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5G NR TESTBED AND PERFORMANCE EVALUATION

Master's Thesis

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Author's declaration of originality

I hereby certify that I am the sole author of this thesis. All the used materials, references to the literature and the work of others have been referred to. This thesis has not been presented for examination anywhere else.

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Abstract

The Third Generation Partnership Project (3GPP) published Release 16 at the end of 2019 which includes Vehicle-to-Everything (V2X) communication standards. These standards are aiming for intelligent transportation systems, for example, truck platooning.

Release 16 is based on 5G, it can offer high reliability and low latency on its applications. After this release, researchers and developers started working on publishing papers about 5G New Radio (NR) Sidelink and developing simulations or real-time tests on this topic. However, since this technology is still brand new, there are relatively few studies or papers published on 5G NR Sidelink.

This thesis offers gathered information on the physical layer of sidelink communication from Release 12 to Release 16 of 3GPP. Moreover, the work aims to use this information for developing a 5G NR Sidelink testbed where 2 user equipment are synchronized with each other. Besides the development process, 5G NR simulation and physical layer testbed are also included. In these testbeds, as a software tool, OpenAirInterface (OAI) and as a Radio Frequency (RF) module, software-defined radio (SDR) are used. Moreover, MATLAB is used for the 5G NR throughput simulation.

The main blocks for 5G NR Sidelink development are, testing OAI software codes for 5G NR and understanding the embedded system inside of it. In this work, these blocks are provided with the 5G NR Sidelink synchronization development process.

This thesis is written in English and is 45 pages long, including 6 chapters, 35 figures and 3 tables.

Annotatsioon

5G NR Testplatvormi ja Jõudluse Hindamine

Kolmanda põlvkonna partnerlusprojekt (3GPP) avaldas 2019. aasta lõpus tarkvaraversiooni 16 (Release 16), mis sisaldab sõidukilt-kõigele (V2X) kommunikatsioonistandardeid. Nende standardite eesmärk on luua alus tarkadele transpordisüsteemide, näiteks veoauto rühmituste, arendamiseks.

Release 16 põhineb 5G tehnoloogial, mis suudab oma rakendustes pakkuda kõrget usaldusväärsust ja madalat latentsust. Pärast seda väljalaset alustasid teadlased ja arendajad tööd 5G New Radio (NR) Sidelink valdkonnas artiklite avaldamisega ja simulatsioonide või reaal-aja testide arendamisega. Kuid kuna see tehnoloogia on veel täiesti uus, on 5G NR Sidelink kohta avaldatud suhteliselt vähe uuringuid või dokumente.

See lõputöö koondab teadmisi Sidelink-i kommunikatsiooni füüsilise kihi kohta 3GPP tarkvaraversioonist 12 kuni 16. Lisaks on töö eesmärk kasutada seda infot 5G NR Sidelink-i testpesa arendamiseks, kus 2 kasutajaseadet sünkroniseeritakse teineteisega. Arendusprotsessi kõrval on kaasatud ka 5G NR simulatsioon ja füüsilise kihi testpesa. Nendes testpesades kasutatakse tarkvaravahendina OpenAirInterface (OAI) ja raadiosagedus (RF) moodulina tarkvaral põhinevat raadiot (SDR). MATLABi kasutatakse 5G NR läbilaskevõime simuleerimiseks.

5G NR Sidelink-i arenduse peamised klotsid on OAI tarkvara koodide testimine 5G NR-i osas ja selle sisemise manussüsteemi mõistmine. Selles töös on need klotsid ette nähtud 5G NR Sidelink sünkroniseerimise arendusprotsessiga.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 45 leheküljel, 6 peatükki, 35 joonist, 3 tabelit.

List of abbreviations and terms

3GPP	The Third Generation Partnership Project
AGC	Automatic Gain Control
AWGN	Additive White Gaussian Noise
CDL	Clustered Delay Line
CN	Core Network
CP	Cyclic Prefix
CSI-RS	Channel State Information Reference Signal
D2D	Device to Device
DMRS	Demodulation Reference Signal
LTE	Long-Term Evolution
MAC	Medium Access Control
MCS	Modulation Coding Scheme
MIB-SL	Master Information Block Sidelink
NR	New Radio
OAI	OpenAirInterface
OFDM	Orthogonal Frequency-Division Multiplexing
PBCH	Physical Broadcast Channel
PDCP	Packet Data Convergence Protocol
PER	Packet Error Rate
PHY	Physical Layer
PRB	Physical Resource Block
ProSe	Proximity Services
PSBCH	Physical Sidelink Broadcast Channel
PSCCH	Physical Sidelink Control Channel
PSDCH	Physical Sidelink Discovery channel
PSFCH	Physical Sidelink Feedback Channel
PSS	Primary Synchronization Signal
PSSCH	Physical Sidelink Shared Channel
PSSS	Primary Sidelink Synchronization Signal

PT-RS	Phase Tracking Reference Signal
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RAN	Radio Access Network
RLC	Radio Link Control
SC-FDMA	Single Carrier – Frequency Division Multiple Access
SCI	Sidelink Control Information
SCS	Subcarrier Spacing
SIB	System Information Block
SLSS	Sidelink Synchronization Signals
SNR	Signal to Noise Ratio
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
SSSS	Secondary Sidelink Synchronization Signal
TDL	Tapped Delay Line
UE	User Equipment
USRP	Universal Software Radio Peripheral
V2X	Vehicle to Everything

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1 Introduction

Sidelink is the communication type where the cellular devices no longer need a network to be able to communicate with each other. This means that mobile phones, cars or even robots do not need any intermediary network, and they can create their own. This type of communication is getting more and more credits every day with the new areas of usage such as public safety scenarios, vehicle communications, etc [1] .

Over the past decade, the devices that connected to the network have grown massively which generates huge traffic volume. Eventually, the enhancements on the network were targeting new use cases to solve this growth where the device to device (D2D) communication is designed with Release 12 of 3GPP to solve some of these use cases such as network applications for proximity services, storage and data transfer. In addition to these, the public safety use case is also one of the major D2D focuses which starts the evolution of sidelink communication.

As a next step, another type of sidelink communication, Vehicle to Everything (V2X) communication was created with Release 14 of 3GPP aiming to have an intelligent transportation system with communication between vehicles, pedestrians, road side units, and the network. Decreasing the number of accidents and reducing fuel consumption with greener vehicles are some of the goals of this transportation system [2] .

With the current phase, Release 16 of 3GPP, V2X communication use cases are extended with the 5G technology. Since the new technology has the potential to provide extensive bandwidth, high throughput, low latency, and high reliability, sidelink communication becomes more important with its features [3] . The four new use cases under New Radio (NR) V2X are vehicle platooning, advanced driving, remote driving, and extended sensors which need the performance that 5G provides.

Since Release 16 is new, there is no open-source simulation or real-time test development yet. Moreover, there are very few papers studied on 5G NR sidelink

communication. This thesis focuses on the evolution of sidelink standardization on the physical layer (PHY) to bring the information from standards and the other related works together which aims to help developers to access the PHY layer information easily. Moreover, using this information for developing a testbed to have sidelink communication can be called the main goal of the thesis. In addition to 5G NR sidelink development, setting a testbed to ensure that the 5G NR PHY is reliable to take it as a reference to build the NR Sidelink and also, simulating 5G NR throughput with MATLAB are the side focuses.

The thesis is organized as follows. The introduction of the thesis and the problem statement compose Chapter 1. In Chapter 2, the standardization for sidelink communication is studied. This chapter is mainly focusing on the PHY layer enhancements and differences between the releases. Moreover, an analysis of the related works is at the end of this chapter. The 5G throughput simulations in MATLAB are presented in Chapter 3. Then, Chapter 4 presents the testbed setup for the 5G NR physical layer as a simulation and a real-time application. In Chapter 5, the development process of 5G NR Sidelink is explained. Finally, in Chapter 6, the conclusion and future work are provided.

1.1 Problem Statement

This thesis aims to give an overall summary for sidelink standardization in the PHY layer and developing an algorithm to test 5G NR sidelink, and its performance. To achieve these, this work is focused on four important problems:

- Simulating 5G throughput
- Setting a testbed to experiment with the 5G NR PHY layer.
- Testbed implementation of 5G NR Sidelink Synchronization.

2 Evolution of Sidelink Standardization

In this chapter, the overview history of Sidelink standardization from LTE through 5G is explained. The focus of the explanation is the overall capabilities of the releases and the physical layer standardization. Moreover, at the end of the chapter, related works are presented.

2.1 LTE Sidelink

Proximity Services (ProSe) is one of the main fields leading the creation of the sidelink communication, a 3GPP study to take care of public safety scenarios after LTE had become a worldwide success [4] . These services include Direct Discovery and Direct Communication. Direct Discovery enables two user equipment (UE) that can identify each other. Moreover, it can also be used in non-public safety use cases such as for commercial purposes. On the other side, Direct Communication provides data and voice exchange between two synchronized UEs which uses LTE resources for communication. In this subchapter, system aspects and PHY layer for Direct Communication is studied concerning 3GPP Release 12.

2.1.1 System Aspects

ProSe (Proximity Services) concerns about public safety in 3GPP Release 12. When public safety usage is the main focus, it brings the scenario that the devices might not be in coverage of the base station. That is why ProSe communication should not depend on the base station which results in different types of coverage scenarios in D2D communication. Figure 1 illustrates partial coverage, in coverage and out of coverage scenarios. UE uses preconfigured resources for the out of coverage case when there is no coverage on the frequency used for D2D communication.

