Understanding V2X: A physical layer comparison between 5G NR and NR V2X sidelink

University of Oulu
Information Processing Science
Master’s thesis
Vesa Lehtinen
2024

Abstract

This study examines the relevant 3GPP specifications to provide a coherent comparison between the current 5G NR deployments and the NR-V2X sidelink from the point of view of physical layer (L1) software and digital signal processing. The study aims to provide a coherent comparison between these two technologies while also providing an analysis of what kind of implications this new technology has on the physical layer software implementation and the potential problems that should be considered in an NR-V2X implementation. To achieve this, the current 5G NR functionality is compared to NR-V2X functionality using the technical specifications given in 3GPP releases 16 and 17.

do we need this?

Some release 18 documents are also considered to point out important upcoming changes which a V2X developer should be aware of, but these are not examined in detail. In short, the study examines the sidelink related changes introduced by NR-V2X specifications in contrast to existing base station-to-UE NR communications.

The findings of this study indicate that NR-V2X sidelink largely re-uses the concepts and techniques present in 5G NR communications. Based on the L1 comparison, it could be said that NR-V2X is essentially a simplified version of the existing 5G NR, with some V2X specific additions. Although the sidelink communication path reuses many 5G NR concepts, it also introduces many new concepts that an L1 developer should be aware of.

could be broken into two sentences?

The results also indicate that the specification documents include some problem points, such as functionalities that have strict timing requirements, but the proposed algorithms to achieve these functionalities are nondeterministic in their execution time.

This study is carried out as a literature review. More specifically, it follows a narrative literature review approach. The study focuses on industry standard literature, such as the official specifications provided by the 3GPP. Along with the technical specifications provided by the 3GPP, other relevant literature is also examined and used to complement the narrative of the review.

Keywords: 3GPP, Release 16, Release 17, Release 18, V2X, PC5, NR, Sidelink, Sidelink channels, PC5 channels, Sidelink signals, PC5 signals, Physical layer, L1 software

Supervisors:

PhD, Pertti Seppänen from University of Oulu.

MSc. Jukka Toivanen as technical supervisor from MediaTek.

FOREWORD

I am grateful to MediaTek Wireless Finland for giving me the opportunity to write my thesis on this topic. While writing this thesis, I have learned a lot about the physical layer operations of both 5G NR and NR-V2X, and telecommunications in general. Having the opportunity to work closely with the 3GPP specifications has also been enlightening, as before this thesis I found working with them quite daunting. Both the technical knowledge and the acquired specification handling skills will surely prove useful in my future career.

I would like to thank all of my colleagues at MediaTek from whom I asked for insights on specific topics during the writing process. You know who you are. Of my colleagues, I would especially like to thank Jukka Toivanen, the technical supervisor of this thesis, for his endless patience and active guidance with both the technical aspects as well as the general structure of the thesis. I would also like to thank my manager Antti Törmänen for suggesting this topic and organizing the opportunity for this thesis work on my behalf.

Finally, I would like to thank my supervisor from the University of Oulu, Pertti Seppänen, for supervising this thesis.

Abbreviations

16-QAM	16-Quadrature Amplitude Modulation
64-QAM	64-Quadrature Amplitude Modulation
3GPP	Third Generation Partnership Project
5G NR	5G New Radio
ADAS	Advanced Driver Assistance System
BSM	Basic Safety Message
BWP	Bandwidth Part
CA	Carrier Aggregation
CAM	Cooperative Awareness Message
CAN	Controller Area Network
CP	Cyclic Prefix
CRC	Cyclic Redundancy Check
CSI-RS	Channel-State Information Reference Signal
C-V2X	Cellular Vehicle-to-Everything
D2D	Device-to-Device
DC	Dual Connectivity
DCI	Downlink Control Information
DENM	Decentralized Environmental Notification Message
DFT	Discrete Fourier Transform
DL	Downlink
DM-RS	Demodulation Reference Signals
DOT	Department of Transportation
DSRC	Dedicated Short-Range Communication
eNB	Evolved Node B (LTE basestation)
eV2X	Enhanced Vehicle-to-Everything
FCC	Federal Communications Commission

FDD	Frequency Division Duplex
FEC	Forward Error Correction
FR1	Frequency Range 1
FR2	Frequency Range 2
gNB	Next Generation Node B (NR basestation)
GNSS	Global Navigation Satellite System
HARQ	Hybrid Automated Repeat Request
HPLMN	Home Public Land Mobile Network
ITS	Intelligent Transport System
L1	Layer 1 (Physical Layer)
LiDAR	Light Detection and Ranging
LTE	Long-Term Evolution
LTE-V2X	Long-Term Evolution Vehicle-to-Everything
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
ME	Mobile Equipment
MIMO	Multiple Input Multiple Output
mmWave	Millimeter wave
NR	New Radio
NR-V2X	New Radio Vehicle-to-Everything
NSA	Non-Standalone
OBU	Onboard Units
OFDM	Orthogonal Frequency-Division Multiplexing
OSI	Open Systems Interconnection
PBCH	Physical Broadcast Channel
PC5	Interface for direct device-to-device communication
PCF	Policy Control Function
PDCCH	Physical Downlink Control Channel

PLMN	Public Land Mobile Network
PRACH	Physical Random-Access Channel
PRS	Positioning Reference Signal
PSBCH	Physical Sidelink Broadcast Channel
PSCCH	Physical Sidelink Control Channel
PSFCH	Physical Sidelink Feedback Channel
PSS	Primary Synchronization Signal
PSSCH	Physical Sidelink Shared Channel
PT-RS	Phase-Tracking Reference Signal
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoS	Quality-of-Service
QPSK	Quadrature Phase Shift Keying
RAT	Radio Access Technologies
RB	Resource Block
RF	Radio Frequency
RIM-RS	Remote Interference Management Reference Signal
RRC	Radio Resource Control
RRI	Resource Reservation Interval
RSRP	Reference Signal Received Power
RSU	Roadside Unit
RV	Redundancy Version
SA	Standalone
SC-FDMA	Single-Carrier Frequency-Division Multiple Access
SCI	Sidelink Control Information
SCS	Subcarrier Spacing
SI	Study Item
SL PT-RS	Sidelink Phase-Tracking Reference Signal

SL	Sidelink
SPS	Semi-Persistent Scheduling
S-PSS	Sidelink Primary Synchronization Signal
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
S-SSB	Sidelink Synchronization Signal Block
S-SSS	Sidelink Secondary Synchronization Signal
SUL	Supplementary Uplink
TB	Transport Block
TDD	Time Division Duplex
UCI	Uplink Control Information
UE	User Equipment
UICC	Universal Integrated Circuit Card
UL	Uplink
UU	Communication interface for basestation-to-UE
V2I	Vehicle-to-Infrastructure
V2N	Vehicle-to-Network
V2P	Vehicle-to-Pedestrian
V2R	Vehicle-to-roadiside unit
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
VRU	Vulnerable Road Users
WI	Work Item

Contents

1 Introduction

The automotive industry is currently moving towards creating an intelligent transport system (ITS), which aims to improve the safety of road users by creating a co-operative communication system in which both the surrounding infrastructure and road users (vehicles and pedestrians) coordinate and predict potential hazards (Ganesan et al., 2019). In addition to the safety use cases, ITS is envisioned to improve the efficiency and quality of transportation by providing vehicles with comprehensive data that allows them to make more informed decisions regarding their route to avoid congested traffic areas and potentially hazardous road conditions (ETSI, 2018). As the foundation of the existing ITS, Advanced Driver Assistance Systems (ADAS) play an important role. ADAS systems equip vehicles with different sensors such as light detection and ranging (LiDAR) devices, radar, cameras, and ultrasonic sensors. The sensors used in ADAS have been designed to complement each other, addressing different use cases. For example, the radar has been incorporated into this array of sensors to augment the capabilities of the other sensors in low sunlight and poor weather conditions (Kawser et al., 2019). Together, the real-time data generated by these integrated sensors form the foundation for situational awareness and dynamic decision making in the current ITS. For example, ADAS can be used to implement emergency braking systems, adaptive cruise control and parking assistance.

Is this the
format

In addition to ADAS, the existing dedicated short-range communication (DSRC) technology based on the 802.11p standard has shown impressive results in terms of latency, interference, and reliability even in poor weather conditions (Petrov et al., 2021). However, one of the primary limitations of DSRC is that it is only limited to vehicles and infrastructure. To improve the robustness and reliability of the current DSRC system, cellular vehicle-to-everything (C-V2X), based on 3GPP standardized cellular modem technology, has been introduced. The unique advantage of C-V2X in comparison to DSRC is its ability to incorporate information also from pedestrians and the network (Yang et al., 2022). According to Moradi-Pari et al., (2023), the DSRC system can be thought of as a "WLAN-based V2X", essentially a modification of Wi-Fi, whereas C-V2X is a modification of the existing cellular technologies, long-term evolution (LTE) and new radio (NR). Currently, DSRC and C-V2X can be seen as competing alternatives.

On a general level, the term V2X refers to a system where vehicles communicate with their surrounding entities to exchange information about themselves and their surrounding environment. In literature, the term "C-V2X" is often used to describe systems where vehicles communicate with each other through cellular connectivity. For this reason, it is important to make the distinction between the two types of C-V2X currently specified by 3GPP. The first type is called Long-Term Evolution (LTE) V2X, which enables vehicles to communicate using existing 4G LTE architecture. The second type is called New Radio (NR) V2X, which utilizes the 5G new radio (5G NR) architecture. In most research on the topic of V2X, the term V2X is used as a synonym for C-V2X. This convention is adopted for this study as well, and therefore the term V2X always refers to C-V2X, unless explicitly determined otherwise. In the context of this study, the terms NR-V2X and LTE-V2X are used to differentiate between these generations of V2X communication, based on their underlying cellular technologies. Additionally, the term user equipment (UE) is used to refer to end-user devices such as cars or mobile phones. This is because UE is commonly used in 3GPP documents when referring to end-user devices.

1.1 Research question and method Problem Statement

The purpose of this study is to provide a coherent comparison between the physical layer properties and procedures between the current 5G NR networks and the NR-V2X system. The study aims to highlight any potential problems in the specifications which are relevant from a developer's perspective. In examining NR-V2X, this study focuses on sidelink communication, as the UU interface closely resembles the existing base station-to-UE communication. The study aims to answer the following research questions:

1. "What are the differences between the physical layers of 5G NR and NR-V2X?"

2. "What are the novel features that NR-V2X introduces?"

3. "What are the potential challenges that an NR-V2X developer should be aware of?"

The study is carried out as a narrative literature review focusing mostly on the technical documentation provided by the 3rd Generation Partnership Project (3GPP) organization. This is because 3GPP specifications are industry standard literature which lay out the requirements to which all cellular devices should conform, and therefore they are the most reliable source for finding up to date information regarding both 5G NR and NR-V2X. In addition to this, prior research and other sources are used to supplement the review where relevant. With this approach the study strives to provide a coherent and easy to understand examination of the technical standards while also considering findings from other studies to create a holistic understanding of NR-V2X. Since the topic of NR-V2X is very broad, the scope of the study has been limited to only cover concepts which are either 1) relevant for a general understanding of NR-V2X, 2) directly related to the physical layer implementation of NR-V2X or 3) directly related to a significant difference between 5G NR and NR-V2X. Whenever more detailed explanations of specific concepts need to be left out due to scope concerns, the study attempts to provide sources for further exploration for interested readers.

An effort is made to handle all the material objectively and in a nonbiased manner whenever sources other than the official technical specifications are used. In addition, as NR-V2X is a quickly evolving technology, the study aims to include mostly recent sources, preferably ones which have been published during the last ten years. Older studies could quickly become irrelevant and outdated, as the technical specifications evolve to cater for the rapidly changing needs of society. Some exceptions are made when an older study is deemed relevant for the narrative of the review, such as when discussing the evolution and history of V2X.

The technical specifications used in the study are gathered from the official 3GPP documentation portal by searching for documents which relate to either general V2X concepts or the physical layer implementations of 5G NR and NR-V2X. External studies and materials are gathered from multiple different search engines such as IEEEXplore, Google Scholar and the University of Oulu search engine, which indexes multiple databases. From these search engines, the material is gathered using keywords such as "V2X", "NR V2X", "New Radio V2X", "Vehicle-to-Everything", "DSRC", "C-V2X", "D2D communication", "Physical Layer V2X", "Layer 1 V2X", "Physical Layer NR V2X" and "Layer 1 NR V2X".

is this needed?

In addition to these search engines, relevant studies are also gathered by following the references in other studies, whenever a cited study seems relevant to the topic of this thesis. When sources other than the 3GPP specifications are examined, a conscious effort is made to include mostly peer-reviewed studies. Some possibly relevant material had to be excluded due to limited access.

Finally, some technical books are used to understand and explain how the compared concepts are currently specified in 5G NR. The most prominent book used for this purpose was Dahlman et al's (2018) book, "5G NR: The Next Generation Wireless Access Technology".

2 Introduction to V2X

Background

The primary applications of V2X are vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I), vehicle-to-network (V2N) and vehicle-to-pedestrian (V2P) (3GPP, 2021b).

In V2V applications, vehicles communicate directly with each other. This type of communication enables reliable and fast exchange of diverse data, which can be used to enhance road safety, traffic efficiency and autonomous driving. An example of useful data that could be communicated to other vehicles would be the vehicle's speed, direction, and intentions, such as turning or braking. Vehicles could also warn each other about potential hazards on the road, such as obstacles or poor road conditions.

In V2I applications, vehicles communicate with infrastructure or local application servers to exchange information. Local application servers serve specific geographic areas, such as vehicles in a specific part of a city. For example, by utilizing V2I communication, emergency vehicles can send signals to local traffic management infrastructure to gain priority at an upcoming intersection (3GPP, 2021b). V2I communication can be further specified to vehicle-to-road side unit (V2R) communication, when the vehicle communicates with a specific type of infrastructure known as a roadside unit (RSU).

V2N applications are used to connect vehicles to cloud-based services (3GPP, 2021b). With V2N, vehicles can provide valuable traffic data such as congestion, road condition and accident information. This information can then be shared and used for various purposes in V2V, V2I or V2P applications. One example of this would be using traffic data to dynamically adjust the routes vehicles take. Additionally, V2N could be useful for smart city use cases, such as seeing vacant parking spaces on the infotainment system, reducing the congestion caused by vehicles looking for vacant parking space.

Finally, in V2P applications, pedestrian devices exchange information with nearby vehicles and their on-board units (OBU). The primary function of V2P applications is to provide warnings to both drivers and vulnerable road users (VRU) about potential hazards, such as a rapidly approaching vehicle around the corner or a pedestrian attempting to cross the road while being obscured by buildings or other vehicles (3GPP, 2021b). In the context of autonomous driving, V2P applications play an especially important role in reducing the risk of potentially fatal accidents caused by autonomous vehicles. Although the principle between V2V and V2P applications is quite similar, the primary reason for separating V2P and V2V into their own categories is the UE capability. In V2P applications, the devices carried by pedestrians might, for example, have a limited battery capacity which needs to be considered in V2P specific requirements (3GPP, 2021b).

2.1 Communication interfaces

This chapter discusses the radio frequency (RF) communication interfaces that are used in V2X, namely the PC5 and the UU, as seen in Figure 1**.** Both PC5 and UU are available in both non-standalone (NSA) and standalone (SA) deployments, as well as both LTE and NR communication. However, as LTE and NR deployments differ greatly in their underlying mechanisms, so do the procedures surrounding the PC5 and UU interface as well.

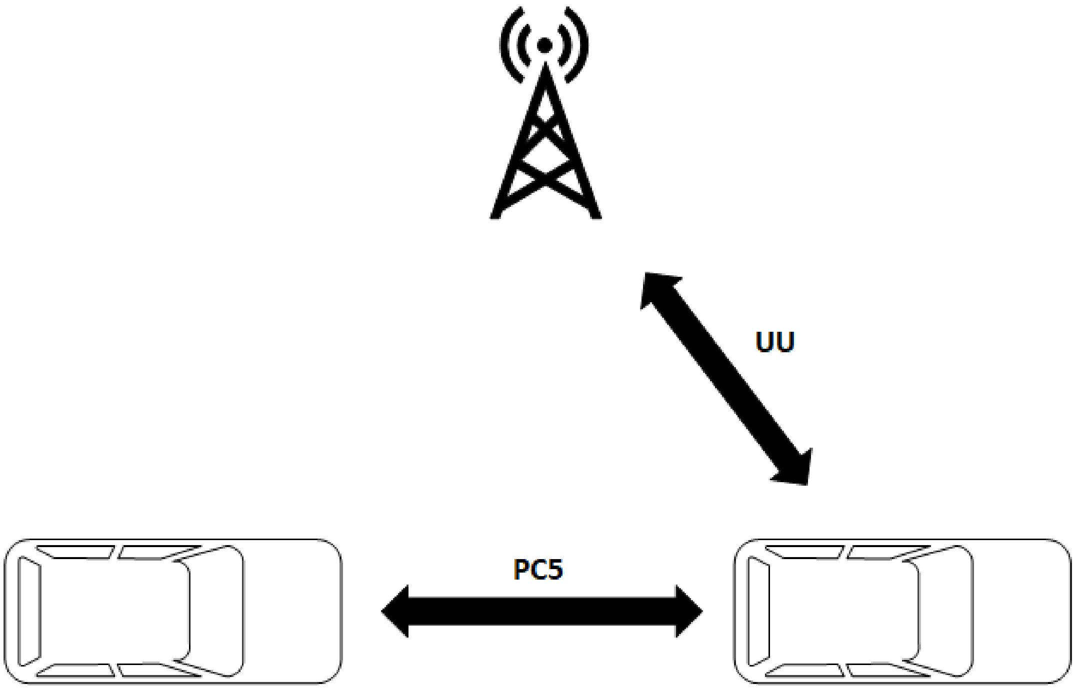

Figure 1. The PC5 and UU communication interfaces in V2X.

2.1.1 PC5 interface

The PC5 interface is used for sidelink (SL) communications. Sidelink allows vehicles (or other entities) to establish reliable low latency connections directly with each other without base station involvement. In NR-V2X, the direct communication path combined with the high data rate of the NR architecture creates unique opportunities for modern NR-V2X applications, which are often referred to as eV2X (enhanced V2X) applications. Examples of eV2X applications include vehicle platooning, semi-automated or fully automated driving, remote driving and data exchange using extended sensors (3GPP, 2022m).

It should be noted that there are two kinds of PC5 reference points, the NR PC5 reference point and the LTE PC5 reference point (which supports only broadcast). UEs can choose between the reference points depending on their supported services and configurations. The main difference is that the NR PC5 supports control plane signalling for unicast communication management, whereas the LTE PC5 does not (3GPP, 2022f).

Better to tabularize the differences like this

The PC5 interface also enables a unique feature called sidelink relay (Figure 2). This mechanism allows vehicles (or other UEs) to relay information to other devices outside the communication range of the initial broadcast (3GPP, 2021c). In practice, the transmitting (TX) UE sends data to the receiving (RX) UE through relay UEs, sort of like a mesh-network. This is especially useful in areas with poor network coverage as it allows vehicles to maintain reliable communication despite changing network conditions. With sidelink relaying, the data can be transferred to the Rx UE through multiple paths, making the connection more robust and fault tolerant.

not clear

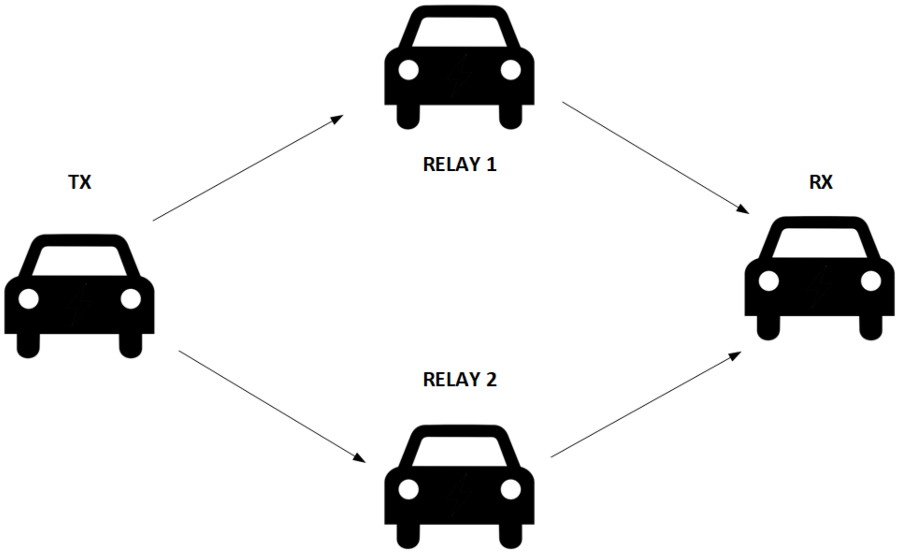

Figure 2. Sidelink relaying

In summary, the PC5 interface enables direct communication between UEs and the relaying of data from one UE to another through relay UEs.

2.1.2 UU interface

The UU interface is used for cellular network communication, utilizing the normal 5G air interface. The UU interface handles the uplink (UL) and downlink (DL) data transmission between the vehicle (or other UE) and the base station. With the UU connection, it is also possible to schedule and manage the PC5 (sidelink) communication so that the base station acts as the centralized control entity. The different scheduling approaches are discussed in more detail in chapter 6.2.3. of this study. The PC5 and UU interfaces are separate, operating on different operating bands. This design allows the PC5 and UU to be operated concurrently, using a set of defined concurrent operating bands (3GPP, 2023). The operating bands are discussed in chapter 6.1.1.

2.1.3 Coexistence of PC5 and UU

When discussing the UU and PC5 interfaces, it is important to note that from a practical perspective, the UE does not necessarily need to support both interfaces. In practice, there can be two types of V2X UEs, ones which support both PC5+UU, and ones that support only the PC5. One of the big differences between these two types is the mechanism they use to receive their RRC configuration from the higher layers.

Define abbreviation here

For a UE that supports both PC5 and UU, it is possible to receive the radio resource control (RRC) configuration directly from the network, which also enables the network to update the configuration dynamically. This approach improves the flexibility of the configuration process, but it is dependent on network connectivity. That is, if the UU connection to the base station is unavailable, the UE would practically have to depend on the current configuration, with only PC5 active.

If a UE supports only the PC5 interface, it has no way to receive RRC (re-)configuration from the network. In this situation, the UE would have to depend on a static preconfiguration. However, as configurations are typically different between geographical areas, the preconfiguration could become invalid if the UE moves from the EU to the USA for example. In practice, the first V2X devices will likely only support the PC5. This means that the UEs will need to have their RRC parameters preconfigured in their hardware, and if the configuration needs to be updated, the UE will need to reboot. The new configuration would then need to be supplied through some other medium. Albeit not practical, one approach would be to directly upload the updated (country specific) configuration to the UE via cable. As many vehicles already implement a form of UU connection through some other device (such as the infotainment system), the external UU connection could possibly also be used to provision new configurations to PC5 only UEs moving from one region to another.

In the upcoming chapters of this study, when V2X communication is discussed, by default it always refers to sidelink traffic over the PC5 interface, unless explicitly stated otherwise.

2.2 Casting types

V2X applications need to establish communications with different groups of surrounding entities to match the needs of different V2X applications. To match the different operating scenarios, rapidly changing conditions, and the need to meet different Quality-of-Service (QoS) standards, V2X devices can utilize one of three casting types (also known as communication modes). These casting types are broadcasting, multi-/groupcasting and unicasting. NR-V2X supports all three of these casting types, whereas LTE-V2X only supports broadcasting (3GPP, 2022c).

2.2.1 Broadcasting

Broadcasting (Figure 3) is used when a vehicle or some other entity needs to send a message that is meant to be received by all the other V2X devices within the range of the broadcast. Therefore, this communication mode is characterized by a one-to-many relationship. Broadcasting can be used to share information about the vehicle's state and intentions. For example, the vehicle could broadcast information regarding its speed, position, and direction to all nearby vehicles. Broadcasting is supported by both NR and LTE V2X devices (3GPP, 2022c). Broadcasting does not support hybrid automatic repeat request (HARQ) feedback (3GPP, 2022c), which is a type of feedback that the receiving UE can send to report whether the data was received correctly. Because of this, the transmitting vehicle does not know if the receiving vehicle received the transmission successfully, it simply sends the message in a wide area and hopes that the surrounding vehicles receive it.

