection is performed without the guidance of these specified sensing procedures. Moreover, it is notable that the observed trend of improved performance persists when operating with a 60 kHz numerology.

Activating sensing procedures is pivotal in improving packet reception accuracy in communication systems. Essentially, by implementing predefined rules and procedures to guide transmitters in selecting available resources, the probability of multiple vehicles selecting the same resources for their transmissions is significantly reduced. It is important to note that incorporating resource selection sensing involves computational costs that require integration into chipsets, with an associated increase in battery consumption. This issue is particularly critical in specific V2X scenarios, including V2P communication or devices integrated into bicycles to issue warnings and enhance road safety. On the other hand, in situations involving Vehicle-to-Network (V2N), Vehicle-to-Vehicle (V2V), or Vehicle-to-Infrastructure (V2I) communications where en-

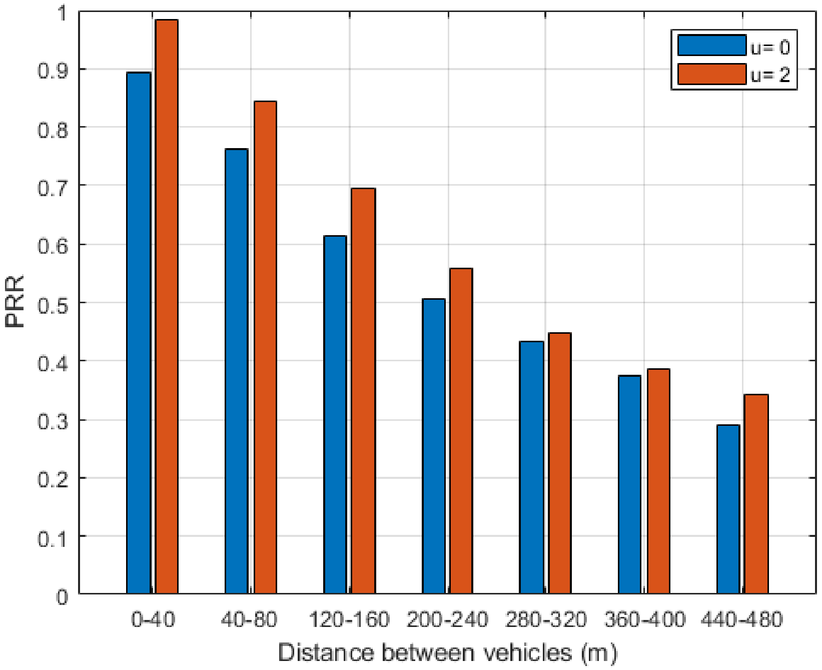

Figure 5.4: Average PRR for various vehicle separation ranges with sensing procedures enabled.

ergy usage is not a constraining factor, activating sensing processes results in significant advantages, leading to improved overall performance. Additionally, the flexibility of these processes to be enabled or disabled as needed for specific potential V2X service requirements is notable, as stated in [72]. Each service has a specific Key Performance Indicators (KPIs) that measures factors such as reliability, latency, throughput, packet size, and coverage area, among others. By customizing the deployment approach, the measurement procedures can be adjusted to meet the specific needs of various V2X applications.

Figure 5.6 shows the Cumulative Distribution Function (CDF) that displays the average PRR across different numerologies, specifically u=0, u=1, and u=2. These results were obtained using a randomized resource selection approach without activated resource selection mechanisms as stipulated by 3GPP. The findings support the hypothesis that higher numerologies result in better PRR performance. Nonetheless, it is worth mentioning the intersection point in the

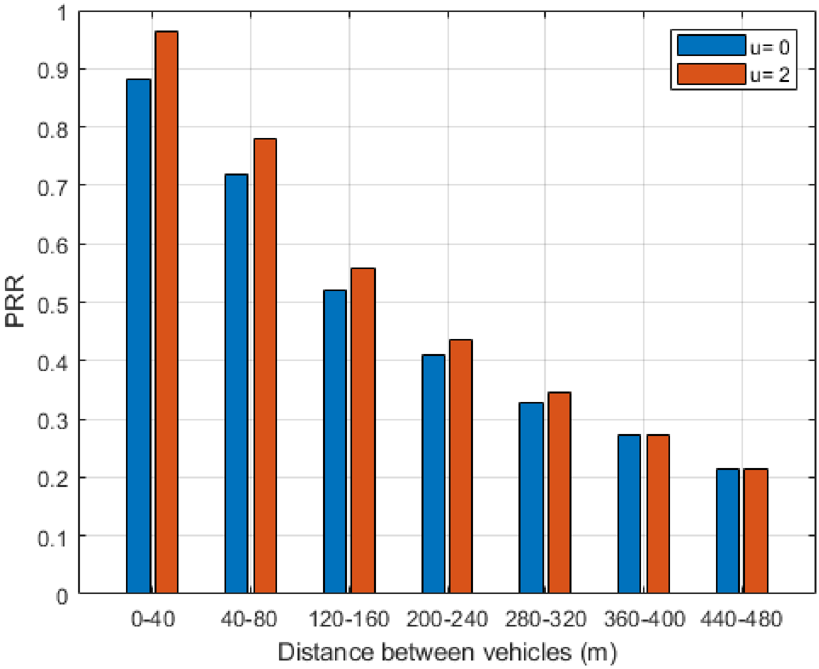

Figure 5.5: Average PRR for different vehicle spacing without enabling resource sensing procedures.

CDF curves for PRR shown in Figure 5.6, which can be attributed to the disparities in temporal and frequency resources resulting from the use of different numerologies. During the conducted simulations, a bandwidth value of 40 MHz was assigned. With a subchannel size of 50 RBs for SL, this results in 4 subchannels for u=0 numerology, 2 subchannels for u=1 numerology, and 1 subchannel for u=2 numerology. As a result, the use of u=0 numerology provides greater frequency resource diversity for vehicles in facilitating their V2X transmissions. However, it should be noted that the random resource selection process may result in interference and compromised packet reception when a vehicle selects the same resources as another. In contrast, increasing the number of resources causes a decrease in frequency diversity while simultaneously reducing the temporal resource selection window. This occurs because the resource selection window is determined by the number of slots between T1 and T2, with higher numerology leading to shorter slot durations. In the present simulations, a 32-slot configuration was assumed for the selection window, resulting in a window duration of $32/2^u$ ms. Therefore, for numerologies u=0, u=1, and u=2, the selection window durations are 32 ms, 16 ms, and 8 ms, respectively. In these simulations, given the fixed resource reservation period of 100 ms, higher numerologies reduce the probability of concurrent resource selection by users, thereby increasing the PRR.

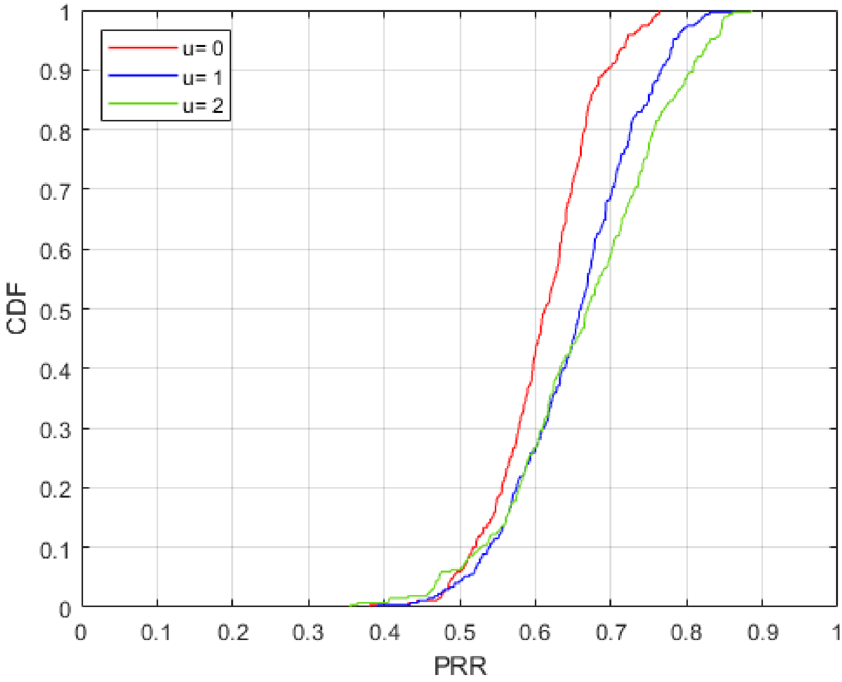

Figure 5.6: CDF of the PRR is calculated for various numerologies when sensing procedures are not activated. The transmission range is limited to a maximum distance of 200 meters between the transmitter and receiver.

Figure 5.7 displays the CDF of the PRR for the three numerologies depicted in Figure 5.6. This representation considers resource-sensing techniques. Activating sensing procedures, following the standards of the 3GPP, notably enhances the PRR. Specifically, it has been observed that in the absence of sensing procedures, the probability of PRR being less than or equal to 0.7 for numerology u=2 is 60%. However, when active sensing is employed, this probability decreases to approximately 30%. Moreover, the trend of superior average performance at higher numerologies continues. The crossover between numerology curves can be explained by sensing procedures affecting vehicles' choice of time and frequency resources for their transmissions. It was previously explained that the RSRP threshold rises when there is a lack of candidate resources for V2X transmissions. This interferes with resources already selected by other vehicles for their transmissions, emphasizing the critical role of high numerologies in enhancing PRR levels. Although u=0 numerology offers a pertinent basis for direct comparison with LTE, given identical time-frequency resources, disparities arise due to nuanced dissimilarities in sensing and resource selection procedures. While low numerologies suffice for basic services with low latency, network reliability, and throughput requirements, high numerologies emerge as imperative for services with more demanding prerequisites, optimizing network performance. Consequently, the transition from NR V2X to LTE V2X services under Radio Access Technology (RAT) operating conditions warrants consideration.

As previously explained, the standard allows for the assignment and activation of additional bandwidth parts with distinct numerologies in specific scenarios or use cases despite a single numerology typically being associated with one bandwidth part on a given carrier frequency. It is important to note that the standard provides flexibility in configuring various parameters even within a single numerology. This entails modifying the SL bandwidth size, subchannel size, and duration of the sensing and selection windows, among other factors. These measures facilitate the system's adaptability to various network conditions and needs, thereby increasing its potential to serve an array of deployment scenarios and applications.

The next experiment involves manipulating the distance between the vehicles in the 78 to 20 meters range. In this scenario, the physical proximity between vehicles is much closer, thus intensifying the interference experienced during communication. Figure 5.8 presents the comparative analysis of the results for numerology u=2. As anticipated, the performance decreases as the inter-vehicle distances reduce, which indicates increased vehicle density. Further, Figure 5.8 demonstrates the enhanced performance associated with the activation of resource sensing. The observable pattern indicates that resource sensing has beneficial effects on communication reliability and, consequently, packet reception ratio in scenarios featuring decreased inter-vehicle distances.

In the following simulation, the density of vehicles on the road was varied, specifically configured to accommodate ten vehicles per lane, for a total of 30 vehicles simultaneously engaged in transmitting and receiving V2X packets. As shown in Figure 5.9, a PRR was observed at lower vehicle densities. This improvement in the PRR in reduced vehicular density conditions can be at-

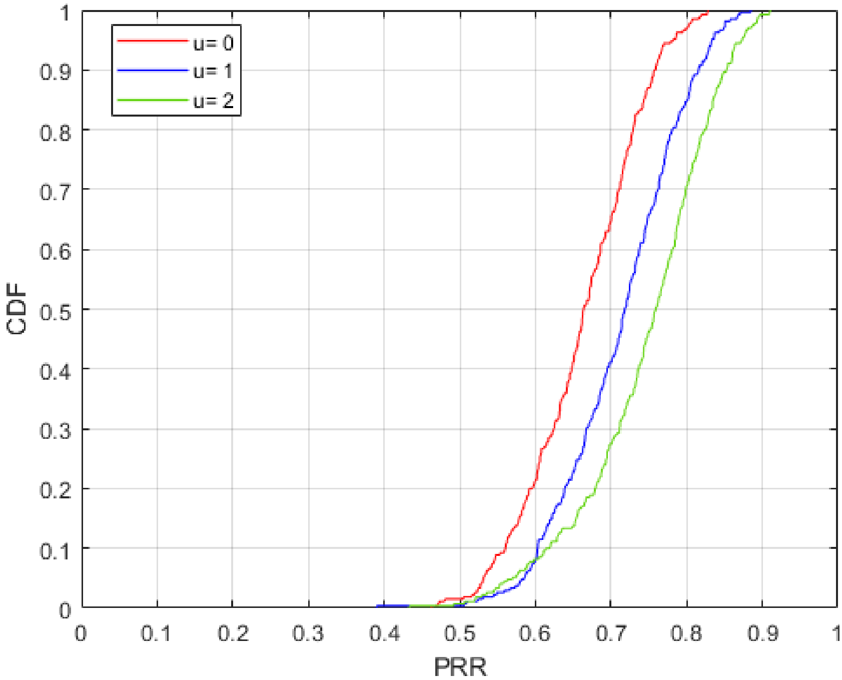

Figure 5.7: CDF of the PRR for different numerologies by activating the sensing procedures. The maximum distance between the transmitter and receiver is 200 meters.

tributed to the reduced interference during the resource selection process, both in the temporal and frequency domains. As the number of vehicles on the road decreases, the interference generated during resource selection is reduced. As a result, vehicles are not as obligated to increase the PRR threshold to achieve the minimum percentage of necessary resources for V2X transmissions. As explained earlier, when vehicles fail to secure the minimum percentage of candidate resources, they must raise the RSRP threshold, which results in using resources already assigned to other vehicles for their transmissions.

Figure 5.10 shows the PRR CDF for numerologies u=0 and u=2 as the subchannel size designated for SL communication varies. The comparison is made between the reduction in the size of SL subchannels from 50 RBs to 20 RBs, as stipulated by the standard. For both numerologies, an improved performance

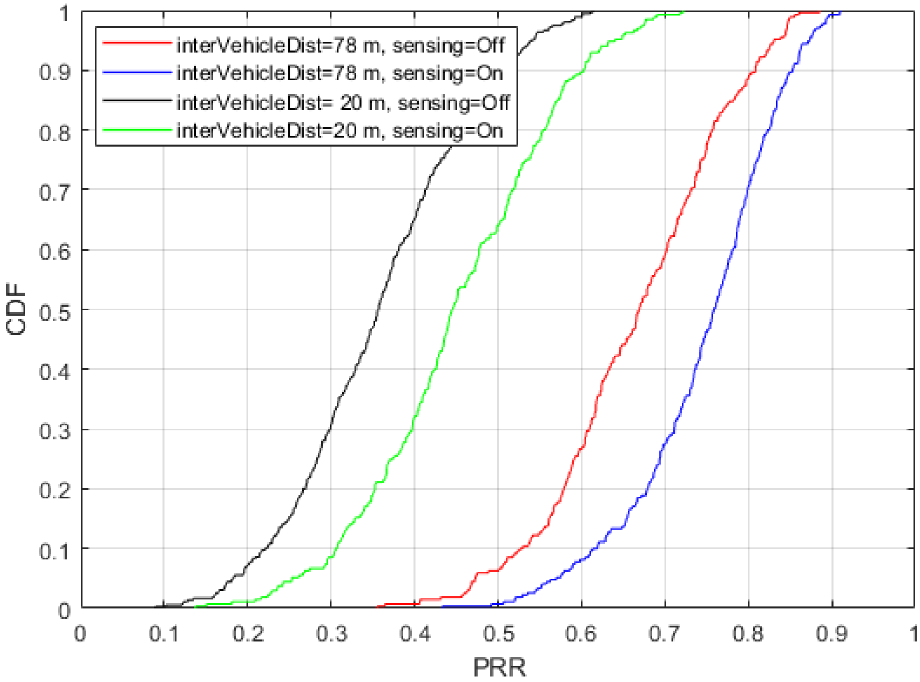

Figure 5.8: The evolution of the PRR CDF over varying distances between vehicles is studied, with particular emphasis on the activation and deactivation of resource sensing.

is evident with a decrease in subchannel size. This improvement is due to the increased diversity of frequency resources available for V2X transmissions by vehicles.

Specifically, when the subchannel size is 50 RBs, there are 4 subchannels for u=0 numerology and 1 subchannel for u=2 numerology. In contrast, with a reduction to 20 RBs, the number of SL subchannels rises to 11 for u=0 numerology and 2 for u=2 numerology. This increase in available subchannels significantly reduces the probability that vehicles employ the same frequency resources. Consequently, the minimum percentage of candidate resources is more likely to be satisfied without increasing the RSRP, thereby minimizing interference.