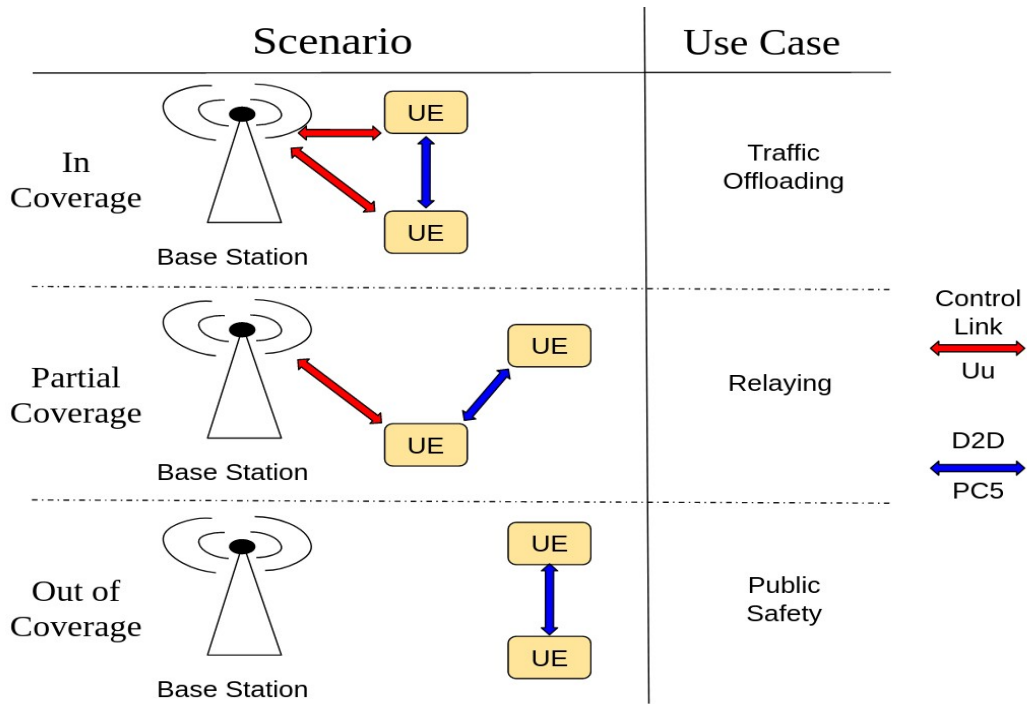


Figure 1. Different coverage scenarios for ProSe communication and example use cases for these scenarios [5] .

The network architecture of ProSe can be seen in Figure 2. In this configuration, PC5 is one of the most important interfaces that combines 2 UEs to direct communication. Moreover, PC3 is a logical interface that connects UEs with ProSe Function. UE can get the authorization and security parameters from ProSe Function through this interface [6]

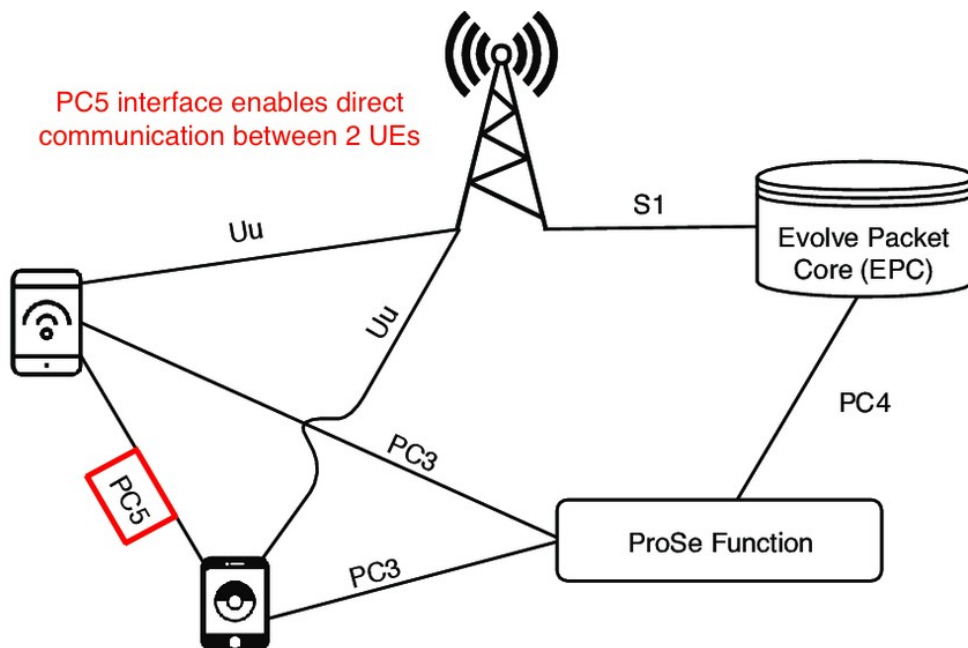


Figure 2. Non-roaming simplified ProSe architecture [7] .

In D2D communication, the data which will be transmitted is created on the application level of the UE. The protocol used for the transmission and reception can be seen in Figure 3.

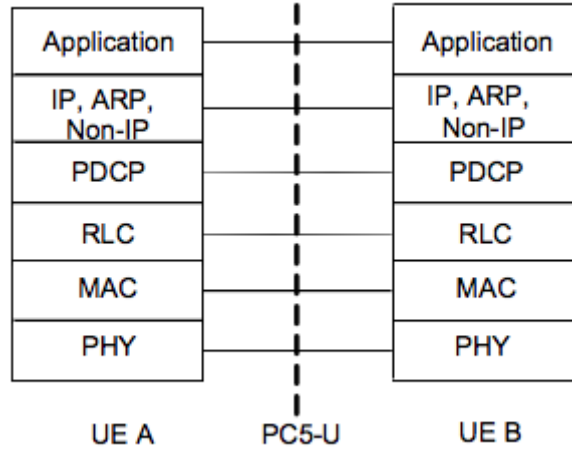


Figure 3. User plane for PC5 interface [8] .

In this protocol, the main focus of this thesis is the PHY layer. The information about other layers such as PDCP (Packet Data Convergence Protocol), RLC (Radio Link Control), and MAC (Medium Access Control) can be found in [9] .

2.1.2 The Physical Layer Structure

In this part, the signals and channels that form the physical layer are studied. First, the synchronization block includes the primary sidelink synchronization signal (PSSS), the secondary sidelink synchronization signal (SSSS), and the physical sidelink broadcast channel (PSBCH) with its demodulation reference signal (DMRS) are explained. Then, the physical sidelink control channel (PSCCH) and shared channel (PSSCH) are clarified with their locations on the resource grid. Table 1 gives a brief introduction about these signals and channels. Since this study is focusing on Direct Communication, the physical sidelink discovery channel (PSDCH) is not included. Last, the resource pool is explained.

Table 1. Abbreviation and the function of the signals and channels.

Signal/ Channel	Abbreviation	Function
Physical Sidelink Syn-chronization Signal	PSSS	Helps to find the centre of the channel bandwidth in

Signal/ Channel	Abbreviation	Function
		the frequency domain and to achieve symbol, slot and subframe synchronization in the time domain[10]
Secondary Sidelink Synchronization Signal	SSSS	Provides radio frame synchronization
Physical Sidelink Broadcast Channel	PSBCH	Carries system information for UE (Master Information Block)
Physical Sidelink Control Channel	PSCCH	Include Sidelink Control Information (SCI) for different types of scheduling information
Physical Sidelink Shared Channel	PSSCH	The channel that includes the message inside.
Demodulation Reference Signal	DMRS	Decodes the channel that belongs to

2.1.2.1 Synchronization Block

The synchronization block is a must-have because the receiver side has to synchronize in time and frequency to the transmitter side to demodulate the data. The synchronization process varies in different scenarios for example in out of coverage scenarios (Type 2- without base station synchronization), transmitter UE becomes a synchronization source if another device's measured received power of synchronization signals are below the threshold. On the other hand, if the transmitter UE is in coverage (Type 1- synchronization with the help of base station), it depends on some configuration as in Figure 4.

When the UE is in coverage, it looks at the Synchronization Control parameter in System Information Block (SIB) which comes from the network. Then, UE checks if the received power is sufficient to be a synchronization source or not.

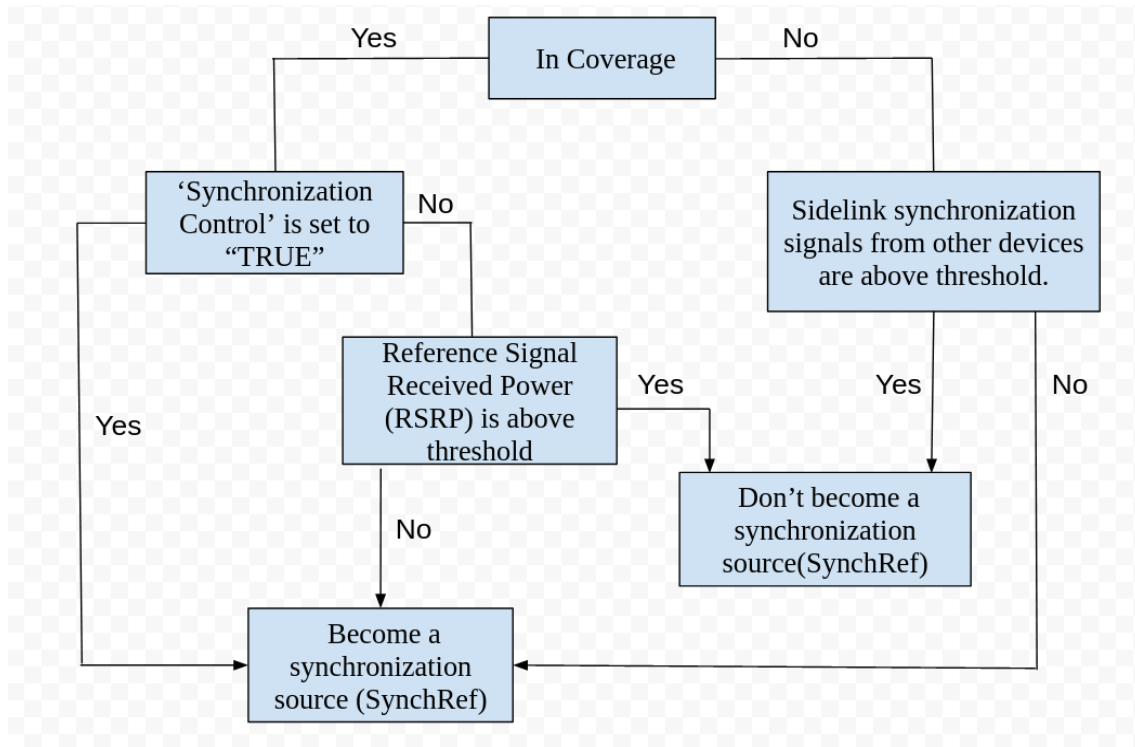


Figure 4. A decision flow of a UE for becoming a synchronization source.