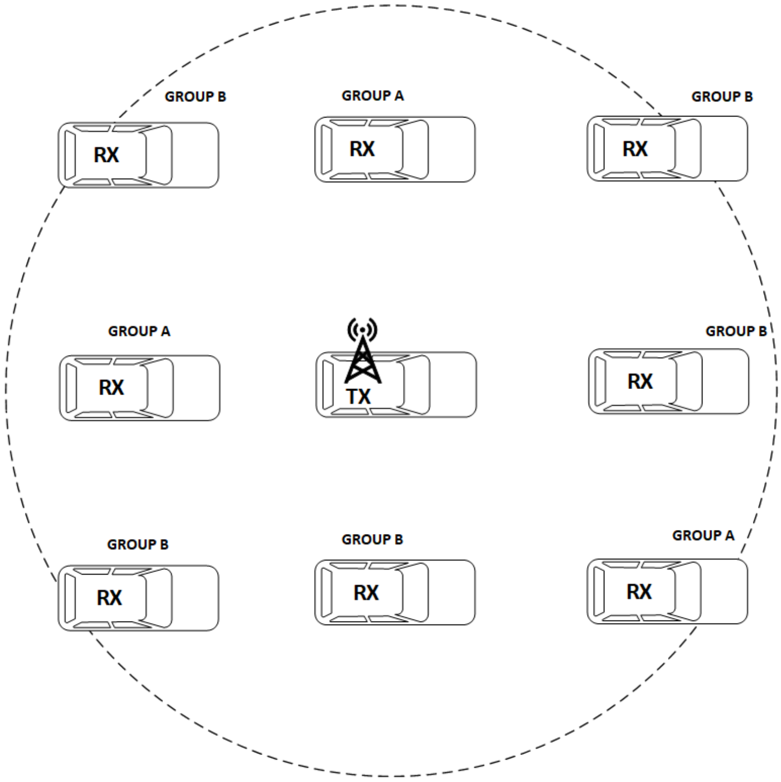

Figure 3. Broadcasting

Arrows
missing

2.2.2 Groupcasting

Groupcasting (also known as multicasting), seen in Figure 4, is used when a V2X device needs to send a message to a specific group of receiving UEs. This type of communication is also characterized by a one-to-many relationship, and it is only supported by NR-V2X (3GPP, 2022c). The intended receivers are defined by using either application-layer V2X identifiers, group size and members IDs, range requirements, communication mode (set to groupcast) or a combination of these (3GPP, 2022g). As groupcasting forms multiple one-to-one links, it is possible for the transmitting vehicle to identify each vehicle that it is communicating with. Because of this, groupcast supports HARQ. This means that the vehicles in the groupcast group are able to report whether they received the data correctly and request a retransmission if not. There are multiple HARQ operation schemes available in NR-V2X. These are discussed in chapter 6.2.5 of this study.

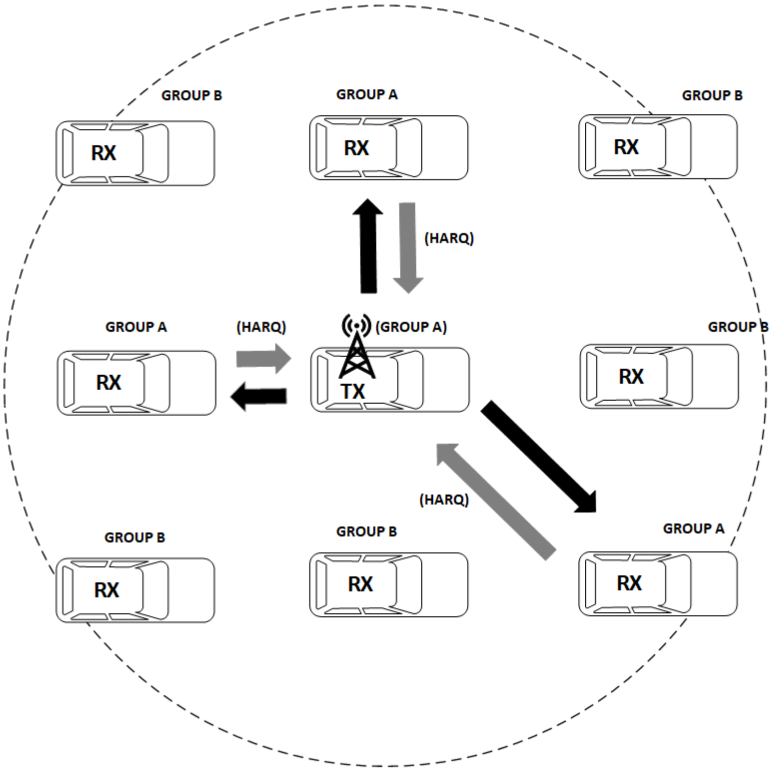

Figure 4. Groupcasting / Multicasting

2.2.3 Unicasting

Lastly, in unicast communications, two UEs communicate directly with each other on a one-to-one basis (Figure 5). In unicast communication, the UE that requests link formation is referred to as the initiating UE, and the other UE as the target UE (3GPP, 2022g). The request sent by the initiating UE contains information regarding the type of V2X service(s) offered. Optionally, the request can also contain information about the intended target UE, but if it doesn't, all UEs interested in the offered services may respond to the request. In this case, the initiating UE is responsible for handling all the received responses and forming the corresponding unicast links (3GPP, 2022g). Unicast links are identified based on their link layer identifiers, also known as Layer-2 IDs. Essentially this means that the devices form a unique pair of IDs which cannot be reused by other concurrent unicast links (3GPP, 2022g). It should be noted, that if the UE is participating in a V2X application that requires privacy support in that geographical area, the Layer-2

ID of the source UE must be changed and randomized over time (3GPP, 2022h). In IP based communications, the source IP needs to be changed over time as well. With privacy support enabled, the UE with an active V2X application can only be tracked and identified by other UEs for a period of time, before their identity is randomized (3GPP, 2022h). The distinction between IP and non-IP traffic is made in the V2X message request made by the higher layers (3GPP, 2022g). As with groupcasting, unicast also supports HARQ feedback.

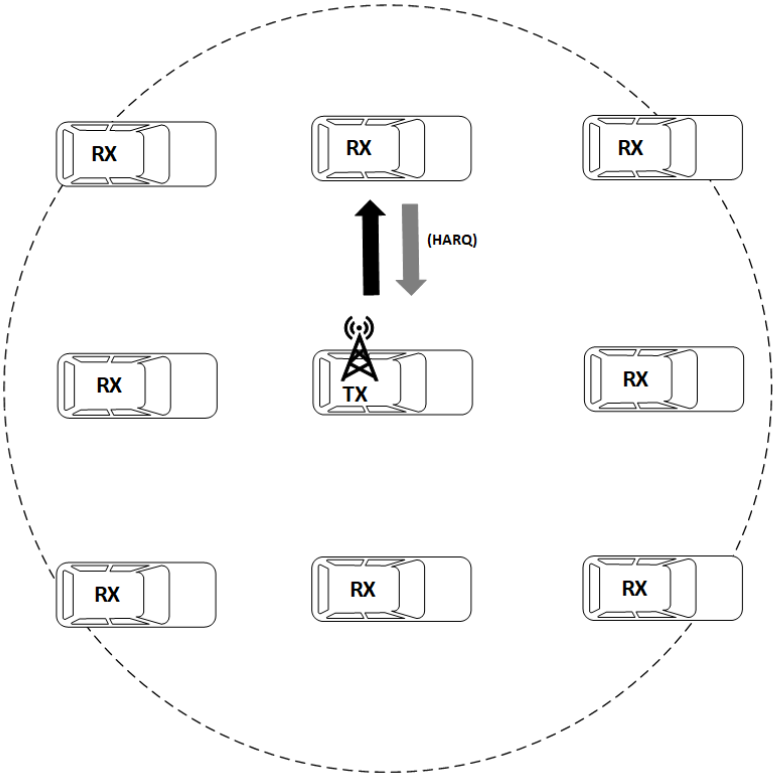

Figure 5. Unicasting

A single device can establish multiple unicast links simultaneously. The maximum number of unicast links is implementation specific, but 3GPP recommends a maximum of 8 concurrent NR PC5 unicast links (3GPP, 2022g).

2.2.4 Choosing the communication mode

Is referencing style correct?

According to 3GPP (2022f), the choice for the communication mode is made based on the available V2X parameters, which can be provided to the UE by multiple sources. When selecting a source of parameters between multiple sources, the UE follows a specific order of priority:

1) Parameters provided or updated by the Policy Control Function (PCF)
2) Parameters provided or updated by the V2X Application Server through the V1 reference point.
3) Parameters configured in the Universal Integrated Circuit Card (UICC), also known as SIM card.
4) Parameters pre-configured in the hardware of the UE. The hardware of the UE is also called mobile equipment (ME).

Practically, the PCF controls the UE's authorization for V2X communication for both UU and PC5 reference points. This means that the PCF is able to both grant authorizations and revoke them using a separate configuration procedure. Authorizations are handled on a per-PLMN (Public Land Mobile Network) basis within the HPLMN (Home Public Land Mobile Network) (3GPP, 2022f). For the purposes of layer 1 (L1) software, it can be summarized that the communication mode is either chosen by the higher layers, preconfigured in the UICC, or preconfigured in the hardware of the UE.

3 The evolution of V2X

This chapter introduces a brief V2X timeline, which provides context to better understand the evolution of intelligent transport systems (ITS) over the years. The chapter also discusses how the modern cellular V2X addresses some of the issues present in previous vehicular communication technologies.

The concept of ITS has been around for a long time. It was officially recognized in 1999, when the United States Federal Communications Commission (FCC) decided to allocate a 75 MHz spectrum in the 5.9 GHz band that was reserved for the use of ITS services (Garcia et al., 2021). This sparked significant research interest worldwide, which lead to major advancements in the development of V2X communication technologies from 1999 to the present day.

The first V2X radio standards, finished in 2010, were derived from the IEEE 802.11p technology, also knowns as dedicated short-range communication (DSRC) (Garcia et al., 2021). According to Kenney (2011), the main motivation behind DSRC was to create collision prevention applications, as the U.S. Department of Transportation (DOT) projected that DSRC-based vehicle-to-vehicle (V2V) communications could prevent up to 82 percent of all crashes involving unimpaired drivers in the United States. Due to this projection, DOT considered making DSRC equipment mandatory in new vehicles in the United States from 2013 onwards (Kenney, 2011). Although this requirement was never put into action, it shows that the benefits of V2V communications were identified well before the advent of the modern, cellular V2X technology.

Between DSRC and modern C-V2X, 3GPP release 12 introduced a technology called LTE device-to-device (D2D) proximity-based services (Ali et al., 2021). D2D is an important predecessor to modern V2X, as it was the first technology to introduce the PC5 interface, which enabled direct device-to-device communication. In addition to defining the PC5 interface, LTE D2D also introduced the concept of relaying network connection to devices with a poor connection to the Evolved Node B (eNB) (Ali et al., 2021), essentially laying the groundwork for the upcoming sidelink relay of the modern V2X architecture. D2D also introduced many of the other foundational concepts which the modern version of C-V2X utilizes, such as sidelink and the related physical channels. D2D was also the first technology to define the modes for distributed scheduling that cellular V2X utilizes today. D2D devices could choose between mode 1, in which the eNB schedules the resources for the UE, and mode 2, in which the devices select the resources autonomously from a common resource pool (Ali et al., 2021). Despite the groundbreaking advancements in direct device-to-device communications, D2D was not really suited for vehicular communications due to the high latency, as delayed or lost packets could have severe consequences for the drivers and the people around them. In summary, D2D can be seen as the first version of the current PC5 device-to-device communication system, but it could not be used in any vehicular use cases due to it being too slow and unreliable.

After D2D, the LTE C-V2X was first introduced in 3GPP Release 14 and further refined in Release 15 (Garcia et al., 2021). This new technology improved the previous D2D system by introducing communication modes 3 and 4, which were designed to address the challenges of vehicular environments, such as the latency requirements, Doppler spreads etc (Ali et al., 2021). The differences between communication modes 1, 2, 3 and 4 are discussed in more detail in chapters 5.3 and 6.2.3 of this study.

Based on LTE-V2X and a group of study items introduced in Rel 15, the development of NR-V2X standards began in release 16, with most of the standardization work items (WI) and study items (SI) taking place between the years 2018 and 2019 (Garcia et al., 2021). Based on the results of this work, Release 16 became the first standard to define V2X functionality that utilizes the 5G NR air interface. According to Ali et al. (2021), NR-V2X initially considered the usage of millimeter wave (mmWave) bands for shortrange V2X use cases requiring very high throughput, but the mmWave development was deprioritized in one of the work items released in 2018. The standardization work for NR-V2X is still ongoing, as needs for new features and improvements are recognized. One example of such an improvement is sidelink positioning, introduced in release 18 (3GPP, 2023b).

NR-V2X addresses several use cases which include requirements that cannot be met with the LTE-V2X technology. NR-V2X enables advanced applications outlined by the 3GPP, some of which are to be deployed in later stages of V2X adoption. These include applications such as vehicle platooning, remote driving and enhanced or semi-autonomous driving (3GPP, 2022m). All the advanced applications require high data rates and low latency, which is why they could not be implemented using any of the prior versions of V2X technology. Ultimately, NR-V2X aims to enable and support enhanced V2X (eV2X) services, which are essential for connected and automated driving.

Nowadays, many autonomously driving vehicles utilize sensors such as cameras, light detection and ranging devices (LiDAR), Radar, controller area network (CAN) and global navigation satellite system (GNSS) access (Miao et al., 2021). Although these traditional sensors will still play an important role in road safety, V2X strives to amplify their effectiveness by solving some of the issues that the existing sensors struggle with. These include issues such as long-range detection and line of sight issues, such as blind-spot detection. It is worth noting that in comparison to the traditional sensors often found in autonomous vehicles, the modern cellular V2X technology is also economically more cost efficient for large scale deployment (Miao et al., 2021).

4 Understanding the L1 layer

The physical layer, also known as L1, is the lowest layer in the open systems interconnection (OSI) model. The responsibilities of the L1 layer are associated with the physical connections between devices and networks. These physical connections can be, for example, electrical signals, optical signals, or electromagnetic waves. Put simply, the physical layer offers data transport services to higher layers by handling different aspects related to data reception and transmission (3GPP, 2020a). In 5G NR, access to different layers is given with a mechanism called channel mapping where each layer maps the channels of their higher layer to their corresponding channels (Dahlman et al., 2018). In Figure 6, logical channels are mapped to transport channels and transport channels are mapped to physical channels. This mechanism creates layered abstraction in the system. As seen in Figure 6, access to physical layer services is granted through transport channels via the medium access control (MAC) sub-layer (3GPP, 2020a). In LTE and 5G NR, each physical channel practically corresponds to a set of time-frequency RF resources which are used to transmit that specific transport channel. Although typically each physical channel has a corresponding transport channel, there are some exceptions. Such channels are called L1/L2 control channels, which are used to provide the device with control information (DCI/SCI) and uplink control information (UCI) (Dahlman et al., 2018). The general purpose and responsibilities of the L1 layer remain the same between 5G NR and NR-V2X.

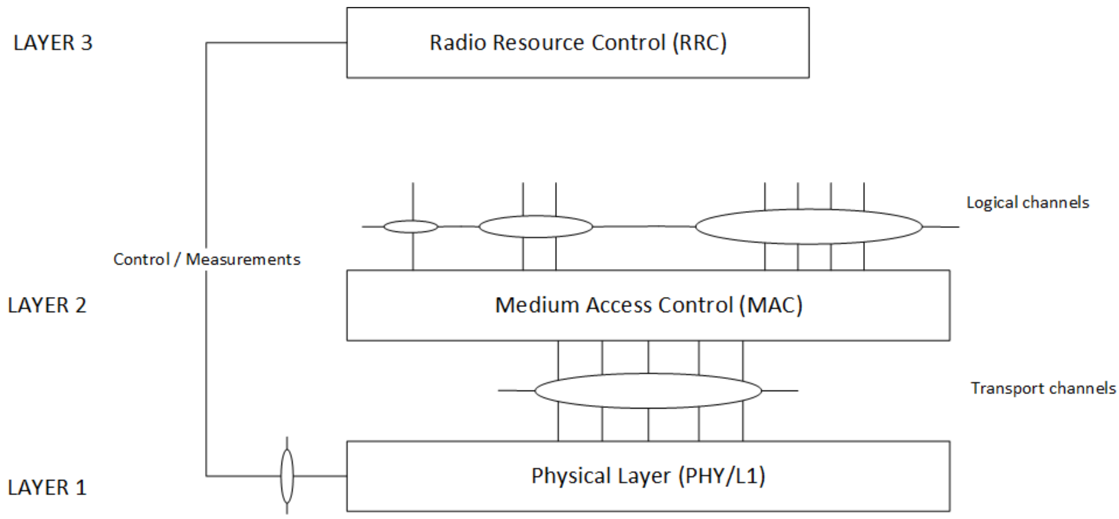

Figure 6. Radio interface protocol architecture as depicted in 3GPP (2022q).

In V2X, there are a handful of new physical channels and signals, which are specific to the PC5 (sidelink) interface. Understanding these channels plays an important role in the design of a V2X capable L1 architecture. The L1 manages these physical channels and defines how data is transmitted over them, and how the transmissions are synchronized between devices, both in terms of time and frequency (3GPP, 2020a). The physical channels are discussed in more detail in chapter 6.1.4 of this study.

4.1 L1 Layer responsibilities

According to 3GPP (2020a), there are 11 different functions that the L1 is expected to perform to provide data transport services for the higher layers:

1) L1 is responsible for error detection on the transport channel and indicating potential errors to higher layers. Especially important in the context of V2X applications where reliable transfer is necessary, the physical layer implements error detection and error correction mechanisms. Examples of such mechanisms include for example cyclic redundancy checks (CRC) and different retransmission strategies such as hybrid automated repeat requests (HARQ) (3GPP, 2022a). With these mechanisms, the L1 plays an important role in ensuring that quality-of-service (QoS) goals are met, reporting the relevant information to the higher layers.

Grammar

2) L1 takes care of forward error correction (FEC) encoding/decoding each transport channel. As a simplified explanation, in FEC encoding, each symbol is sent multiple times to protect it against being corrupted during transmission. The received bits are then examined at the receiver side, and a decision for the correct bit is made based on majority (Sheldon, n.d.). Although the FEC implementation can vary by system, the idea remains the same. The transmitter encodes parity information to the sent data, and the receiver decodes that parity information to correct potential errors. In the case of too many errors, a retransmission is requested.

3) L1 rate matches the coded transport channels to physical channels. The rate-matching functionality has two purposes; it matches the number of coded bits to the available transmission resources and generates different redundancy versions which are necessary for the HARQ protocol (Dahlman et al., 2018). The transmitter generates different redundancy versions of the transmission data by utilizing a circular buffer. This mechanism allows the device to transmit different chunks of coded bits, with each representing the same information in a slightly different way (Dahlman et al., 2018). In practice, the encoded bits (data + parity) are stored in a buffer and based on the available PDSCH/PSSCH (data channel) resources, the bits are then selected to be transmitted in reasonably sized chunks, with the exact bits depending on the redundancy version (RV) (Dahlman et al., 2018). In reality, the logic behind bit selection can be quite complex, as it contains many techniques such as bit interleaving, bit pruning and bit puncturing (3GPP, 2022j; Dahlman et al., 2018). These techniques are used to address needs like robustness against burst errors, adjusting redundancy, and efficient resource usage.

define at the first instance

4) L1 manages Hybrid ARQ soft-combining. HARQ feedback is a core feature in modern 5G NR systems, designed to improve the reliability of communication together with rate matching. With the soft-combining mechanism, received packets are stored in a buffer, and if a retransmission occurs, these buffered bits are used to improve the decoding reliability by combining them with the retransmission's bits. Since the retransmission is encoded slightly differently (thanks to rate matching), the probability of correctly receiving the retransmission bits increases (Dahlman et al., 2018). This means that the receiver also needs to implement a buffer, with the size determined by the soft-buffer capability.

5) L1 maps the transport channels to the corresponding physical channels. Logical channels offered by the MAC layer are mapped to transport channels, and transport channels are then mapped to physical channels which carry information in the air interface.

6) L1 performs power weighting on the physical channels. Practically, the L1 is responsible for adjusting the power levels of the physical channels and observing the signal quality (pathloss). Adjusting the power levels is crucial for optimal signal strength and minimal interference.

7) L1 is responsible for the modulation and demodulation of physical channels and signals. The L1 modulates the transmitted signal to the suitable carrier waves using suitable modulation and coding schemes (MCS). On the receiving end, the L1 layer demodulates the signal to extract the data in a readable format.

8) L1 ensures frequency and time synchronization. To make data transmission and reception possible, L1 needs to ensure that the transmitter and the receiver are synchronized in terms of frequency, phase, and time. To achieve this, the L1 implements reference signal processing. Practically, the transmitter sends a reference signal along with its relevant transport channel. Once received, the receiver is able to compare the acquired reference signal to the known ideal reference values. With this information, the receiver is able to correct frequency and timing errors.

9) L1 performs radio characteristic measurements. L1 is responsible for measuring various radio characteristics, such as signal power, signal quality, signal-to-noise ratio, and interference ratio (3GPP, 2022k). In addition to radio characteristic measurements, L1 optimizes future transmissions by reporting Channel State Information (CSI) to the transmitter, which enables them to adapt their transmission parameters accordingly. This is discussed in more detail in chapter 6.2.4.

10) L1 manages MIMO antenna processing. When it comes to 5G NR, the L1 is the layer responsible for beamforming and managing the multiple-input multiple-output (MIMO) functionality. In essence, beamforming means focusing the transmission on a direction to improve the quality of the signal. This substantially reduces the power usage, as the transmission power is concentrated into precise beams. MIMO practically means utilizing antenna arrays at both the receiver and transmitter to enhance the capacity and reliability of the communication through a mechanism called spatial multiplexing (Dahlman et al., 2018). In modern 5G systems, Massive MIMO and beamforming go hand-in-hand in enabling scalable and efficient data transmissions. In NR-V2X, beamforming remains unspecified, despite some studies proposing potential implementation strategies for it (Montero et al., 2022).

11) The L1 handles all the necessary radio frequency processing for the transmission and reception of the physical signals.

Based on these responsibilities, it could be summarized that the L1 is responsible for transmission and reception control and their synchronization, error correction, and different measurements to indicate the quality of the signal to higher layers.

5 Overview of LTE-V2X

This chapter provides an overview of LTE-V2X. Due to the scope limitations of this study, this chapter is held brief. Chapter 5.1 provides a summary of the coexistence between LTE-V2X and NR-V2X and explains why understanding LTE-V2X is relevant from the point of view of an NR-V2X developer. Chapter 5.2 summarizes some of the most important physical properties, such as frequency ranges and operating bands, frame structure and different physical channels and signals. Finally, chapter 5.3 introduces the resource scheduling modes of LTE-V2X and provides pointers to more in-depth materials for interested readers.

5.1 Coevolution and coexistence of LTE-V2X and NR-V2X

Although the topic of this thesis is primarily NR-V2X, it is important to understand that NR-V2X is not intended to be a replacement for LTE-V2X. Typically, when a new communication technology is deployed, it is first deployed in areas with dense traffic and a clear need for new communication capabilities. After a new technology has been adopted in major cities, it will gradually spread to more remote areas, depending on the strategy chosen by the operator (Dahlman et al., 2018). In the case of 5G NR, this leads to a situation where devices move in and out of 5G coverage areas, meaning that a device that only supports 5G will be unable to function properly when it moves outside the 5G coverage area. On the other hand, devices supporting only LTE cannot utilize the high data rates provided by the 5G technology. For this reason, seamless handovers where a device is moved from a 5G network to a 4G network, have been a critically important part of telecommunications technology ever since the 3G era (Dahlman et al., 2018). It should be noted that V2X makes an exception to this rule, as the devices are able to operate independently, outside base station coverage. Regardless, a gradual adoption of the V2X technology is to be expected due to the relatively higher complexity of NR-V2X in comparison to LTE-V2X. To ensure reliable connectivity for most UEs and other devices, there needs to be a relatively long time period where newer technologies need to be backward compatible with previous systems (Dahlman et al., 2018). A very prominent example of LTE and NR coexistence are the Non-standalone (NSA) networks of current 5G. In an NSA network, the 5G system essentially utilizes the LTE control network, with only the data itself being transmitted over 5G. The standard 5G NR architecture also features a fallback mechanism that allows the UE to seamlessly transition into 4G if the 5G signal becomes weak or if there is not enough traffic to warrant the use of 5G. This fallback mechanism is especially important to provide consistent connectivity, allowing devices to connect to the 4G network if they move outside of 5G coverage. Many devices also support dual connectivity (DC), which allows the UE to simultaneously connect to both LTE and NR networks (Dahlman et al., 2018).