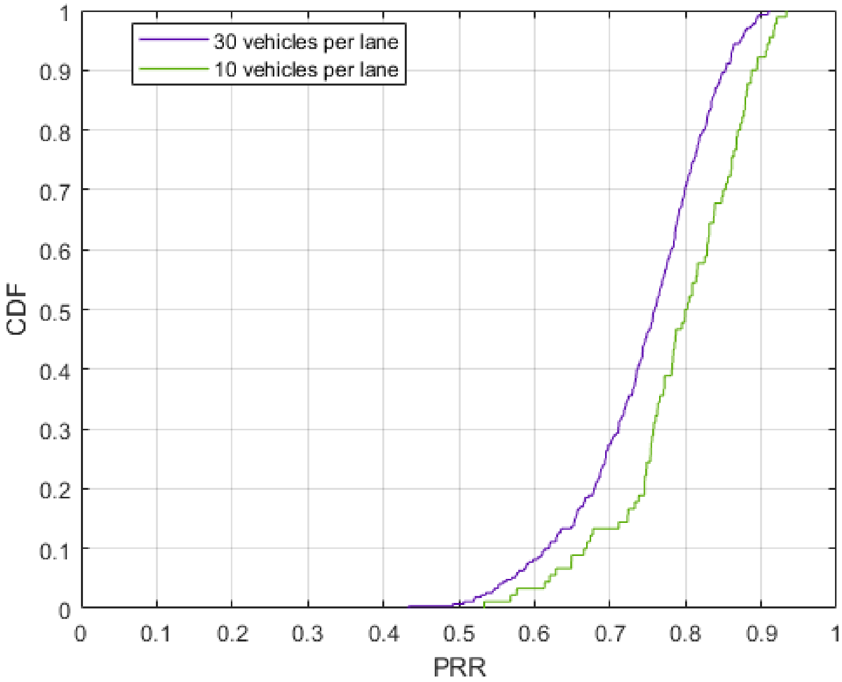

Figure 5.9: The fluctuation in PRR is examined across diverse vehicular densities, with a specific focus on numerology u=2.

Moreover, higher numerologies exhibit superior performance due to a shorter selection window in time. However, as illustrated in Figure 5.11, lower numerology may outperform when the subchannel size is smaller. It is imperative to note that the size and number of subchannels selected by transmitters should be intricately linked to the dimensions of the V2X packets. Larger V2X packets necessitate the selection of either larger subchannels or more subchannels within one or more slots.

The size of the subchannel significantly impacts the decision to activate or deactivate resource sensing. Figure 5.12 shows a comparative analysis of numerology performance under active and deactivated sensing conditions, with channel sizes specified as 50 RBs and 20 RBs. The simulation results show that smaller subchannel sizes lead to superior performance when the resource sensing functionality is disengaged and the numerology remains constant. This

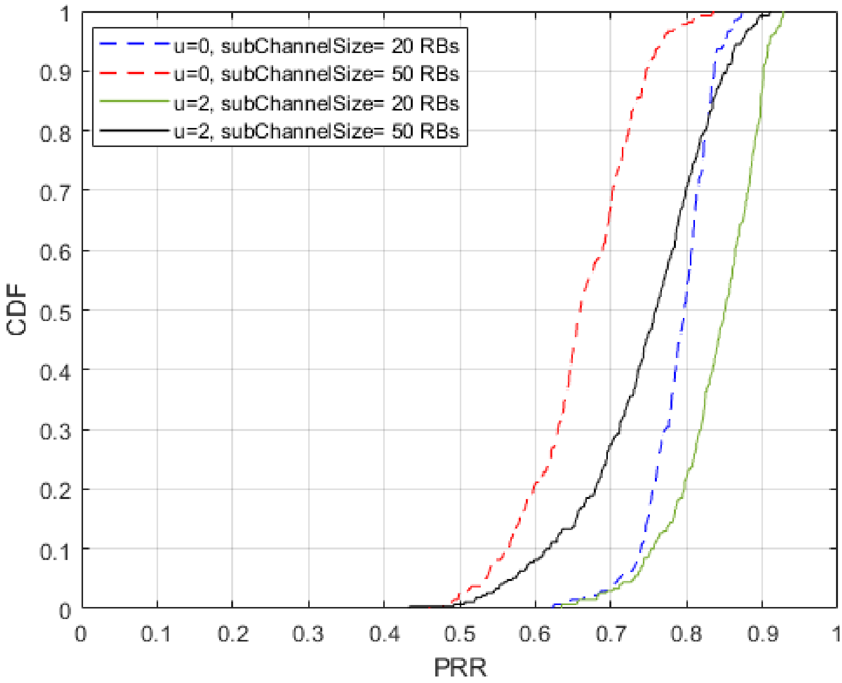

Figure 5.10: Evolution of the PRR CDF for different numerologies and SL subchannel sizes.

configuration is advantageous in scenarios where V2X devices require a minimized power consumption. It is important to note that enabling sensing leads to improved performance under the same operational parameters but at the cost of increased power consumption. This increase is due to the resource measurement, candidate resource determination, and congestion control procedures required by the activation of resource sensing. Therefore, configurations with reduced subchannel sizes and disabled resource sensing may be particularly beneficial in applications where power efficiency is critical.

The duration of the sampling window significantly affects the performance of PRR. Figure 5.13 shows the impact of extending the length of the sensing window, which varies from 100 to 1100 ms according to the established standard for the u=2 numerology. Extending the sensing window provides additional information about the SL resources available for V2X transmissions.

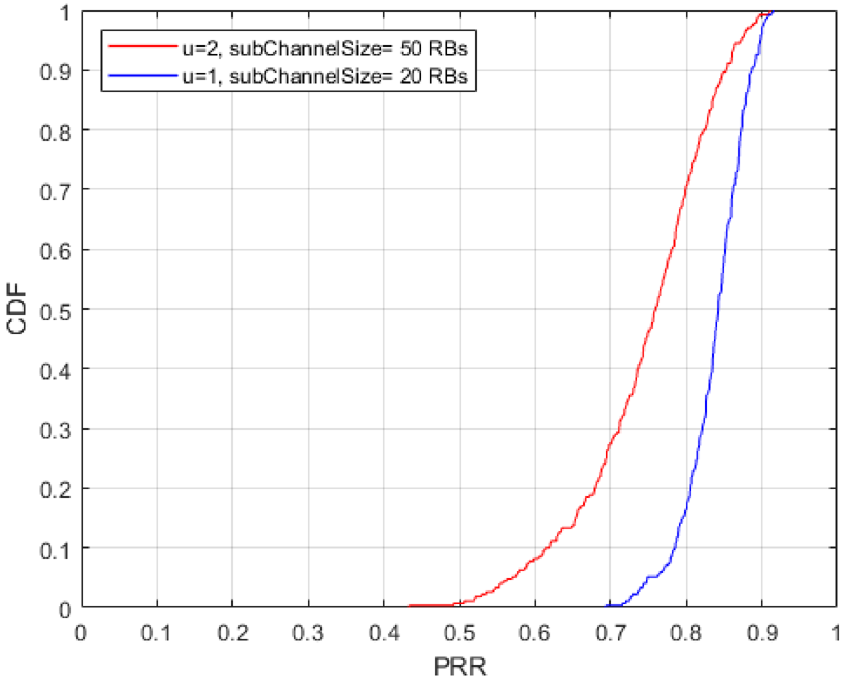

Figure 5.11: The PRR CDF increases in the u=1 numerology compared to the u=2 numerology when the size of the SL subchannels is reduced.

Consequently, vehicles can intelligently release resources that have already been reserved by other vehicles for their transmissions or retransmissions, thereby improving the overall PRR. However, it is important to note that increasing the sensing time can directly impact the energy consumption and computational complexity of the devices. Therefore, using a larger sensing window in scenarios where devices are not constrained by resource availability or battery consumption may be advisable. It is crucial to note that the sensing window, which is defined temporally, results in increased time slots for sensing operations at higher numerologies. Careful consideration of the trade-offs is necessary to optimize performance based on the specific constraints and requirements of the deployment scenario.

The simulation results offer valuable insights into the overall system performance. Optimal performance is generally observed with higher numerologies

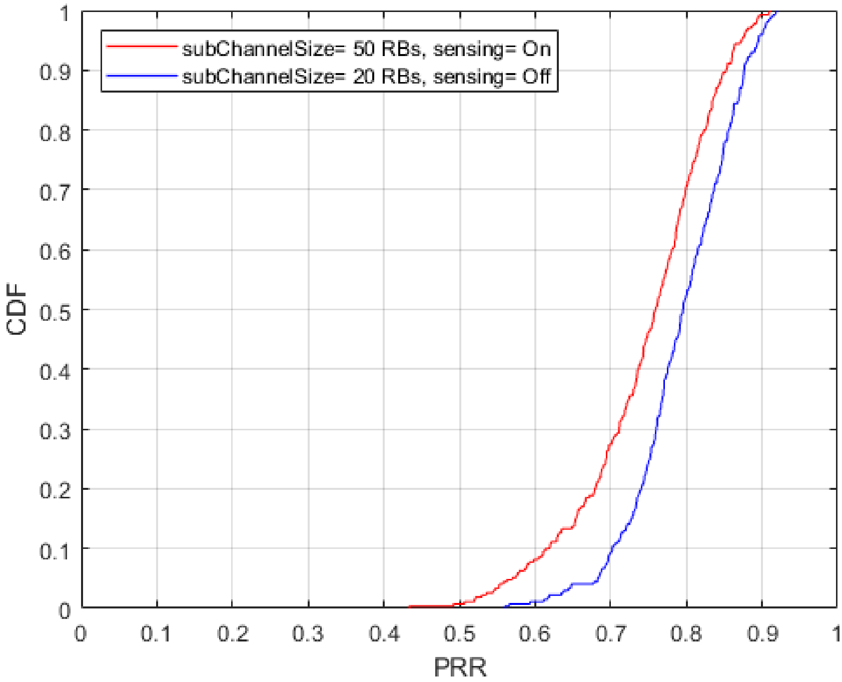

Figure 5.12: Increase PRR under the same numerology obtained by disabling resource detection and smaller SL subchannels.

and the activation of the sensing and resource selection procedures. However, it is essential to note that performance variations exist depending on the specific parameters configured according to the standard specifications. For instance, the standard specifies a set of options for the size of SL subchannels, including 10, 12, 15, 20, 25, 50, 75, or 100 RBs. In these simulations, PRR has been calculated only for selected scenarios with 20 and 50 RBs, but it is imperative to acknowledge that there are additional variations that deserve consideration. Not all subchannel sizes can also be configured for a given channel bandwidth. For example, in a 40 MHz bandwidth, using a SL subchannel size of 100 RBs results in 2 subchannels for u=0 numerology, 1 subchannel for u=1 numerology, and no subchannel for u=2 numerology. This limitation is due to the definition of subchannel sizes in terms of RBs and the need to adhere to a maximum channel bandwidth. The standard allows for defining channel bandwidths of

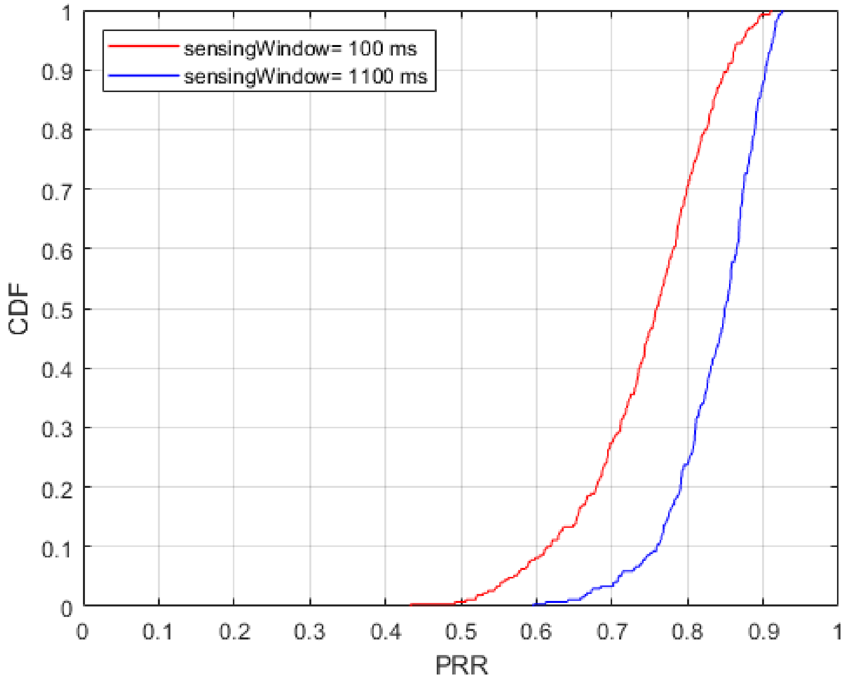

Figure 5.13: Impact of sensing window size on PRR for u=2 numerology.

10 MHz per BWP. To guarantee the availability of at least one SL subchannel, the size of these subchannels must be limited to a maximum of 50, 20, and 12 RBs for numerologies 0, 1, and 2, respectively.

In accordance with 5G NR specifications, a single bandwidth with a specific numerology is allocated for all V2X UE on a given carrier frequency. Within a BWP, individual UEs may be assigned distinct resource pools, allowing for the establishment of diverse pre-configurations as outlined in [63]. These configurations include variations in the number of RBs per subchannel, the number of retransmissions, and the MCS. Illustratively, the simulations presented in Figure 5.11 demonstrate that reducing the number of RBs per subchannel leads to a greater diversity of frequency resources, thereby enhancing PRR. However, it is essential to consider the size of the V2X packets. In scenarios where a single UE needs to select more than one SL subchannel, an alternative approach is to employ a higher MCS to transmit the same V2X traffic without consuming additional frequency resources. It is imperative to note that using a higher MCS is advisable only in environments characterized by low interference or congestion; otherwise, it may prove counterproductive. This underscores the need for a nuanced and context-specific pre-configuration approach to optimize the trade-off between resource efficiency and transmission reliability.

Figure 5.14 compares the performance achieved using a 10 MHz channel bandwidth and a sensing window that varies from 1100 ms to 100 ms, with u=0 numerology. The results show that the variation of the sensing window does not affect the performance achieved in the u=0 numerology. However, previous results demonstrate that reducing the size of the SL subchannels enhances performance by generating a greater diversity of frequency resources.

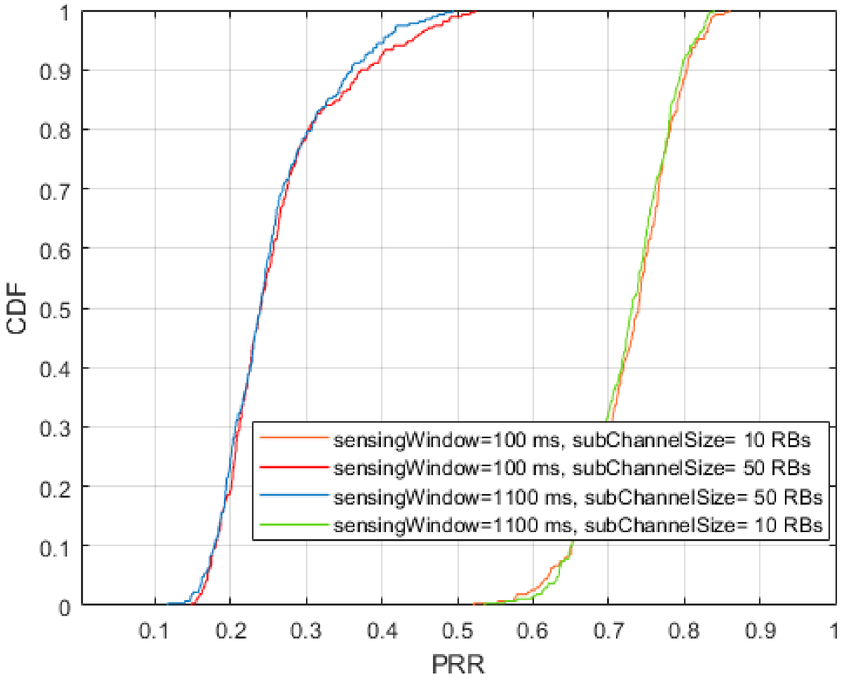

Figure 5.14: Performance achieved for u=0 numerology with a bandwidth of 10 MHz was evaluated by considering different sensing window durations and SL subchannel sizes.