When the UE becomes the synchronization source, it is expected to send 2 types of synchronization signals which are SLSS (Sidelink Synchronization Signals: PSSS and SSSS) and MIB-SL (Master Information Block-Sidelink) [4] . When SLSS helps the receiver UE to understand where the frame begins and ends [10] , MIB-SL has the information that UE is in coverage or not, also includes the frame and subframe number information. With these signals, UE obtains information about channel bandwidth in the frequency domain, and about subframes and slots in the time domain.

The PSSS is based on a frequency domain Zadoff-Chu sequence, SSSS is based on maximum length sequences (m-sequences) [11] . Moreover, PSSS and SSSS signals occupy 62 resource elements in the frequency domain (where Synchronization Block contains 72 resource elements or 6 physical resource block (PRB)) and 2 SC-FDMA (Single Carrier- Frequency Division Multiple Access) symbols in the time domain. In the case of a normal cyclic prefix (CP) (14 symbols in subframe), PSSS is located on

the 2nd and the 3rd symbols when SSSS is on 12th and 13th in the synchronization subframe (Synchronization Block). Moreover, MIB-SL is transmitted in PSBCH which is in the same subframe with the SLSS creating the synchronization block as in Figure 5. The Synchronization Subframe is transmitted every 40 ms even when there is no message to transmit.

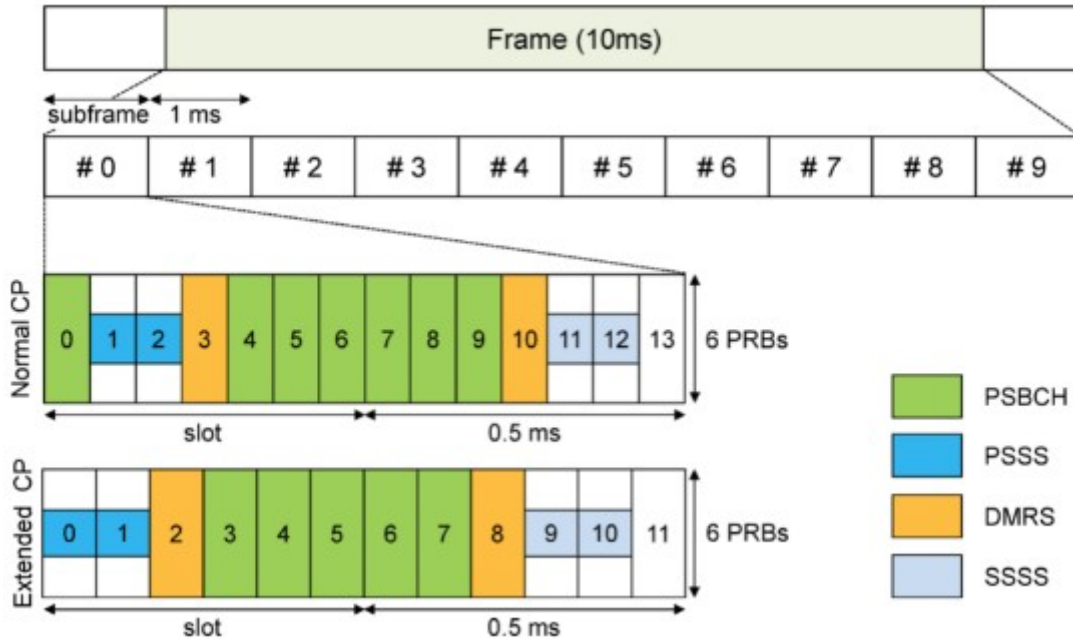


Figure 5. Synchronization Subframe (1ms) configured by higher layers for normal and extended cyclic prefix [12] .

On the other hand, when the case is extended cyclic prefix, PSSS is located on the first 2 symbols when SSSS is on 10th and 11th in the synchronization subframe.

2.1.2.2 Control and Shared Channels

When the synchronization signals are received, then control and shared channels are taking place. PSCCH includes SCI (Sidelink Control information) [13] . The number of allocated resource blocks and the location, modulation and coding scheme, and time resource pattern are some of the information that SCI provides [4] . In other words, the information about the resource allocation of PSSCH is in SCI. Moreover, SCI is sent twice to increase correct demodulation probability.

Physical Sidelink Shared Channel is the channel that carries the message. The message can be received by multiple UEs in a group since one-to-many scheme is valid for sidelink transmission.

2.1.2.3 Resource Pools

A resource pool is where PSCCH and PSSCH sources are defined for the respective channels. These resources repeat themselves with a period range from 40 to 320 ms [14]. This structure is also called the PSCCH period. The resource pool structure is necessary since the transmission of PSCCH or PSSCH is not possible in every physical resource block. For either transmitting or receiving operations, resource pools define the available resource blocks or subframes. Detailed information about D2D resource pools can be found in clause 3.2 of [4].

In Figure 6, the time domain and frequency domain view of a resource pool can be seen. In the time domain, the subframes used for the ProSe application are represented with 'D'. On the other side, in the frequency domain, the resources for Sidelink communication are located in blue blocks called 'ProSe'.

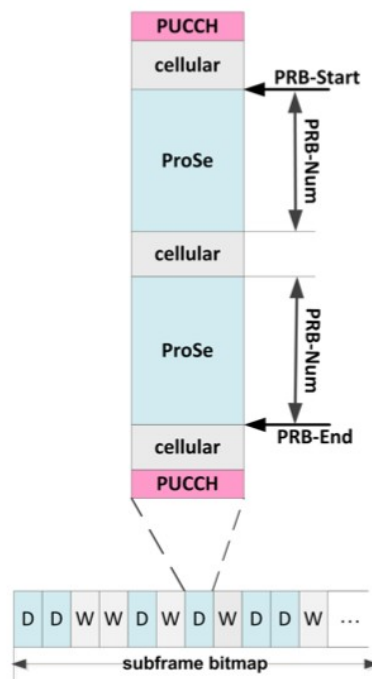


Figure 6. Resource Pool for Sidelink Communication (The frequency domain on the top, the time domain on the bottom)[4].

In Figure 7, an example for PSCCH Period is shown with synchronization signals, SCI and the selected resources in the shared channel. More examples and explanation can be found in [15].

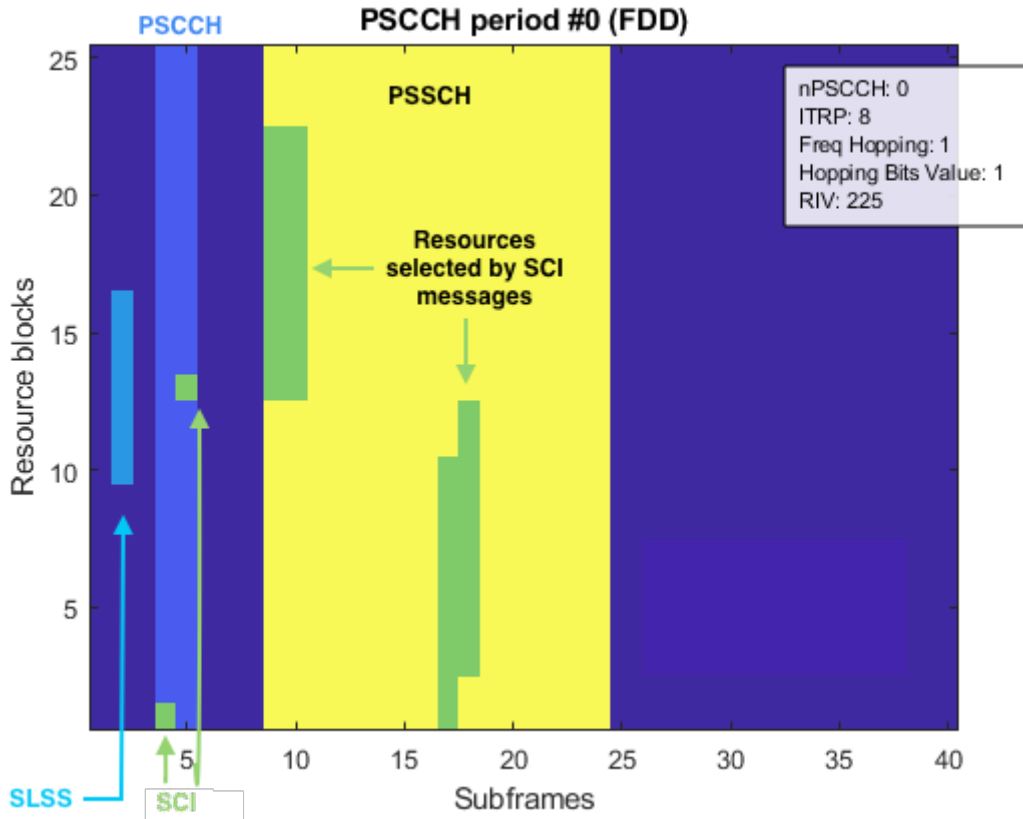


Figure 7. An example of PSCCH period (full-band resource pool) including PSSCH resources selected by SCI [15].