In a modern V2X system, LTE-V2X provides dependable connectivity for V2X applications in which high data rate is not necessary, such as continuously broadcasting messages like basic safety messages (BSM), cooperative awareness messages (CAM) and decentralized environmental notification messages (DENM) (3GPP, 2022c). These messages include information like the speed and the direction of the vehicle. On the other hand, NR-V2X enables advanced use cases which can only be realized with a higher bandwidth, such as connected and automated driving. Therefore, LTE-V2X and NR-V2X should be thought of as the two key components which coexist to form a modern NR-V2X capable system. Much like the current relationship of (5G) NR and (4G) LTE in standard basestation-to-UE communication, LTE-V2X and NR-V2X have been designed to complement each other. It is also important to note that as LTE-V2X and NR-V2X have different PC5 endpoints, some older vehicles might only support LTE PC5. For this reason, NR-V2X systems will need to be compatible with LTE-V2X for the foreseeable future. As LTE-V2X and NR-V2X are both included in an NR-V2X capable device, understanding LTE-V2X is beneficial for a successful V2X implementation.

5.2 The physical properties of LTE-V2X sidelink

This chapter introduces the physical properties of LTE-V2X sidelink. Chapter 5.2.1 discusses the frequency ranges and operating bands. Chapter 5.2.2 Discusses the physical channels and signals present in LTE-V2X. Finally, chapter 5.2.3 discusses the resource and frame structure.

5.2.1 Frequency ranges and operating bands

LTE-V2X supports a single frequency range in sidelink (PC5) connections. This frequency range is known as band 47 or ITS band, which has the frequency range of 5855 - 5925 MHz. According to 3GPP (2022c), LTE sidelink can be operated concurrently with the following bands:

Table 1. Concurrent operating band options in LTE-V2X.

PC5 band	FDD bands	TDD bands	NR UU bands
n47	3	34	n1
	5	39	n8
	7	41	n39
	8		n40
	20		n71
	28		n78
	71		n79

5.2.2 Physical channels and signals

According to 3GPP (2021), LTE-V2X sidelink features the physical channels shown in Table 2, and the physical signals shown in Table 3. LTE V2X employs SC-FDMA (Single-Carrier Frequency-Division Multiple Access) as it's multiple access technique (3GPP, 2022c).

Table 2. LTE-V2X Physical channels in sidelink

Channel	Purpose
Physical Sidelink Broadcast Channel (PSBCH)	Used for synchronization between UEs.
Physical Sidelink Control Channel (PSCCH)	Used to receive **and** transmit control data
Physical Sidelink Shared Channel (PSSCH)	Used to send **and** receive data
Physical Sidelink Discovery Channel (PSDCH)	Used to transmit and receive device proximity information to/from other devices.

In contrast to NR-V2X, LTE-V2X does not have a separate feedback channel since it does not support HARQ feedback.

Table 3. LTE-V2X Physical signals in sidelink

Channel	Purpose
Demodulation Reference Signals (DM-RS)	Used to demodulate their related channels. Each physical channel has its own DM-RS.
Sidelink Primary Synchronization Signal (S-PSS) and the Sidelink Secondary Sychronization Signal (S-SSS)	Used to synchronize the receiver to the transmitter. Together S-PSS and S-SSS form the Sidelink Synchronization Signal Block (S-SSB).

Completed upto here

5.2.3 Resources and frame structure

In the frequency domain, the LTE-V2X physical layer supports both 10MHz and 20MHz bandwidths. These channels are divided into 180kHz resource blocks (RBs). Each RB consists of 12 subcarriers, with each subcarrier being 15kHz wide in terms of frequency (Garcia et al., 2021). Further, the resource blocks are grouped into sub-channels, with each sub-channel consisting of a predefined number of RBs. The number of RBs is configured either by the network or through UE pre-configuration, depending on the available network coverage (Garcia et al., 2021).

In the time domain, each subframe is 1 ms long. Each subframe consists of 14 OFDM symbols, with four of these symbols transmitting Demodulation Reference Signals (DMRs) (3GPP, 2022c). The last symbol of each subframe is referred to as a guard symbol. The guard symbol is used as a buffer to provide the UE enough time to switch between transmission and reception, or to adjust the related timing parameters.

The data within LTE-V2X is organized in Transport Blocks (TBs). Transport blocks are sent and received in the Physical Sidelink Shared Channel (PSSCH), which uses QPSK, 16-QAM or 64QAM as the modulation scheme (Garcia et al., 2021; Ali et al., 2021).

The control information of LTE-V2X is given in sidelink control information (SCI), which is carried in the physical sidelink control channel (PSCCH). This channel is always received directly before the PSSCH, where the data itself resides. For PSCCH, only QPSK modulation is supported (Ali et al., 2021). The SCI and the TB are always transmitted in the same subframe. The SCI contains information that is necessary for decoding the channel, prioritizing the transmission, handling resource reservation periods et cetera (3GPP, 2022p).

5.3 Resource allocation and scheduling in LTE V2X

In LTE V2X, sidelink communications utilize two resource allocation modes, mode 3, introduced in chapter 5.3.1 and mode 4, introduced in chapter 5.3.2.

5.3.1 Mode 3

Mode 3 is used when the vehicle is connected to the basestation (eNB). In this mode, the basestation takes care of the PC5 resource selection and configuration (also called scheduling) at the eNB, which acts as a centralized scheduler (Ali et al., 2021). In mode 3, the system can utilize two distinct scheduling techniques, either dynamic scheduling or semi-persistent scheduling (SPS). These two scheduling types are suited for different transmission needs. Dynamic scheduling allows the UE to request resources separately for each TB, with up to two retransmissions included in the same allocation (3GPP, 2022c).

With SPS, the eNB reserves frequency and time resources (sub-channels and slots) for the requesting vehicle with a specific periodicity and associates that resource reservation with an index value (3GPP, 2022c). The UE can have up to 8 different SPS configurations. The eNB controls the activation of the reservations using downlink control information (DCI) signalling and the identifying index value. Once the resource reservation is activated via DCI, the UE is able to use the resources until they are released by the eNB (3GPP, 2022c). The deactivation is communicated to the device using a separate deactivation DCI.

In NR-V2X, a similar distinction between the dynamic and semi-persistent scheduling types is made using dynamic and configured grants. This is discussed in chapter 6.2.3.2.1 of this study.

5.3.2 Mode 4

While using mode 4, vehicles select their time and frequency resources (sub-channels and slots) autonomously. The information regarding which resources have been reserved for the transmission of a specific TB is relayed to the other vehicles in the 1st-stage SCI. When the UE needs to reserve resources for transmission, it first senses which resources the other UEs have reserved inside a (pre-)configured resource pool (3GPP, 2022c). Using mode 4 enables the UE to operate independently from the Uu connection.

When selecting their transmission resources, V2X devices run into a few issues. That is, to prevent collisions (selecting the same resource) the vehicles must employ separate congestion control mechanisms. Currently, however, the proposed congestion control and sensing algorithm is nondeterministic in terms of execution time in both LTE-V2X and NR-V2X. The sensing algorithm of NR-V2X is discussed in more detail in chapter 6.2.3.2.2. of this study. Interested readers can find a thorough explanation of the LTE sensing approach (Mode 4) in Garcia et al., (2021).

6 Comparison of NR-V2X and 5G NR

This chapter compares the existing 5G NR to NR-V2X, discussing the differences in physical properties in chapter 6.1 and physical layer procedures in chapter 6.2. In the context of their relevant operations, this chapter also discusses features that are completely novel to NR-V2X and examines their implications on the development of an NR-V2X capable system.

6.1 Physical properties

This chapter provides a general overview of the physical properties related to NR-V2X communication, comparing them to their equivalents in 5G NR. Subchapter 6.1.1 provides a comparison of the frequency ranges and operating bands. Subchapter 6.1.2 compares the frame structure and numerologies. Subchapter 6.1.3 compares bandwidth parts (and their handling) as well as resource elements. Finally, subchapter 6.1.4 provides a summary of the physical channels and signals present in both NR-V2X and 5G NR.

6.1.1 Frequency ranges and operating bands

This chapter compares the frequency ranges and operating bands present in 5G NR and NR-V2X.

6.1.1.1 5G NR

5G NR supports two frequency ranges in both the downlink (DL) and uplink (UL) directions: frequency range 1 (FR1), which is **410 MHz - 7.125 GHz** and frequency range 2 (FR2) which is **24.25 GHz - 52.6 GHz**. FR2 is often referred to as the mmWave spectrum, which is especially suitable for short range, high throughput communications (3GPP, 2023). According to 3GPP (2023), 5G NR communication utilizes a total of 61 different operating bands in FR1, ranging from operating band n1 all the way to operating band n104. 5G NR also utilizes multiple FR2 operating bands, but these are not relevant to the NR-V2X comparison, as NR-V2X currently operates only on FR1. The full list of the supported FR1 operating bands can be found in TS 38.101-1 (3GPP, 2023), whereas the FR2 bands can be found in 38.101-2 (3GPP, 2023a).

5G NR provides multiple mechanisms that are designed to improve coverage and capacity, which also utilize their own band combinations (3GPP, 2023). One of these is dual connectivity (DC). According to Dahlman et al. (2018), DC enables the use of two different network nodes simultaneously. It should be noted that DC is also possible between different radio access technologies (RAT). This means that it is possible for a device to either connect to two 5G nodes, two LTE cells or a combination of these (one 5G and one LTE). In addition to DC, 5G NR also supports supplementary uplink bands (SUL) (3GPP, 2023). With SUL, a downlink (DL) frequency band can be configured together with two uplink (UL) bands on the same cell, providing better uplink coverage, suitable for use cases where traffic in the uplink direction needs to be prioritized (Dahlman et al., 2018).

6.1.1.2 NR-V2X

NR-V2X supports the same two frequency ranges in both the UU and PC5 connections, although the initial design is based on FR1 (Harounabadi et al., 2021): Frequency range 1 (FR1), which is **410 MHz - 7.125 GHz** and Frequency range 2 (FR2) which is **24.25 GHz - 52.6 GHz**. The frequency ranges are the same as 5G NR (3GPP, 2023). Currently, NR-V2X is practically FR1 only, which is reflected in the available operating bands. The details around FR2 NR-V2X are yet to be specified. NR-V2X sidelink provides four operating band options in FR1, namely the bands n14, n38, n47 and n79 (3GPP, 2023). The frequency range and duplex mode of these bands is given in Table 4.

Table 4. NR-V2X sidelink operating bands

V2X operating band	Sidelink (SL) operating band (Both transmission and reception)	Duplex Mode	Interface
n14	788 MHz – 798 MHz	HD	PC5
n38	2570 MHz – 2620 MHz	HD	PC5
n47 (ITS band)	5855 MHz – 5925 MHz	HD	PC5
n79	4400 MHz – 5000 MHz	HD	PC5

Completed to here

As seen in the above table, NR-V2X sidelink utilizes the same frequency range for both transmission and reception. This contrasts with 5G NR, where the transmission and reception frequencies can be different. When speaking of NR-V2X operating bands, it is important to note that the band reserved for Intelligent Transport Services (ITS), band n47, is completely reserved to sidelink traffic. This means that n47 can be considered the "defacto" band, which is used for all sidelink communication. This is reflected in Table 2, where PC5 always uses band n47 (3GPP, 2023). Having a dedicated sidelink band makes sense, as for a UE supporting only PC5 without the UU connection, it would be very difficult to configure sidelink traffic amongst other NR traffic in the NR bands, although it is technically possible. However, if the UE supports both the PC5 and UU, it is feasible for it to utilize other NR bands as well, as the UU connection provides a centralized control entity that is aware of the other NR traffic currently taking place on the band. It is also worth noting that according to 3GPP (2023), band 38 is exclusively used in sidelink traffic in some geographic regions, but not globally. They also note that if band 14 is used for safety services, the same band is used both while in-coverage and out-of-coverage.

To enable parallel UU and PC5 communication, NR-V2X supports eight different inter-band con-current operating band configurations (Table 5) and one intra-band configuration (3GPP, 2023).

Table 5. NR-V2X interband combinations

Interband combination	Bands per interface
V2X_n1_n47	UU: n1 PC5: n47
V2X_n5_n47	UU: n5 PC5: n47
V2X_n8-n47	UU: n8 PC5: n47
V2X_n39-n47	UU: n39 PC5: n47
V2X_n40-n47	UU: n40 PC5: n47
V2X_n41-n47	UU: n41 PC5: n47
V2X_n71-n47	UU: n71 PC5: n47
V2X_n78-n47	UU: n78 PC5: n47
V2X_n79-n47	UU: n79 PC5: n47

At the time of writing this study, the only available intra-band configuration is n79-n79, meaning that both UU and PC5 use this band when operating with intra-band concurrency (3GPP, 2023).

In addition to the operating band combinations, another meaningful difference between 5G NR and NR-V2X sidelink can be found in the maximum bandwidths. Depending on the used bands, the maximum FR1 bandwidth per carrier can reach up to 100MHz in 5G NR (3GPP, 2023). In contrast, the sidelink dedicated band (n47) is only able to support 40MHz maximum carrier bandwidth (3GPP, 2023). Due to the smaller maximum bandwidth, the maximum data rates of NR-V2X sidelink are limited in comparison to 5G NR.

In conclusion, the frequency ranges between 5G NR and NR-V2X are the same, but the operating bands of NR-V2X are a small subset of the 5G NR band options. The maximum bandwidth of NR-V2X is limited to 40 MHz per carrier due to the available bands, whereas 5G NR supports up to 100 MHz per carrier. 5G NR also supports many flexibility enhancements that NR-V2X does not, such as SUL and DC. For NR-V2X, there are currently no operating bands defined for FR2, and therefore NR-V2X is only able to operate in FR1 until FR2 bands are defined.

Completed
until here

6.1.2 Frame structure and numerologies

This chapter compares the frame structure and numerologies in 5G NR and NR-V2X, discussing their system-level impacts.

6.1.2.1 5G NR

In 5G NR, transmissions can be viewed in two dimensions: frequency and time. In the time dimension, transmissions are split into frames with the duration of 10ms. Each carrier provides two sets of frames, one for downlink and one for uplink (3GPP, 2022b). Each frame is split into two half-frames of the same size (Figure 7). Each frame consists of ten subframes, each with a 1ms duration (3GPP, 2022b). Finally, each subframe is divided into several slots, with the duration and number of slots per subframe varying based on the subcarrier spacing configuration (SCS) according to Table 6. The 60kHz SCS configuration supports both normal and extended cyclic prefix, which affects the number of symbols per slot (3GPP, 2022b). By default, each slot with a normal cyclic prefix contains 14 symbols. In 5G NR, the combination of SCS and cyclic prefix (CP) is called a numerology.

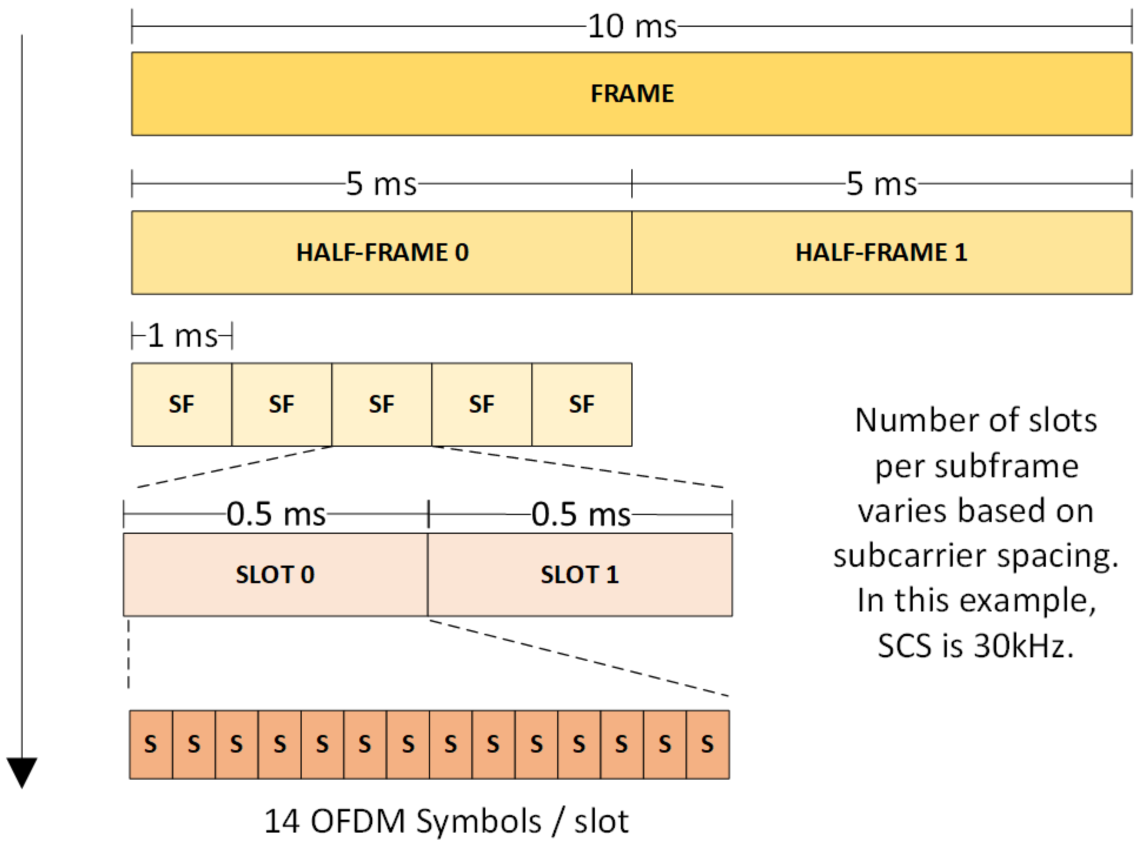

Figure 7. The frame structure of 5G NR.

In the frequency dimension, the resources are divided into resource blocks (RB), where each RB corresponds to the frequency of twelve continuous subcarriers. One subcarrier represents the smallest possible frequency unit in 5G NR (Dahlman et al., 2018).

The total frequency covered by a resource block is a matter of simple multiplication; SCS * 12. For example, a resource block with the SCS value 15 corresponds to 180kHz of total frequency, as it contains 12 subcarriers with a 15kHz frequency. By combining one subcarrier (one frequency unit) and one OFDM symbol (one time unit), we get the smallest possible resource unit which contains both dimensions, the resource element (RE) (Dahlman et al., 2018). In industry literature, this structure is often described with a resource grid (Figure 8).

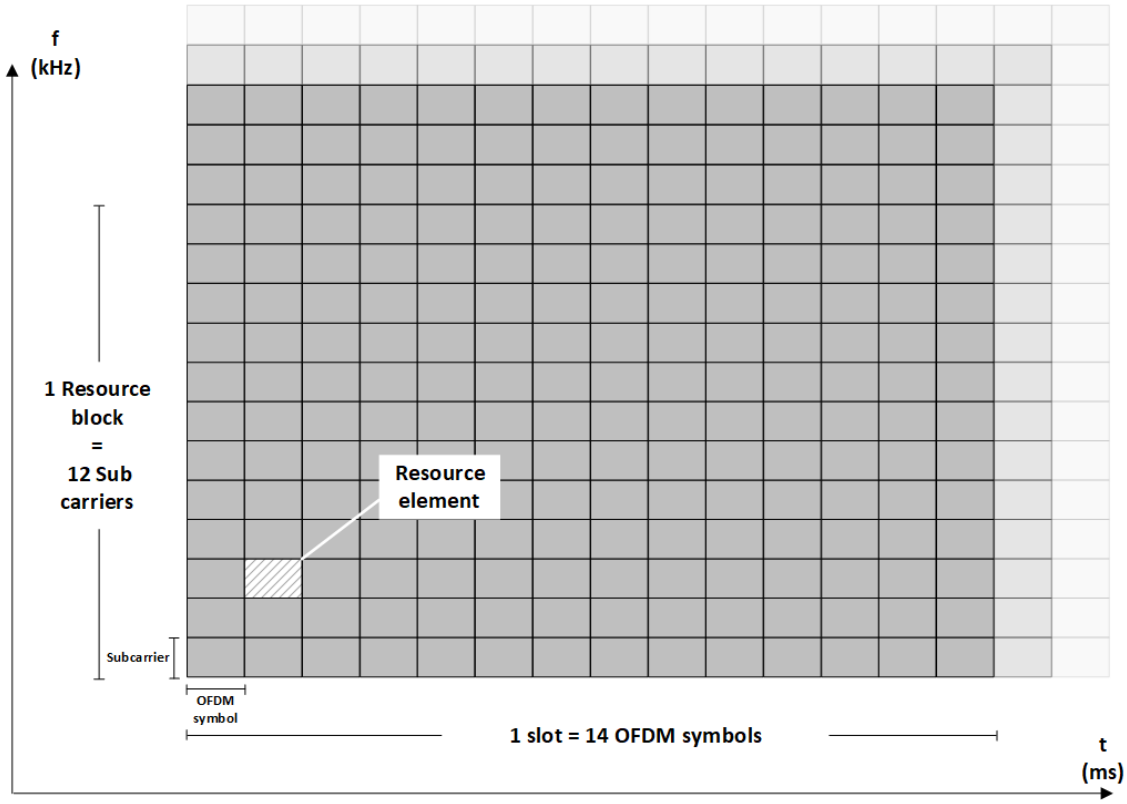

Figure 8. Resource grid combining the time- and frequency dimensions.

Table 6. Subframe variations based on chosen numerology, 5G NR

SCS Configuration μ	Number of OFDM symbols per slot	Subcarrier spacing [kHz]	Slots per subframe	Cyclic Prefix	Supported FR type
0	14	15	1	Normal	FR1
1	14	30	2	Normal	FR1
2	14 (normal CP) or 12 (extended CP)	60	4	Normal and extended	FR1 & FR2
3	14	120	8	Normal	FR2
4	14	240	16	Normal	FR2
5	14	480	32	Normal	FR2
6	14	960	64	Normal	FR2

As we can see, the chosen numerology directly affects the frame structure by adjusting the number of slots and symbols in each subframe. The SCS value determines the bandwidth of each subcarrier. Higher SCS values correspond to wider subcarrier bandwidths. The SCS value is inversely proportional to symbol duration, and therefore using a higher SCS allows the system to fit more data into a shorter timeframe at the cost of increased frequency resource usage, reducing the overall latency (Holma et al., 2020). In summary, numerologies allow us to adjust the so-called “latency-bandwidth ratio” of transmissions, so we can decide whether we want to utilize short-range communication with high data rates (and low latency) or long-range communication with lower data rates depending on the desired use case. For this reason, a wide range of different numerology choices is crucial for the system’s overall flexibility. SCS configuration factors 0 - 2 are used for FR1, and factors 2 - 6 are used for FR2 (3GPP, 2022d).

6.1.2.2 NR-V2X

NR-V2X utilizes the same frame and resource structures as 5G NR (3GPP, 2022b). Due to the flexible OFDM waveform, NR sidelink supports multiple different SCS and CP combinations, just like 5G NR. The supported transmission numerologies of NR-V2X are effectively a subset of the supported numerologies present in 5G NR, as can be seen in Table 7. In FR1, 15kHz, 30kHz and 60kHz are supported as SCS values, while 60kHz and 120kHz are supported for FR2 (3GPP, 2022b). It is worth noting that as FR2 bands are not yet defined for NR-V2X, the FR2 specific SCS configurations are not used either. However, the inclusion of the 120kHz SCS option is a clear indication that FR2 is envisaged for future NR-V2X.