Within the u=0 numerology and with a subchannel size of 10 RBs in a 10 MHz bandwidth, a maximum of 5 SL subchannels can be achieved. However, when adhering to the NR standard with a bandwidth of 50 MHz, the potential number of SL subchannels increases to 27. Figure 5.15 shows that increased frequency resources improve performance. This is because vehicles have more subchannels to choose from, allowing them to make better decisions about their data transmissions.

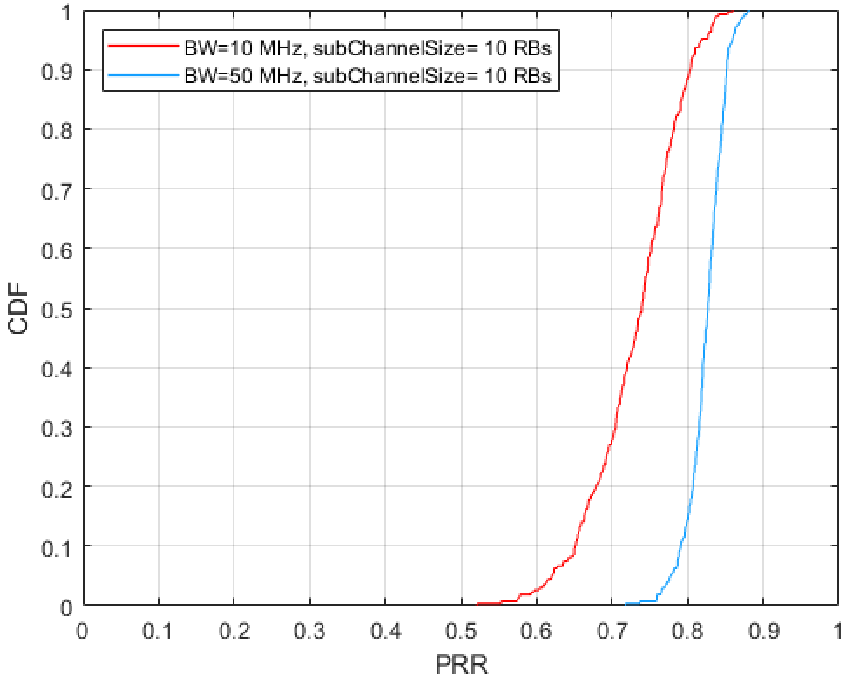

Figure 5.15: PRR variation for u=0 numerology, when varying the channel bandwidth from 10 to 50 MHz, and with different SL subchannel sizes.

For V2X applications or services that require larger packet transmission sizes, it is necessary to expand SL subchannels. Therefore, to increase the channel bandwidth, a viable approach is to increase SL subchannel sizes without compromising performance. As shown in Figure 5.16, the comparison indicates that configuring a 10 MHz bandwidth with a subchannel size of 10 RBs within the u=0 numerology produces performance similar to that achieved with a 50

MHz bandwidth and a SL subchannel size of 50 RBs. Both configurations allow up to five subchannels per slot, resulting in comparable performance outcomes. The feasibility of achieving desired transmission characteristics can be emphasized by appropriately adjusting the channel bandwidth and subchannel size parameters.

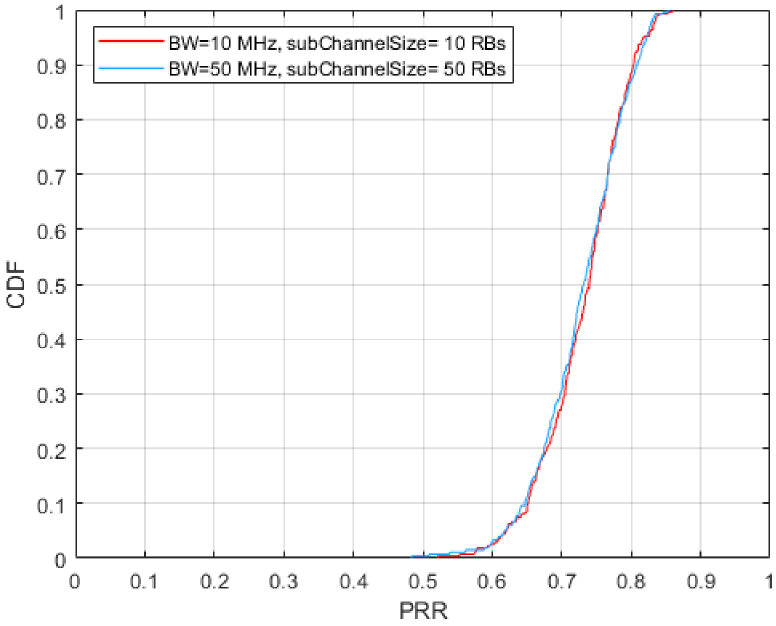

Figure 5.16: Similar performance can be achieved by combining different channel bandwidths and SL subchannel sizes for u=0 numerology.

NR V2X sub-6 GHz allows channels up to 100 MHz for u=2 numerology. Figure 5.17 elucidates the performance outcomes of the numerology u=0, with a bandwidth of 10 MHz and the SL subchannels comprising 10 RB, compared to the numerology u=2, with a bandwidth of 100 MHz. In this scenario, u=0 numerology yields up to 5 SL subchannels, whereas u=2 numerology yields up to 13 SL subchannels. The enhancement in performance can be attributed to the increased bandwidth, which facilitates a broader diversity of resources while maintaining identical SL subchannel dimensions.

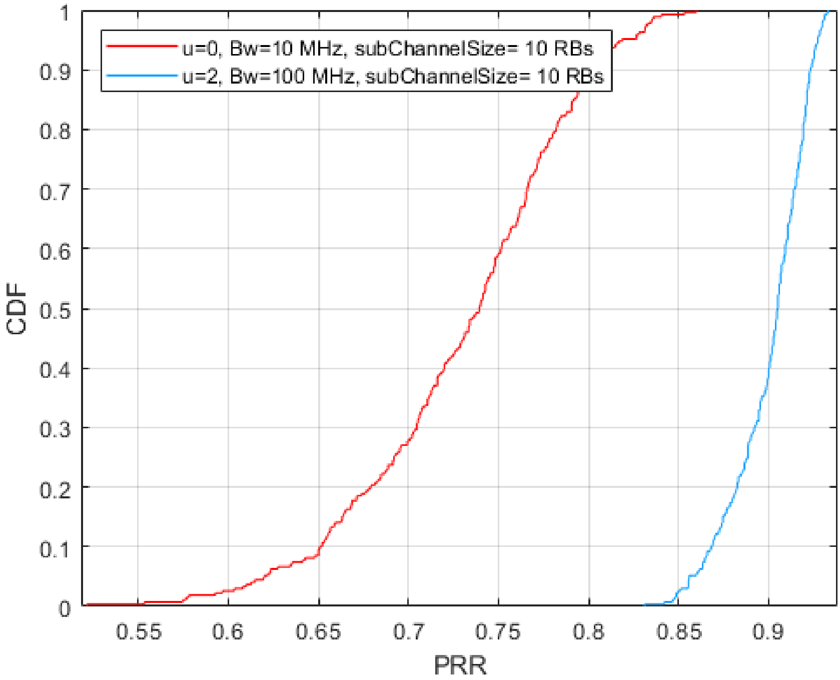

Figure 5.17: The performance of NR V2X is enhanced when the u=2 numerology is configured with a bandwidth of 100 MHz.

5.4 Comparative Analysis of LTE V2X and NR V2X Performance

Both mode 4 and mode 2 adhere to decentralized paradigms for LTE and NR standards, respectively. Resource allocation is independent of the coverage of the cellular network. Instead, these modes employ autonomous sensing, reservation, and resource selection procedures in the temporal and frequency domains. Notable similarities exist in the resource selection mechanisms prescribed by the 3GPP for mode 4 —Release 14— and mode 2 —Release 15 and later. The differences between these procedures mainly stem from the new PHY and MAC layer considerations introduced in the context of NR V2X, as summarized in Table 5.2.

Table 5.2: Differences between the main PHY and MAC layer parameters of LTE V2X and NR V2X.

Parameter	*LTE V2X*	*NR V2X*
MCS	QPSK, 16-QAM, 64-QAM	QPSK, 16-QAM, 64-QAM, 256-QAM
Multiple Access	SC-FDMA	OFDMA
Frequency operation	sub-6 GHz	sub-6 GHz, mmWave
Subcarrier Spacing	15 kHz	15 kHz, 30 kHz, 60 kHz, 120 kHz
Communication modes	mode 3, mode 4	mode 1, mode 2
Sensing window	1000 ms	100 ms, 1100 ms
Channel Bandwidth	max. 20 MHz	max. 400 MHz
SL subchannels	max. 50 RBs	max. 100 RBs
TTIs	1 ms	1 ms, 0.5 ms, 0.25 ms, 0.125 ms

Table 5.3: PRR performance for LTE V2X and NR V2X for a reference distance of 200 m.

LTE V2X	NR V2X			
	u=0		u=2	
	10 MHz	100 MHz	10 MHz	100 MHz
PRR=55%	PRR=85%	n/a	PRR=87%	PRR=94%

As previously stated, one of the primary distinctions between NR V2X and LTE V2X is related to subcarrier spacing. In LTE V2X, the exclusive use of 15 kHz subcarrier spacing is observed. In contrast, NR V2X permits the utilization of subcarrier spacings of up to 60 kHz within the FR1 frequency range and up to 120 kHz within the mmWave bands. Moreover, the NR V2X standard specifies wider channel bandwidths than LTE V2X, according to the numerology employed. For FR1, channels up to 100 MHz are specified, while for mmWave, channels can reach up to 400 MHz. In order to facilitate a comparative analysis of the performance of LTE V2X and NR V2X, the identical scenario that was previously simulated in Chapter 4 was configured in the 5G LENA simulator. The results of the performance comparison between LTE V2X and NR V2X, under different configuration parameters set by the standard, are presented in Table 5.3.

For a reference distance of 200 meters between transmitter and receiver, defined as the maximum distance at which V2X packets are considered relevant [73], it is possible to compare the performance of LTE V2X and the various numerologies and channel bandwidths supported by NR V2X. Simulation results indicate that the PRR for the reference distance of 200 meters is 55% for LTE V2X. In contrast, in NR V2X with u=0 numerology, the PRR reaches up to 85%. This 30 percentage points difference in the rate of correctly received packets evidences that the performance of NR V2X is superior to that of LTE V2X in the same scenario. Moreover, this performance remains superior even under the same channel bandwidth and carrier spacing of LTE V2X.

As the standard allows the configuration of higher numerologies with higher bandwidths in NR V2X, the performance of NR V2X was simulated with the maximum numerology and bandwidth defined for sub-6 GHz bands, thus maintaining the same operating frequency as in the scenario simulated for LTE V2X. In this case, it was demonstrated that NR V2X can enhance PRR levels by up to 39 percentage points in comparison to LTE V2X. This increase can be attributed to the fact that, with a numerology of u=2 and a bandwidth of 100 MHz, the diversity of resources in time and frequency is significantly greater than that of LTE V2X. Consequently, the probability of vehicles selecting the same resources for their transmissions is reduced. In addition to the aforementioned aspects, the enhanced performance of NR V2X can be attributed to its more robust technology, which employs improved sensing and resource selection mechanisms, higher-order modulation schemes, new channel coding techniques, and shorter transmission times, among other factors.

Given that NR V2X is designed to support a greater range of advanced use cases than LTE V2X, it is evident that, in addition to enhancements in the reliability of V2X packet transmission, a reduction in communication latency is also observed. This is of particular importance in certain applications where response time is a critical parameter. The simulations indicate that, for u=0 numerology in NR V2X, the average latency reduction due to retransmissions is up to 30 percentage points compared to LTE V2X. Conversely, when employing u=2 numerology, this reduction in average latency due to retransmissions reaches up to 39 percentage points. Furthermore, the utilization of high numerologies in NR V2X enables a reduction in Transmission Time Intervals (TTIs) due to the decrease in slot duration. Accordingly, the slot duration is 1 ms, 0.5 ms, 0.25 ms, and 0.125 ms for u=0, u=1, u=2, and u=3 numerologies, respectively. Consequently, it can be inferred that the reduction in transmission times in NR V2X FR1 may be up to four times greater than that observed in LTE V2X, and up to eight times greater in NR V2X FR2. These factors permit a notable reduction in the average latency of NR V2X in comparison to LTE V2X. In addition, in NR V2X, the high numerologies exhibit a larger subcarrier spacing, thereby conferring enhanced resilience to phenomena such as the Doppler effect, phase shift, and inter-symbol interference. This further substantiates the superiority of NR V2X over LTE V2X in terms of latency and reliability in advanced vehicular communication scenarios.

5.5 Performance Evaluation of NR V2X in mmWave Bands

Given that the standards defined by 3GPP for NR also consider using mmWave bands, performing a performance evaluation of NR V2X under these conditions is of interest. The software used to perform these simulations is known as Millicar [30]. This open-source tool is essentially an ns3 module that allows testing various V2V communication scenarios under specifications defined for 5G NR. Thus, Millicar adds functionalities related to PHY and Media Access Control (MAC) layers, such as using mmWave bands, mini-slots, flexible numerologies, and adaptive modulation. Additionally, Millicar integrates the channel model proposed by 3GPP, as well as V2V-Highway and V2V-Urban scenarios, along with 3 states in which vehicles can be found on the road: Line-of-Sight (LOS), Non-Line-of-Sight (NLOS), and vehicle Non-Line-of-Sight (NLOSv). In the latter case, it is assumed that the blockage is due to the position of other vehicles.

The simulations were conducted using parameters set in three of the scenarios available in the examples folder of the Millicar module. This simulator complies with the specifications of the 3GPP for vehicular communications in mode 2. Additionally, it is configured with the parameters established in the specifications for using mmWave bands. Such bands are of interest due to the availability of spectrum, which allows for the assignment of large bandwidths per channel, thus enabling higher transmission rates and reduced latency in communications. The latter is crucial for specific potential requirements for V2X services and applications, as indicated in Section 3.2.

The first scenario involves two vehicles traveling on a road one after the other at constant speeds. In this scenario, parameters such as vehicle speed, distance between vehicles, bandwidth, and packet interval were modified. In the second scenario, two groups of vehicles, each with two vehicles, one behind the other, travel in the same direction, either in the same lane or in different lanes, with a predetermined separation of 20 meters between the two groups of vehicles. In each group, the vehicle at the rear acts as a server and transmits packets to the vehicle at the front. In this scenario, parameters such as vehicle speed, distance between vehicles in each group, and distance between vehicle groups were modified. Finally, the third scenario involves three vehicles, two moving in the same direction at a constant speed. The third vehicle travels away from the first two at the same speed. One of the vehicles acts as a server, retransmitting the packets sent by the others. The packets exchanged between vehicles are of the User Datagram Protocol (UDP) type with 1024 bytes. As a result, throughput and PRR metrics were obtained.

After executing the different simulations, ns3 generates tables with metrics related to the abovementioned three scenarios. For the first scenario, constant speeds of 5 m/s, 20 m/s, and 40 m/s were configured. The vehicles' separation varied between 50 m, 150 m, and 250 m. The bandwidth is 100 MHz, and the center frequency is 28 GHz. The numerology used is u=3, which means 120 kHz subcarriers [64]. The results consist of the average throughput in Mbps obtained based on the number of correctly received packets in the simulation time, as shown in Figure 5.18.

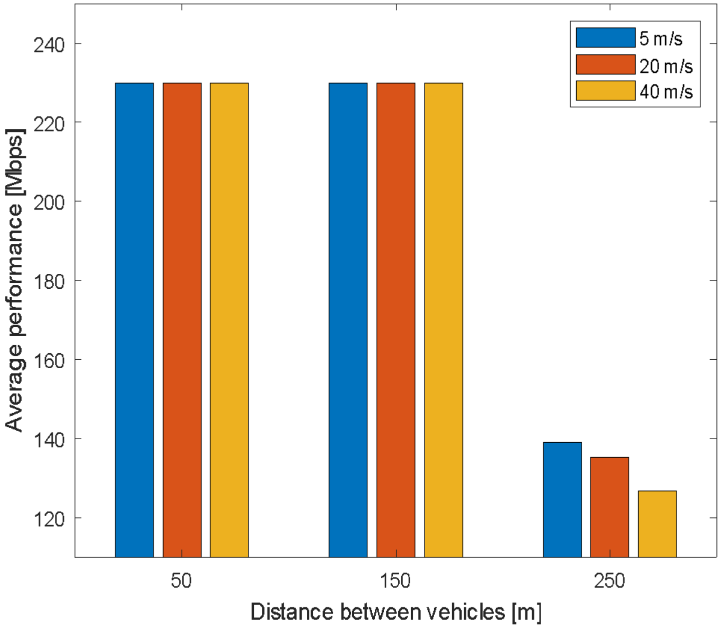

Figure 5.18: Performance achieved for scenario 1, utilizing a 100 MHz channel bandwidth.