In PSCCH period, synchronization signals are located in the middle of the frequency domain. Moreover, we can see that SCI is transmitted twice to secure that control information is transmitted. Lastly, with the information coming from SCI, the resource locations inside the shared channels are represented in this figure.

The physical layer of D2D communication in Release 12 is studied in this subchapter. In the next subchapter, Release 14 standards are explained for sidelink communication.

2.2 LTE Vehicle to Everything (V2X)

The improvements with Release 14 is studied in this subchapter under the name of LTE ‘Vehicle to Everything’ communication. The ‘X’ inside V2X refers to V-Vehicle, P-Pedestrian, I-Infrastructure, and N- Network as in Figure 8.

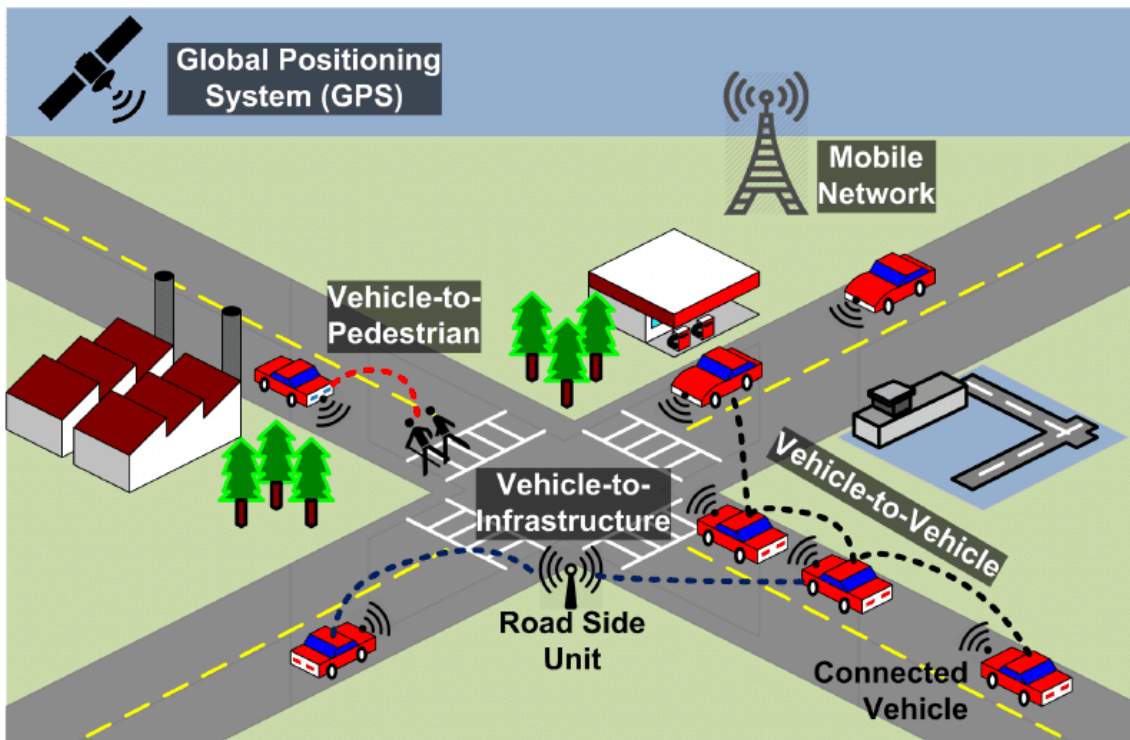


Figure 8. V2X use cases [16] .

The physical layer changes after D2D, new modes, and new features are explained within the scope of the PHY layer.

2.2.1 Overall Enhancements

Since D2D communication was aiming at public safety solutions, it was not providing the requirements for V2X communication. Moreover, D2D communication was a bit problematic with latency handling. Release 14 proposes two more modes added to the existing D2D modes, to achieve requirements to have V2X communication. In the end, the 4 modes are:

- Mode 1: D2D with the help of a base station,
- Mode 2: D2D out of coverage (without the base station),
- Mode 3: V2X with the help of a base station,
- Mode 4: V2X without the base station.

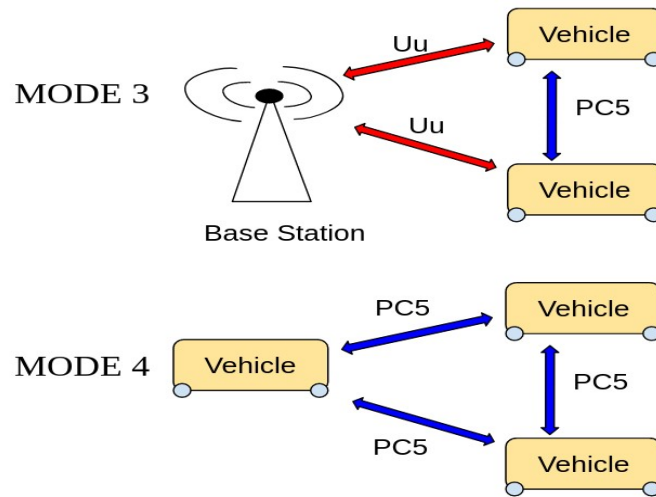


Figure 9. Release 14 V2X communication modes [17] .

Since V2X is bringing new use cases, it also comes with new problems. Release 14 has some characteristic attributes in comparison to Release 12 such as high Doppler shifts due to vehicle movements, high reliability and low latency requirements, etc [18] .

Besides the comparison, multiple bandwidth options are available in LTE-V2X such as 1,4 MHz, 5 MHz, 10 MHz, and 20 MHz [19] . Furthermore, it also provides fixed subcarrier spacing which is 15 kHz.

2.2.2 The Physical Layer Improvements

The differences between V2X and D2D in the sense of signals, channels, resource allocation, and resource pool are studied in this part.

The LTE V2X uses the same signals and physical channels as in D2D which are, PSSS, SSSS, DMRS, PSBCH, PSCCH, PSSCH. Also, LTE-V2X uses SC-FDMA transmission scheme as in D2D.

2.2.2.1 Synchronization Block

The differences in the synchronization block with Release 14 is generally with the resource allocation. SLSS side of the synchronization block, i.e. PSSS and SSSS are generated in the same way as in the D2D, even the locations in the synchronization subframe are the same (PSSS: 2nd and the 3rd symbols, SSSS: 12th and 13th symbols).

On the other hand, the location of PSBCH and its DMRS in the synchronization is changed as in Figure 10. DMRS are transmitted in the 5th, 7th, and in 10th symbols of the subframe. Moreover, the period of the transmission of MIB-SL inside PSBCH is also changed to 160 ms from 40 ms.

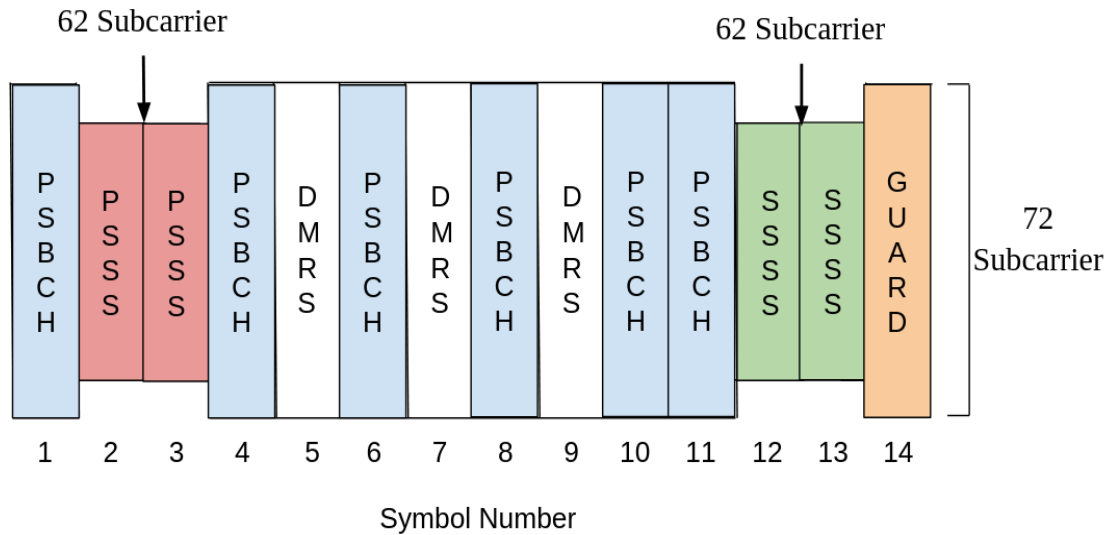


Figure 10. LTE-V2X synchronization subframe with the normal cyclic prefix [20].

As can be seen in the figure, synchronization signals are located in the middle of the synchronization block in terms of frequency. In other words, SLSS with 62 subcarriers are located in the middle of 72 subcarriers (6 PRBs) of the synchronization block.

2.2.2.2 Resource Pools

The resource pool configuration for all the modes is explained very well in reference [21] with Figure 11. In this figure, the comparison of resource pools between Modes 1-2 and Modes 3-4 is shown. At three different moments, the packets (50, 7 and 120 Bytes) arrive from higher layers. The arrows from SCI show which places will be occupied with the message inside the shared channel. The first difference between these two resource pools, (a) and (b), is the latency difference. In Mode 1-2, the packets are waiting for t_1 , t_2 , and t_3 amount of time. On the other hand, for Mode 3-4, the waiting time for packets are t_1' , t_2' , and t_3' which are a lot less than the ones in Mode 1-2. This explains why Mode 3-4 resource pool structure provides low latency. The second is spectral efficiency. Figure 11, for the 7 Bytes packet, the subchannel is barely used and the rest of the subchannel cannot be used for transmission or by other UEs. Since the data transmission has to start from the lowest point of the subchannel, the scheduling

flexibility of the resource allocation is decreased. This fact also brings higher collision probability in the case where multiple UEs transmit at the same time.