Table 7. Subframe variations based on SCS and CP, NR-V2X

SCS Configuration μ	**Number of OFDM symbols per slot**	**Subcarrier spacing**	**Slots per subframe**	**Cyclic Prefix**	**Supported FR type**
0	14	15	1	Normal	FR1
1	14	30	2	Normal	FR1
2	14 (normal CP) or 12 (extended CP)	60	4	Normal and extended	FR1 & FR2
3	14	120	8	Normal	FR2

In conclusion, the differences between 5G NR and NR-V2X lie in the available numerologies, as the frame structure itself is the same as 5G NR. The broader range of SCS and CP configurations offered by 5G NR makes the 5G NR system more flexible in comparison to NR-V2X’s more limited configuration set.

6.1.3 Carriers, bandwidth parts and resource pools

This chapter compares how carriers, bandwidth parts and resource pools are handled in 5G NR and NR-V2X.

6.1.3.1 5G NR

5G NR supports a wide range of carrier aggregation (CA) bands for both intra-band and inter-band CA (3GPP, 2023). In short, carrier aggregation means that a device is able to use multiple frequency ranges in parallel to increase the available data rate and bandwidth. Carrier aggregation can be done in two ways, either intra-band CA or inter-band CA. In intra-band CA, multiple carriers within the same frequency band are used. In inter-band CA, the used carriers reside on different frequency bands. The details of the available CA band configurations can be found in (3GPP, 2023).

In 5G NR, a bandwidth part is a portion of the total carrier bandwidth that is given to a specific UE (Holma et al., 2020) (**Figure 9**). The concept of bandwidth parts (BWP) was introduced to support UEs that do not have the capabilities to handle very wide bandwidth. BWPs create implicit flexibility, as receiving wide bandwidths consumes a lot of power (Dahlman et al., 2018). The flexible bandwidth also opens the possibility of using a narrower bandwidth for most low bitrate operations and using a wider bandwidth when a large amount of data is scheduled to be received or transmitted (Dahlman et al., 2018). For example, if a carrier has the bandwidth of 100 MHz, UE1 could be allocated to use the full 100 MHz, UE2 could use 50 MHz, and UE3 could use 10 MHz. Using narrow bandwidths is common in reduced capability (RedCap) devices and IoT devices. Thus, BWPs allow devices with different capabilities to coexist within a single carrier bandwidth and allows UEs to optimize their power consumption and resource usage in the network (Holma et al., 2020).

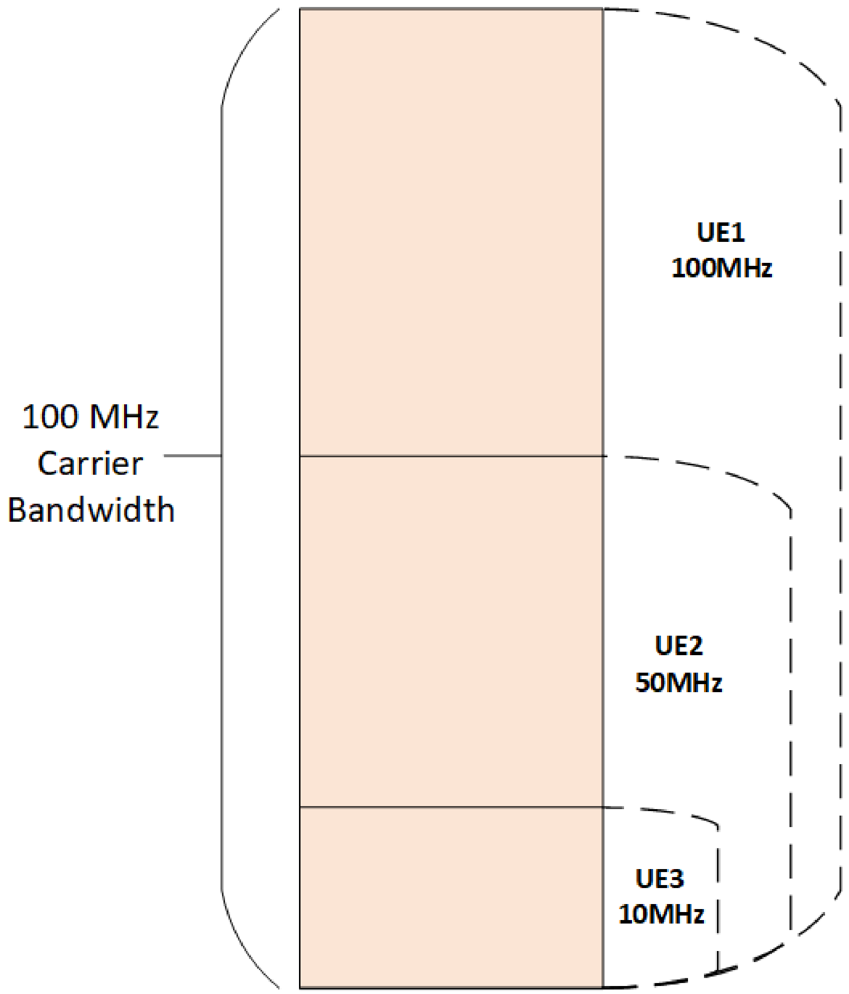

Figure 9. 5G NR BWP. UEs can utilize only a part of the total carrier bandwidth.

When a device is connected to a cell, one BWP is activated for both uplink and downlink, meaning that the device always has one active DL BWP and one active UL BWP. Using downlink control signalling (DCI), the device is then able to switch between bandwidth parts as needed, to match different bandwidth requirements (Figure 10). Typically, all traffic is expected to be transmitted and received on the active (TX or RX) BWP, with a few exceptions, such as some measurements (Dahlman et al., 2018; 3GPP, 2022b). In 5G NR, the higher layers configure the bandwidth parts for the serving cell. The downlink and uplink BWPs are given to L1 in their own parameters (3GPP, 2022a). Outside of this standard case, 5G NR includes a set of BWP procedures for special cases. For example, for UEs with a dedicated BWP configuration, the first active BWP is determined using separate parameters. Additionally, unpaired spectrum operation and situations where the initial downlink BWP is not provided also have their own ways of determining the BWP. The details for all these scenarios can be found in clause 12 of 3GPP, (2022a). In short, the device must have a configured UL BWP to transmit data, and a configured RX BWP to receive data, and 5G NR has multiple ways of determining the BWP, depending on UE needs. Although it is good to be aware of the BWP allocation differences, they do not really affect the physical layer, as the active BWPs are given to the physical layer in the RRC configuration, regardless of the higher layer procedures used to determine it (3GPP, 2022a).

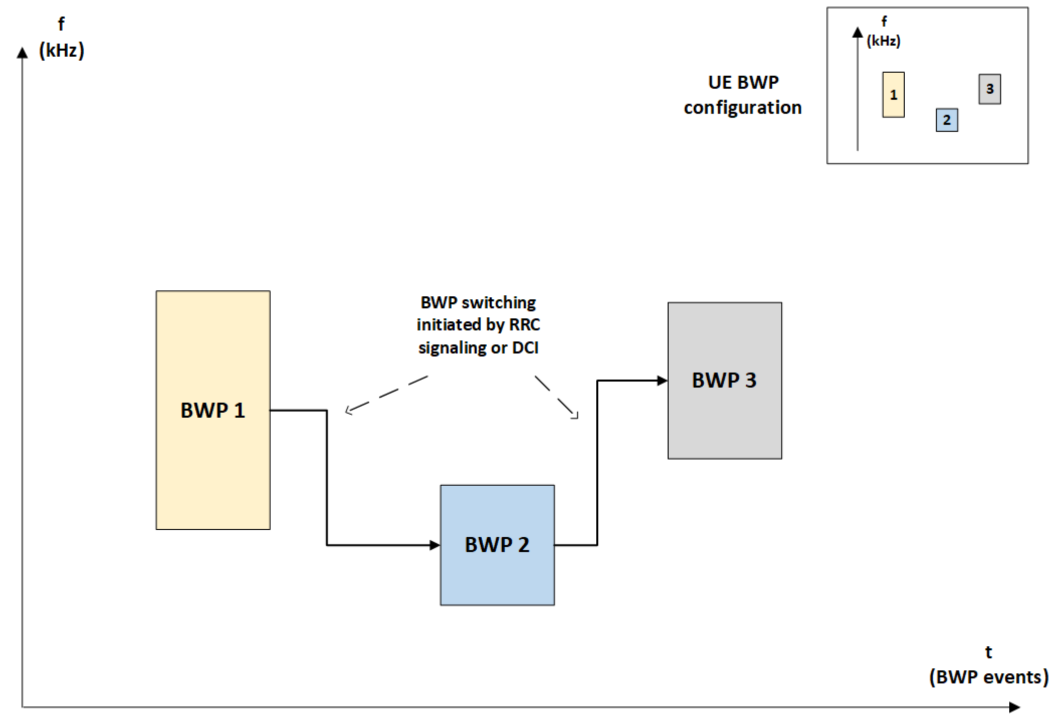

Figure 10. *BWP switching operation in 5G NR. Both RX and TX can have up to 4 configured BWPs.*

6.1.3.2 NR-V2X

According to 3GPP (2024), NR-V2X sidelink supports carrier aggregation, although prior to release 18 it was envisaged to only utilize a single component carrier (CC). In sidelink CA, each involved carrier chooses its resources independently. This means that each carrier must also carry out the sensing procedure. If CA is used for synchronization purposes, the UE must use a single synchronization reference for all the aggregated carriers and may choose which carrier is used to transmit its own synchronization information (3GPP, 2024). CA related UE capability exchange is carried out in the PC5

RRC. Although release 18 introduces sidelink CA, it might not be a feasible feature to implement early in V2X adoption due to its high technical complexity, and therefore the first NR-V2X implementations will most likely not support CA.

NR-V2X utilizes bandwidth parts similarly to 5G NR. However, as 5G NR supports up to 4 bandwidth parts configured at a time (with one active at once), NR-V2X sidelink utilizes only one sidelink BWP (SL BWP), which is configured for all UEs (3GPP, 2022c). This same BWP is used for all sidelink operation both out of coverage and while connected to the Next Generation Node B (gNB) (3GPP, 2022c). Therefore, in contrast to 5G NR, NR-V2X is significantly less flexible in terms of adaptive bandwidth allocation. On the other hand, using a single BWP makes communication less complex as all sidelink traffic is expected to be received and transmitted on the same BWP. This means that devices are only expected to transmit or receive on a single numerology at a time (3GPP, 2022c & Garcia et al., 2021). Using a single BWP also simplifies the BWP handling process, as there is no need to carry out any BWP switching procedures. Other than these differences, the concept and structure of bandwidth parts is the same as it is in 5G NR.

It is worth noting that the UE has a few expectations regarding the sidelink BWP when it is used simultaneously with an UL BWP. First, the UE expects that the numerology of the SL BWP matches the numerology of the active UL BWP, within the same carrier and cell. The SL BWP is deactivated if the numerologies are different from each other (3GPP, 2022a). Secondly, the UE expects to monitor only one cell for physical downlink control channel (PDCCH) and the associated DCI.

6.1.3.3 Resource pools

In NR-V2X, certain slots (time resources) and resource blocks (frequency resources) are (pre-)configured for UEs to use for transmitting and receiving PSCCH and PSSCH (3GPP, 2022c). This subset of resources that is specifically meant for sidelink communication is called a resource pool (Figure 11). The resource pool is always defined inside the SL BWP. According to Garcia et al., (2021) the resource blocks inside the SL resource pool are called physical resource blocks (PRBs). The practical difference between common resource blocks (RBs) and PRBs is that common RBs can be found anywhere in the sidelink BWP, whereas PRBs are only found within the resource pool, meaning that they have been confined to specific time and frequency resources (Garcia et al., 2021).

The resource pool is divided into a set of smaller frequency bands, called sub-channels. These sub-channels are made up from adjacent PRBs in a slot, meaning that the sub-channels are directly next to each other in frequency domain, with no gaps in between (Garcia et al., 2021). Information regarding the resource pool configuration of a specific sidelink BWP is given in the SL-BWP-config (3GPP, 2022d). SL transmissions can use one or multiple subchannels (Garcia et al., 2021). The sub-channels within the SL-BWP can have the size of 10, 12, 15, 20, 25, 50, 75 or 100 PRBs (3GPP, 2022d; Garcia et al., 2021).

The slots included in the resource pool are indicated with the *sl-TimeResource* parameter, which provides a bitmap of length (10…160), occuring with a peridiocity of 10240ms (3GPP, 2022a; 3GPP, 2022d). The bitmap indicates which slots are included in the resource pool. According to 3GPP (2022d), for each slot in the resource pool that is available for PSSCH transmission, a variable number of symbols can be reserved for sidelink traffic, between 7 to 14 symbols. Out of these symbols, 5 to 12 symbols can be used for the PSSCH, with the remaining symbols used for the other sidelink channels and symbols such as the PSCCH and AGC.

In sidelink resource allocation mode 2, the UE makes its resource selections by sensing the available resources within the resource pool for that specific channel (3GPP, 2022c). Resource pools can be shared between sidelink UEs and they can be used with all three casting types (Garcia et al., 2021). It should be noted that resource pools are configured separately for both transmission (TX pool) and reception (RX pool) (3GPP, 2022d; 3GPP, 2022c). However, in terms of the practical implementation, this mechanism should be examined separately from the point of view of mode 1 and mode 2. This is because splitting the SL BWP into TX and RX pools is not practically feasible for mode 2 operation. The differences between the mode 1 and mode 2 resource pools are discussed in more detail in chapters 6.1.3.3.1 and 6.1.3.3.2, respectively.

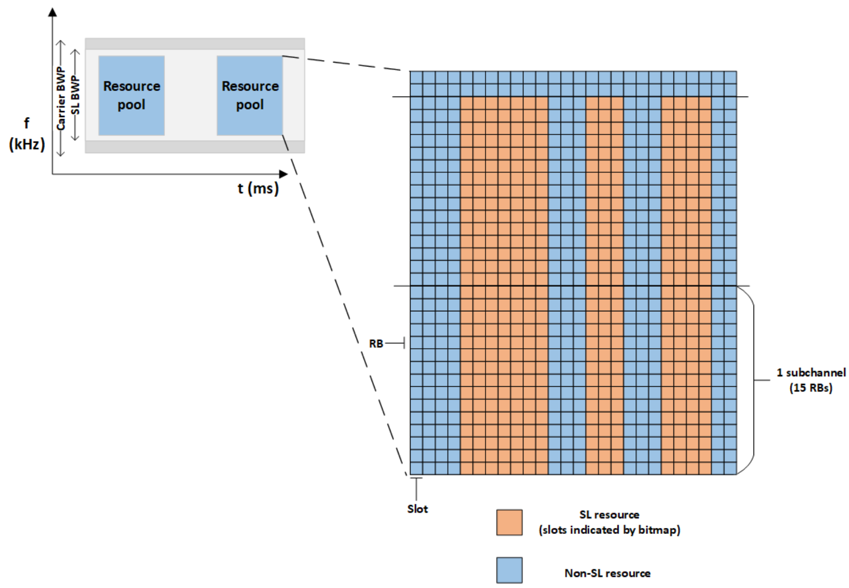

Figure 11. *Sidelink resource pool with 2 subchannels consisting of 15 RBs.*

As the SL resource pool is split into non-SL resources and SL resources, it is possible for ordinary NR transmissions or other signalling to occur during the non-SL slots. Practically, however, this distinction only exists when using a band other than n47, as within the n47 band all resources are reserved for SL traffic by default.

6.1.3.3.1 Resource pools in Mode 1

When a UE is connected to the base station, it is possible for the base station to allocate separate TX and RX resource pools for each UE (Figure 12). In this approach, TX pools are used for sensing and transmissions, whereas RX pools are used for data reception. In Mode 1, the base station must configure the resource pools so that the TX pool of UE 1 is the RX pool of UE 2, and vice versa. This enables a UE to monitor for potential PSCCH, thus being able to receive traffic from other UEs that are transmitting in a different resource pool (3GPP, 2022c). According to 3GPP (2022c; 2022d), if UEs do not have a stable TX resource pool configuration, they can temporarily select random resources from exceptional resource pools. These exceptional pools are used for different control operations, such as handovers, transitioning from RRC IDLE to RRC connected, switching from one dedicated resource pool to another and for handling radio link failures (RLF). Exceptional resource pools are configured in the serving cell's SIB21 or through dedicated signalling (3GPP, 2022c).

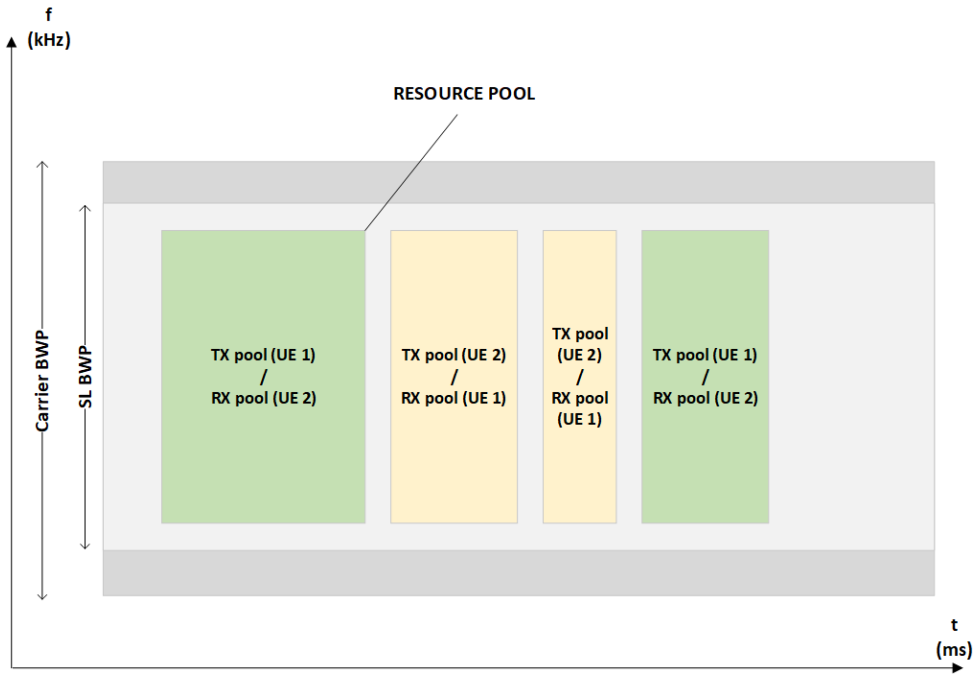

Figure 12. *Sidelink resource pool structure in mode 1. TX pools are used for transmission, RX pools are used for sensing and data reception.*

6.1.3.3.2 Resource pools in Mode 2

When UEs are operating without UU connection, there is no way to reliably assign these TX and RX pools for each UE, as there is no centralized control entity to do so. Because of this, Mode 2 does not have a reliable way of scheduling other traffic amidst the SL resources. Therefore, the split structure of Figure 12 only practically applies to resource pools in Mode 1. In Mode 2, it would make no sense to not utilize the whole resource pool for SL traffic, since non-SL resources cannot be used for any other traffic either way. Because of this, in Mode 2 the TX and RX pools are effectively combined into general blocks of resources, losing their inherent TX/RX split (Figure 13). The resource pool can be seen as continuous, since there is no possibility to differentiate between non-SL resources and SL resources, as discussed earlier. This means that in Mode 2, the SL BWP simply contains available SL resources. Each UE receives traffic on all these resources and autonomously selects its own TX resources based on the sensing outcome.

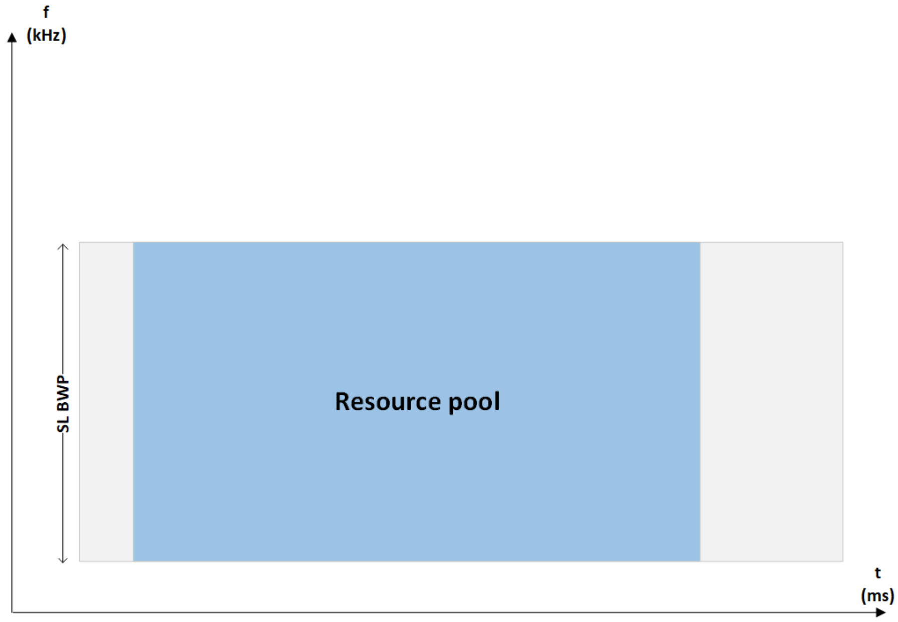

Figure 13. *Sidelink resource pool structure in mode 2.*

In conclusion, the differences between 5G NR and NR-V2X have to do with bandwidth part flexibility and BWP switching operations. 5G NR allows for 1 to 4 bandwidth parts per device, per service cell. This offers better flexibility for devices that have limited capabilities in processing wide bandwidths. In addition, dynamically switching between BWPs can be beneficial from an energy efficiency point of view. NR-V2X's single BWP approach simplifies the system considerably, as BWP switching operations are not needed, but also reduces the overall flexibility. NR-V2X sidelink introduces the new concept of resource pools, where portions of the bandwidth part are reserved for the use of the PSSCH and the PSCCH. Reserving portions of the bandwidth part for specific channels is somewhat reminiscent of the CORESETs present in 5G NR, but these are only utilized for PDCCH transmission, whereas the resource pools of NR-V2X are used for both PSCCH and PSSCH.

6.1.4 Physical channels and signals briefly

This chapter introduces the physical channels given in 3GPP (2022q) and the physical signals given in 3GPP (2022b), briefly summarizes their purpose in each system and highlights the differences in how 5G NR and NR-V2X sidelink channels and signals are designed. In chapter 6.2, the physical channels and signals are discussed in more detail in the context of their related physical procedures.

6.1.4.1 Downlink channels and signals

In 5G NR, downlink (DL) refers to the data transmissions which the UE receives from the base station. It uses orthogonal frequency division multiplexing (OFDM) as the standard transmission scheme (Dahlman et al., 2018). The main purpose of downlink is to deliver both user data and control information from the base station to the UE. The control information transmitted in the downlink contains information such as scheduling decisions and resource allocations (Dahlman et al., 2018).

Table 8 provides a summary of the downlink physical channels and their purposes in the overall system architecture. Downlink features its own set of physical signals which are used for purposes such as channel quality estimation, demodulation reference and synchronization, as seen in Table 9.

Table 8. 5G NR Physical channels in downlink

Channel	Purpose
Physical Broadcast Channel (PBCH)	Used for synchronization
Physical Downlink Control Channel (PDCCH)	Used to receive control information
Physical Downlink Shared Channel (PDSCH)	Used to receive data

Table 9. 5G NR Physical signals in downlink

Channel	Purpose
Demodulation Reference Signals (DM-RS)	Used to demodulate their related channels. Each physical channel has its own DM-RS.
Channel-State Information Reference Signal (CSI-RS)	Used to perform channel quality estimation for measurements and channel quality feedback.
Positioning Reference Signal (PRS)	Used for positioning purposes and location services.
Remote Interference Management Reference Signal (RIM-RS)	Used to measure inter-cell interference and report interference to other cells.
(FR2 ONLY) Phase-Tracking Reference Signal (PT-RS)	Used to reduce the effects of phase offsets in FR2.
Primary Synchronization Signal (PSS) and Secondary Synchronization Signal (SSS).	Used to synchronize the receiver to the transmitter and for cell search purposes. Together PSS and SSS form the Synchronization Signal Block (SSB).