The results indicate that under 100 MHz bandwidth conditions, there are no variations in performance when the distance parameters are varied between 50 m and 150 m, and speeds of 5 m/s, 20 m/s, and 40 m/s are employed. Consequently, an average performance of 229.97 Mbps is achieved. However, the performance decreases significantly when the distance between vehicles increases to 250 m. This can be attributed to the fact that interference and channel attenuation do not impact packet reception at shorter distances. Conversely, as the distance between the transmitter and receiver increases, the packet loss rate also rises, consequently affecting performance.

As observed in Figure 5.19, at a 250-meter separation between vehicles, the increase in speed directly impacts the average performance due to considerable channel degradation in mmWave bands. One way to counteract this effect in vehicular communication scenarios is by utilizing V2X nodes, known as Road Site Units (RSUs). RSUs are installations positioned along roadways that extend the range of communications between vehicles. It is worth noting that an RSU is not necessarily a 5G node but rather a V2X element that expands coverage while maintaining resource allocation in an autonomous mode outside the scope of the cellular network.

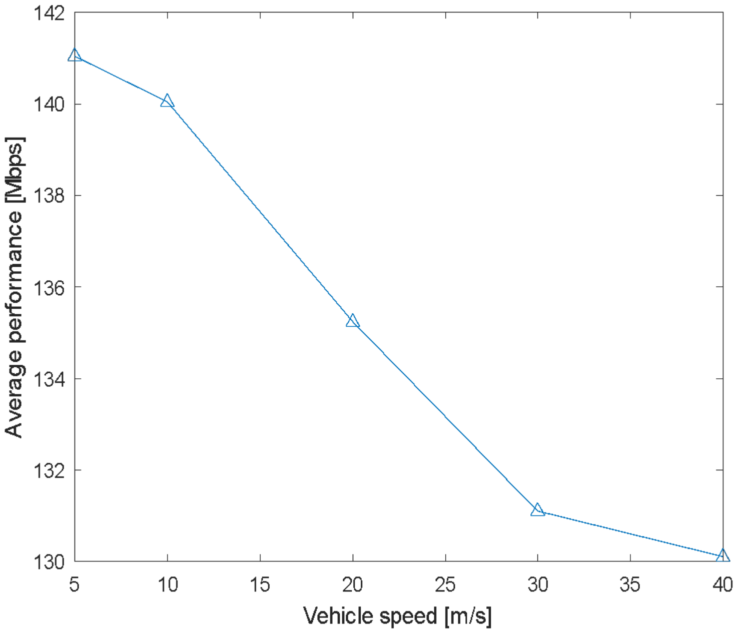

Figure 5.19: Results of the performance tests conducted for a bandwidth of 100 MHz, a vehicle separation of 250 meters, and different speeds.

Figure 5.20 illustrates the performance achieved when the bandwidth is increased to 400 MHz. It is worth noting that this parameter is feasible in 5G-V2X for numerology 3, according to the specifications of 3GPP [64]. As expected, the increased channel bandwidth directly influences the performance obtained. In this case, a throughput of approximately 273 Mbps is achieved. Figure 5.20 illustrates that similar to the performance obtained when utilizing a 100 MHz bandwidth, the performance remains comparable for vehicle distances of 50 m and 150 m, even at different speeds. However, the performance decreases significantly when the distance between vehicles increases to 250 m. For instance, at vehicle separation distances of 250 meters and speeds of 40 m/s, the performance decreases to 89.58 Mbps.

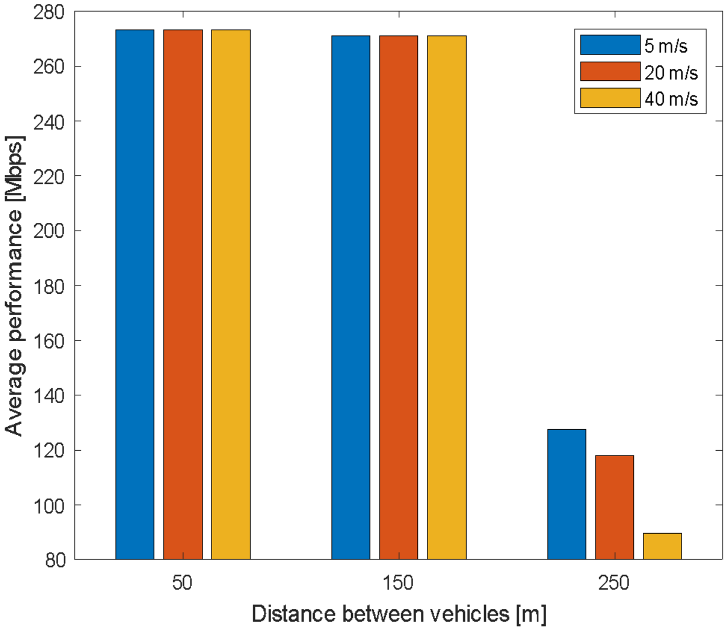

Figure 5.20: Performance achieved for Scenario 1, considering a 400 MHz channel bandwidth.

For the same case of a 400 MHz bandwidth, Figure 5.21 depicts the decrease in performance as vehicle speeds increase and the separation distance between them is 250 meters.

Based on scenario 2 described above, simulations were conducted to analyze the variation of the PRR under different speeds and distances between vehicles. Figure 5.22 presents the results of the PRR variation for separation distances between vehicles of 50 m, 150 m, and 250 m within the same group of vehicles. For each separation distance between vehicles, speeds of 5 m/s, 20 m/s, and 40

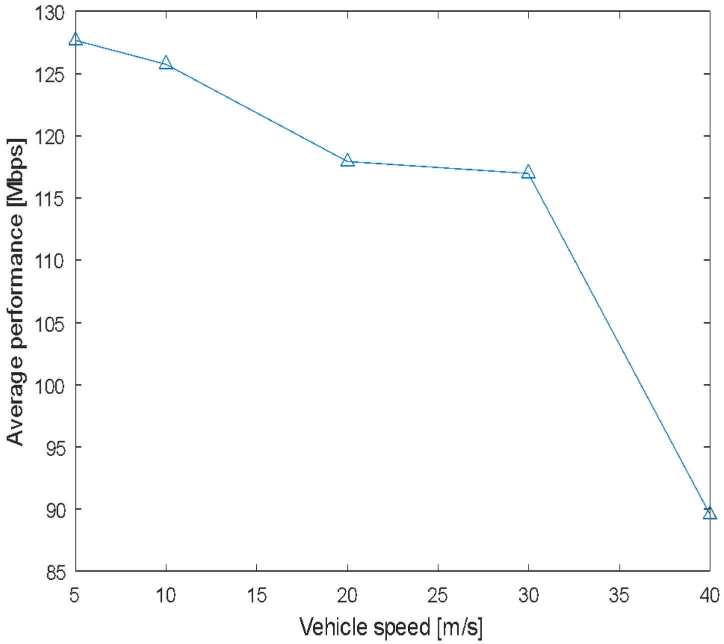

Figure 5.21: Results of the performance tests conducted for a bandwidth of 400 MHz, a vehicle separation of 250 meters, and different speeds.

m/s were configured. Figure 5.22 illustrates that for low speeds of 5 m/s and separation distances between vehicles of 50 m and 150 m, the packet reception rate ideally reaches 100%. Conversely, as vehicle speeds increase to 20 m/s and separation distances between vehicles are set at 150 meters, the PRR decreases by 20%. Moreover, for separation distances between vehicles of 250 meters, the PRR diminishes by 40%. In this scenario, it is observed that for all vehicle speeds examined in the simulations, the PRR remains below 60%.

For the third scenario, simulations were conducted to calculate performance considering bandwidths of 100 and 400 MHz, according to the standard. Figure 5.23 depicts the average performance achieved as a function of different vehicle speeds. As anticipated, maximum performance is achieved at user speeds of 5 m/s, reaching 118.53 Mbps. At 40 m/s, the performance decreases to approximately 91 Mbps. In the latter case, there is a 23% increase in packet loss compared to when the vehicle speed is 5 m/s.

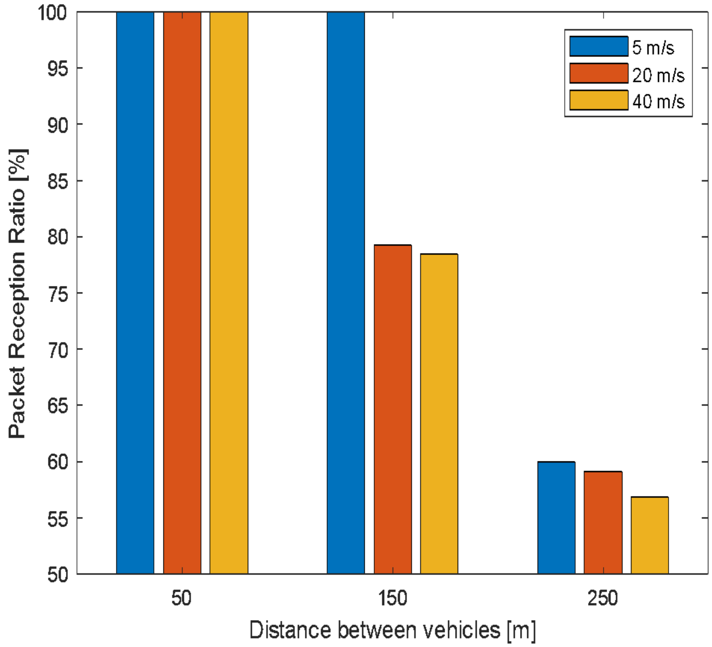

Figure 5.22: PRR achieved for scenario 2 under different speeds and vehicle separation.

Figure 5.24 presents the results obtained when the channel bandwidth is increased to 400 MHz. An increase in channel bandwidth should manifest as improved performance. Similarly to the previous simulation, maximum performance is achieved when the lowest vehicle speed is set, that is, 5 m/s. In this instance, an average transmission rate of 444.119 Mbps is reached. As depicted in Figure 5.24, an increase in vehicle speed directly influences performance decline. When vehicle speed reaches 40 m/s, the performance decreases to 323.87 Mbps. Thus, there is a 30% increase in packet loss compared to when the vehicle speed is 5 m/s.

5.6 Conclusions

This chapter has provided a detailed examination of the key aspects of the PHY and MAC layers associated with NR V2X, along with an analysis of the results

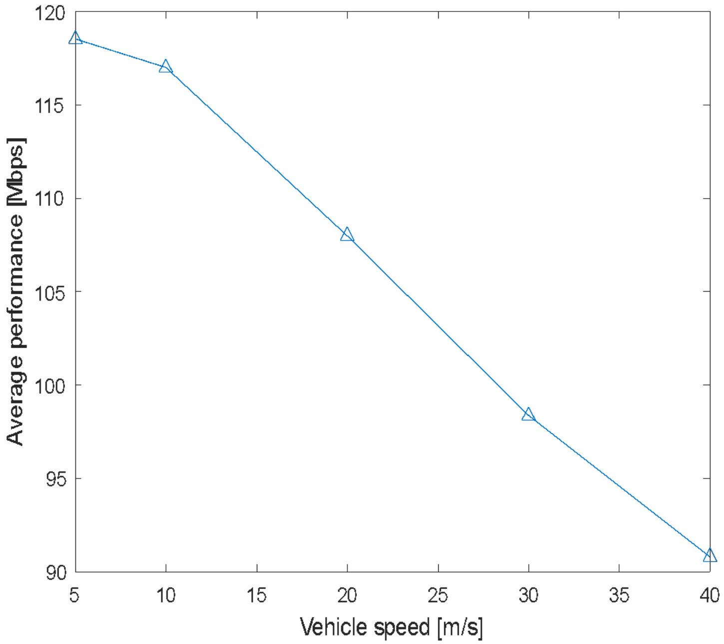

Figure 5.23: Performance achieved for scenario 3, across varying speeds and inter-vehicle distances.

of evaluating mode 2 performance across various scenarios. The sensing and resource selection mechanisms established for NR V2X exhibit certain similarities with the procedures defined for LTE V2X. However, significant differences exist, such as the information transmitted over control channels, resource reselection, and the utilization of different numerologies.

Moreover, an additional channel has been defined to enable V2X receivers to provide feedback to transmitters. In mode 2 of NR V2X, UEs autonomously manage the utilization of radio resources in time and frequency. The divergence between LTE V2X and NR V2X has significant technical implications, given that these technologies are incompatible. However, a commercial V2X module can integrate LTE V2X and NR V2X technologies, enabling one technology or another according to varying usage scenarios.

The results indicate that the optimal performance in terms of PRR is attained when employing higher numerologies. This is attributed to the relationship between the number of resources in time and frequency and the spacing

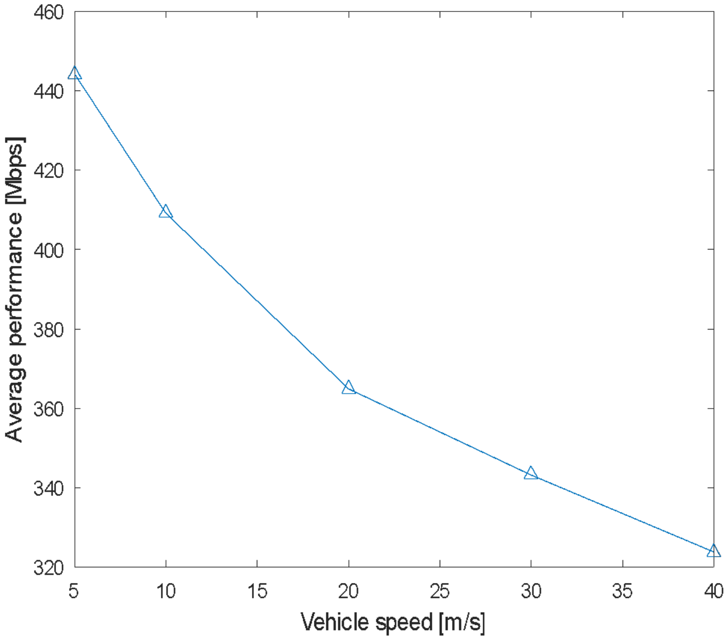

Figure 5.24: Performance obtained in scenario 3 when the channel bandwidth is increased to 400 MHz.

between subcarriers. When a higher numerology is employed, fewer resources are available in frequency. However, since the resource selection window is determined by the number of slots, it is larger in time. Consequently, simulations indicate a reduced likelihood of transmitters selecting the same resources, thereby reducing interference and enhancing the rate of correctly received packets. It is crucial to highlight that the utilization of high numerologies entails technical considerations, as it necessitates the deployment of more sophisticated hardware capable of sustaining higher sampling frequencies in the converters and synchronizing OFDM symbols with shorter durations. The simulations indicate that, when a baseline PRR greater than 80% is considered and the sensing procedures are activated, 10% more vehicles experience PRR levels above 80% when changing from u=0 to u=1 numerology. Similarly, when changing from u=1 to u=2 numerology, 10% more vehicles present a PRR above 80%. Consequently, comparing the change from u=0 to u=2 numerology reveals that 20% more vehicles achieve a PRR above 80%.

As anticipated, an elevated vehicular density on the roadways results in a reduction in the PRR levels experienced by vehicles. For instance, simulations demonstrated that when the density of vehicles on the road changes from 10 to 30 vehicles per lane, 20% more vehicles exhibited PRR levels below 80%.

About the sensing techniques defined by 3GPP, the results indicate that the PRR performance improves when these procedures are enabled. The simulations demonstrated that, when the sensing procedures are active, at distances exceeding 120 meters, the PRR experienced by vehicles is less than 80%. However, when the sensing procedures are not active, the distance is reduced to 40 meters for both u=0 and u=2 numerologies. However, since their utilization involves measurements and data processing, a random resource selection mode may be necessary for transmitters with energy constraints. When sensing procedures are active, sensing, reservation, selection, and reselection of radio resources, entail a greater computational expenditure, leading to higher power consumption. In V2P devices that typically use batteries, a random selection of resources for V2X transmissions may be necessary. Nevertheless, this configuration is not recommended in environments with a high density of V2X users due to the potential for increased interference.