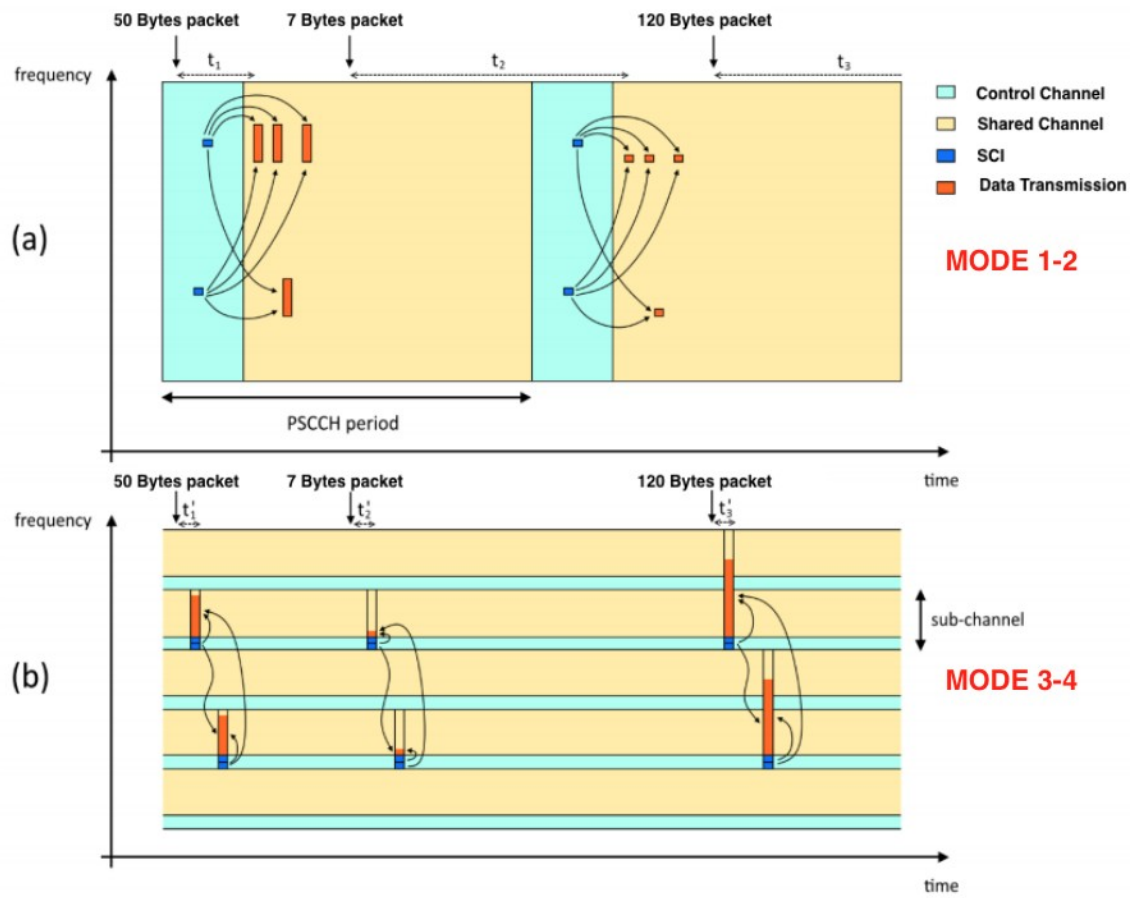


Figure 11. Resource Pool structure: (a) Mode 1-2, (b) Mode 3-4 [21] .

These are showing that one of the main focus in the new design of the resource pool is on the latency problem, to be affected by Doppler Shift in minimum amount.

Until now, the standards until Release 14 is explained. In the following chapter, 5G NR Sidelink with Release 16 is studied in the aspect of the physical layer.

2.3 5G New Radio Sidelink

3GPP has shared the specifications about 5G NR Sidelink starting with Release 16. In this part of the thesis, overall information about 5G NR Sidelink, the features in the PHY layer that come with the newest releases, and comparison with the previous releases also with the 5G NR structure are studied.

2.3.1 Overall New Radio Sidelink

5G NR V2X includes more advanced use cases than LTE V2X such as vehicular platooning, extended sensors, advanced driving, and remote driving. Some of the requirements that suggested cases need are 1Gbps throughput, 1000 meters of maximum sidelink range, 99.999% reliability, and 3 ms latency [22] . Some of the features that added to 5G NR Sidelink to fulfil these requirements are [3] :

- In addition to broadcast, groupcast and unicast are also supported. Moreover, a new physical channel (Physical Sidelink Feedback Channel (PSFCH)) is designed to make the receiver UE give feedback about decoding to the transmitter UE.
- New resource allocation procedure with a new version of PSCCH.

Besides these, in 5G NR V2X, the number of modes dropped to 2 from 4 as in Figure 12.

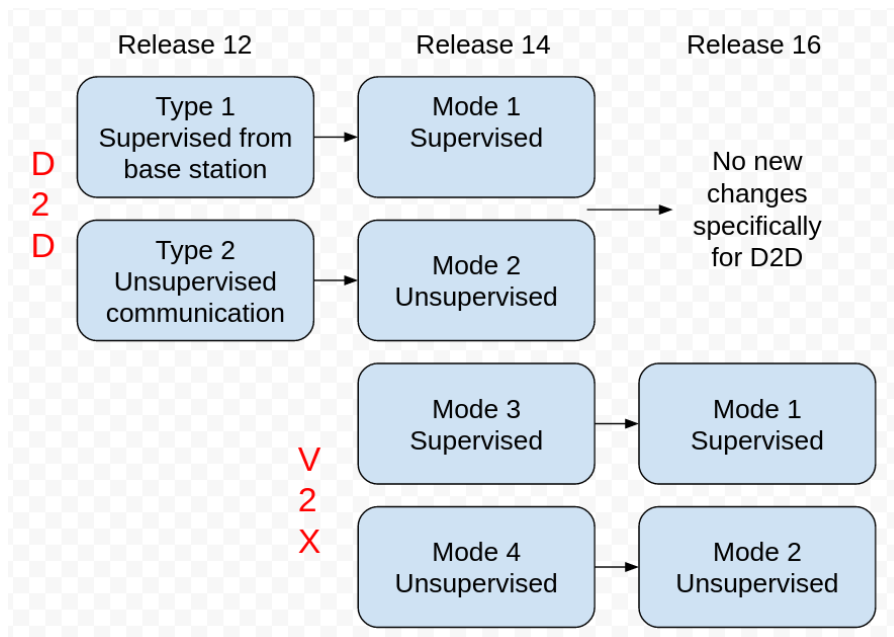


Figure 12. Modes of sidelink communication in different releases.

In Release 16, the design and new features of 5G NR Sidelink are aiming for V2X applications, that is why there are no new features specifically on D2D communications.

2.3.2 The Physical Layer Structure

The 5G NR sidelink supports not only 15 kHz subcarrier spacing (SCS) as in LTE but also supports 30, 60, and 120 kHz SCS [23] . As a result, the symbol duration shrinks by a factor of 2 when SCS is doubled. This can be used against the Doppler effect to increase the robustness with low symbol durations. Moreover, 5G NR Sidelink uses OFDM (Orthogonal Frequency-Division Multiplexing) symbols instead of SC-FDMA symbols.

The physical channels and signals that 5G NR sidelink uses are PSBCH and its DMRS, PSCCH and its DMRS, PSSCH and its DMRS, PSFCH, PSSS, SSSS, PT-RS (Phase Tracking Reference Signal), and CSI-RS (Channel State Information Reference Signal). Also, the modulation schemes that are available in 5G NR sidelink are QPSK, 16-QAM, 32-QAM, and 64-QAM[20] .

2.3.2.1 Synchronization Block and SLSS

The MIB is transmitted every 160 ms in 11 resource blocks with possible repetitions in the period. DMRS for PSBCH is located in every symbol for PSBCH. Moreover, PSSS and SSSS are transmitted in 127 subcarriers of the synchronization block bandwidth. The 2nd and 3rd symbols are occupied by PSSS, 4th and 5th symbols are occupied by SSSS which use M-sequence and Gold sequence respectively. In Figure 13, a synchronization block MATLAB visualization and the locations of the signal on the right is shown. In every symbol for PSBCH, it carries DMRS in every 4th subcarrier starting from the first.

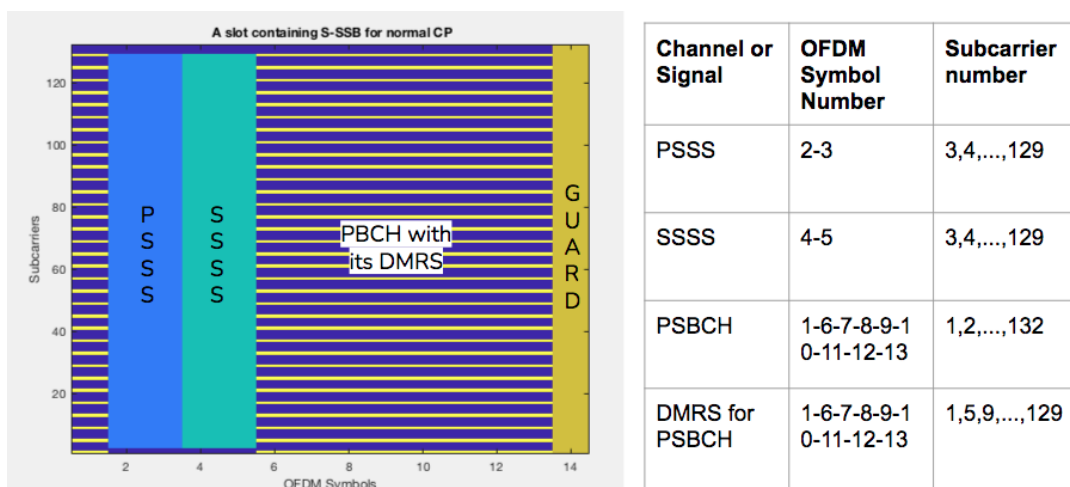


Figure 13. An example of NR sidelink synchronization block for normal CP.