6.1.4.2 Uplink channels and signals

As an opposite of downlink, the uplink (UL) refers to transmissions from the UE towards the base station. In 5G NR, OFDM is used as the default uplink transmission scheme, with DFT-precoded OFDM as a complementary option (Dahlman et al., 2018). This means that the uplink and downlink waveforms are not necessarily symmetrical. DFT-precoding is practically used in 5G NR uplink to reduce the temporary power spikes caused by waveform overlap by spreading the information of subsequent signals over multiple subcarriers. With this, the average power of each subcarrier can be made more uniform, which makes it easier for radio frequency (RF) handling purposes. However, the downside of DFT precoding is that the operation of spreading the information practically costs the system some bandwidth. Additionally, DFT precoding requires an additional Fast Fourier Transform (FFT) component in the hardware. (What is DFT-s-OFDM? (n.d.); DFT-S-OFDM Explained. (n.d.)).

Table 10 provides a summary of the uplink physical channels and their purposes in the overall system architecture. Much like the downlink, uplink also features its own set of physical signals which are used for purposes such as channel sounding and demodulation referencing, as shown in Table 11.

Table 10. 5G NR Physical channels in uplink

Channel	Purpose
Physical Random-Access Channel (PRACH)	Used for initial access procedures (forming connection)
Physical Uplink Control Channel (PUCCH)	Used to transmit control information
Physical Uplink Shared Channel (PUSCH)	Used for data transmissions

Table 11. 5G NR Physical signals in uplink

Channel	Purpose
Demodulation Reference Signals (DM-RS)	Used to demodulate their related channels. Each physical channel has its own DM-RS.
Sounding Reference Signal (SRS)	Conceptually the uplink equivalent of CSI-RS.
(FR2 ONLY) Phase-Tracking Reference Signal (PT-RS)	Used to reduce the effects of phase offsets in FR2.

6.1.4.3 Sidelink channels and signals

The physical channels designed for the direct device-to-device communication of NR-V2X sidelink are presented in Table 12, together with the sidelink physical signals shown in Table 13. NR-V2X only uses OFDM with a cyclic prefix, meaning that the uplink and downlink are always symmetric in terms of their waveform (Garcia et al., 2021).

Table 12. NR-V2X Physical channels in sidelink

Channel	Purpose
Physical Sidelink Broadcast Channel (PSBCH)	Used for synchronization between UEs.
Physical Sidelink Control Channel (PSCCH)	Used to receive **and** transmit control data
Physical Sidelink Shared Channel (PSSCH)	Used to send **and** receive data
Physical Sidelink Feedback Channel (PSFCH)	Used to send and receive HARQ feedback

Table 13. NR-V2X Physical signals in sidelink

Channel	Purpose
Demodulation Reference Signals (DM-RS)	Same as 5G NR
Channel-State Information Reference Signal (CSI-RS)	Same as 5G NR
(FR2 ONLY) Phase-Tracking Reference Signal (PT-RS)	Used to reduce the effects of phase offsets. Only used in FR2.
Sidelink Primary Synchronization Signal (S-PSS) and the Sidelink Secondary Sychronization Signal (S-SSS)	Used to synchronize the receiver to the transmitter. Together S-PSS and S-SSS form the Sidelink Synchronization Signal Block (S-SSB).

Based on the provided summary, it can be said that NR-V2X sidelink essentially simplifies the current 5G NR approach by combining many of the channels which were previously split into uplink and downlink direction in to one, symmetric two-way channel which handles both the reception and transmission activities. In terms of physical signals, sidelink reuses a lot of the existing signals, but does not include all of them. It should be noted that although the PRS is not included in sidelink yet, it might be included in the future, as some of the release 18 documents mention sidelink positioning as a potential future use case. For this use case the inclusion of the PRS could be beneficial.

6.2 Physical layer procedures

This chapter discusses the physical layer procedures and how they differ between 5G NR and NR-V2X. In each chapter, the subchannels discussed in chapter 6.1.4 are examined in more detail, in the context of their relevant physical layer procedures.

Subchapter 6.2.1 discusses the synchronization procedures in 5G NR and NR-V2X. Subchapter 6.2.2 discusses the differences between the data reception procedures, along with the relevant control structures, DCI and SCI. Subchapter 6.2.3 discusses resource allocation, introducing the different allocation modes offered by NR-V2X. Additionally, the subchapter introduces the sensing procedure, which is a novel resource selection feature in NR-V2X. In subchapter 6.2.4, the differences in CSI are examined. Finally, subchapter 6.2.5 discusses the differences in the available HARQ feedback schemes and the related feedback channel.

Due to the scope of this study, power control has been left out in its entirety. The discussed physical layer procedures (and the relevant channels) were chosen so that each one of them highlights a large conceptual or system-wide difference.

6.2.1 Synchronization

6.2.1.1 5G NR

In 5G NR, the UE always synchronizes itself to the base station (gNB/eNB) with no other options available. The synchronization procedure depends on two key components, the physical broadcast channel (PBCH) and synchronization signal blocks (SSB). The physical broadcast channel (PBCH) primarily handles the initial access procedures and the connection setup, as it carries the master information block (MIB) from the RRC layer (Dahlman et al., 2021). SSBs are used for the initial cell search and the subsequent mobility between cells. By receiving the PBCH and the SSB, the UE is able to synchronize itself with the bases station.

In 5G NR, the SSB consists of primary synchronization signal (PSS), secondary synchronization signal (SSS), PBCH and the associated DM-RS (3GPP, 2022b). In the time domain, the synchronization signal block (SSB) consists of 4 OFDM symbols, with the PSS occurring on the first OFDM symbol, and the SSS on the third OFDM symbol (3GPP, 2022b). The PBCH and DM-RS are mapped together across the second and fourth OFDM symbols to ensure that the PBCH can be reliably detected and demodulated as needed (Dahlman et al., 2018).

NR cells transmit the SSB periodically in their downlink, with a periodicity varying between 5 ms and 160 ms (Dahlman et al., 2018). In terms of frequency, the SS/PBCH block spans 240 subcarriers, from 0 to 239. In NR, each frequency band has a so-called synchronization raster, which is a set of possible locations where the SSB can be found (Dahlman et al., 2018). To transmit the SS/PBCH block, the UE uses antenna port 4000. The PBCH channel is scrambled prior to modulation with a cell-specific 31-length Gold sequence based pseudo-random sequence (3GPP, 2022b). The PBCH is QPSK modulated, and the UE assumes that the PSS, SSS, PBCH and the relevant DM-RS have the same SCS and cyclic prefix length (3GPP, 2022b).

6.2.1.2 NR-V2X

One of the fundamental differences between NR-V2X's and 5G NR's synchronization are the synchronization sources themselves. In 5G NR, synchronization is provided by the gNB, while in NR-V2X, it is possible for devices to synchronize using the gNB/eNB, global navigation satellite system (GNSS) or through other UEs. Each synchronization source is associated with a different priority (3GPP, 2022d). UEs that offer synchronization reference by transmitting the sidelink synchronization signals (SLSS) are called SyncRef UEs (Garcia et al., 2021; 3GPP, 2022c). Implementing the SyncRef UE functionality is optional (3GPP, 2022c).

In general, the UE always attempts to synchronize to either the gNB/eNB or GNSS based on its (pre-)configuration (3GPP, 2022c). The full list of scenarios and synchronization reference priorities can be found in 3GPP (2022d). For a general understanding, 3GPP (2022c) provides a concise summary of the synchronization priorities:

1) If possible, the UE synchronizes to its preferred source according to its (pre-)configuration, either GNSS or the gNB/eNB. The sidelink frame timing is calculated from GNSS UTC as specified in chapter 5.8.12 of 3GPP (2022d).
2) If direct connection to the preferred source is not available, the UE synchronizes to it through “one hop”, meaning that it synchronizes itself to a SyncRef UE that is directly connected to the preferred source.
3) If such SyncRef UEs are not found, the UE synchronizes itself to a SyncRef UE that is connected to its preferred source through “two hops”, meaning that the first SyncRef UE is synchronized to another SyncRef UE, that is directly connected to the preferred source.
4) If no such SyncRef UEs are found, the UE synchronizes to the source which was not set as its preferred synchronization source (step 1), either GNSS or the gNB/eNB.
5) If direct connection to the secondary source is not found, the UE repeats steps 2 and 3 with the secondary synchronization source. It first looks for a “one hop” source, and then a “two hops” source.
6) If such SyncRef UEs are not found, the UE synchronizes to any SyncRef UE connected to either gNB/eNB or the GNSS, regardless of the needed hop count.
7) Finally, if nothing more accurate is found, the UE is synchronized to its own internal clock. Even then, despite this being quite obviously a terrible synchronization reference, the UE might still transmit SLSS if configured to do so.

These mechanisms ensure that the V2X devices always attempt to use the best possible synchronization source, and if they can only find a poor source, they operate on a "better than nothing" principle until finding a better one. According to Garcia et al. (2021), the relative strengths of SyncRef UEs are differentiated using a set of SLSS IDs and an in-coverage indicator, included in the sidelink synchronization signal block (S-SSB). They also state that if multiple SyncRef UEs with the same priority level are found, the UE decides the synchronization source by choosing the source with the better received signal received power (RSRP) value, based on the SyncRef UEs PSBCH DMRS.

In NR-V2X, the sidelink specific version of the PBCH is called physical sidelink broadcast channel (PSBCH). The PSBCH transmits the S-SSB and carriers the V2X master information block (MIB-V2X) from the RRC layer to the physical layer (3GPP, 2022c). Both S-SSB and MIB-V2X occur with a periodicity of 160 ms (3GPP, 2022d; 3GPP, 2022c). In some cases, the S-SSB transmission can be repeated during the same transmission period. The MIB-V2X contains the information shown in Table 14 (3GPP, 2022d):

Table 14. The contents of the sidelink Master Information Block (MIB).

Field	**Length**
Sidelink TDD configuration indicator	12 bits
In-coverage indicator	1 bit (Boolean)
Direct Frame Number	10 bits
Slot Index	7 bits
Reserved bits	2 bits

The V2X version of the synchronization signal block is referred to as sidelink synchronization signal block (S-SSB). The S-SSB contains the sidelink primary synchronization signal (S-PSS), sidelink secondary synchronization signal (S-SSS) and the physical sidelink broadcast channel (PSBCH) (3GPP, 2022b). In the frequency domain, the S-SSB block spans 132 subcarriers (3GPP, 2022b), which translates to 11 resource blocks (Garcia et al., 2021). In the time domain it consists of 13 OFDM symbols for normal cyclic prefix, 11 for extended, with the last symbol being a guard symbol (Figure 14). For more information on the resource mapping between the OFDM symbols and the subcarrier numbers, see 3GPP (2022b). Just like in 5G NR, the UE uses antenna port 4000 for the transmission of all these sidelink equivalents (S-PSS, S-SSS, PSBCH, DM-RS and PSBCH), and expects the same cyclic prefix length and SCS for all of them (3GPP, 2022b). The S-SSB is expected to have the same numerology as the PSCCH/PSSCH in the carrier (3GPP, 2019). Additionally, it is expected that the frequency location of the S-SSB is preconfigured, which means that the UE is always able to find the S-SSB within a carrier without hypothesis detection in the frequency domain (3GPP, 2019).

The S-PSS and S-SSS are always transmitted in the same S-SSB as the PSBCH. Together, the S-PSS and S-SSS form the SLSS ID, which is a UE specific identifier that conveys the priority of the UE if it is acting as a SyncRef UE (3GPP, 2022c; Garcia et al., 2021). The associated DMRS is transmitted in every symbol of the S-SSB slot (3GPP, 2022c). As their scrambling sequences, the S-PSS and S-SSS use the same sequences as the 5G NR counter parts, with S-PSS using the M-Sequence, and S-SSS using the Gold sequence (3GPP, 2022c) and they are BPSK modulated (Garcia et al., 2021).

Table 15 presents a summary of the differences between the S-SSB block of NR-V2X and the SSB block of 5G NR.

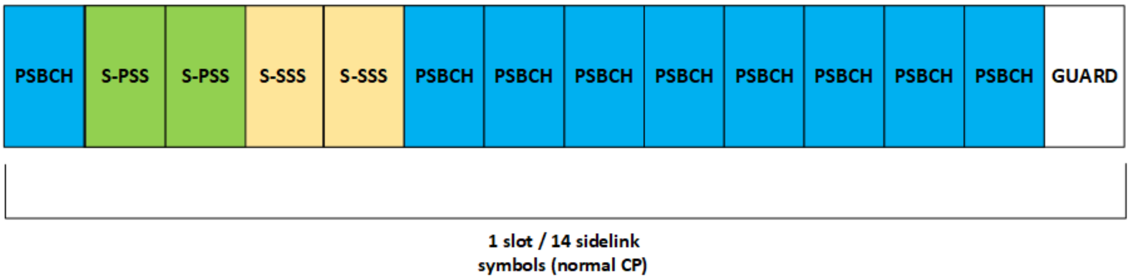

Figure 14. *The structure of a PSBCH slot with a normal cyclic prefix.*

The S-SS/PSBCH block is relatively simpler in comparison to the 5G NR version, as the 5G NR SS/PBCH block features some additional details such as a separate higher layer parameter to indicate subcarrier offsets (3GPP, 2022b). Also, the SS/PBCH has some separate assumptions that the UE can make when using the FR2 frequency range. The specifications do not mention any FR2 specific assumptions or separate subcarrier offsets when it comes to NR-V2X. Notably, the PSBCH is transmitted in 9 symbols and 132 subcarriers, whereas the PBCH is transmitted in 2 symbols and 240 subcarriers, which means the PSBCH symbols occur at a relatively higher density, which should make PSBCH reception more reliable in comparison to PBCH.

Table 15. Comparison of synchronization signal block structure.

Concept	5G NR	NR-V2X
OFDM symbols	4	13 or 11
Subcarriers	240 contiguous	132 contiguous
Mapping to symbols	PSS & SSS – 0, 2 PBCH 1, 3 DM-RS 1, 2	S-PSS – 1, 2 S-SSS – 3, 4 PSBCH – 0, 5, 6 … (9 total) symb_ssb – 1 DM-RS – 0, 5, 6…symb_ssb - 1
Antenna port	4000	4000
Cyclic prefix and SCS	Maintain same CP and SCS for channels and signals	Maintain same CP and SCS for channels and signals
Subcarrier offset	Separate parameters	Value fixed to 0
UE assumptions	Quasi-colocation, FR2	No mention
Block types	A, B	No mention (one type)
Synchronization source	Basestation	Multiple
SSB Periodicity	Multiple options	Single periodicity

6.2.2 Receiving data

In both 5G NR and NR-V2X, data reception depends on control information, which is used to decode the received data. In 5G NR, control information is delivered as a package called Downlink Control Information (DCI) on the PDCCH, whereas in the NR-V2X sidelink, it is received as Sidelink Control Information (SCI) in two parts, on both the PSCCH and the PSSCH. Subchapters 6.2.2.1 discusses the DCI and the PDCCH (5G NR) and subchapter 6.2.2.2 discusses the SCI and the PSCCH (NR-V2X sidelink).

6.2.2.1 Downlink Control Information (DCI) and the PDCCH

In 5G NR, the reception of control signaling is done on a dedicated control channel, the PDCCH. It carries all the required control information for successful data reception, contained within a data element called downlink control information (DCI) (Dahlman et al., 2018). In 5G NR, the network transmits the PDCCH to the UE. To transmit the PDCCH, the network could use multiple different DCI formats. The full list of the different DCI formats and their contents can be found in 3GPP (2022j). The different formats have different lengths, although many of them share the length.

The PDCCH is scrambled so that it can only be decoded by the device holding a specific radio network temporary identifier (RNTI). In general, RNTI values can be viewed as either UE-specific RNTIs or common RNTIs (Dahlman et al., 2018). A good example of a UE specific RNTI is the C-RNTI. The C-RNTI is a sort of unique identifier, which ensures that only the selected recipient is able to decode the message correctly. On the other hand, a good example of a common RNTI is the SI-RNTI, which is used to scramble system information. The SI-RNTI has a constant value defined in the specifications (3GPP, 2022r). For common RNTIs, multiple UEs can share the same RNTI values, and therefore multiple UEs are able to decode the same data.

For PDCCH, RNTIs act as identifiers that indicate which UE the DCI (within PDCCH) is intended for. In order to find the control information (DCI) intended for that specific UE, the UE needs to look through several locations. According to Dahlman et al. (2018), control resource sets (CORESET) define the areas of the time-frequency grid where the UE should try to decode the PDCCH. However, the presence of a CORESET is not a promise. It is simply a possible location where the gNB might transmit PDCCH. The network decides the location of the CORESETs, and their placement is extremely flexible. According to Dahlman et al. (2018), CORESETs can be set to any part of a slot, and anywhere within the frequency range of the carrier (Figure 15**)**. Each device is then expected to look for CORESETs within their own bandwidth part. In the time domain, each CORESET spans up to three symbols (Dahlman et al., 2018).

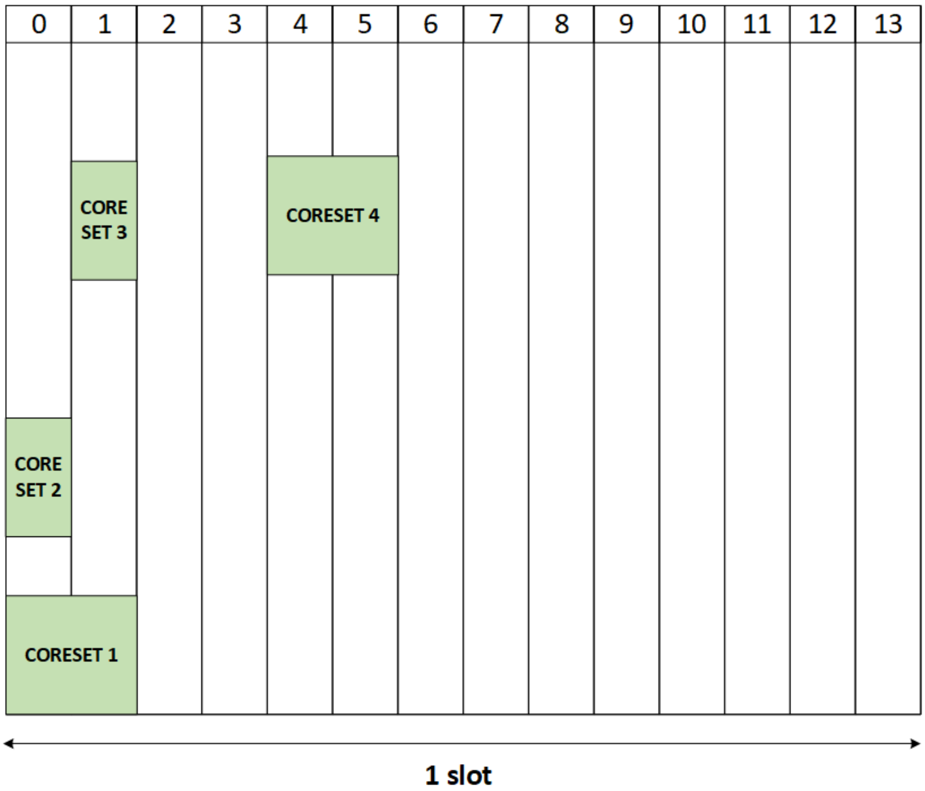

Figure 15. Example CORESETs within a slot.

Within the CORESETs, the UE monitors RNTIs defined by the search space, linked to the coreset. In simple terms, search spaces define which PDCCH candidates the UE should look for within the CORESET, limiting the number of decoding attempts.

As the UE is now aware of the possible locations of the PDCCH transmission (CORESETs), and the PDCCH candidates it should attempt to decode (search spaces), it needs to start the decoding process to find the PDCCH that is meant to be received by it. This is where the problem of blind decoding arises. The used DCI essentially conveys the data layout within the PDCCH. As the UE does not know which DCI format the network used to transmit the PDCCH, the UE needs to attempt decoding each PDCCH candidate by assuming different DCI sizes (Dahlman et al., 2018). If the UE is monitoring for multiple different RNTIs, it also needs to repeat each decoding attempt with all the RNTIs it is monitoring for. Successful decoding is indicated by a cyclic redundancy check (CRC). If it checks (passes), the UE knows that the PDCCH candidate is intended for it and can be interpreted according to the assumed DCI format. If not, it means that the DCI was either meant for another UE or the assumed format was wrong.

The problem with this approach is that this so-called blind decoding process is inherently resource intensive, as the device is required to loop through multiple candidates, with different RNTI values and assumed DCI formats. Furthermore, having to spend time looking for the PDCCH also imposes some overhead on reception activities, as data cannot be received before the PDCCH has been successfully decoded.

6.2.2.2 Sidelink Control Information (SCI) and the PSCCH

The PSCCH is the dedicated control channel of NR-V2X, which carries the first part of sidelink control information (SCI). The SCI corresponds to the DCI in NR. The SCI is split into two parts, the 1st-stage SCI, and the 2nd-stage SCI. The 1st-stage SCI is carried on the PSCCH, whereas the 2nd-stage SCI is carried on the PSSCH (Figure 16**)**.

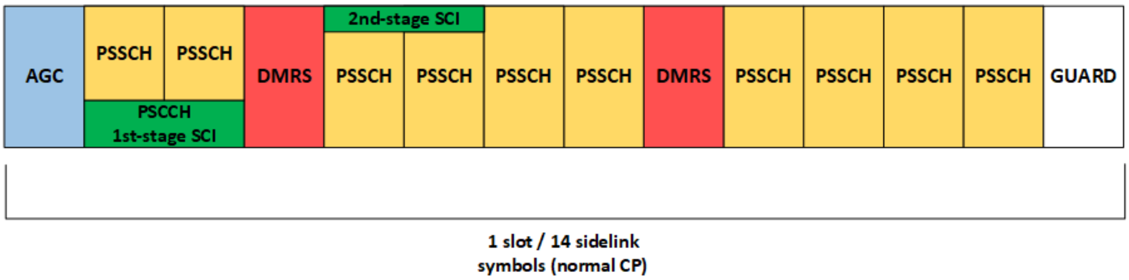

Figure 16. Example slot depicting 1st-stage and 2nd-stage SCIs.

The PSCCH is always transmitted in two frequency-adjacent PRBs (3GPP, 2022c). Practically, the UE is required to constantly monitor these two PRBs to check if the PSCCH has been transmitted within them. In comparison to 5G NR that has a lot of flexibility for the location of the PDCCH (control channel) in relation to the PDSCH (data channel), NR-V2X always transmits the PSCCH in the same subframe (and slot) as it's associated PSSCH (3GPP, 2022c; Garcia et al., 2021). Practically this means that the control information required to decode the incoming data is always received in the same slot as the data itself, which is not always the case in 5G NR. This concurrent reception is enabled by multiplexing the PSCCH in non-overlapping resources with the related PSSCH (3GPP, 2019).

In the time domain, the PSCCH begins from the 2nd symbol of a slot, and occupies 2 or 3 continuous symbols, depending on the configuration of the resource pool (Garcia et al., 2021; 3GPP, 2022d). Additionally, the first OFDM symbol (including DM-RS, CSI-RS etc.) is always duplicated to the previous OFDM symbol (Garcia et al., 2021). Information regarding the number of continuous symbols is signaled to the UE with a higher-layer parameter *sl-TimeResourcePSCCH-r16*, with the possible values of {2, 3} (3GPP, 2022d). In the frequency domain, the PSCCH begins from the lowest PRB within the lowest sub-channel of the associated PSSCH. The number of resource blocks that the PSCCH occupies is defined by higher layer signaling, through the parameter *sl-FreqResourcePSCCH-r16* with the possible values of: {10, 12, 15, 20, 25} RBs (3GPP, 2022d). This is done to ensure that it is easy for the receiving (and transmitting) UEs to determine the location of the PSCCH without the need for calculations, blind decoding or additional signaling. This predictability is also very beneficial for the sensing process, that depends on the 1st-stage control information to determine which resources the surrounding devices are currently using. The higher layer parameters configuring the PSCCH handling are delivered to L1 through RRC (pre-)configuration.