Furthermore, it was demonstrated that an increase in the variation of the sensing window has a significant impact on the PRR levels obtained. This difference is particularly evident in the highest numerology defined for NR, specifically u=2. Thus, it was shown that an increase in the length of the sensing window from 100 to 1100 ms resulted in a 50% increase in the number of vehicles experiencing PRR levels above 80%. This is attributed to the significant increase in time resources that vehicles detect before selecting them for transmissions. Table 5.4 delineates the principal outcomes derived from the simulations executed for NR V2X mode 2.

A comparison of the performance of decentralized C-V2X modes in the same scenario revealed that NR V2X exhibited superior performance to LTE V2X, with an improvement of up to 39%. This improvement can be attributed to the fact that NR is a more robust cellular technology, which includes advanced transmission techniques and improved sensing and resource selection mechanisms. It can be concluded that the use of high numerologies with higher channel bandwidths can be beneficial in increasing the diversity of resources in time and frequency that vehicles can use for their transmissions. This results in enhanced network reliability with NR V2X in comparison to LTE V2X. Moreover, the average latency is reduced in NR V2X due to the implementation of high numerologies, which results in fewer retransmissions and shorter transmission times.

Given that the standard allows for varying the size of SL subchannels, it can be concluded that PRR performance increases when the size of SL subchannels

Table 5.4: Comparative analysis of NR V2X mode 2 across various performance benchmarks.

		u=0	u=1	u=2
CDF, PRR≤80%	sensing on	90%	80%	70%
	sensing off	100%	98%	90%
CDF, PRR≤80%	10 vpl	-	-	50%
	30 vpl	-	-	70%
Range, PRR≤80%	sensing on	>40 m	-	>120 m
	sensing off	>40 m	-	>40 m
CDF, PRR≤80%	sw=100 ms	-	-	70%
	sw=1000 ms	-	-	20%

is reduced. This is because a greater diversity of resources in frequency is available, thereby reducing interference when vehicles select candidate resources. It is also important to note that reducing the size of SL subchannels implies that less information can be transmitted in this bandwidth. This depends on the size of the V2X messages defined for a service, and it can be compensated, if possible, by increasing the MCS. This increase in the modulation scheme can be leveraged in scenarios with low user density, where interference is minimal. Finally, increasing the detection window gives transmitters more information about candidate resources, thereby improving PRR. Consequently, simulations have led to the conclusion that for advanced V2X services that require stricter functionality, optimal configuration parameters are related to the use of higher numerologies, wider bandwidths, and the respective compensation of the size of SL subchannels to avoid a reduction in the diversity of resources in time and frequency that V2X UEs can select for their transmissions. Consequently, using high numerologies confers advantages in reduced latency, augmented data capacity, enhanced support for high mobility, and enhanced spectral efficiency. These advantages are paramount for advanced applications such as autonomous driving, traffic management, and emergency response.

Moreover, using millimeter-wave bands can result in substantial advantages, including the potential for enhanced transmission rates. This is because, in FR 2, larger channel bandwidths are allowed due to the greater spectrum availability. Nevertheless, using higher frequencies may result in a decline in performance as the distance between the transmitter and receiver increases. This can be interpreted as an advantage in urban environments, where the likelihood of interference between nearby devices is reduced, allowing more efficient spectrum reuse. Conversely, in highway scenarios, using mmWave bands could be paramount to guarantee user connectivity in highly mobile conditions. This approach is justified by the ability of the mmWave bands to support the use of high numerologies, which are less susceptible to unwanted phenomena such as the Doppler effect. The simulations demonstrated that the operation of NR V2X in mmWave bands enables the attainment of higher throughput rates, attributed to the wider bandwidths that can be configured. In the simulated scenario, an increase in the bandwidth from 100 to 400 MHz resulted in a throughput improvement of approximately 19%. It is evident that the performance of this system is contingent upon the distance between the transmitter and receiver, as well as the velocity of the vehicles. To illustrate, when the bandwidth is 100 MHz and the distance between vehicles increases from 50 to 250 meters, the throughput decreases by 40%. Conversely, an increase in vehicle speed from 5 to 40 m/s results in a 30% reduction in throughput. In the second simulated scenario, a 40% reduction in PRR was observed when the distance between vehicles increased from 50 to 250 meters.

Chapter 6

Multiple Radio Access Technologies for V2X Communications

In previous chapters, the performance analysis of different standards for Cellular-based Vehicle-to-everything (V2X) (C-V2X) communications has been conducted independently. However, there is a focus on the standard that allows combining various Radio Access Technology (RAT) and communication interfaces, termed multiple RAT (multi-RAT). This approach can be adapted to V2X communications involving both Third Generation Partnership Project (3GPP) and Institute of Electrical and Electronic Engineers (IEEE) technologies. This chapter outlines the need to incorporate multi-RAT to improve the interoperability of V2X services operating under different RAT, communication modes, transmission modalities, connection interfaces, and with support for scenarios involving different Mobile Network Operators (MNOs).

The complex needs of advanced use cases demand strict bandwidth, latency, and reliability requirements, as well as expansive coverage ranges beyond the capabilities of a single RAT network. As a result, a paradigm shift towards network architectures that can accommodate these indicators is necessary. One promising solution for addressing this challenge is the deployment of Multi-RAT Dual Connectivity (MR-DC) architectures. This approach aims to integrate Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), and Vehicle-to-Network (V2N) communications by combining diverse technologies, including Long Term Evolution (LTE) V2X and New Radio (NR) V2X, and communication interfaces such as LTE Uu, NR Uu, and PC5 for LTE Sidelink (SL) and NR SL.

The MR-DC framework guarantees resilient and trustworthy communications by redundantly transmitting duplicate information across various interfaces. In addition, the integration of V2I and V2N communications expands the communication range. Nevertheless, it is necessary to recognize the correlated rise in communication latency due to the obligatory routing of traffic through transmission nodes in both scenarios.

Adaptability is a crucial aspect of the MR-DC strategy, enabling the use of different communication modes that are customized to meet the unique needs of each service, as demonstrated in Tables 3.4 and 3.5. In addition, a fundamental principle underlying this approach is leveraging the high transmission rates, extremely low latencies, and enhanced reliability typical of Fifth Generation (5G) NR networks. This chapter outlines the necessity of MR-DC architectures, detailing their use of various communication interfaces and radio access technologies to ensure Quality of Service (QoS) for advanced use cases in multi-operator scenarios with cross-border operations.

This chapter is structured as follows:

- Section 6.1 details the multi-RAT architectures supported by the standard for integration into V2X communications.
- Section 6.2 describes MR-DC scenarios that can be implemented to support V2X services using both LTE and NR technologies.
- Section 6.3 presents an assessment of V2X multi-RAT performance based on integrating a Multi-RAT Manager (MRM) entity tasked with managing communications across different radio access technologies and communication interfaces.
- Section 6.4 presents the conclusions of this chapter.

6.1 MR-DC Architectures for V2X multi-RAT

The implementation of V2X multi-RAT systems stands to gain significant advantages from adopting dynamic resource selection. This approach allows for the adaptive allocation of resources, tailoring resource distribution based on the specific requirements of diverse V2X use cases and prevailing traffic conditions. As we approach an era where intelligent algorithms and machine learning techniques are poised for practical application, the prospect of predicting resource needs and making real-time resource allocation decisions becomes increasingly viable. Recent datasets, exemplified by [74], offer a valuable foundation for exploring this approach. The overarching aim is to optimize resource allocation across a spectrum of applications and traffic scenarios, ensuring efficient utilization and minimizing resource wastage. Moreover, ensuring the seamless integration of NR V2X with existing and future communication technologies is essential for the system's long-term viability. This requires adhering to standardized communication protocols, establishing common frequency bands, and enabling cross-technology communication interfaces. Consequently, achieving a harmonious coexistence among diverse V2X RAT requires pivotal interoperability testing and compliance with communication standards.

A crucial consideration in achieving optimal performance is balancing various aspects, such as the size of SL subchannels for interference reduction. This balance requires extensive simulations and evaluations of diverse traffic scenarios and mobility patterns. This meticulous analysis aims to determine the optimal configuration for resource size and allocation, taking into account the intricate interplay between these parameters. Ensuring high QoS in multi-RAT V2X scenarios is crucial, especially for critical V2X applications such as collision avoidance and real-time traffic management. Robust QoS management mechanisms that leverage the potential of multi-RAT configurations must be implemented. These mechanisms prioritize and allocate resources to time-sensitive V2X messages, ensuring low latency and reliable communications. This approach aligns the performance of V2X multi-RAT systems with the stringent requirements of critical applications, contributing to the overall safety and effectiveness of Intelligent Transportation Systems (ITS).

Integrating 5G into the operational framework of an LTE operator is crucial for network expansion and ensuring reliable network communications. This has been recognized by the 3GPP Release 16, which has examined coexistence scenarios to address safety-related concerns. Technical Specification (TS) 22.186 [42] is a relevant document in this context, serving as a precursor for the implementation of solutions involving multi-RAT. The coexistence considerations explained by Release 16 allow for the simultaneous use of multiple 3GPP RAT for direct SL transmissions, including both NR and Evolved Universal Terrestrial Radio Access (E-UTRA) based technologies. However, it is important to note that there is no mutual inter-operation between NR and LTE SL transmissions. In essence, Release 16 allows for the simultaneous deployment of RAT but does not facilitate their mutual collaboration or interoperability in the context of SL transmissions between NR and LTE.

For example, Figure 6.1 shows a cross-border scenario examined by the European Commission-funded 5G-CARMEN project [75]. The scenario features MR-DC and multi-RAT within a generic 5G Non-Standalone (NSA) deployment. In this context, cooperative maneuvering procedures are expected to begin among road vehicles located 2 km ahead, some operating on the opposite side of the transnational border. The initiation is triggered within one minute of receiving a back-situation awareness message regarding the imminent arrival of an emergency vehicle. To successfully execute cooperative maneuvering, vehicles connected to diverse networks must promptly and preemptively determine whether they are at risk of re-selecting or switching to another network technology. This involves the potential integration of multiple technology interfaces, such as NR Uu, NR PC5, LTE Uu, and LTE PC5. In addition, the complexity is increased by unforeseen circumstances, including transient variations in radio coverage, which make it difficult to accurately predict the likely future occurrence of such network events within a given timeline.

Figure 6.1 outlines four possible solutions for improving robustness through redundancy:

1. The use of multiple interfaces is demonstrated by the simultaneous transmission through both PC5 and Uu interfaces in NR communications;

2. Simultaneous dual RAT Uu transmissions involve the concurrent deployment of NR and LTE Uu communications;

3. multi-RAT: The reciprocal inter-operation of NR and LTE SL communications denotes the collaborative functioning and compatibility between the SL communications of NR and LTE;

4. Cross-RAT: The coexistence of LTE and 5G SL technologies without inter-operation implies their simultaneous presence without collaborative interoperability.

In these contexts, it is important to evaluate the dependability of redundant interfaces. The redundancy management is facilitated by mechanisms embedded in the protocol stack, such as the ability to designate packets as redundant. This allows for discarding redundant packets that no longer contribute meaningfully to the communication objectives. In vehicular communications, redundant packets can be considered obsolete when environmental information has been updated. For instance, redundant packets may be discarded if an obstacle on the road has been removed, a vehicle's route or destination has been altered, weather conditions have changed, or an emergency event has concluded. In addition, redundant packets may be discarded if received from vehicles that have exceeded a certain distance, rendering their position and V2X packets irrelevant. Other redundant packets received with a higher latency may not be helpful in advanced V2X services.

In the context of V2X multi-RAT networks, the reliability of the available network interfaces significantly influences the challenges inherent in deploying

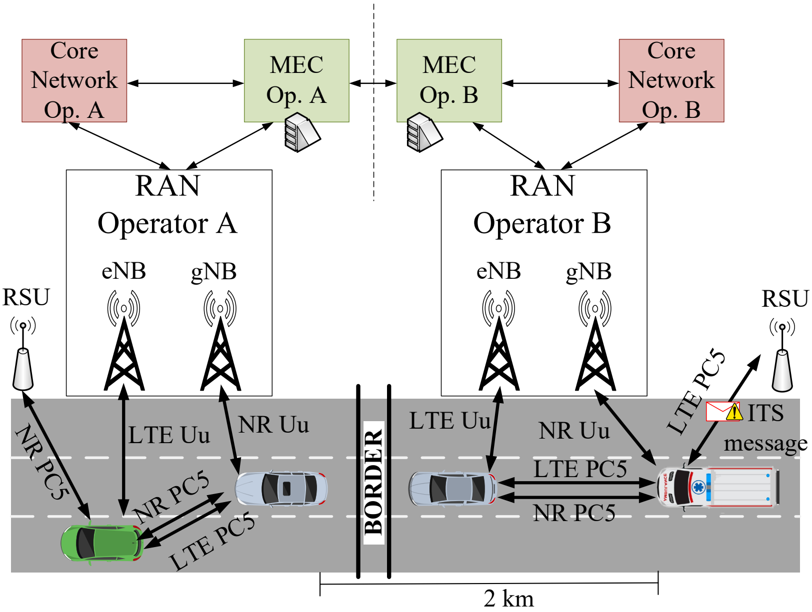

Figure 6.1: Illustration of collaborative maneuvering and concurrent back-situation awareness within the context of V2X multi-RAT.

communication networks. This reliability factor crucially shapes the sustainable expansion of capacity provisioning by a MNO. Anticipating diverse scenarios, areas with heightened reliability may be envisaged, ensuring continuous vehicle connectivity through the Uu interface, complemented by a dependable PC5 interface facilitating the maintenance of an updated map of neighboring vehicles. Conversely, less optimal regions may experience a decline in the quality of redundant communication channels. In these areas, maneuvering assistance may be reduced or unavailable, requiring a shift to reliance on onboard sensors or manual driving. The coexistence of these scenarios highlights the complex nature of managing multi-RAT. V2X networks have implications for both the seamless progression of automated driving in reliable environments and adaptive responses in less favorable circumstances.

Therefore, adopting a use case-aware approach in the context of multi-RAT V2X for enhanced reliability, while incorporating inherent considerations for performance characteristics driven by the utilization of 3GPP MR-DC, emerges as a compelling prospect. Additionally, maintaining awareness of the underlying 3GPP radio access support for Dual Connectivity (DC) User Equipments (UEs) is beneficial in ensuring the overall reliability of the communication infrastructure.

6.2 MR-DC Scenarios

When leveraging the multi-connectivity operational choices outlined in 3GPP TS 37.340 [76], based on E-UTRA and NR radio access technologies, various MR-DC scenarios can be envisioned. These scenarios encompass both LTE V2X SL communications and NR SL communications. It is crucial to note that, as of Release 16, only the Master Node (MN) is authorized to control and configure the UEs engaged in NR SL communications and/or LTE V2X SL communications [76]. This signifies that the Secondary Node (SN) is restricted from initiating an E-UTRA Radio Resource Control (RRC) connection reconfiguration procedure or an NR RRC reconfiguration with SL fields for LTE SL or NR SL. The implication is that the MN assumes the responsibility for receiving this control signaling, presenting three possible options (Figure 6.2):

1. NR-E-UTRA Dual Connectivity (NE-DC): A standalone Next Generation Node B (gNB), serving as an independent 5G NR node, is linked to the 5G Core Network (5GC). SL communications are governed and configured by the MN, functioning as a 5G gNB within this context;

2. NG-RAN E-UTRA-NR Dual Connectivity (NGEN-DC): A standalone next generation evolved Node B (eNB) (ng-eNB), which operates as an Evolved UMTS Terrestrial Radio Access Network (E-UTRAN) node with LTE radio functionalities, can establish connections with the 5GC. SL communications within this framework are controlled and configured by the ng-eNB —MN—;

3. E-UTRAN NR Dual Connectivity (EN-DC): A standalone LTE eNB connected to the Evolved Packet Core (EPC). In this configuration, SL communications are controlled and configured by the eNB —MN.