The differences between Figure 10 and Figure 13 shows that the location of the SSSS and DMRS are changed.

2.3.2.2 Control, Shared and Feedback Channels with Resource Pools

In 5G NR sidelink, SCI is transmitted differently than the previous releases since in the new design, SCI is sent in 2 stages. The first part of the SCI is inside PSCCH with the information about resources for PSSCH and about decoding the second stage of SCI. The second part is in PSSCH with the remaining scheduling information for PSSCH [3]

The receiver UE can have the new channel, PSFCH, in groupcast and unicast [3]. This channel transmits 1 bit of feedback to the transmitter side in order to acknowledge that transmission is succeeded or not.

An illustration of a slot example for in time and frequency multiplexing between PSCCH, PSSCH and PSFCH can be seen in Figure 14.

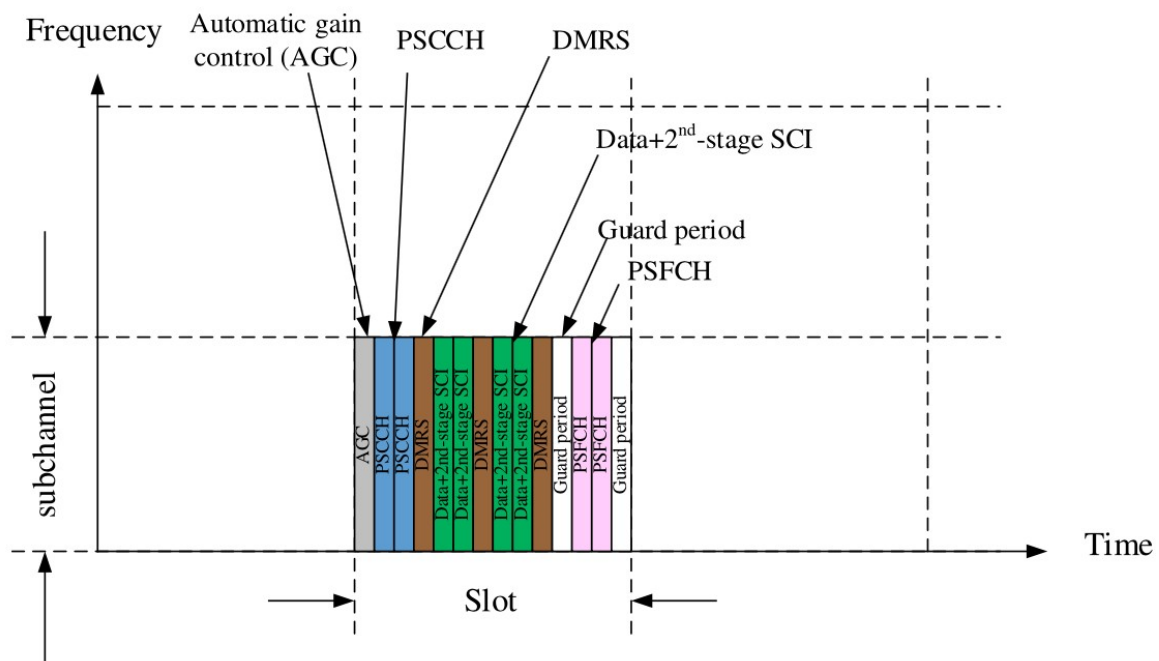


Figure 14. Multiplexing of PSCCH, PSSCH and PSFCH [3].

14 OFDM symbols constitute a symbol for the normal cyclic prefix (12 OFDM symbols for extended CP). Since the subcarrier spacing is not fixed in 5G, a slot can vary from 1 ms to 0.125 ms. When SCS is 15 kHz, a slot becomes 1 ms. Also, when SCS is 120

kHz, a slot is 0.125 ms. Furthermore, the automatic gain control (AGC) in Figure 14 is a duplicated symbol of the second symbol located in the first symbol of the slot [24] .

2.3.3 Synchronization Block Differences Between 5G NR and 5G NR Sidelink

This comparison is for understanding the differences in synchronization blocks to develop sidelink from 5G NR. The synchronization block has 4 symbols and 20 Resource Blocks (RB) in 5G NR while 5G NR sidelink has 14 symbols and 11 Resource Blocks [25] . 5G NR synchronization block can be seen in Figure 15.

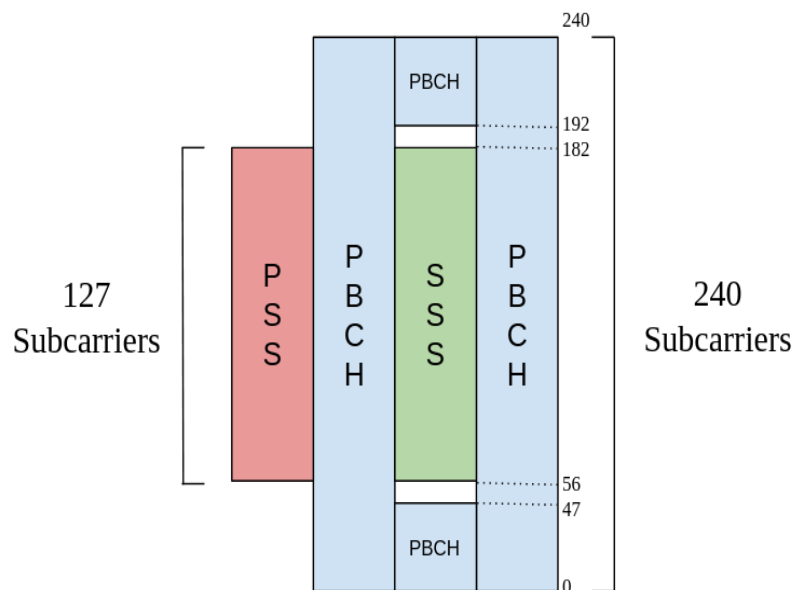


Figure 15. 5G NR Synchronization Block [26] .

The sequence generation for PSS and SSS is almost the same as PSSS and SSSS respectively. The only difference is in the sequence generation between PSS and PSSS which can be seen in clauses 7.4.2 and 8.4.2. in [25] respectively. Moreover, Physical Broadcast Channel (PBCH) includes its DMRS in every 4th subcarrier as in 5G NR sidelink.

2.4 Related Work Analysis

In this subchapter, the works related to this thesis are studied. In Table 2, the novel studies are shown with their focuses.

Since the main references are the 3GPP standards, they are separated from the table below. In order to find all of the 3GPP references check [27] , and also, all V2X related 3GPP standards can be accessed from [28] . Moreover, the standards that are used directly in this thesis are [8] , [9] , [13] , [20] , [22] , [25] , [34] , and [35] .

Table 2. List of the newest Sidelink communication-related works.

Reference	Focus
[3] (2020)	Essential knowledge of 3GPP 5G NR sidelink transmission regarding Release 16 and evaluation of the new design of SCI.
[24] (2021)	A detailed study on 3GPP Release 16 5G NR V2X and explanation for the concepts, the architecture, and all of the key aspects.
[29] (2020)	Analyzing V2X standards and optimizing 5G with V2X.
[30] (2020)	A paper of 3GPP Release 16 capabilities on NR V2X.
[31] (2020)	A new structure proposal for non-AGC symbol design for the physical channels in 5G NR V2X.
[32] (2020)	A thesis for analyzing the concepts for V2X Mode-4.

All of these references are good sources that support 3GPP standards. Since these standards could be hard to understand, these papers clear out the idea and make it easier to understand for the researchers.

In the following chapter, 5G performance is studied with MATLAB simulator to understand the improvements on 5G and also for 5G NR Sidelink.

3 5G New Radio Throughput Simulator

In this chapter, a simulation using MATLAB to test 5G throughput with power transmission, between a base station and user equipment is explained. First, a UE is located at a configurable distance from the base station with defined maximum transmission power of the base station. After the first distance is taken (starting from 1m), the simulator calculates signal to noise ratio (SNR). With the found SNR, the data rate or latency or packet error rate (PER) is calculated depending on the simulation type. Then, this process repeats while the distance is increasing until the decided distance (ending at 500 m). Moreover, this simulation is repeated for 5 different maximum power values to compare.

When the simulator got the SNR, it chooses a modulation coding scheme (MCS) which defines two aspects, modulation and code rate. Modulation is representing how many bits will be carried by a single resource element where QPSK, 16 QAM, 64 QAM, and 256 QAM modulation types are supported by 5G NR. On the other hand, code rate defines the ratio of useful bits over total transmitted bits [33] . 32 MCS indexes are supported by 5G NR when the last 3 indexes are reserved and used for re-transmission. As an example, the 256 QAM table can be seen in Figure 16 which can be used when the radio connection is very good. This figure shows the modulation order, the target code rate and the spectral efficiency for every MCS index.

The simulation is choosing one of these MCS indexes with respect to found SNR. If the SNR is high, which means signal quality is high, and power can afford a high coding rate. In this case, the MCS index will be chosen from one of the higher values since a high MCS index (until 27) means a high code rate. A higher code rate will result in a higher data rate, lower latency and lower PER.