Similarly to 5G NR's DCI, a 24-bit CRC is attached to the SCI before transmission. The channel coding (Polar encoding) and modulation (QPSK) are also the same between the SCI and the DCI (3GPP, 2022a; 3GPP, 2022b). The scrambling procedures between these two channels differ slightly. Although both PDCCH and PSSCH utilize a pseudo-random sequence, they initialize the sequence differently. The PDCCH uses a more complex RNTI and ID based initialization, whereas the PSSCH scrambling is initialized with a simple initializer value (1010). In 5G NR, the DCI is always masked with a specific RNTI, either UE specific or common.

In contrast to 5G NR, in sidelink the SCI is not masked with an RNTI value (3GPP, 2022j) (Figure 17). This makes sense since other devices need to be able to decode the 1st-stage SCI to determine which resources are available for their transmission needs. If they were masked, only the device holding the correct identifier would be able to decode the information.

It is worth noting that although the direct device-to-device communication does not use any RNTI values, when the gNB is allocating resources for sidelink (Mode 1), the 3GPP specifies some sidelink specific RNTI values. These include SL-RNTI, SL-V-RNTI and the SL Semipersistent Scheduling V-RNTI (3GPP, 2022r). The type of used RNTI practically differentiates between the dynamic and semi-persistent scheduling schemes when the network is allocating resources to NR sidelink communication via the PDCCH (3GPP, 2022r). Mode 1, in which these formats are utilized, is discussed in chapter 6.2.3.2.1 of this study.

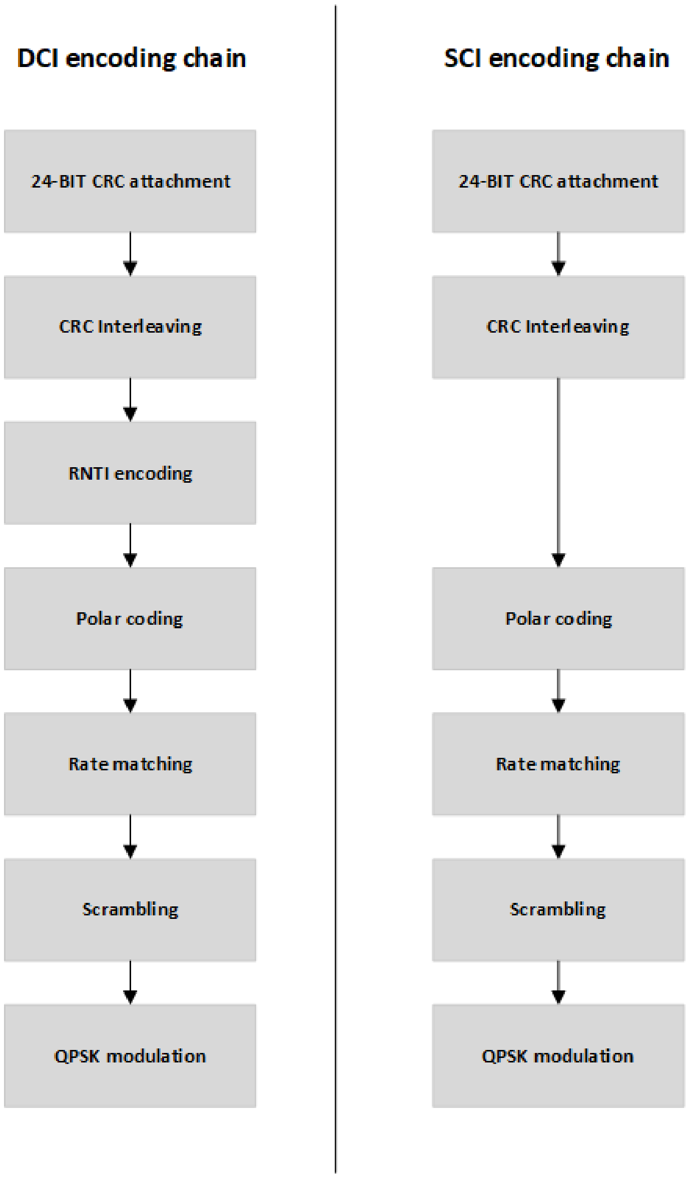

Figure 17. The encoding chains of DCI and SCI. SCI is not RNTI encoded.

In terms of the overall channel structure, the PDCCH is more complex due to the presence of control-channel elements and control resource sets, which define where in the time-frequency grid the UE should look for its PDCCH. In NR-V2X sidelink, this is not necessary due to the static location of the control channel.

6.2.2.2.1 1-st stage SCI

3GPP (2022p) provides the format and contents of both the 1-st stage SCI and the 2nd-stage SCI. The structure of the 1st-stage SCI is shown in Figure 18.

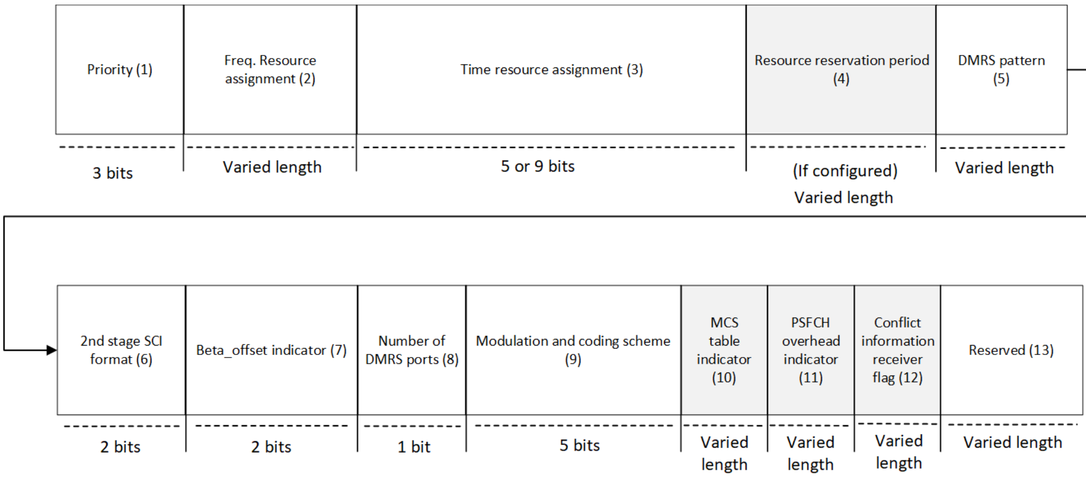

Figure 18. The structure of the 1-st stage SCI.

1) The priority field conveys the relative priority of the message. It consists of three bits, with the priority increasing with the numerical value of the field. For example, value "000" corresponds to priority 1, "001" correspond to priority 2, and so on.
2) Frequency resource assignment is used to indicate on which frequency resources the UE is transmitting the PSSCH (data channel). The number of bits varies based on the maximum number of resources that are allowed to be reserved in one reservation and the number of sub channels. The formulas for determining the number of bits can be found it TS 38.212 (3GPP, 2022j).
3) The time resource assignment field is used to specify the time resources (slots) that should be used for potential retransmissions. If the maximum number of reservable resources is set to 2, this field spans 5 bits, if 3 reservations are allowed, it spans 9 bits (3GPP, 2022j).
4) Now that the frequency and time resources have been defined in fields 2 and 3, the fourth field indicates the period for which they can be reserved. The process for determining the value of this field can be found in TS 38.212 (3GPP, 2022j). If this is not configured, the length of this field defaults to zero bits.
5) The value of the DMRS pattern field indicates the DMRS pattern used for the PSSCH transmission.
6) The 2nd-stage SCI format field acts as a format indicator for the upcoming 2nd-stage SCI, transmitted on the PSSCH. Practically, this field conveys the layout and content of the 2nd-stage control information. The values and explanations of this field's values can be found in Table 16.
7) The seventh field is the beta_offset indicator. In short, beta offsets are a type of factor that adjust the rate matching procedure. The indicator value included in the 1st-stage SCI is used to index a table that determines the corresponding factor (3GPP, 2022e). The reason why it is needed in the 1st-stage SCI is that both the 2nd-stage SCI decoding and the PSSCH decoding depend on this information. The meanings behind the different beta_offset indicator values can be found in 3GPP, (2022a), table 9.3-2.

8) The number of DMRS ports determines which antenna ports are used for the transmission. Value 0 corresponds to antenna port 1000, and value 1 corresponds to antenna ports 1000 and 1001.
9) The modulation and coding scheme is defined in clause 8.1.3 of 3GPP, (2022p). It conveys the index that is used to access the MCS table.
10) The MCS able indicator field indicates the MCS table used for this transmission if there are multiple tables provided in the RRC configuration. The length of this field is either 0, 1 or 2 depending on the number of additional tables defined.
11) The PSFCH overhead indicator practically indicates whether PSFCH (HARQ) is in use.
12) Finally, the conflict information flag conveys whether the UE is able to receive resource selection conflict information from other UEs.

Although not explicitly stated in the specifications, the reserved bits at the end of the 1st-stage SCI are most likely used to ensure that the SCI retains a consistent length regardless of the other fields. The consistent length of the 1st-stage SCI is especially important for sidelink communication, as it allows the system to avoid blind decoding different SCI lengths.

In addition to format 1-A, which was previously the only 1st-stage SCI format present in NR-V2X, release 18 introduces a new type of 1st-stage SCI that is used for sidelink positioning functionality, format 1-B (3GPP, 2024a). The addition of a second 1st-stage SCI format could potentially reintroduce a need for blind decoding, as the length of the 1st-stage SCI could vary. Based on the field descriptions given in 3GPP (2024a), it seems like format 1-B is much larger in terms of bits in comparison to 1-A. Although not explicitly mentioned, the reserved bits present in both formats could potentially be used to offset this difference, ensuring that they remain the same length.

Table 16. The values of the 2nd-stage SCI format field.

Value of 2nd-stage SCI format	2nd-stage SCI format
00	SCI format 2-A – ACK/NACK, only NACK or no HARQ
01	SCI format 2-B – Only NACK or no HARQ
10	SCI format 2-C – Inter-UE coordination
11	Reserved

6.2.2.2.2 2nd-stage SCI

The 2nd-stage SCI, carried on the PSSCH, is used to transport the rest of the control information that is required for decoding the PSSCH. In general, the flexible length of the 2nd-stage SCI enables great flexibility in the control information delivery. The 1st-stage SCI’s constant length allows UEs to efficiently sense the surrounding traffic, while a flexible length payload can be delivered in the second part of the control information.

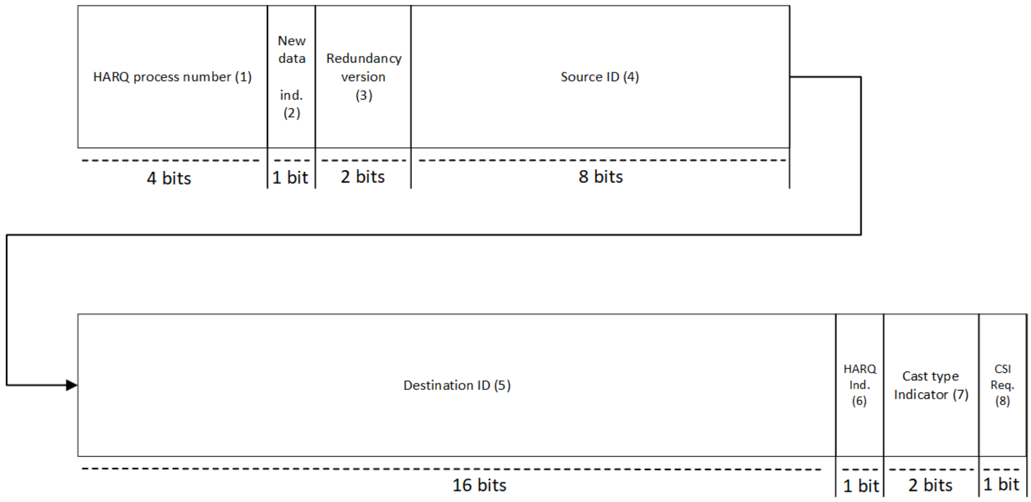

Figure 19. The structure of the 2nd stage SCI format 2-A.

As the format 2-A supports all of the HARQ operation schemes, it can be seen as the "standard" 2nd-stage format for most V2X operation scenarios (Figure 19). Therefore, the contents of this format are examined closer. The format 2-A is used when decoding the PSSCH in all HARQ configurations, ACK/NACK, NACK-only and no HARQ feedback. Format 2-A includes the following fields:

1) The HARQ process number identifies the HARQ process related to the current transmission.
2) The new data indicator creates a distinction between previously received data (retransmission) and completely new data. This information guides the HARQ combining procedure.
3) Redundancy version is related to the HARQ soft-combining mechanism, indicating the specific redundancy version that the included bits represent.
4) The Source ID identifies the transmitting UE.
5) The Destination ID identifies the receiving UE.
6) The HARQ indicator is used to indicate whether HARQ feedback is requested from the recipient or not.
7) The cast type indicator is used to determine the type of the transmission between broadcast, groupcast and unicast. It is also used to communicate the type of desired HARQ feedback, if any. With this information, the receiver is able to determine what kind of transmission it received and act accordingly.
8) The CSI request field is similar to the HARQ feedback indicator. It is used to request a CSI report from the RX UE. CSI is discussed in more detail in chapter 6.2.4.

In addition to format 2-A, 3GPP, (2024a) defines three other formats. Format 2-B is used when the possible HARQ configurations are limited to NACK-only and no HARQ feedback. Format 2-C is used for decoding the PSSCH when the UE either provides or requests inter-UE coordination information. Finally, format 2-D is used for the sidelink positioning functionality introduced in release 18, together with format 1-B.

6.2.3 Resource allocation and scheduling

This chapter discusses the differences in resource allocation and scheduling. Chapter 6.2.3.1 provides a brief summary of the general resource allocation and scheduling approach in 5G NR, whereas 6.2.3.2 discusses the different resource allocation and scheduling modes present in NR-V2X.

6.2.3.1 5G NR

In 5G NR, the base station scheduler is responsible for all scheduling decisions. As a centralized control entity, the base station considers variables such as channel-quality reports, traffic priorities and different service quality requirements before making its scheduling decisions (Dahlman et al., 2018). To receive the scheduling decisions, each UE periodically monitors the PDCCH candidates assigned to it. Once the UE finds the PDCCH, it follows the instructions contained within it, either receiving or transmitting a transport block (TB), which is essentially one unit of data (Dahlman et al., 2018). 5G NR supports two scheduling types. The default scheduling type is the dynamic grant, which practically grants resources for each transmission upon request. The other possible type is the static allocation method, where resources are allocated in advance, so that the UE is able to use these resources until the grant is revoked. This reduces the latency caused by the dynamic grant scheme (Dahlman et al., 2018).

6.2.3.2 NR-V2X

In NR-V2X, sidelink communication utilizes two different resource allocation modes, Mode 1 and Mode 2.

6.2.3.2.1 Mode 1

Mode 1 of NR-V2X is comparable to Mode 3 in LTE-V2X, although it lacks the SPS scheduling mode and uses two types of grants instead. In this mode, resource allocations are done by the gNB, meaning that the vehicle must be within network coverage to use mode 1. In Mode 1, the resources are allocated using two different grant types, sidelink dynamic grants (DG) and sidelink configured grants (CG) (3GPP, 2022c). On a conceptual level, these are very similar to the dynamic and static grant schemes in 5G NR.

In Mode 1, Sidelink transmissions are scheduled using DCI formats 3_0 and 3_1. Format 3_0 is used for scheduling NR PSCCH and PSSCH (control and data channels), whereas format 3_1 is used for scheduling LTE PSCCH and PSSCH (3GPP, 2022j).

6.2.3.2.1.1 Mode 1 with dynamic grants

Dynamic sidelink grants can allocate a varying number of resources for TB transmissions (Figure 20). They also support HARQ procedures, if enabled. Practically, using dynamic grants means that the UE must request resources for every TB that it intends to transmit on sidelink, and inform the surrounding UEs about the resources it intends to use for the transmission of its TB(s) (3GPP, 2022c; Garcia et al., 2021). The resource request also takes into account the resources that would be used for potential retransmissions of the TB(s). Naturally, having to separately request resources for each transmission increases the communication delay. The UE requests the grant by sending a Scheduling Request

(SR) over PUCCH, and the network responds to the request via DCI on the PDCCH (Garcia et al., 2021). The network response provides parameters for the transmission and up to two retransmissions.

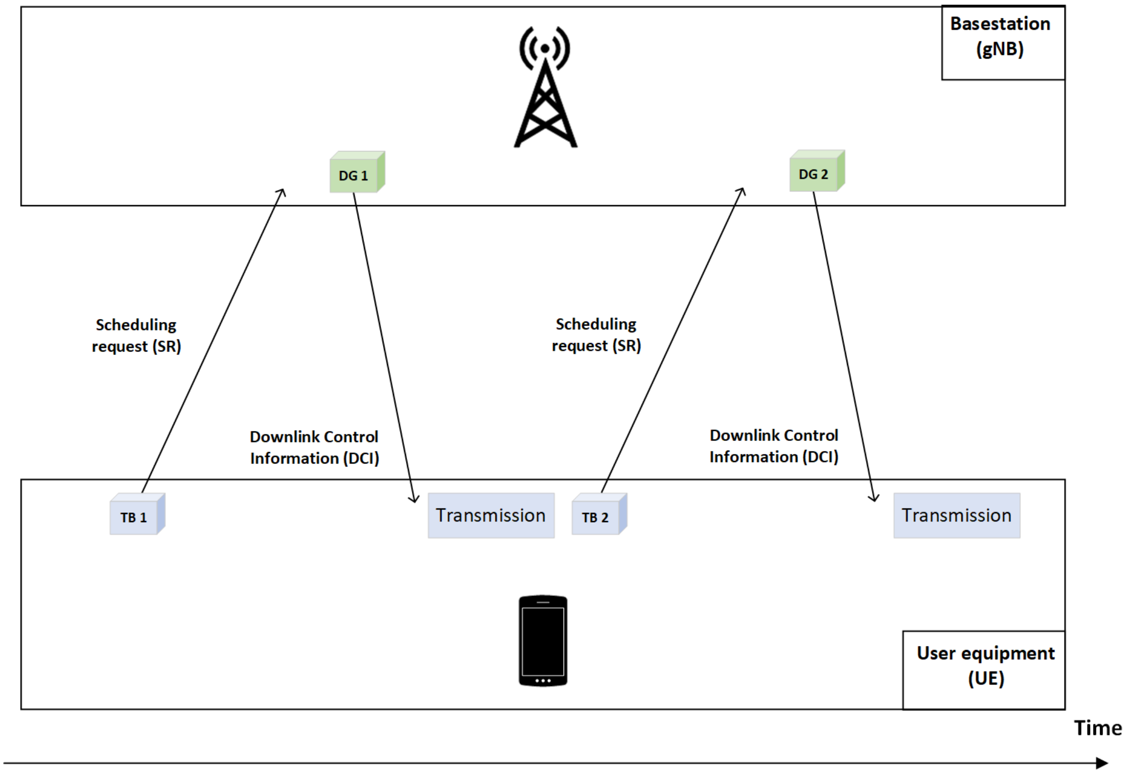

Figure 20. The dynamic grant scheme in NR-V2X mode 1.

6.2.3.2.1.2 Mode 1 with configured grants

Sidelink Configured Grants (CG) can be used to pre-allocate sidelink resources for a UE (Figure 21). According to Garcia et al. (2021), the UE must first send a message that contains UE assistance information to the base station. This message contains information regarding the expected sidelink traffic, such as the periodicity of the TBs, the maximum size of TBs and QoS information. QoS information includes metrics such as latency, priority, and the required reliability. With this information, the gNB is able to create a grant that satisfies the requirements of the UE.

For sidelink configured grants, 3GPP defines two types:

Type 1 - A type of sidelink grant that the UE can use until released either by RRC signaling or by the expiration of the Radio Link Failure (RLF) detection timer. The RLF detection timer is started when physical layer problems or beam failure is detected. Once the timer expires, the UE falls back to an exception resource pool (3GPP, 2022c), releasing the resources it was using. The UE is able to utilize the granted resources instantly, as the grant is activated immediately upon configuration (Garcia et al., 2021). It is possible to configure multiple type 1 CGs at the same time, however, the resources allocated in each grant are reserved for that UE, and therefore the unused resources cannot be utilized by other UEs unless the grant is deactivated (Garcia et al., 2021).

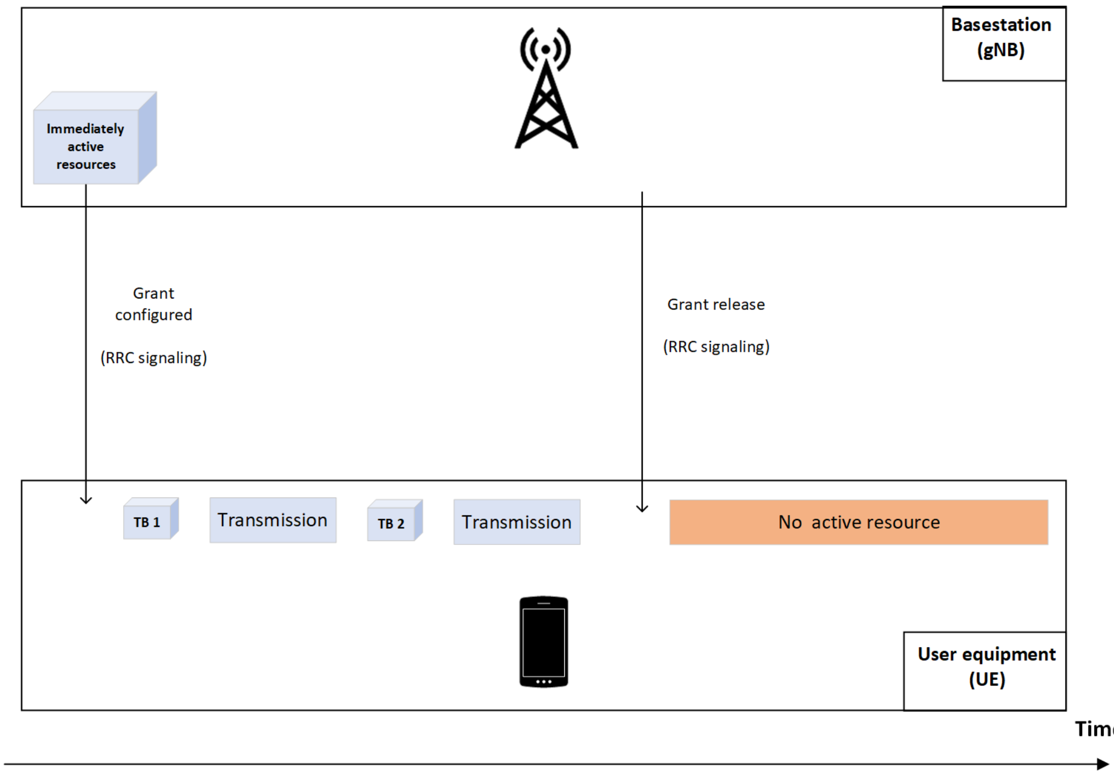

Figure 21. Configured grant type 1 in NR-V2X mode 1.

Type 2 - A type of sidelink grant that is configured but cannot be used before the gNB indicates the activation of the grant to the UE (Figure 22). Both the activation and deactivation of type 2 CGs is handled with a specific MAC control element called Sidelink Configuration Grant Confirmation MAC CE (3GPP, 2022r). A core difference between type 2 CGs and type 1 CGs is that although it is possible to configure multiple grants of both types, in type 2 the resources used by inactive grants can be used by other UEs, whereas in type 1 grants they cannot (Garcia et al., 2021). Both grant types allocate a periodic set of resources, matching the needs of the requested V2X traffic. Multiple grants can be configured at once, which allows the gNB to switch between grants based on the needs of the UE (3GPP, 2022c). In essence, type 2 grants enable more precise control of the grants and their active time windows at the cost of increased signaling, and type 1 allows a straight-forward, immediately active resource allocation.