The conclusions drawn in this Thesis underscore the importance of an intelligent approach to capacity provisioning to foster sustainable growth in implementing V2X communications in ITS. Strategically managing a heterogeneous network's multi-RAT aspect that facilitates V2X services appears promising. This management strategy involves diversifying RAT selection decisions based on predefined geographical regions that align with the statistical triggering of MR-DC procedures. This approach is justifiable because the reliability of vehicular UEs is spatially correlated. Implementing a regional management strategy

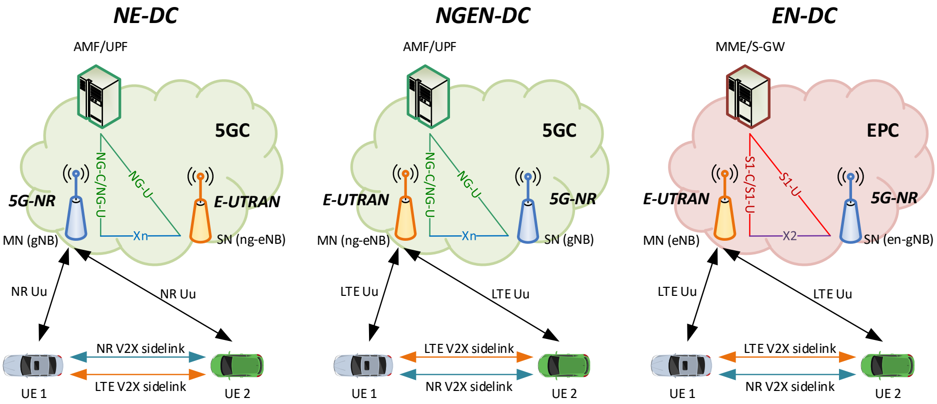

Figure 6.2: The use of multi-RAT in V2X communication, along with MR-DC architectures, requires UE configuration options for NE-DC on the left, NGEN-DC in the center, or EN-DC on the right.

allows for a more nuanced and context-specific adaptation to the communication needs of UEs. This strategy is also advantageous when specific UEs provide limited data, but their recent geographical positions are known. In cases like this, utilizing previous knowledge about the sequential geographical triggering of MR-DC procedures can improve the effectiveness of the proposed approach. Therefore, managing the multi-RAT nature of heterogeneous networks regionally is a wise and promising strategy for optimizing V2X communication in ITS.

As shown in Figure 6.3, the scenario depicts a UE —represented by a green vehicle— navigating a roadway within a 5G NSA deployment that employs the EN-DC architecture. The trajectory of the UE involves encountering multiple procedures of MR-DC as it moves between MN, SN, and exits the region covered by 5G NSA deployment.

To clarify the process of making decisions about multi-RAT selection, a possible strategy is to divide the geographical area into separate zones based on the overall reliability and range-related Key Performance Indicators (KPIs) associated with each considered RAT, as shown in Figure 6.4. Each zone would then be associated with a specific multi-RAT decision that aligns with the QoS requirements. For example, a RAT with high reliability can be used for cases that require long-range sensitivity, such as cooperative maneuvering. In this scenario, transmitting remote alerts reliably to distant vehicles is crucial. In addition, the QoS conditions for multi-RAT configurations could be used

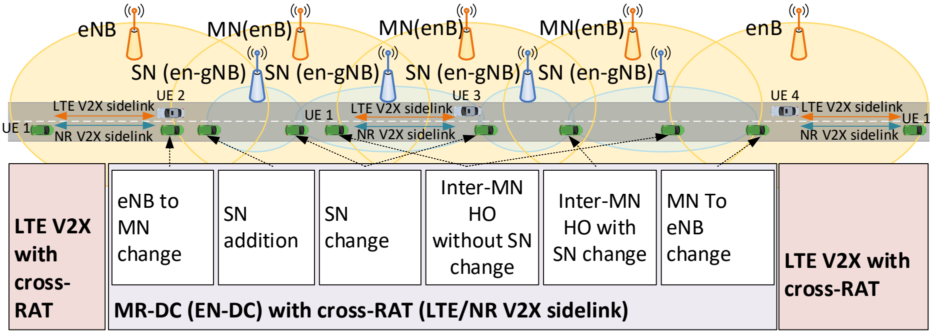

Figure 6.3: A vehicle equipped with multi-RAT requires consecutive implementations of MR-DC procedures while moving along a road.

as a basis for recommending different levels of automation based on the expected performance of the 5G communication system in different geographical areas. Anticipated improvements in coverage distance and network reliability are expected due to the redundancy inherent in transmitting information across multiple interfaces. This facilitates the efficient provisioning of new use cases. Furthermore, it is important to evaluate the subcarrier spacing and modulation schemes that yield optimal performance in V2X communications, following standard specifications, when incorporating numerologies in 5G networks. This comprehensive assessment ensures the maximal efficacy of V2X communication within the 5G framework.

This research proposes a MRM entity for the regional management of 5G V2X multi-RAT within the architecture of the 5G System (5GS). The MRM would be co-located within the V2X Application Server (AS) as shown in Figure 6.5. It operates as an Application Function (AF) and uses the AF-based service parameter provisioning for V2X communication to provide recommendations to the V2X application on the UE via the V1 interface.

The MRM implements procedures enabling the making of multi-RAT management decisions based on various inputs. Thus, the MRM is assigned the following five subtasks, each with its associated signaling defined:

- Supplying information to the MRM involves the reception of current data from the Next Generation - Radio Access Network (NG-RAN), the Session Management Function (SMF), and the Access and Mobility Management Function (AMF) via a newly introduced Information Element (IE) termed *InformationForMultiRATManagement*. The MRM

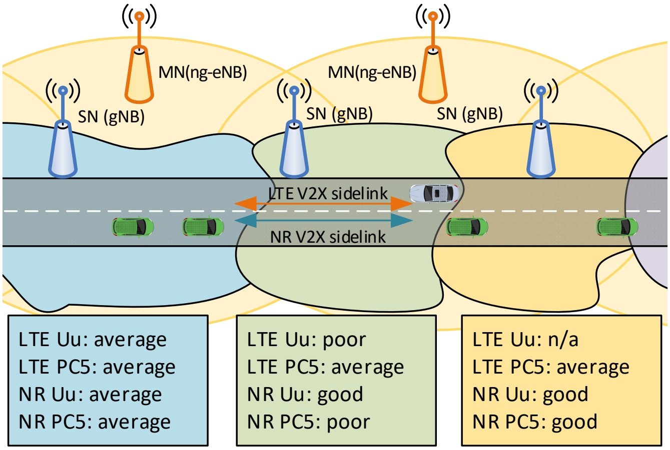

Figure 6.4: Regional segmentation based on measured reliability.

receives updates on the QoS performance of individual RAT interfaces through regular refreshes of this IE by the NG-RAN.

- The MRM is responsible for generating recommendations for multi-RAT management based on the received information. The algorithm employed can be tailored to the nature of the KPI being addressed. In this study, the influence of MR-DC is weighted to assist in defining geographical regions where the level of RAT interface reliability is considered homogeneous. This process involves assessing potential configurations against previously trained models or past behavioral occurrences. Conclusions that may be drawn by the MRM include identifying a need for increased segmentation in a specific region, validating the necessity for improvement in the current RAT conditions in an area, and reducing redundancy levels.

- Once the MRM has concluded, such as by region, the recommendation is conveyed through the control plane to the network entity responsible for managing V2X communications —in this approach, the AF. However, the MRM can be co-located within the AF.

- The AMF provides UE location predictions to the AF. When delivering multi-RAT management recommendations by region, the network must be aware of the UE's position. One potential solution is for the AMF

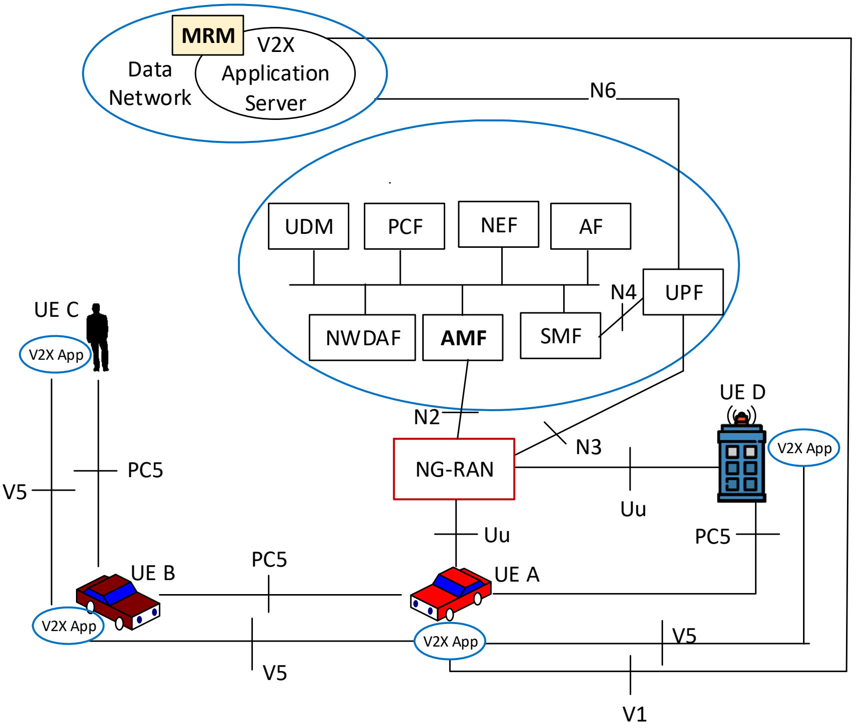

Figure 6.5: NR V2X architecture where the presence of the MRM entity is highlighted.

to request the AF to update recommendations due to predicted location changes.

- The AMF provides recommendations to the UE. The AF informs the UE about the multi-RAT recommendation. The message exchanged between the UE and the AF is *multi-RATRecommendation*. This could, for example, trigger changes in the level of automation of an autonomous vehicle.

The following data may be included in the InformationForMultiRATManagement Information Element:

- Mobility-related data: UE speed, direction, and location.
- Coverage-related data: radio link failures, handover dysfunctions.

- Geopositioning of UEs triggering MR-DC procedures.
- Status reports on network resource pools in LTE and NR SL.
- Radio-related data and KPIs include timing advance, channel baseband power, Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Received Signal Strength Indicator (RSSI), Channel Busy Ratio (CBR), and Packet Reception Rate (PRR).
- Performance indicators related to scheduling, such as information about the state of the queues in the coexistent cross-RAT being managed.

6.3 Performance Evaluation Resulting from the Integration of the MRM Entity

A simplified performance analysis was conducted using MATLAB to obtain more precise conclusions regarding the improvement resulting from implementing the multi-RAT management proposal. The simulations were focused on examining the behavior of a test network scenario deployed at a real geographical location within the corridor investigated by the 5G-CARMEN project [75]. The objective was to ascertain whether the integration of the MR-DC aware approach and the delineation of regional recommendation zones could enhance the reliability of future Cooperative Maneuvering (CM) and Back-Situation Awareness (BSA) services.

The simulations focus on the cross-border communications scenario depicted in Figure 6.6, centered on a specific section of the Brennero Pass. The studied area encompasses the region delimited by the red polygon, including approximately 15 km of the A22 highway located at the border between Italy and Austria —highlighted in yellow—, as well as some secondary roads. The topology was obtained from OpenStreetMap, and the 5G-CARMEN D6.2 [77] report contributed to characterizing the road parameters of the Brennero Pass. Additionally, real traffic flow measurements from 2019 provided by Autostrada del Brennero were used, along with mobility assumptions such as an uncongested average speed of 60-80 km/h and a maximum speed of 120 km/h.

The proof-of-concept scenario presented in Figure 6.3 was heuristically transferred to the Brennero Pass, resulting in Figure 6.6. The primary priority was to emulate the sequence of network sites as closely as possible to trigger the successive MR-DC procedures in the original order depicted in Figure 6.3. Notably, the nodes ng-eNB1, ng-eNB2, and ng-eNB3 in Figure 6.6 were placed at real-world locations of previously existing sites. Additionally, the nodes ng-eNB5, gNB1, gNB2, gNB3 —inside the tunnel—, and gNB4 were positioned at

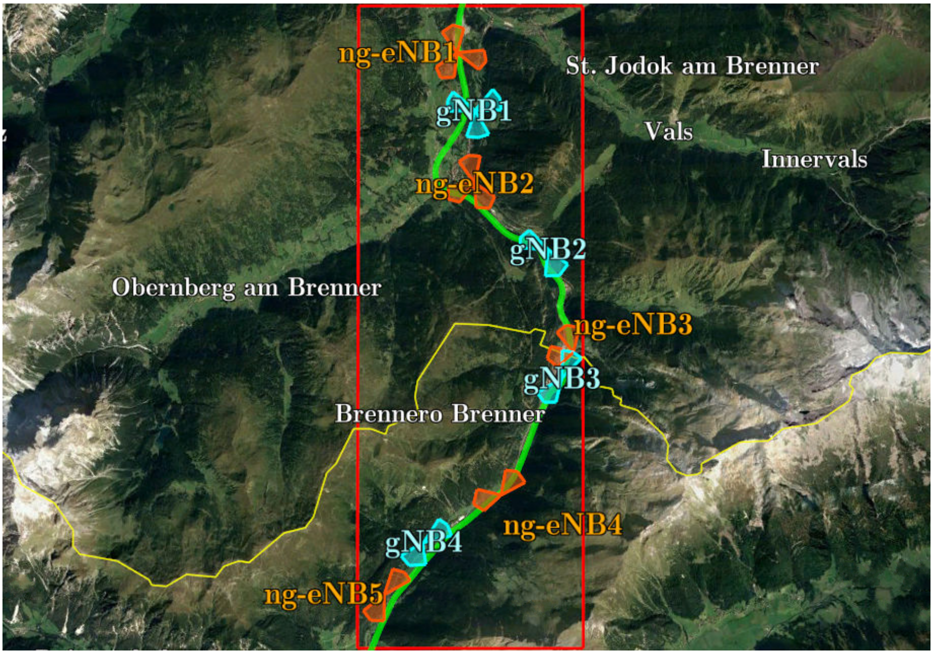

Figure 6.6: The Brennero Pass simulated scenario included LTE —orange— and 5G —blue— sites.

fictitious locations based on the heuristic attempting to match the conditions of Figure 6.3. Finally, it should be noted that the gNBs in Figure 6.3 were explicitly placed outside co-located positions. However, this is unrealistic for economic reasons, as LTE to 5G upgrades are expected to reuse the already deployed infrastructure. Still, this decision was justified because this validation study required the activation of MR-DC handover-related procedures.

In the simulations, each ng-eNB operates in the band B28 —700 MHz, with a bandwidth of 20 MHz—, while each gNB utilizes band n78 —3.5 GHz, with a bandwidth of 100 MHz. The transmission power is fixed at 45 dBW, with an antenna height of 25 m and an antenna gain of 20 dB. Additionally, the SL bandwidth is set to 10 MHz. The transmission power of the UEs is 20 dBm, with an omnidirectional antenna of height 1.6 m, equipped with 2 full-duplex antennas for simultaneous transmission and reception of cellular and SL signals. The simulation encompasses both V2V and V2N transmissions. For V2V, the SL channel model follows Technical Report (TR) 37.885 [71] without considering fast fading. However, the random distribution of vehicle blockage losses is simplified to a fixed value of 5 dB. Regarding V2N transmissions, propagation losses are modeled according to the updated guidelines in TR 38.901 [78] Release 16 for a Rural Macro-cell (RMa) model, valid up to 7 GHz, and accommodating high-speed vehicles with a minimum distance of 35 m to a macro site with 3 sectors. Additionally, a Non-Line-of-Sight (NLOS) version is included to model expected obstructions in scenarios with mountainous terrain. Shadowing is performed according to [79] using a log-normal distribution with a standard deviation of 7.8 dB and a decorrelation distance of 50 m. According to the Extended Vehicular A power delay profile in TS 36.104 [80], the fast fading model corresponds to a tapped delay line model.

In the context of mobility management within the MR-DC framework, simulation studies focus on standard events utilized by UEs, as delineated in TS 36.331 [81]. One illustrative instance involves reporting other technologies' detection through B1 and A2 events, which aid in streamlining the "eNB to MN handover" and "MN to eNB handover" procedures within MR-DC.