MCS Index I_{MCS}	Modulation Order Q_m	Target code Rate $R \times [1024]$	Spectral efficiency
0	2	120	0.2344
1	2	193	0.3770
2	2	308	0.6016
3	2	449	0.8770
4	2	602	1.1758
5	4	378	1.4766
6	4	434	1.6953
7	4	490	1.9141
8	4	553	2.1602
9	4	616	2.4063
10	4	658	2.5703
11	6	466	2.7305
12	6	517	3.0293
13	6	567	3.3223
14	6	616	3.6094
15	6	666	3.9023
16	6	719	4.2129
17	6	772	4.5234
18	6	822	4.8164
19	6	873	5.1152
20	8	682.5	5.3320
21	8	711	5.5547
22	8	754	5.8906
23	8	797	6.2266
24	8	841	6.5703
25	8	885	6.9141
26	8	916.5	7.1602
27	8	948	7.4063
28	2	reserved	
29	4	reserved	
30	6	reserved	
31	8	reserved	

Figure 16. Modulation and Coding Scheme Table for 256 QAM [34].

The setup of the simulation and the results are presented in the following sub-chapters. Furthermore, the number of the chosen index during the simulation is provided at the end of the simulation results.

3.1 Simulation Setup

The simulation parameters are shown in Table 3.

Table 3. Simulation Parameter Setup

Simulation Parameter	Type/Value
Channel Model	CDL (Clustered Delay Line) and TDL (Tapped Delay Line) [35]

Simulation Parameter	Type/Value
Noise	AWGN (Additive White Gaussian Noise)
Scenario	Non-line-of-sight-propagation
Layout	Single Cell
Path Loss Exponent	2.75
Antenna Configuration	Single Antenna
Interference Type	No Inter-Cell Interference

3.2 Simulation Results

The simulation results are based on the data rate, transmitter power, latency, and PER.

3.2.1 Data Rate vs Distance

In Figure 17, the simulation result shows the curve of data rate vs distance when the maximum power of the signal that the base station transmits changes. The maximum power of the transmitted signal varies from 14 dBm to 44 dBm. When the power is high, SNR is high. Consequently, the MCS index chosen from the simulator is high which results in high useful bits (high data rate). As the power decreases, the data rate decreases with the change of MCS. On the other hand, when the distance between the base station and user equipment increases, the data rate decreases. In Figure 17, when the distance between the transmitter and the receiver is 500 meters, the data rate dropped almost 0 when the power is low (14 dBm), however, for high power, the data rate drops slightly from 21 Mbps to 18.5 Mbps.

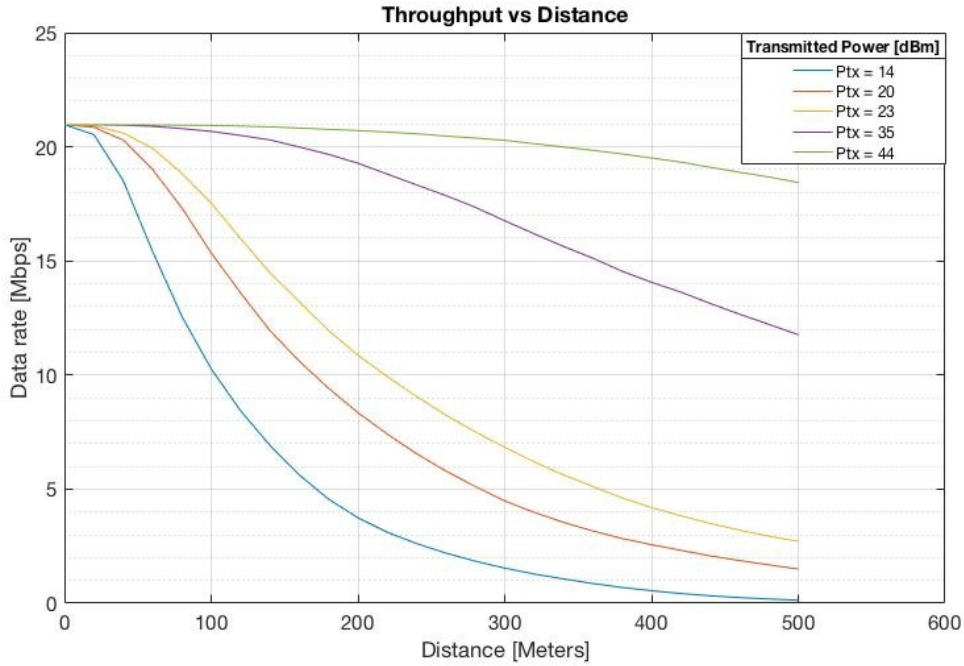


Figure 17. Data Rate vs Distance simulation results.

3.2.2 Latency vs Distance

In this part, latency comparison is made with different power levels of transmission and different packet sizes.

For the power level comparison, when power decreases, the data rate decreases as in the previous chapter. With low data rates, the data transmission takes a long time which results in higher latency as in Figure 18.

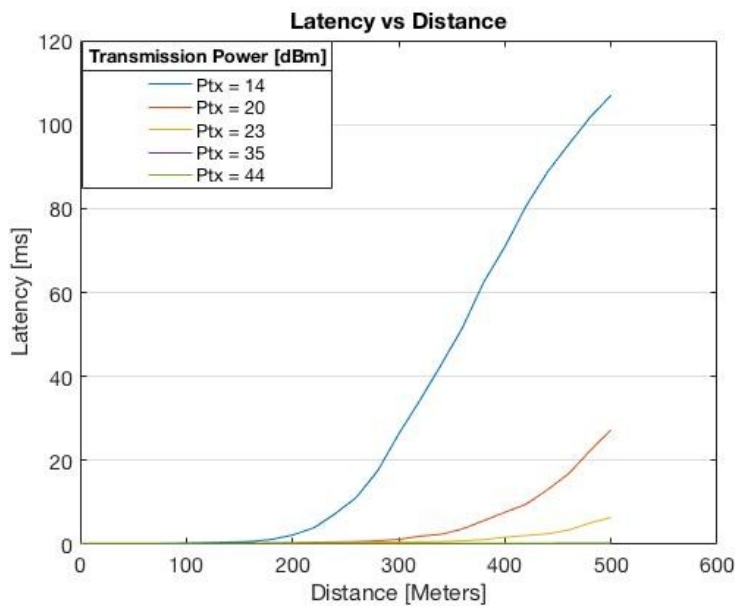


Figure 18. Latency vs Distance simulation results.

3.2.3 PER vs Distance

The packet error rate is the proportion of received packets with an error in percent for evaluating the performance of a receiver. In this part of the simulation, PER has been represented for different values of maximum transmission power. As in Figure 19, PER goes to 1 faster with increasing distance when the power is low. In other words, more maximum transmission power means less error rate in the received packets.

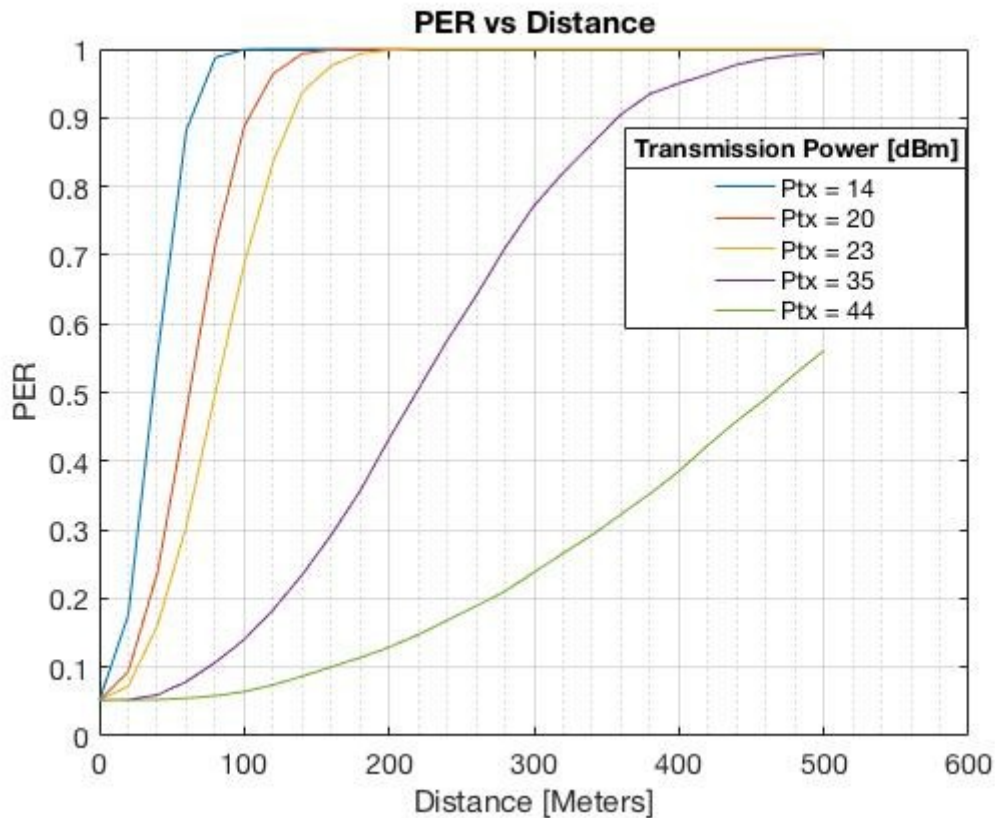


Figure 19. PER vs Distance simulation results.

3.2.4 Modulation and Coding Scheme Selection

In the simulation, 28 MCS indexes are used, and from Figure 20 and Figure 21, the density of usage per index can be seen in the MCS index histogram. When Figure 20 presents the histogram for 200 meters, Figure 21 shows the histogram for 500 meters.