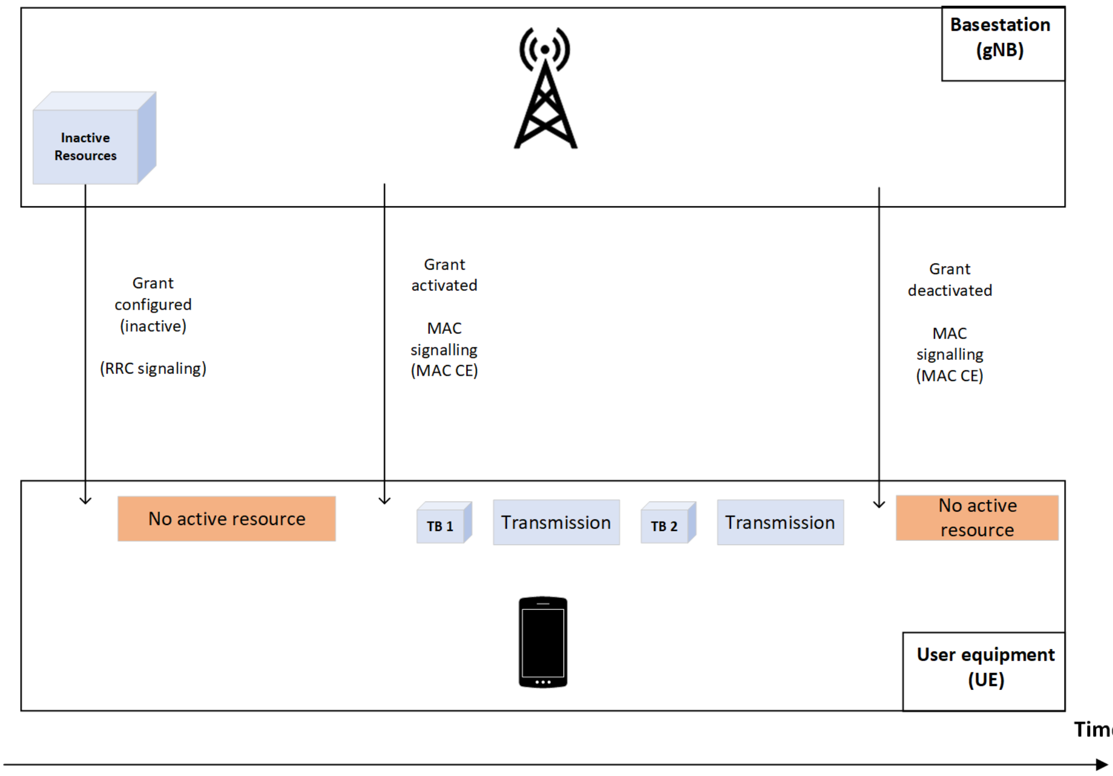

Figure 22. Configured grant type 2 in NR-V2X mode 1.

6.2.3.2.2 Mode 2

Mode 2 of NR-V2X is used for autonomous resource selection in the sidelink (3GPP, 2022c). The basic working principle is that the UE senses available resources within a (pre-)configured resource pool and chooses the required resources autonomously. Within mode 2, there are two types of resource allocation schemes, the dynamic resource allocation scheme, and the semi-persistent scheme. In the dynamic scheme, the UE needs to reserve resources for each TB and its possible retransmissions separately, with each TB requiring its own allocation process (Garcia et al., 2021). In the semi-persistent scheme, the UE is able to reserve resources for multiple TBs and their retransmissions (Garcia et al., 2021). The sensing and allocation procedures are the same for both schemes. According to Garcia et al (2021), when using the semi-persistent scheme, the periodicity of the UE's reservations is defined by the *Resource Reservation Interval (RRI)* parameter, which the UE defines autonomously based on its own transmission needs. The UE must choose it's RRI value from a predefined list of possible values. The list includes values 0-99ms, 100ms, 200ms, 300ms… and so on, in increments of 100 milliseconds up to 1000 milliseconds. For each resource pool, the list of possible RRI values can contain a maximum of 16 different RRIs (Garcia et al., 2021).

The number of TBs included in each reservation is defined by the *Reselection Counter* parameter, based on the chosen RRI. The value of the reselection counter is chosen randomly in a range of values. For RRIs larger than 100ms, the value is chosen randomly within the range [5, 15]. For RRIs smaller than 100ms, the value is chosen randomly in the range $[5 \times \frac{100}{\max(20*RRI)}, 15 \times \frac{100}{\max(20*RRI)}]$ (3GPP, 2022r; Ali et al., 2021). The chosen reselection counter is then decremented by one each time a TB is transmitted. In summary, with semi-persistent scheduling, the UE indicates how often it needs to repeat its transmission with the RRI and gets assigned a random number of TBs that it is allowed to transmit with the repeating resources before it needs to start considering resource reselection. The reason for "considering" resource reselection is because the UE is not strictly required to reselect resources when the reselection counter hits zero. Instead, after the counter hits zero, the devices are given a set *probability* for resource reselection on their next transmission on the same resources, with the probability left up to UE implementation (Garcia et al., 2021). In addition, a UE needs to reselect their resources if a TB does not fit into the already reserved frequency resources, or if the resources are too far apart in the time domain to satisfy TB latency deadlines (Garcia et al., 2021). According to Ali et al. (2021), the specifications also define an absolute limit for how many times the same resource can be used before resource reselection has to be triggered, regardless of the probability. This value is equal to ten times the reselection counter.

In NR-V2X, the sensing procedure revolves around two fundamental components: the sensing window and the resource selection window. The sensing window is used to identify available sidelink resources. Based on the sensing results, available resources are then selected during the selection window (Figure 23).

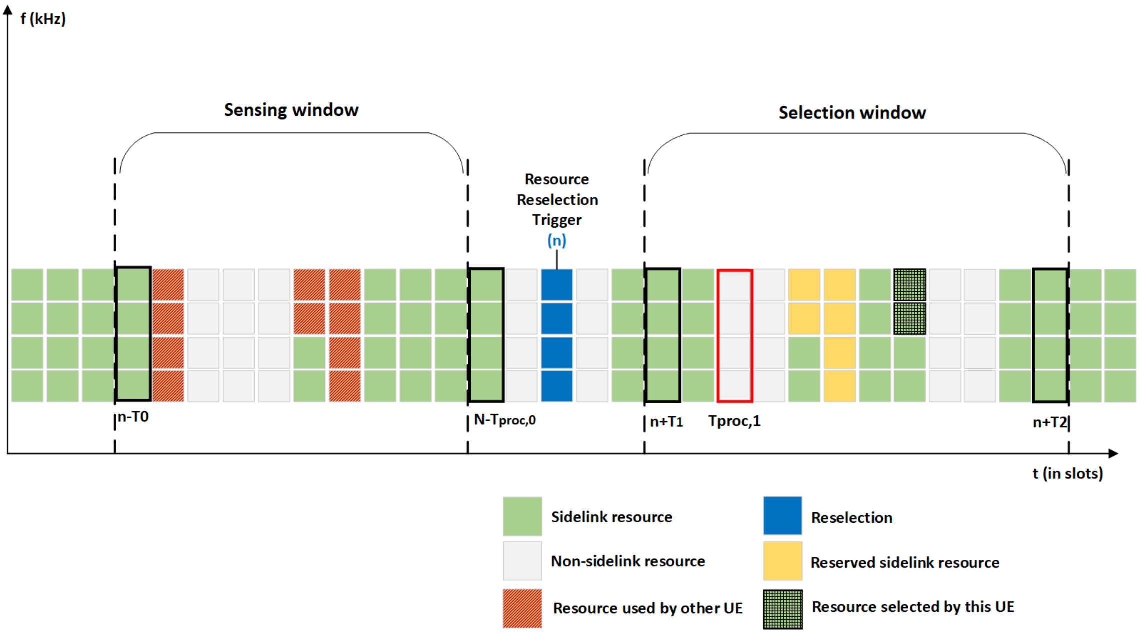

Figure 23. Sensing and selection with SCS 30kHz.

During the sensing window, the UE examines sidelink resources to determine which resources have been reserved by other UEs. The sensing window begins from the current slot (n) in which resource reselection was triggered. From the current slot, the sensing window extends backward in time based on the sensing duration (T0). The unit used for T0 is slots, but the value must be set to a number of slots corresponding to either 100 ms or 1100 ms, as decided by the resource pool configuration (Ali et al., 2021; Garcia et al., 2021).

To determine which resources are reserved by other UEs, the sensing UE decodes the 1st-stage SCIs received from the surrounding UEs. The 1st-stage SCI contains information on the reserved resources, both for the current transmission and potential future transmissions (3GPP, 2022p). Once the sensing UE decodes these 1st-stage SCIs, it stores them to keep track of reserved resources. Simultaneously with the SCI decoding, the UE performs RSRP measurements, which it stores together with the corresponding 1st-stage SCI information. With this information, the UE is now aware which resources are currently in use, whether they are also reserved for future transmissions and what the signal strengths of the resources within the sensing window are. This process is carried out until the end of the sensing window. The sensing window ends just before the sensing processing time (Tproc,0) begins (Ali et al., 2021). The processing time ensures that the UE has enough time to process the information that it received during sensing, and to prepare for the upcoming resource selection procedure. The sensing processing time is relatively short. According to Garcia et al. (2021), the value for Tproc,0 depends on the SCS. For 15kHz and 30kHz, it is equal to one slot, 2 slots for 60kHz and 4 slots for 120kHz.

After the sensing procedure, the UE moves into the resource selection window. During this window, the UE looks for resources which are suitable for transmitting its own transport block (TB). The sensing window begins after T1, which is the selection processing time (Ali et al., 2021). The selection processing time conveys the actual time it takes (in slots) for the UE to find suitable candidate resources and make the selection decision (Ali et al., 2021). T1 is bounded by Tproc,1, which conveys the maximum processing time that can be used for selection. The value of the maximum processing time depends on the SCS. The possible Tproc,1 values are 3 slots (3 ms) for 15kHz, 5 slots (2.5 ms) for 30kHz, 9 slots (2.25 ms) for 60kHz and 17 slots (2.125 ms) for 120kHz (Garcia et al., 2021). However, the value of T1 must always be smaller or equal to Tproc,1 (Garcia et al., 2021). In Figure 23**,** 30 kHz is used, and therefore the maximum processing time is 5 slots. The selection window ends at n+T2. Therefore, T2 signifies the last possible slot in which the transmission can take place, essentially functioning as a transmission deadline (Ali et al., 2021). T2 has been left up to UE implementation, but there are a couple of rules to determine its value. First, T2 must be smaller than the maximum packet delay budget (PDB), which essentially conveys the maximum latency that is acceptable for the TB transmission (Ali et al., 2021). Second, T2 must be larger than the minimum achievable latency (T2min). T2min is determined based on the priority of the TB and the used SCS. In practice, the possible values for T2min are 1 ms, 5 ms, 10 ms and 20 ms. The rules for T2 can be summarized as $T2min \leq T2 \leq PDB$ (Ali et al., 2021; Garcia et al., 2021).

To select resources within the selection window, the UE undertakes a two-step selection process. The following simplified explanation is based on the more detailed explanation of Garcia et al., (2021). First, the UE looks at the information that it gained during the sensing window to exclude resources. The exclusion step can be viewed in two parts. The first part excludes resources based on the selecting UEs own transmissions, whereas the second part excludes resources based on the transmissions of other UEs. The procedure for the first part goes as follows:

1) Find all slots in which the selecting UE itself was transmitting. Based on the list of allowed resource reservation interval (RRI) values, exclude any resources that might have been reserved by other UEs during these slots.
2) If using semi-persistent scheme, find all slots which overlap with the selecting UEs future transmissions (our own future transmissions) and exclude them.

The procedure for the second part, based on other UEs reservations, goes as follows:

1) Look for slots which are reserved by another UEs SCI. If their reference signal received power (RSRP) values are above the defined threshold, exclude them.
2) If using semi-persistent scheme, find all slots which overlap with other UEs future transmissions. If their reference signal received power (RSRP) values are above the defined threshold, exclude them.

After excluding resources in step 1, the UE must check if there are enough remaining candidate resources to choose from, to ensure a low risk of collision. If the percentage of available candidates dips below a threshold (20%, 35% or 50% based on TB priority), the UE then iteratively repeats the exclusion procedure by increasing the RSRP threshold until it is left with enough candidate resources to satisfy the minimum percentage requirement (Garcia et al., 2021). Increasing the RSRP threshold can be thought of as increasing the probability that the transmission overlaps with other UEs transmissions. If the UE does not find enough resources with the original RSRP criteria, it begins accepting slightly worse resources until the pool is large enough. Logically thinking, the point of gradually increasing the RSRP threshold is probably to make sure that the resources where overlap is likely are limited to resources that are used by far-away UEs, indicated by the low RSRP value of their transmission. Notably, this part of the exclusion algorithm is nondeterministic in its execution time, as there is no way to guarantee how long it takes for the UE to find enough suitable resources, i.e., how many times it needs to iterate with a different RSRP threshold.

Now that the UE has determined a pool of resources to choose from, it begins the second step, the resource selection procedure. First, the UE randomly selects the required resources from the pool of available candidate resources, considering both the initial TB transmission and potential retransmissions. This random selection has a few bounding rules. The selecting UE is only able to select resources up to a specified time limit, up to 32 slots in the future, as this is the maximum number of slots that the 1st-stage SCI can communicate (Garcia et al., 2021; 3GPP, 2022p). The UE also has a limit on the maximum number of resources that it can reserve, which is indicated in the resource pool configuration. Every UE is able to indicate one transmission and up to two retransmissions (Garcia et al., 2021). This mechanism works similarly to a linked list, as each 1st-stage SCI indicates the next resource that this UE has reserved for its transmissions. If at this stage of the procedure the UE is unable to reserve enough resources for its TB, it can select the rest of the required resources randomly, regardless of the previous SCI limitations (Garcia et al., 2021). Practically this means that the UE can randomly select resources to ensure that the transmission can still occur even if optimal resources cannot be found.

Once the UE has reserved the required resources, it is then able to transmit on these resources until resource reselection is triggered (3GPP, 2022c). In Mode 2, the UE is able to perform the initial transmission of a TB directly after sensing and resource selection. If the UE reserves resources for (re-)transmissions, it indicates the resources in the SCI scheduling that TB (3GPP, 2022c). If the UE selects resources that will be used for the initial transmission of a later transport block, these resources are indicated in the current TB's SCI (3GPP, 2022c).

In addition to the sensing procedure itself, NR-V2X introduces three other features that improve the flexibility of the resource scheduling procedures, the *Re-evaluation mechanism*, *Pre-emption mechanism* and *Congestion control*. A more detailed explanation of these procedures can be found in Garcia et al. (2021). For the purposes of this comparison, a simplified explanation for each mechanism is given.

The re-evaluation mechanism enables UEs that have already selected a resource to use the rest of their sensing window to continue sensing other transmissions. In practice, it is allowed for the UE to evaluate the available resources again given that it has enough time to do so before the maximum allowed resource selection time, which is determined by the UEs processing capabilities (Garcia et al., 2021). The decision to re-evaluate the available resources is left up to UE implementation. Based on the following sensing information, the UE is then able to select a different resource if it finds that the currently reserved resource would now be excluded (due to RSRP getting worse or another UE with higher priority reserving it) (Garcia et al., 2021). If the currently selected resource is still available (not excluded or taken), it is not allowed for the UE to reselect its transmission resource. The pre-emption mechanism allows UEs to prioritize traffic in Mode 2 (Garcia et al., 2021). As a simplified description, the pre-emption mechanism dictates that a UE must release its reserved resource if it detects that some other UE with a higher priority will use the resource that it has reserved. The decision to release the resource is based on a resource pool specific priority threshold (Garcia et al., 2021). The pre-emption mechanism is tied into the re-evaluation mechanism, as the UE would have no way to know that a UE with higher priority is intending to use the same resource unless it has re-evaluated the situation after its initial reservation. Practically, if the UE determines that it must free its own resource due to a higher priority TB, it must select a new resource within the currently defined selection window unless it has time to complete the whole sensing and selection process before the deadline (Garcia et al., 2021).

The specifications do not determine an algorithm to the used for congestion control, but instead they define two metrics, the Channel occupancy Ratio (CR) and the Channel Busy Ratio (CBR) that can be used to estimate how much of the channel the TX UE occupies (Garcia et al., 2021). In practice, the TX UE uses the channel specific CBR and CR values to determine if it needs to adjust its own transmission to help alleviate channel load. Each UE is given a CBR (+CR) table that defines the maximum channel occupancy for the TX UE (Garcia et al., 2021). To alleviate channel load, the UE could, for example, adjust its MCS or reduce the number of reserved retransmissions.

Based on the above explanations it can be concluded that in comparison to 5G NR where resource selection and scheduling is handled by the base station, NR-V2X presents the unique challenge of autonomously selecting transmission resources in Mode 2. On a conceptual level, all devices need to act as both the UE and the base station simultaneously, as the responsibility of the base station is shifted to the devices themselves. From an implementation standpoint, everything in mode 2 is completely novel in comparison to 5G NR. This includes operations such as sensing, selection window processing, re-evaluation, pre-emption and congestion control. Consequently, these procedures are the most obvious potential pain points of an NR-V2X implementation, as implementing them in practice could potentially be resource intensive, which encourages heavy optimization in their algorithms and other practical implementation details. For example, as sensing expects all devices to perform full sensing (apart from pedestrian UEs) all the time, a lot of signal processing is required to constantly monitor the surrounding traffic. The general selection algorithm proposed by the 3GPP is by no means optimal as it is nondeterministic in its execution time, which further encourages innovation for its practical implementation. Furthermore, the specifications do not define an algorithm for congestion control, and many of the other mechanisms, such as the decision to undertake the re-evalution procedure, are left up to UE implementation. Because of this, the responsibility of implementing efficient congestion control algorithms and decision-making mechanisms is left to the UE manufacturers.

Mode 1 operation of NR-V2X is very similar to the 5G NR scheduling approach. It should be noted that although both technologies offer a type of configured (static) grant, the NR-V2X configured grant needs to be explicitly activated, whereas the 5G NR version is instantly active after allocation. Table 17 provides a summary of the NR-V2X transmission modes.

Table 17. Summary of NR-V2X transmission modes.

<table>
<tr><th>Transmission mode</th><th>Scheduling type</th><th>Operation principle</th></tr>
<tr><td rowspan="3">Mode 1
Only within network coverage</td><td>Dynamic grant</td><td>The UE requests resources from gNB for every TB + potential retransmissions.</td></tr>
<tr><td>Configured grant (Type 1)</td><td>The UE has a periodic resource allocation that it can use until released by RRC signaling or RLF.</td></tr>
<tr><td>Configured grant (Type 2)</td><td>The UE has a periodic resource allocation that is implicitly activated and deactivated by the gNB (indicated via DCI).</td></tr>
<tr><td rowspan="2">Mode 2
Usable out of coverage and without UU connection</td><td>Dynamic scheduling</td><td>The UE autonomously selects resources for each TB, only able to retransmit the same TBs that resources were reserved for.</td></tr>
<tr><td>Semi-persistent scheduling</td><td>The UE autonomously selects resources for consecutive TBs using a Resource Reservation Interval (RRI).</td></tr>
</table>

6.2.4 Channel State Information (CSI)

6.2.4.1 5G NR

In 5G NR, a mechanism called channel sounding is used to measure or estimate the channel characteristics. Channel sounding can be done either on the basestation side or on the UE side. For example, the UE could measure the characteristics of a received downlink channel and report these back to the basestation to optimize future transmissions. If both uplink and downlink channels are similar, it is possible for the basestation to estimate the characteristics of either path independently as well, controlling future transmissions based on the estimations (Dahlman et al., 2018). Typically, channel sounding is based on two elements. In the downlink direction, channel-state-information reference signals (CSI-RS) are used. Uplink sounding is done with sounding reference signals (SRS). In 5G-NR, there are different report configurations, which can be used to indicate which measurements are desired (3GPP, 2022d). The first common report configuration essentially requests the device to report values which are essential in determining channel state. In general, the channel state information (CSI) itself consists of three primary elements, the channel-quality indicator *(*CQI), pre-coder matrix indicator (PMI) and the rank indicator (RI) (Dahlman et al., 2018). When channel state information is requested, it typically refers to a combination of these three elements. Another common measurement configuration centers around signal strength, which is reported using the reference-signal received power (RSRP) value (Dahlman et al., 2018). This measurement is essential for beam management operations. In 5G NR, CSI reports are configured by the network, and reporting can be either periodic or aperiodic (Dahlman et al., 2018). The CSI report is sent over PUCCH / PUSCH, where the latency requirements are defined by the network. The resource mapping of 5G NR CSI is quite flexible, as various CSI-RS patterns can be used for different scenarios.

In 5G-NR, CSI can use up to 32 antenna ports, between ports 3001 and 3031 (Ashour, 2023). Each port signifies one sounded channel. According to Dahlman et al. (2018), one CSI-RS occupies one resource element, and it is expected not to collide with any of the configured CORESET transmissions, PDSCH reference signals or transmitted SS blocks. In simpler terms, this means that CSI-RS cannot be scheduled in a resource block that contains relevant control information, synchronization information or DMRS that are used to demodulate the data itself.

6.2.4.2 NR-V2X

In NR-V2X, CSI is used only in unicast communications (3GPP, 2022c; Garcia et al., 2021). For a device to transmit CSI-RS, there are two conditions. The higher layers must have enabled the CSI functionality through the *sl-CSI-Acquisition* parameter, and the 2nd-stage SCI sent by the Tx UE must contain a report request, indicated by setting the corresponding *CSI request* bit to 1 in the 2nd-stage SCI (GPP, 2022p). In practice, the Rx UE is able to provide Sidelink Channel State Indication (SL CSI) information back to the Tx UE. This information can be used for sidelink link adaptation and rank adaptation in unicast communications. (3GPP, 2022c). According to 3GPP (2022c), NR-V2X uses a simplified version of the ordinary NR CSI-RS design. In NR-V2X, only CQI and RI are reported within a PSSCH transmission. The CSI report itself is carried within a MAC control element (3GPP, 2022r), consisting of CQI, RI, and three reserved bits. The sidelink CSI reporting is always aperiodic, which is contrast to the periodic and aperiodic options present in 5G-NR. In contrast to the 5G NR CSI, the SL CSI-RS can be transmitted from either 1 or 2 antenna ports. This means that the possible values of RI can be either 1 or 2 (Garcia et al., 2021). As SL CSI does not include the precoding matrix indicator (PMI), it can be deduced that signal precoding is not supported either, which leads to a relatively simpler transmitting procedure. The antenna port limitation together with the lack of PMI leads to a considerable simplification overall as many complex procedures present in 5G NR can be left out in their entirety, such as multi-antenna precoding and beamforming. For CSI-RS specifically, mapping the reference signals to physical antennas becomes straightforward, as it would not make sense to include any complex spatial filtering, and instead the CSI-RS can be mapped directly to the physical antennas. As Dahlman et al. (2018) state in the context of 5G NR, it does not make sense to have more CSI-RS ports than physical antennas, as there simply would not be enough antennas available for the CSI-RS mapping. Notably, as NR-V2X supports only two antennas, this means that it only has two spatial layers. This limitation leads to NR-V2X only being able to support a maximum of two MIMO layers.

In NR-V2X, the Tx UE sets the latency bound for the SL CSI report in the PC5-RRC (3GPP, 2019a, as cited in Garcia et al., 2021). This is practical since the Tx UE is aware of the priority and other characteristics of the traffic it plans to transmit. The Tx UE is unable to request another CSI report until the report is either received or the related latency bound expires. In NR-V2X as well, there are limitations as to where SL CSI-RS can be scheduled. It is expected that SL CSI-RS is not scheduled on symbols which contain either PSCCH, 2nd-stage SCI or PSSCH DMRS (3GPP, 2022p).

6.2.5 HARQ Feedback

This chapter discusses the HARQ Feedback and the different feedback schemes in both 5G NR and NR-V2X sidelink. Chapter 6.2.5.1 discusses HARQ feedback in 5G NR, whereas chapter 6.2.5.2 discusses HARQ feedback in NR-V2X.