Simulations presuppose that vehicular UEs are consistently connected to the ng-eNB with maximum power, which also serves as the MN when operating within the MR-DC context. Each ng-eNB configures the B1 event on UEs, along with a list of gNBs to be evaluated based on indicators such as RSRP, RSRQ, and RSSI. When the value of such indicator exceeds a certain threshold, UEs utilize the B1 event to report the signal's power, strength, and/or quality from any neighboring gNB of interest. Upon receiving this report and if the UE lacks MR-DC connection, the ng-eNB initiates the "eNB to MN handover" procedure to establish an MR-DC connection between the UE and the current ng-eNB —now acting as MN— and thereby initiate a SN addition procedure for the selected gNB. Similarly, the A2 event notifies when the indicator falls below a configured threshold, triggering the "MN to eNB handover" procedure, at which point the MN disconnects the UE from the SN and conditions revert to single connectivity between the UE and the ng-eNB. Typical events are also configured to determine other procedures, such as "SN handover", "inter-MN transfer without SN change" and "inter-MN transfer with SN change" as specified in [81]. To simplify, all simulation events were adjusted to the RSRP parameter. LTE and 5G cellular regions are delineated in Figure 6.7. These boundaries were generated by processing historical data to calculate the most probable location of vehicles that previously activated relevant MR-DC procedures. Although coverage extends beyond the depicted boundaries, for visualization purposes, Figure 6.7 includes only points where the RSRP value is not deficient or worse than -110 dBm.

In addition, certain further assumptions were made. It was established that the handover procedure, which allows UEs to connect to the MN with the best-received power —or to the best SN when using MR-DC—, incurs a delay

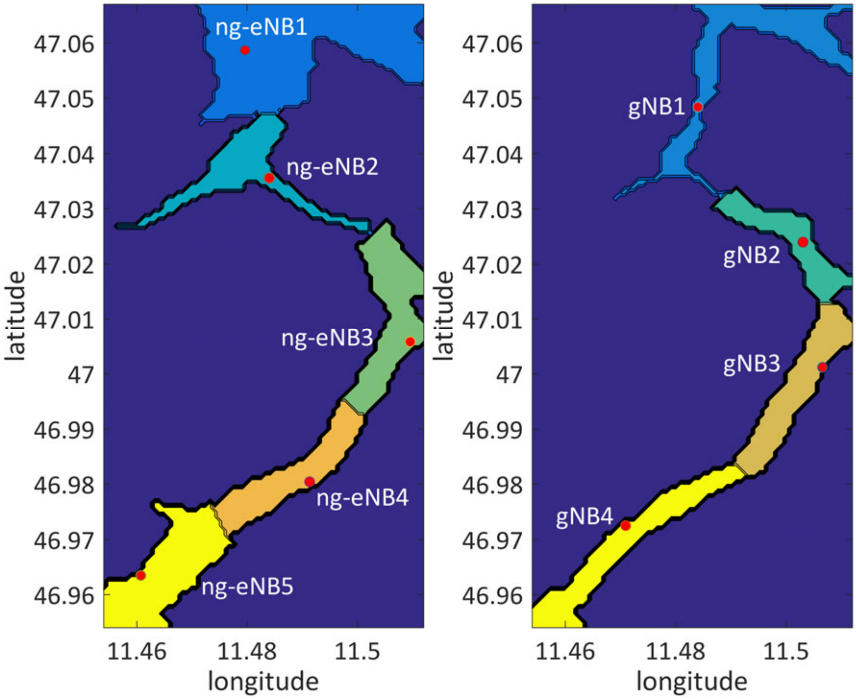

Figure 6.7: LTE —left— and 5G —right— MR-DC cell boundaries.

of less than 100 ms. Furthermore, the worst-case setup time for transitioning from single connectivity to MR-DC was 500 ms. It is assumed that MR-DC UEs only utilize resources from the associated SN. This assumption is based on [82], which confirms that MR-DC when configured with split bearers, offers performance gains similar to MR-DC configured with data bearers in the SN. This is logical given the capacity potential offered by 5G compared to LTE. Consequently, for the user plane, vehicular UEs rely exclusively on a single service node, either the MN in the case of single connectivity or the SN in the context of MR-DC.

For network traffic, a single type of traffic is employed, emulating periodic transmission of location awareness information, such as Cooperative Awareness Message (CAM), under the specifications in TR 37.885 [71]. The interval between packet arrivals is set at 100 ms, and the packet size is maintained at a low payload of 300 bytes. CAM messages are relevant for all vehicles located within a radius of up to 2000 m from the vehicle initiating the transmission. For the

SL interface, the functional performance details of the scheduler are emulated. The set of Resource Blocks (RBs) is divided into 5 subchannels, each requiring 2 control RBs. It is assumed that the transmission of CAMs only requires one subchannel and one subframe. The V2X SL resource manager provides semi-persistent resource allocation, with a subchannel assigned at a given periodicity. The resource allocation entity, controlled by the centralized network, seeks to maximize the spatial distance between vehicles sharing the same resources. It is presupposed that this entity possesses knowledge of the position of all vehicles and that the allocation decision is updated when a vehicle's position varies by more than 100 m, representing an appropriate balance between the relevance of location information for the decision-making process and the number of allocation decisions. Additionally, the scheduler prioritizes users with better channel quality in each subframe to reduce transmission latency, aiming to maximize system capacity under a maximum end-to-end (E2E) latency of 100 ms.

In the simulations, the NG-RAN transmits specific data to the MRM, which includes: i) a map with averaged RSRP measurements defining cell boundaries triggered by relevant MR-DC procedures; ii) parameters related to reliability, such as the spatial distribution of the average PRR for CAM messages transmitted by users with LTE and/or NR SL, the performance curve of average PRR as a function of distance for SL transmissions, and an indication of the coverage range considered for PRR —2,000 m— are presented. Conversely, the SMF transmits to the MRM an indication of the desired minimum PRR —set at 99% in this critical scenario. Additionally, it is assumed that the AMF frequently updates the UE's position to the MRM in order to achieve satisfactory tracking accuracy.

Concerning the management of multiple RAT, the inherent simplicity of CAMs allows the simulated MRM to focus exclusively on multi-RAT management by region. Utilizing input data from the NG-RAN, the MRM projects the boundaries of regions that may exhibit problematic support for the PRR target. Consequently, regions with insufficient reliability —PRR<99%— prompt the MRM to recommend multi-RAT utilization for redundancy purposes to UE entering those locations. Consequently, UEs receive multi-RAT management recommendations whenever the system anticipates that they may be about to enter or exit a region based on the MRM's calculations. In those problematic regions, CAM transmissions are replicated on other interfaces to elevate the PRR above the set target. As CAMs have the potential to reach multiple users, each user may trigger the generation of an additional SL transmission, as well as an uplink V2N transmission, which is then followed by several downlink transmissions within the relevant area.

Figure 6.8 illustrates the simulation results for the average PRR measured at different distances between the transmitter and receiver. Three vehicular communication options were evaluated: (i) dual 5G Uu and 5G PC5 interfaces, utilizing MRM to manage redundant transmissions; (ii) the same, but with MRM deactivated; and (iii) dual LTE Uu and LTE PC5 interfaces.

Concerning cross-RAT, it should be noted that control of LTE SL by the 5G network is permitted —in the first two approaches—, and vice versa —in the third approach. Furthermore, the first two options can switch to an eNB for a complete fallback to LTE if the NR signal weakens. As observed, the presence of a multi-RAT aware MR-DC management entity, such as the MRM, which implements smarter management of available communication paths —in this case, directing CAM duplication in problematic regions to enhance overall reliability—, results in an improvement in PRR. The PRR results provide initial insights into the potential upper operating limits —non-system level MATLAB simulations have inherent limits. This also exemplifies the impact of managing redundant transmissions through an MRM approach.

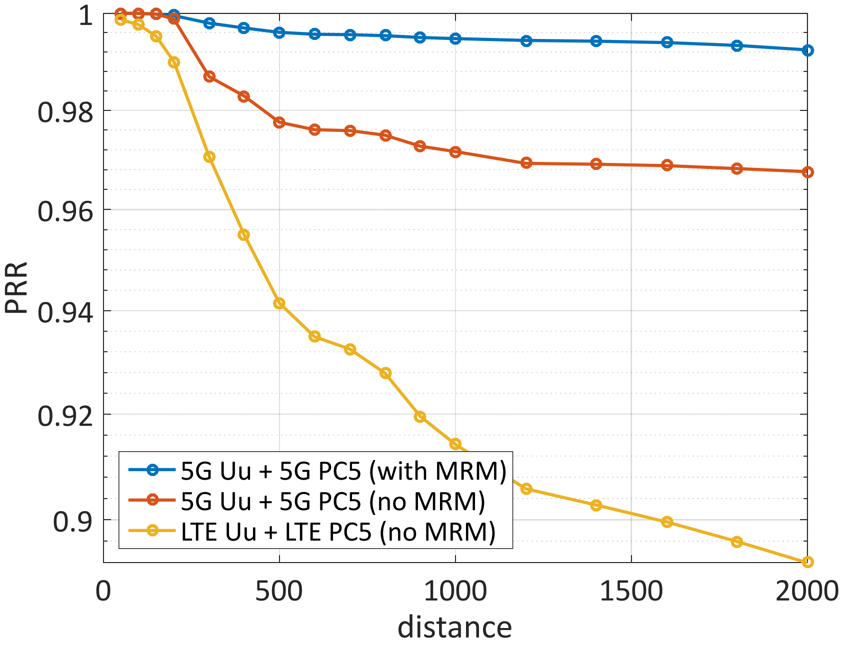

Figure 6.8: PRR variation as a function of distance for different RAT and connection interfaces.

6.4 Conclusions

This chapter has delineated the intrinsic advantages and usage scenarios associated with integrating multiple access technologies to enhance performance in C-V2X communications. In V2X multi-RAT deployments, interoperability issues arise from the differences in protocol standards between LTE and 5G NR. Protocol conflicts may occur due to inconsistencies in modulation schemes and channel access methods, which can result in communication errors. Hardware compatibility issues arise from the incompatibility of heterogeneous components operating with different configuration parameters under different frequency bands. These challenges require rigorous testing and standardization efforts. It is, therefore, imperative to address these challenges to guarantee seamless integration and reliable communication in V2X multi-RAT environments.

In evaluating the performance of V2X multi-RAT, applying principles such as those outlined in this Thesis is of paramount importance. A comprehensive assessment involves scrutinizing the dynamics of NR V2X in conjunction with other RAT, particularly understanding its operational coexistence with communication technologies like LTE.

To understand the smooth switching mechanisms in situations where vehicles face coverage limitations or congestion, it is essential to examine the complex interactions between different RAT. This requires exploring handover procedures and the latency between NR and LTE, ensuring uninterrupted connectivity and minimizing disruptions during RAT transitions. Furthermore, multiple communication technologies highlight the need to optimize spectrum resource allocation to increase system capacity and reduce interference. Employing advanced resource allocation algorithms, such as Dynamic Spectrum Sharing (DSS) is essential. This approach enables the simultaneous use of LTE and 5G cellular wireless technologies in the same frequency range, dynamically allocating bandwidth based on user requirements. It facilitates the efficient distribution of available resources between NR and LTE V2X systems. However, a meticulous evaluation of spectrum-sharing mechanisms, coexistence protocols, and interference management techniques is necessary to enhance overall performance and elevate data transmission rates.

This chapter has specifically focused on the simulation of the effects of incorporating an MRM entity into the NR V2X network architecture. It has been demonstrated that with a proper configuration of parameters corresponding to the various elements comprising the multi-RAT scenario, optimal performance is achieved when utilizing 5G NR interfaces. Furthermore, performance is further enhanced when the MRM entity manages communications based on different occurring events.

The MR-DC approach enables the combination of multiple technologies for different V2X services, thus facilitating the employment of varying configuration parameters for V2X services based on their potential requirements. In other words, certain fundamental services may function adequately with parameters corresponding to those permitted by the LTE V2X standard. Conversely, for more advanced services, the configuration of NR V2X technologies can be employed to capitalize on the capabilities of a more robust network. MR-DC V2X facilitates the integration of multiple RATs within V2X communication systems, including LTE and 5G NR. This enables vehicles to connect simultaneously to different networks, improving data throughput, coverage, and reliability. By aggregating bandwidth and resources from multiple technologies, MR-DC V2X optimizes network performance, reduces latency, and enhances the overall quality of V2X communication. This technology is of paramount importance for supporting advanced V2X applications, ensuring seamless connectivity, and enhancing safety and efficiency on the roadways.

Chapter 7

Conclusions and Future Work

7.1 Concluding Remarks

This thesis has focused on characterizing, studying, and evaluating standards for cellular network-based vehicular communications, Cellular-based Vehicle-to-everything (V2X) (C-V2X). Given that Third Generation Partnership Project (3GPP) standards define a series of reports and technical specifications with parameters and procedures that can be configured for both Long Term Evolution (LTE) V2X and New Radio (NR) V2X, it has been determined that there is a need to evaluate these standards in different usage scenarios.

In order to assess the efficacy of C-V2X standards, it was essential to perform a comprehensive analysis of the various reports and specifications defined by 3GPP for LTE V2X and NR V2X in Releases 14, 15, 16, and 17. Consequently, the information presented in these technical documents allowed a comprehensive understanding of the parameters and procedures that must be considered for a thorough evaluation and configuration of scenarios for both LTE V2X and NR V2X. The main parameters under consideration relate to the Physical (PHY) and Media Access Control (MAC) layers.

Concerning C-V2X, it was demonstrated that 3GPP standards support fundamental services related to packet transmission for collision prevention, emergency stop alerts, and alerts of emergency vehicles in the vicinity, among other applications. These services are considered basic because they tolerate certain latency, periodicity of V2X packet transmission, coverage range, and network reliability. In order to achieve this, 3GPP has defined two modes of communication from Release 14 onward. These modes enable vehicles to exchange V2X packets with other vehicles, devices carried by pedestrians, V2X infrastructures, and the cellular network.

The first mode, designated as mode 3 in the standard, is a centralized mode in which the network, through NBs, allocates radio resources for the communications of V2X UEs that require it. However, it should be noted that mode 3 is subject to the limitation that it necessarily requires cellular network coverage. In real-world scenarios, such as highways or rural areas, there are instances where coverage is lacking, rendering mode 3 inoperable. Consequently, the 3GPP has defined a decentralized mode, designated as mode 4, in which V2X UEs are preconfigured to manage the sensing and resource selection procedures for V2X packet transmission. This decentralized mode is of greater interest because it does not require coverage. Thus, the necessary configuration parameters must be ensured to avoid high interference and poor performance in the different use cases defined for C-V2X.

System-level simulations conducted allowed verifying that the performance of LTE V2X mode 4 can vary depending on the configuration parameters used. Therefore, it was identified that a high periodicity of V2X packets and a scenario with high vehicle density negatively influence the obtained Packet Delivery Ratio (PDR). This decrease in performance can be justified, firstly, because as the signal propagation distance increases, the signal is degraded. On the other hand, the sensing procedures defined for LTE V2X consider that vehicles sense the available resources for V2X transmissions and reserve a minimum percentage of resources for their transmissions. If they do not meet this minimum percentage of available resources, then they increase the power threshold at which they consider certain resources as candidates. Consequently, in scenarios with higher vehicle density or requirements for packet transmissions with higher periodicity, the probability that two or more V2X User Equipments (UEs) use the same resources increases, thereby increasing interference in communications. Simulations conducted on the LTE V2X mode 4 indicate that an increase in the periodicity of packet transmission rate is associated with a decrease in PDR. For instance, with a packet transmission rate of 1 packets per second (pps), a PDR of more than 80% is guaranteed for transmitter-receiver distances of less than 450 meters. However, when the V2X packet transmission periodicity increases to 5 pps, this level of PDR is only guaranteed at distances of less than 250 meters. At packet transmission periodicities exceeding 5 pps, a pronounced decline in PDR is observed as the separation distance between the transmitter and receiver increases. For example, at a distance of 250 meters, the PDR is reduced to 50% for a periodicity of 50 pps. The observed degradation can be attributed to the fact that a greater periodicity of V2X packet transmission implies greater use of time and frequency resources by the vehicles, which increases interference. Another factor contributing to the decreased PDR is the increased density of vehicles that need to establish V2X transmissions. This decrease is more noticeable at high packet transmission periodicity since channel congestion is increased by higher transmission periodicity and vehicle density. Simulations indicate that, for a packet transmission periodicity of 10 pps and transmitter-receiver distances of 300 meters, the PDR is reduced by approximately 20 percentage points when the vehicle density increases from 0.06 to 0.12 vpm.

As with mode 4, in LTE V2X mode 3, the PDR may be diminished as the distance between transmitter and receiver increases, when the periodicity of V2X packets increases, and when the density of vehicles requiring V2X transmissions is higher. In contrast, mode 3 generally exhibits superior performance due to its centralized nature, in which the network allocates resources. For instance, at 300 meters between transmitter and receiver, a vehicle density of 0.06 vpm and a packet transmission periodicity of 10 pps, the PDR achieved in mode 3 is 40 percentage points higher than the PDR obtained in mode 4.