6.2.5.1 5G NR

Hybrid Automatic Repeat Request (HARQ) is a mechanism that improves the reliability of transmissions by combining forward error correction (FEC), error detection codes and the automatic repeat request (ARQ) retransmission strategy (Dahlman et al., 2018). With HARQ, it is possible for the receiver to send feedback to the transmitter to report whether a certain transmission was received correctly. The feedback can either be acknowledged (ACK) or negative acknowledged (NACK), with ACK indicating that the message was received successfully, and NACK indicating that the reception was unsuccessful (Dahlman et al., 2018). If NACK is received, a retransmission is triggered for that transport block. HARQ can be further divided into two categories, chase-combining HARQ (CC-HARQ) and incremental redundancy HARQ (IR-HARQ), depending on the soft combining method used by the receiver (Ding & Shikh-Bahaei, 2023). IR-HARQ is generally used in wireless communication systems, as the coding gain is significantly better in comparison to CC-HARQ. Overall, the HARQ mechanism improves the reliability and efficiency of communication, as faulty packets can be re-sent upon request, either partially or as whole messages. The downside of this mechanism is the increased complexity, which could lead to higher battery consumption.

5G NR uses asynchronous hybrid-ARQ protocol in both directions, with the adopted scheme signaled to UEs in the DCI (Dahlman et al., 2018). As large transport blocks (TBs) are split into multiple codeblocks, each with their own CRC, it is possible for 5G

NR systems to retransmit either the whole transport block or a codeblock group. This mechanism has been introduced to address a few pain points: 1) If individual codeblocks are to be retransmitted, it incurs a lot of signaling overhead. 2) If the whole transmission block is transmitted, it leads to poor spectral efficiency, as transport blocks can be very large, consisting of hundreds of codeblocks (Dahlman et al., 2018). The timing of uplink transmission (ACK/NACK) is controlled using a separate HARQ timing field in the DCI, which sets the timing relative to the received PDSCH (Dahlman et al., 2018).

6.2.5.2 NR-V2X

NR V2X supports Hybrid Automatic Repeat Requests (HARQ) based on ACK/NACK feedback for both unicast and groupcast services (3GPP, 2022c). Groupcast services also support a NACK-only HARQ scheme. NACK-only operation means that the Rx UEs only request a HARQ re-transmission if they fail to decode the incoming data. This way, the UEs can conserve radio resources by minimizing the amount of required signaling, as all UEs are able to send their NACK messages within the same time- and frequency resources. Additionally, NR V2X supports blind re-transmission schemes for resource allocation modes 1 and 2 (3GPP, 2022c). Blind re-transmissions mean that some re-transmissions can be done without receiving any HARQ feedback, to improve the probability of the transmit block being delivered successfully despite not receiving any actual feedback from the receiver (Garcia et al., 2021).

In ACK/NACK HARQ operation, the HARQ procedure is very similar to the NR UU scheme present in current 5G deployments. HARQ feedback is provided based on the reception status of a whole transport block (3GPP, 2022c). According to 3GPP (2022c), NACK-only operation is mainly intended for situations where a large number of Rx UEs send feedback to the same Tx UE. As seen in Figure 24, the range of the NACK-only feedback can be restricted to a specific radius. The minimum range requirement is provided by the higher layers (service layer), with the associated QoS parameters (3GPP, 2022c). The HARQ process ID along with the new data indicator and redundancy version is given in the 2nd-stage SCI, transmitted on the PSSCH (Garcia et al., 2021). The process ID is used to recognize which TB was retransmitted.

The HARQ feedback consists of one bit, which the Rx UE sends to the Tx UE via the PSFCH. If the UE is using resource allocation mode 1 (connected to gNB), it informs the gNB of the computed HARQ feedback via the PUCCH or PUSCH. This mechanism ensures that the gNB has the required information to schedule the re-transmissions for that specific dynamic or configured grant (3GPP, 2022c).

There are two sidelink HARQ feedback options, option 1 and option 2. In option 1 (Figure 24), of the Rx UEs in the groupcast group, only RX UEs within a specified communication range send HARQ feedback to the TX UE (Garcia et al., 2021). This communication range is decided based on the Tx UE's zone ID, given in the 2nd-stage SCI (Garcia et al., 2021 & 3GPP, 2022c). In option 1, the feedback scheme is NACK-only, meaning that Rx UEs only send HARQ feedback if they are not able to receive the transmission correctly. It is worth noting that with option 1 (NACK only), all the Rx UEs share the same resource to send their HARQ feedback (Garcia et al., 2021). Consequently, the Tx UE is not able to determine which UE(s) sent the NACK feedback, and hence it only knows that at least one UE within the communication range failed to receive the transmission properly (Garcia et al., 2021). Thus, with option 1, unless the Tx UE receives a NACK message, it assumes that all Rx UEs in the communication range have received the message correctly.

According to Garcia et al. (2021), In option 2 (Figure 25), all Rx UEs within the groupcast group send feedback. The feedback scheme is ACK/NACK, with each UE using a separate resource for their HARQ feedback. Therefore, option 2 allows the Tx UE to recognize which UE(s) sent the feedback, but it requires more resources. The choice between option 1 (NACK only) and option 2 (ACK/NACK) is indicated by the Tx UE in the 2nd-stage SCI (Garcia et al., 2021; 3GPP, 2022p).

For a more thorough explanation regarding the multiplexing of HARQ transmissions, resource selection for PSFCH and simultaneous transmission/reception of PSFCH, see (Garcia et al., 2021).

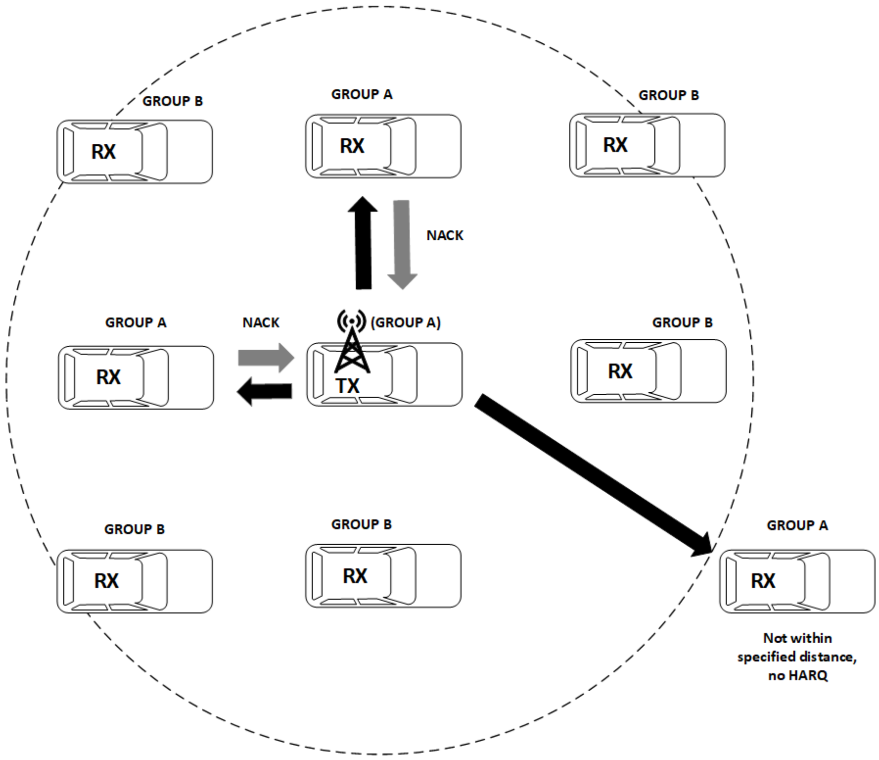

Figure 24. NACK-only feedback scheme of NR-V2X.

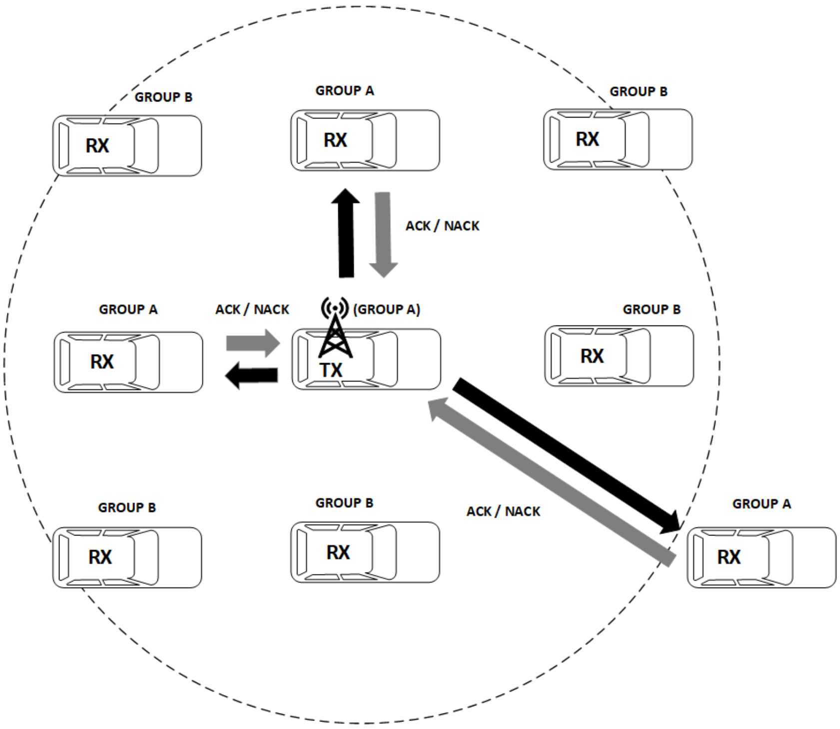

Figure 25. ACK/NACK feedback scheme of NR-V2X.

In NR-V2X, HARQ feedback is sent within the Physical Sidelink Feedback Channel (PSFCH). The resources reserved for PSFCH are configured so that one PSFCH symbol (that is copied over the preceding AGC symbol) is included every 1, 2 or 4 slots (after the PSCCH/PSSCH) and if no resources are configured, HARQ feedback is disabled (Garcia et al., 2021). Therefore, the PSFCH resources have configurable periodicity (in slots) in relation to the PSCCH/PSSCH for which the retransmission resources are reserved, indicated by the parameter *sl-MinTimeGapPSFCH*, given to the physical layer in the RRC configuration (3GPP, 2022d). Currently, the NR-V2X PSFCH features only one format, PSFCH format 0. Practically, the PSFCH is sent over two symbols in the last symbols before the last guard symbol of the slot, as seen in Figure 26. (3GPP, 2022c). The PSFCH utilizes antenna port 5000 for its transmission (3GPP, 2022b).

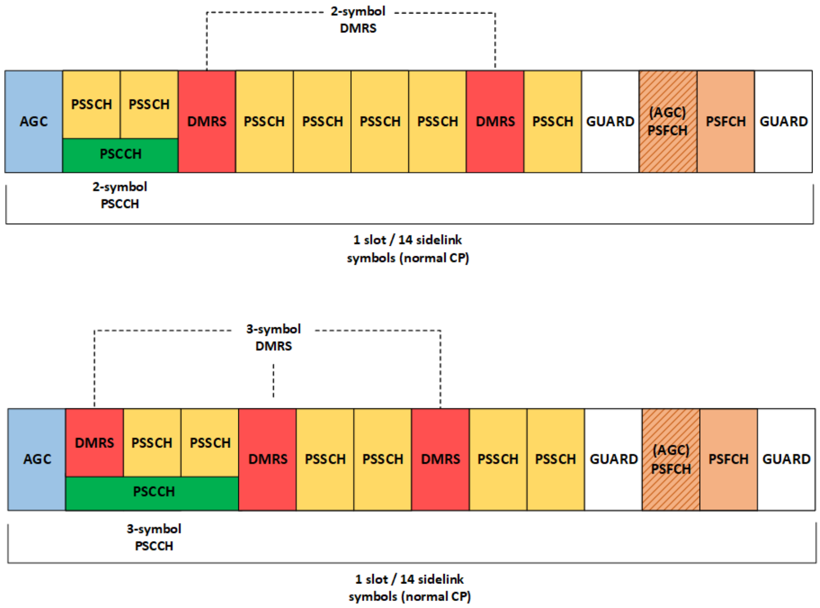

Figure 26. Example slot formats with PSFCH.

7 Discussion

This thesis focused on identifying the differences and similarities between 5G New Radio (NR) and New Radio Vehicle-to-Everything (NR-V2X). Specifically, the thesis focused on the sidelink (SL) interface of NR-V2X. The information provided in the thesis allows current 5G NR developers to draw meaningful conclusions as to which parts of the existing 5G NR technology are applicable to NR-V2X, either directly or with V2X specific adaptations. In short, the findings indicate that NR-V2X reuses many aspects of 5G NR. Many of the reused aspects have been simplified or modified to suit the needs of vehicular communications.

The physical layer of NR-V2X features significant similarities to 5G NR, which suggests that there is a good possibility that existing designs in both software and hardware could be reused effectively when developing an NR-V2X capable device. For instance, NR-V2X uses the same frame structure as 5G NR, and its supported numerologies are a subset of the numerologies supported by 5G NR. As an example of a simplified reuse case, NR-V2X utilizes bandwidth parts, but it does so by only configuring a single BWP per device, which removes the need for the BWP switching operations present in current 5G NR.

Although NR-V2X sidelink reuses many of the existing concepts from 5G NR, it also includes multiple significant adaptations and completely novel features which are not present in 5G NR. As an example of a significant adaptation where the conceptual functionality remains like 5G NR, the physical channels of NR-V2X have been made to include both uplink and downlink directions in a symmetrical fashion. This contrasts with 5G NR, where multiple channels are split into separate uplink and downlink components, such as the physical uplink control channel (PUCCH) and the physical downlink control channel (PDCCH). Both the significant adaptations and novel features introduce some challenges which need to be addressed when evaluating the reuse of existing 5G NR designs to NR-V2X. Some of the most prominent challenges include the half-duplex nature of V2X, where vehicles are unable to receive data while they are transmitting, combined with the complexity of the autonomous resource allocation scheme. In many aspects, NR-V2X essentially requires each device to undertake the responsibilities of both the gNB and the UE. In 5G NR, the UE does not need to concern itself with resource scheduling operations. Instead, it simply requests resources from the gNB, which allocates them in a centralized manner.

In terms of novel features, the sensing operation can be seen as the most significant feature, as most devices are required to perform full sensing all the time, which could potentially be very resource intensive if done with unoptimized algorithms. For sensing operations specifically, novel algorithmic solutions need to be created to implement a reliably functioning NR-V2X device. The 3GPP provides simple algorithms for these operations, but these are clearly not sufficient for a real implementation. Regardless, they provide a guideline for developers to understand the order of operations, based on which novel algorithms can be created.

7.1 Limitations of this study

As this study focuses on identifying the most fundamental differences between 5G NR and NR-V2X, the scope of the study makes it necessary to omit comprehensive discussion of some topics. As the author of this study, I realize that many additions such as a detailed description of the PSSCH and many other topics would be required for a complete understanding of how an NR-V2X device should be implemented.

To maintain a clear and easily understandable narrative, this study simplifies many complex aspects to ensure that both the scope and the pacing of the study remain reasonable. This could lead to major oversimplifications in some aspects and leaves some physical layer operations and properties completely outside the scope of this study. As an example of this, the power control functionality had to be entirely excluded from the study.

The general limitations of this study have to do with the broad and complex nature of 5G NR and NR-V2X. As both the literature and technical specifications surrounding these topics are extremely detailed, this comparative study could only cover a small portion of all the potential topics that could have been discussed in the context of the NR-V2X physical layer. Despite the author’s best efforts, some important details are bound to go unnoticed, as it would be impossible to completely cover all the relevant material due to the sheer volume of it.

Finally, the explanations of certain topics rely heavily on specific literature. Although these sources are reliable and trustworthy, written by industry experts, relying on them could introduce bias to the study. This is because the complex technical specifications provided by the 3GPP could be interpreted differently across different sources, and any misinterpretations could potentially affect the findings of this study as well.

8 Conclusion

Can be a single paragraph

In conclusion, NR-V2X sidelink was found to share many foundational concepts with the existing 5G NR systems. To tailor the existing 5G NR architecture to the vehicular communications use case, NR-V2X sidelink introduces many unique modifications and new features. These modifications and new features introduce unique challenges, both in terms of algorithmic solutions and various other implementation aspects.

Although many implementation aspects are left up to the UE manufacturers, addressing any concerns or improvements to the overall NR-V2X system needs to be done with the collaborative effort of both industry partners and the 3GPP standardization organization. As NR-V2X implementations begin entering their testing phases, performance evaluations will likely yield many findings that will need to be considered in the coming revisions of the NR-V2X standard to create safer and more efficient intelligent transport services in the future.

9 References

3GPP. (2019). NR; Study on NR Vehicle-To-Everything (V2X) (3GPP TR 38.885 version 16.0.0 Release 16).

3GPP. (2019a). MCC Support, "Final Report of 3GPP TSG RAN WG1 #100bis-e v1.0.0", 3GPP TSG RAN WG1 Meeting #101-e, June 2020.

3GPP. (2020a). 5G; NR; Services provided by the physical layer (3GPP TS 38.202 version 16.1.0 Release 16).

3GPP. (2021) LTE; Evolved Universal Terrestial Radio Access (E-UTRA); Physical channels and modulation (TS 36.211 version 16.6.0 Release 16).

3GPP. (2021b). Service requirements for V2X services (3GPP TS 22.185 version 17.0.0 Release 17).

3GPP (2021c). Study on NR sidelink relay (3GPP TR 38.836 version 17.0.0 Release 17).

3GPP. (2022a). 5G; NR; Physical layer procedures for control (3GPP TS38.213 version 17.1.0 Release 17).

3GPP. (2022b). 5G; NR; Physical channels and modulation (3GPP TS 38.211 version 17.1.0 Release 17).

3GPP. (2022c). Overall description of Radio Access Network (RAN) aspects for Vehicle-to-everything (V2X) based on LTE and NR (3GPP TR 37.985 V17.1.0.)

3GPP. (2022d). 5G; NR; Radio Resource Control (RRC); Protocol specification (3GPP TS 38.331 version 17.0.0 Release 17).

3GPP. (2022e) LTE; Service requirements for V2X services (3GPP TS 122 185 version 17.0.0 Release 17)

3GPP. (2022f) 5G; Architecture enhancements for 5G System (5GS) to support Vehicle-to-Everything (V2X) services) (TS 23.287 version 17.2.0 Release 17)

3GPP. (2022g) 5G; Vehicle-to-Everything (V2X) services in 5G System (5GS); Stage 3 (3GPP TS 24.587 version 17.6.0 Release 17)

3GPP. (2022h) Universal Mobile Telecommunications System (UMTS); LTE; Architecture enhancements for V2X services (3GPP TS 23.285 version 17.1.0 Release 17)

3GPP. (2022j). 5G; NR; Multiplexing and channel coding (3GPP TS 38.212 version 17.1.0 Release 17)

3GPP. (2022k). 5G; NR; Physical layer measurements (3GPP TS 38.215 version 17.1.0 Release 17)

3GPP (2022m). Service requirements for the 5G system (3GPP TS 22.261 version 17.11.0 Release 17).

3GPP (2023b). Study on expanded and improved NR positioning. (3GPP TR 38.859 version 18.0.0, release 18).

3GPP. (2022p). 5G; NR; Physical layer procedures for data (3GPP TS 38.214 V17.1.0 Release 17).

3GPP. (2022q). 5G; NR; Physical layer; General description (3GPP TS 38.201 version 17.0.0 Release 17).

3GPP. (2022r). 5G; NR; Medium Access Control (MAC) protocol specification (3GPP TS 38.321 version 17.1.0 Release 17).

3GPP. (2024). Overall description of Radio Access Network (RAN) aspects for Vehicle-to-everything (V2X) based on LTE and NR (3GPP TR 37.985 V18.0.0.)

3GPP. (2024a). 5G; NR; Multiplexing and channel coding (3GPP TS 38.212 version 18.2.0 Release 18).

3GPP. (2023). 5G; NR; Use Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (3GPP TS 38.101-1 version 17.8.0 Release 17)

3GPP. (2023a). 5G; NR; Use Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (3GPP TS 38.101-2 version 17.8.0 Release 17)

Ali, Z., Lagen, S., Giupponi, L., & Rouil, R. (2021). 3GPP NR V2X Mode 2: Overview, Models and System-Level Evaluation. IEEE Access, 9, 89554–89579. https://doi.org/10.1109/access.2021.3090855

Ashour, M. E. (2023). Deep dive: 5G CSI-RS. LinkedIn. Retrieved April 23, 2024, from https://www.linkedin.com/pulse/deep-dive-5g-csi-rs-mohamed-eladawi-ashour

Dahlman, E., Parkvall, S., & Johan Skold. (2018). *5G NR - the Next Generation Wireless Access Technology : the Next Generation Wireless Access Technology*. Elsevier Science & Technology.

Ding, W., & Shikh-Bahaei, M. (2023). HARQ delay minimization of 5G wireless network with imperfect feedback. In *ICASSP 2023 - 2023 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)* (pp. 1-5). Rhodes Island, Greece. https://doi.org/10.1109/ICASSP49357.2023.10095827

ETSI. (2018). Intelligent Transport Systems. https://www.etsi.org/images/files/ETSITechnologyLeaflets/IntelligentTransportSystems.pdf

Ganesan, K., Mallick, P. B., Lohr, J., Karampatsis, D., & Kunz, A. (2019). 5G V2X architecture and radio aspects. *2019 IEEE Conference on Standards for Communications and Networking (CSCN)*. https://doi.org/10.1109/cscn.2019.8931319

Garcia, M. H. C., Molina-Galan, A., Boban, M., Gozalvez, J., Coll-Perales, B., Sahin, T., & Kousaridas, A. (2021). A Tutorial on 5G NR V2X Communications. IEEE Communications Surveys & Tutorials, 23(3), 1972–2026. https://doi.org/10.1109/comst.2021.3057017

Harounabadi, M., Soleymani, D. M., Bhadauria, S., Leyh, M., & Roth-Mandutz, E. (2021). V2X in 3GPP Standardization: NR Sidelink in Release-16 and Beyond. IEEE Communications Standards Magazine, 5(1), 12-21. https://doi.org/10.1109/MCOMSTD.001.2000070

Holma, H., Toskala, T., Nakamura T., (2020). *5G technology: 3GPP New Radio*. John Wiley & Sons.

Kawser, M., Sajjad, S., Fahad, S., Ahmed, S., & Rafi, H. (2019). The Perspective of Vehicle-to-Everything (V2X) Communication towards 5G. *19*, 146-155.

Miao, L., Virtusio, J. J., & Hua, K. L. (2021). PC5-Based Cellular-V2X Evolution and Deployment. Sensors (Basel, Switzerland), 21(3), 843. https://doi.org/10.3390/s21030843

Montero, L., Ballesteros, C., de Marco, C., & Jofre, L. (2022). Beam management for vehicle-to-vehicle (V2V) communications in millimeter wave 5G. Vehicular Communications, 34, 100424. https://doi.org/10.1016/j.vehcom.2021.100424

Moradi-Pari, E., Tian, D., Bahramgiri, M., Rajab, S., & Bai, S. (2023). DSRC versus LTE-V2X: Empirical performance analysis of direct vehicular communication technologies. IEEE Transactions on Intelligent Transportation Systems, PP (1), 1. https://doi.org/10.1109/TITS.2023.3247339

Petrov, T., Sevcik, L., Pocta, P., & Dado, M. (2021). A Performance Benchmark for Dedicated Short-Range Communications and LTE-Based Cellular-V2X in the Context of Vehicle-to-Infrastructure Communication and Urban Scenarios. *Sensors (Basel, Switzerland)*, *21*(15), 5095. https://doi.org/10.3390/s21155095

Sheldon, R. (n.d.). Forward error correction. TechTarget. https://www.techtarget.com/searchmobilecomputing/definition/forward-error-correction Accessed 31.03.2024

What is DFT-s-OFDM? (n.d.). everythingRF. Retrieved April 9, 2024, from https://www.everythingrf.com/community/what-is-dft-s-ofdm

DFT-S-OFDM Explained. (n.d.). Electronics Notes. Retrieved April 9, 2024, from https://www.electronics-notes.com/articles/radio/multicarrier-modulation/dft-s-ofdm.php

Kenney, J. B. (2011). Dedicated Short-Range Communications (DSRC) Standards in the United States. Proceedings of the IEEE, 99(7), 1162-1182. https://doi.org/10.1109/JPROC.2011.2132790

Yang, X., Shi, Y., Xing, J., & Liu, Z. (2022). Autonomous driving under V2X environment: state-of-the-art survey and challenges. Intelligent Transportation Infrastructure, 1, liac020. https://doi.org/10.1093/iti/liac020