Since 3GPP continued from Release 15 with a new generation of more robust mobile networks known as 5G NR, new standards were also advanced to adapt the improvements of this new technology to V2X communications services and use cases. There are differences in the sensing and resource selection procedures for NR V2X, which are inherent to the changes in the PHY and MAC layers defined for 5G NR. Consequently, NR V2X allows the allocation of larger channel bandwidths, thereby enabling the expansion of Sidelink (SL) subchannels in accordance with the specifications of diverse V2X services. Additionally, multicast and groupcast transmission modes are supported and essential in certain C-V2X use cases. Furthermore, an additional channel is supported, enabling receivers to transmit feedback information, thus allowing packet retransmission in scenarios with high interference.

A further notable distinction between LTE V2X and NR V2X is the use of numerologies. As higher numerologies increase the number of symbols in time and the size of SL subchannels, this can be adapted to achieve greater diversity of resources in time and frequency, thereby minimizing the probability of two or more V2X UEs selecting the same resources for their transmissions. Link-level simulations have demonstrated that the performance of NR V2X can be enhanced using higher numerologies. However, this may depend on the dimensions of the SL subchannels. In other words, simply increasing the numerology does not necessarily imply a greater diversity of resources in frequency. This is because the RBs that make up a SL subchannel also occupy more frequency space, thus reducing the number of available SL subchannels. Consequently, an alternative approach to maintaining a greater number of SL subchannels is to increase the channel bandwidth, which is a viable option in 5G NR systems.

An additional approach to enhance the diversity of resources in frequency is to reduce the size of the SL subchannels, expressed in terms of the number of RBs while considering the dimensions of the V2X packets to be transmitted. The simulations revealed that, under active sensing procedures, augmenting the spacing between subcarriers leads to a 10 percentage points decrease in the proportion of vehicles encountering a PRR below 80%. Consequently, as previously indicated, superior performance is attained with elevated numerologies attributable to the enhanced diversity of resources across the temporal and frequency domains.

It was also observed that comparable performance can be achieved by adjusting the channel bandwidth and SL subchannel size parameters for two distinct numerologies. For example, a numerology u=0, with 10 MHz of bandwidth and SL subchannels of 10 RBs, offers the same Packet Reception Rate (PRR) performance as a numerology u=2, with 50 MHz of bandwidth and SL subchannels of 50 Resource Blocks (RBs). However, with the second configuration, it is possible to send more information, which in the context of V2X communications equals sending larger packets. Furthermore, in environments with low interference, a higher-order modulation scheme can be advantageous in order to avoid the reduction of diversity in frequency resources. It can be seen that when u = 0 numerology is employed, the spacing between LTE V2X and NR V2X subcarriers is identical. Consequently, it can be concluded that NR V2X exhibits superior performance due to its capacity to allocate larger channel bandwidths within the same SL subchannel size. Following the standard, bandwidths of up to 50 MHz can be allocated, resulting in enhanced resource utilization and improved performance compared to LTE V2X.

About the sensing and resource selection mechanisms established by 3GPP, it was observed that when these are activated, superior PRR performance is consistently achieved in all cases. Nevertheless, random resource selection may reduce communication latency, which could be advantageous in low congestion and interference scenarios. This is because the probability that two or more V2X UEs will utilize the same resources will be lower. The evaluation of the NR V2X performance shows that, for both u=0 and u=2 numerologies, when the sensing procedures are active, the PRR is less than 80% at distances greater than 120 meters. On the other hand, the PRR degradation is higher when the sensing procedures are not active, so PRR drops below 80% for transmitter-receiver distances greater than 40 meters for both numerologies. Regarding u=2 numerology, when the sensing procedures are active, the probability that PRR is less than 80% is 70%. On the other hand, when the sensing procedures are not active, the probability of obtaining a PRR less than 80% is about 98%. Thus, it can be concluded that activating the sensing procedures leads to better performance.

Moreover, it was ascertained that, owing to the extended time-sensing window in NR V2X, there is a 65 percentage points increase in vehicles under u=0 numerology experiencing a PRR below 80% as compared to the u=2 numerology configuration. Furthermore, u=0 numerology demonstrates improved performance under equivalent subcarrier spacing conditions when larger channel bandwidths are utilized. The simulation outcomes revealed that, within the u=0 numerology, 90% of vehicles exhibit a PRR below 80%, whereas this proportion reduces to 20% for u=2 numerology. Additionally, it can be inferred that when the highest numerology and bandwidth are configured in NR V2X, 2.59% of vehicles experience a PRR below 85%, while for u=0 numerology, this percentage escalates to 99%. Consequently, 96 percentage points more vehicles achieve a PRR above 85% under NR V2X configuration with u=2 numerology and 100 MHz channel bandwidth.

From the comparative analysis of the decentralized modes of LTE V2X and NR V2X, it was generally observed that NR V2X exhibits superior performance relative to LTE V2X. According to established guidelines, an identical simulation scenario was configured for both LTE V2X and NR V2X. It can be concluded that NR V2X offers superior performance to LTE V2X, due to advanced transmission techniques, numerologies, shorter transmission times, enhanced sensing and resource selection mechanisms, higher-order modulation techniques, and other factors. The simulations demonstrated that, in the configured scenario, NR V2X exhibited superior performance, up to 30 percentage points higher in the PRR, when configured with the same bandwidth and spacing between subcarriers. Furthermore, NR V2X performance was enhanced by up to 39 percentage points when utilizing the maximum subcarrier spacing and channel bandwidth. This increase in the rate of correctly received packets reduces the average latency of communications, since fewer retransmissions are required. Consequently, in NR V2X latency can be reduced by up to 39 percentage points compared to LTE V2X. This reduction in average latency can also be attributed to high numerologies, which result in transmission times up to eight times shorter than in LTE V2X. Furthermore, high numerologies enhance transmissions' resilience against phenomena such as the Doppler effect, phase shift, and inter-symbol interference, which is crucial in vehicle communications at high speeds.

In V2X use cases associated with potential requirements for higher transmission rates, simulations demonstrated that in Millimeter Wave (mmWave), the achieved performance significantly improves because it is possible to allocate larger channel bandwidths. In particular, for numerology u=3, channels of up to 400 MHz bandwidth can be utilized. In such circumstances, the diversity of resources in time and frequency increases, resulting in enhanced throughput and PRR performance. Nevertheless, it is essential to acknowledge that, at high frequencies, the signal quality deteriorates with increasing propagation distance in the mmWave spectrum. This is an important consideration in V2X use cases, where potential requirements are related to large coverage distances. Simulations of NR V2X performance in millimeter bands showed that, in the first scenario configured with 100 MHz bandwidth and u=3 numerology, the throughput obtained is 229.97 Mbps. However, when the bandwidth increases to 400 MHz, the increase in throughput is approximately 19%. This throughput is affected when the vehicle speed increases or at greater distances between the transmitter and receiver. For example, with a channel bandwidth of 100 MHz, when the separation between the vehicles changes from 50 to 250 meters, the throughput decreases by 40%. On the other hand, with a channel bandwidth of 400 MHz and a vehicle separation of 250 meters, when the speed of the vehicles increases from 5 to 40 m/s, the throughput decreases by approximately 30%. In the other scenarios configured for the NR V2X mmWave simulation, it could be seen that both PRR performance and throughput are affected at higher speeds and vehicle separation distances. For example, in scenario 2, the PRR is reduced by 40% when the distance between the transmitter and receiver changes from 50 to 250 meters.

Using V2X communications with multiple Radio Access Technology (RAT) (multi-RAT) shows great potential to establish a strong foundation for developing transportation systems. The integration of RAT in V2X, including technologies like NR and LTE, significantly enhances the reliability and resilience of V2X systems. This is particularly advantageous when one RAT encounters coverage limitations or congestion. The seamless transition to an alternative RAT ensures uninterrupted connectivity and communication between vehicles and their surrounding environment. This smooth transition improves driving safety conditions and enables critical V2X applications, such as collision avoidance and real-time traffic management, to operate effectively. Furthermore, V2X multi-RAT improves resource utilization by leveraging multiple communication technologies. This optimally allocates available spectrum resources, mitigating congestion and maximizing system capacity. As a result, V2X applications see improved performance with increased data transmission rates and reduced latency. The flexibility of multi-RAT technology allows for efficient use of resources. V2X expands to include dynamic resource selection customized to meet the specific needs of various V2X use cases, ensuring optimal resource allocation across different applications and traffic conditions. It is important to note that multi-RAT serves as a mechanism to support the interoperability and future-proofing of current V2X systems. As cellular network technologies evolve and new generations emerge, such as Sixth Generation (6G), the capability to integrate multiple RAT ensures compatibility with existing systems, facilitating a seamless transition to future technologies. This adaptability enables diverse communication protocols and standards to coexist, ensuring backward compatibility, mitigating costs, and promoting the adaptability and scalability of V2X systems in conjunction with technological advancements.

The deployment of V2X multi-RAT environments exhibits specific characteristics contingent upon the diverse scenarios and the potential requirements of the V2X use cases or services. For instance, the deployment may vary in scenarios related to smart cities, highways, and urban environments. In the context of smart cities and urban environments, deploying V2X multi-RAT may be related to integrating existing infrastructure, which generates and sends data to the cloud using technologies not only 3GPP but also based on IEEE standards. In this way, multiple radio access technologies enable the forwarding of vehicle-generated data. For example, vehicles can exchange data related to parameters such as speed, position, route, notifications of malfunctions in the vehicle systems, and information from integrated cameras, radars, or sensors. These data, which can be transmitted through various interfaces and communication modes, can be integrated into the cloud to facilitate deploying sophisticated road safety and traffic management applications.

In the context of smart cities, centralized C-V2X modes are anticipated to be the optimal solution to transmit information to the cloud, given the probable availability of cellular networks, either LTE and/or NR. Although the speed of vehicles in these scenarios is relatively low, a higher density of vehicles or V2X UEs requiring to establish communications is expected. Therefore, the centralized mode will offer better management of radio resources to minimize interference. In this scenario, using the NR Uu interface or dual connectivity in conjunction with LTE may be necessary to transmit large volumes of information to the cloud.

Table 7.1 presents a summary of the principal advantages, disadvantages, and potential applications of LTE V2X mode 3 and LTE V2X mode 4, based on the criteria established in the standard and the results of the simulations carried out in this Thesis. Table 7.2 elucidates these aspects for NR V2X mode 2 and NR V2X mmWave.

7.2 Future Research Lines

Since 3GPP continuously works on the development of enhancements and supports new technologies that can be integrated into 5G NR, these can also be incorporated for C-V2X communication-based services. Therefore, it is necessary to adequately evaluate the performance of these technologies and mechanisms in different scenarios and use cases. Consequently, considering the 3GPP

Table 7.1: Summary of the features of LTE V2X modes 3 and 4.

Communication mode	*Aspect*	*Characteristics*
LTE V2X Mode 3	Advantages	-Increased coverage -Uses LTE infrastructure -Efficient resource management -Possibility of implementing advanced algorithms for radio resource management -Higher PRR than in mode 4
	Disadvantages	-Higher latency compared to mode 4 -Requires LTE network infrastructure -Intrinsic limitations of an LTE network -No standardized mechanism for resource sensing and selection
	Potential applications	-Basic C-V2X services: Forward Collision Warning, Emergency vehicle warning, Emergency Stop, Queue Warning, Automated Parking System, V2N Traffic Flow Optimization, Road Safety Services -Urban Scenarios
LTE V2X Mode 4	Advantages	-Low latency —decentralized mode— -No cellular coverage required -Autonomous resource management -Suitable for low vehicle densities -Standardized resource sensing and selection mechanisms -Operation in multi-RAT scenarios
	Disadvantages	-Coverage is lower than with mode 3 -High interference with higher V2X UE densities -The maximum channel bandwidth is 20 MHz -Broadcast transmission mode only -SL subchannels of max. 50 RBs
	Potential applications	-Basic C-V2X services: Forward Collision Warning, Emergency vehicle warning, Emergency Stop, Pre-crash Sensing Warning, Road Safety Services -Highway Scenarios

standards corresponding to Releases 17 and 18, the future work related to this thesis will focus on the following aspects:

- It is essential to ascertain the efficacy of V2X communications, particularly considering the feedback channel. This channel enables receivers to notify transmitters of instances where V2X packets have not been received correctly. This channel is anticipated to enhance the reliability of communications, albeit with an augmented latency due to the use of retransmissions.
- In Release 18, the standard establishes the possibility of using unlicensed bands in the 5 GHz and 6 GHz ranges for SL communications. A proper evaluation of the performance of C-V2X in these bands is expected to be beneficial in achieving greater coverage compared to mmWave bands.

Table 7.2: Summary of the features of NR V2X modes 2 and NR V2X mmWave.

Communication mode	*Aspect*	*Characteristics*
NR V2X Mode 2	Advantages	-Low latency —decentralized mode— -No cellular coverage required -Autonomous resource management -Numerologies:u=0, u=1, u=2 -Standardized resource sensing and selection mechanisms -Random resource selection -Variable sensing window: 100 ms, 1100 ms -Unicast, groupcast, and broadcast transmissions -Feedback channel -SL subchannels up to 100 RBs -Channel bandwidths up to 100 MHz -Higher PRR levels with high numerologies -Operation in multi-RAT scenarios -Support in the latest 3GPP Releases
	Disadvantages	-Higher power consumption than LTE V2X mode 4 -Not compatible, in principle, with LTE V2X -Increased computational expense -Random selection performance decreases at high densities of V2X UEs
	Potential applications	-Advanced C-V2X services: Pre-crash Sensing Warning, Vehicle Platooning, Advanced Driving -Highway Scenarios
NR V2X mmwave	Advantages	-Large channel bandwidths -High numerologies: u=2, u=3 -Small slots -Higher PRR levels with high numerologies -No cellular coverage required -Enhanced transmission techniques, e.g. beamforming Channel bandwidths up to 400 MHz Support in the latest 3GPP Releases
	Disadvantages	-Higher power consumption -Limited coverage -High losses due to interference and obstructions
	Potential applications	-Basic and advanced C-V2X services: Forward Collision Warning, Pre-crash Sensing Warning, Vehicle Platooning, Advanced Driving, Extended Sensors -Highway Scenarios -Urban Scenarios

- It is necessary to evaluate the performance achieved by including carrier aggregation technology in C-V2X communications. Thus, it is expected that the inclusion of this technology will enable support for advanced use cases related to potential high throughput requirements.
- The application of beamforming techniques can also be regarded as a technology that facilitates enhanced performance in scenarios character-

ized by high interference levels. In order to achieve this, it is necessary to establish appropriate beam selection mechanisms in C-V2X that operate in mmWave bands.

- In Release 18, the potential for utilizing a channel that permits the coexistence of LTE V2X and NR V2X with resource sharing in a semi-static and dynamic manner is also established. It is essential to evaluate these mechanisms thoroughly, given that LTE V2X and NR V2X were incompatible in previous releases.

- The MR-DC approach for V2X communications also requires a comprehensive assessment of use cases involving integrating multiple technologies, communication interfaces, communication modes, transmission modes, and the interconnection of V2X UEs belonging to different MNOs and operating in different regions.

Furthermore, potential avenues for research should be directed toward advancing more resilient cellular networks that can coexist with LTE V2X and NR V2X technologies. Consequently, 6G could be employed in the deployment of V2X services that are subject to rigorous requirements. Some of the 6G-related technologies that require proper performance evaluation in V2X scenarios are:

- Ultra-Reliable and Low Latency Communications (uRLLC): The objective is to achieve lower communication latencies —below 1 ms— by employing high numerologies. Although some of these have been defined for NR, the standard does not yet support their use in NR V2X. Furthermore, reliability can be enhanced by using higher bandwidths at higher frequencies and advanced modulation and coding techniques.

- Artificial Intelligence (AI) and Machine Learning (ML): Applying AI and ML techniques can be fundamental for V2X services. This includes processing large volumes of data, traffic prediction, and decision-making in autonomous vehicles, as well as the network's efficient management of radio resources. For example, implementing AI-based radio resource sensing and selection mechanisms is a promising approach. These mechanisms can enable the use of different RATs, interfaces, and communication modes depending on the conditions of the environment and the V2X service.

- Security and privacy: A paramount consideration in the generation and transmission of data among the diverse components of a network is safeguarding data security and privacy. Consequently, it is imperative to investigate security and data encryption solutions that can be adapted to V2X communications without affecting performance.

Exploring these research areas will contribute to the evolution of V2X multi-RAT environments, optimizing their performance and expanding their applications in different scenarios.

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