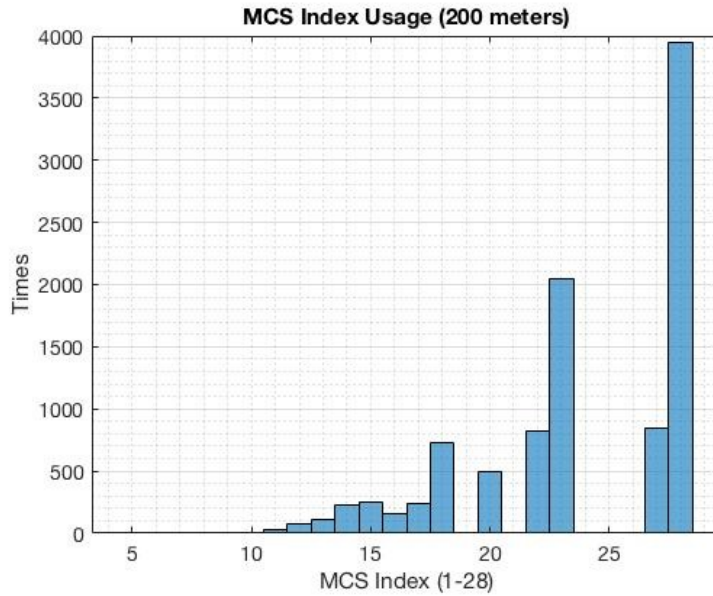


Figure 20. Histogram for MCS Index Usage for 200 meters.

Figure 20 shows that when the distance is relatively short, the simulator tends to choose higher MCS indexes, which results in a higher data rate.

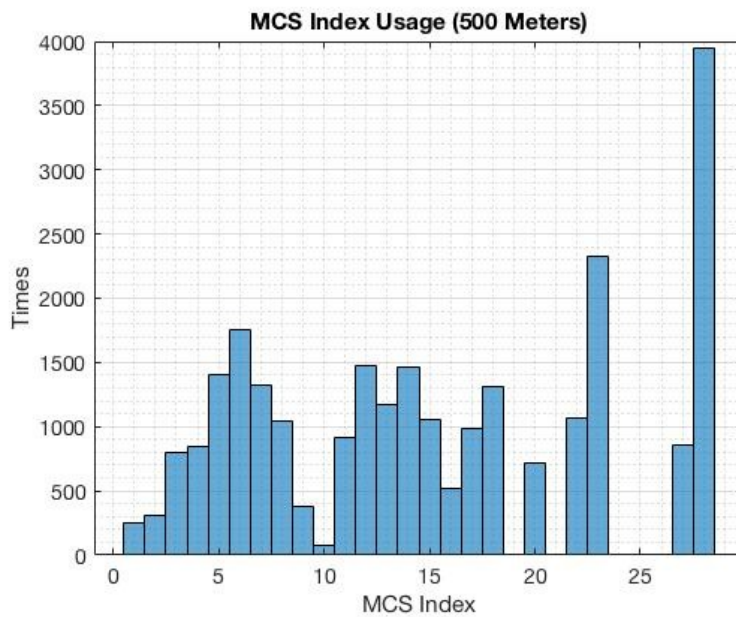


Figure 21. Histogram for MCS Index Usage for 500 meters.

On the other hand, Figure 21 supports the idea that when the distance is further than 200 meters, the simulator chooses lower MCS indexes in order to have safe transmission, results in lower data rate and higher latency.

4 5G New Radio Testbed

The main idea of the work is to develop an algorithm for the sidelink physical layer to be implemented in 5G New Radio. For this purpose, OpenAirInterface (OAI) has been chosen as a software tool to have a 5G Radio Access Network (RAN) as a first step which will be explained more in the following subchapter. The second step in the development is making sure of having a working PHY layer on 5G NR since the sidelink will be an attachment on that configuration. Therefore, a couple of tests and simulations have been done on the software to see whether OAI software is convenient to meet the requirements on developing the sidelink physical layer. When the 5G NR physical layer is working without any issues, which means sidelink can be developed on top of it.

In this chapter, the testing process of the software is explained thoroughly. First, there will be configuration details for the development setup of the system and the software related information. Then, the connection details between UE and the base station will be explained. Finally, the results that led to proceed with sidelink will be shown.

4.1 OpenAirInterface

OpenAirInterface is an open software to build wireless cellular Radio Access Network (RAN) and Core Network (CN) technologies [36] . 5G RAN is an ongoing project within the OAI which is aiming to have an end-to-end deployment of a 5G network [37] . To achieve that, the 5G protocol stack for UE has been built which is necessary to have sidelink communication in 5G. The main goal of the project is to provide all layers of the 5G RAN protocol stacks specified by 3GPP. Since OAI Project Group has already provided the PHY layer for the UE and gNB, it was a sufficient choice to work with OAI.

In this software, there are four main executables which are called “soft modems” representing UEs and base stations for both LTE and 5G NR. UE soft modems (lte-

uesoftmodem and nr-uesoftmodem) are coded so that they can establish a connection with the network as a smartphone does in everyday life. On the other hand, base station softmodems (lte-softmodem as eNB and nr-softmodem as gNB) are representing the base stations to supply RAN to its users. The features of these soft modems can be found in [38] and the information has been updating continuously with the project.

4.2 Development Setup

In this subchapter, the details of the setup for the testbed which are the requirements for the OAI 5G RAN setup, are explained.

To test the 5G NR connection between the base station and a UE which supports 5G, the soft modem that represents gNB (nr-softmodem) should be run on a communication platform (USRP Software Defined Radio Device [39]). On the other hand, to have a user connection on the network, another USRP is needed to run UE soft modem (nr-uesoftmodem) on it. In Figure 22, an example of a USRP board is shown.



Figure 22. An example of USRP B210 device

As a communication device, USRP B210 is used. This platform can support up to 30.72 MHz of bandwidth in a 2x2 MIMO configuration [40] . This amount of bandwidth is feasible for testing 5G NR Sidelink, however, for general 5G NR usage, the latest version of the USRP (N310) would be a better choice in sense of bandwidth (up to 100 MHz). USRP B210 device will behave as both user equipment and base station depending on the configuration.

To run the soft modems, Ubuntu 16.04 or 18.04 LTS is needed [41] . All of the source codes and header files are created using the C programming language. In Figure 23, the USRPs with mini computers can be seen.

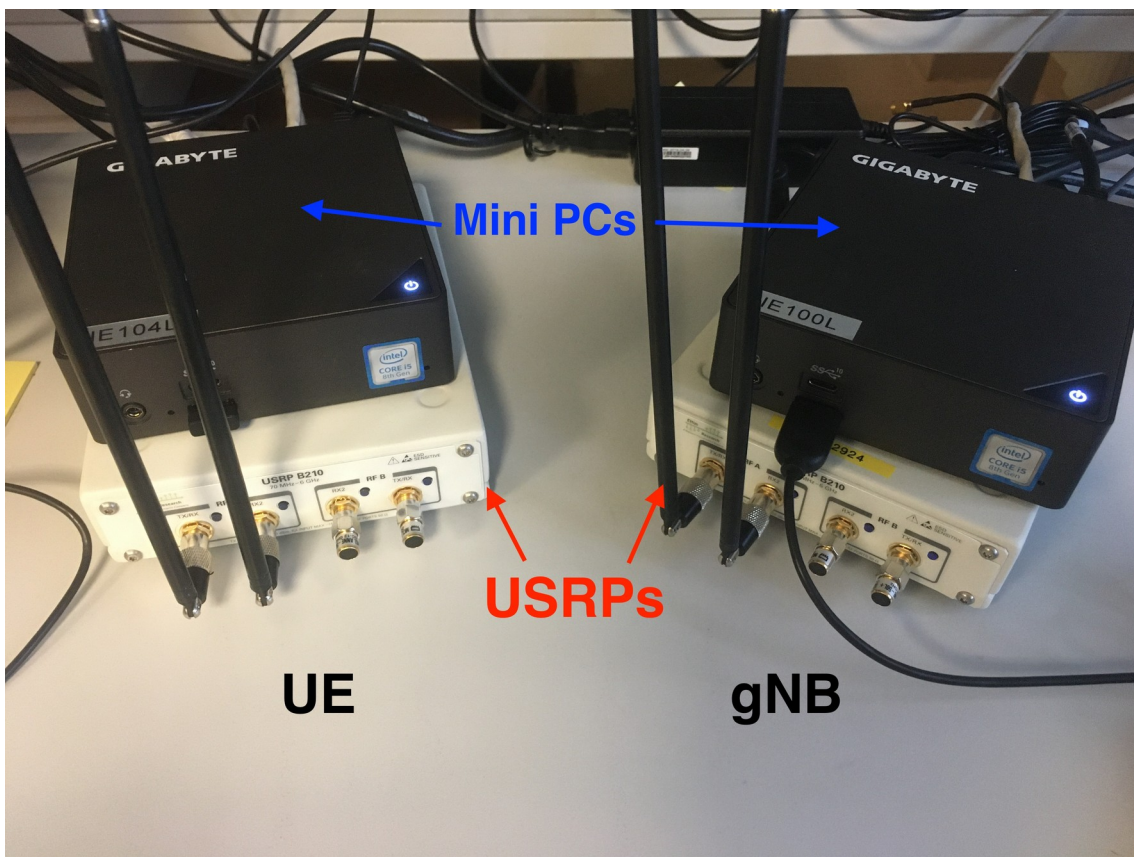


Figure 23. USRPs with mini PCs running OAI software (UE on the left side, gNB on the right side).

To set up the software, the documentation supported by OpenAirInterface has been followed and at the end of this setup, the four different soft modems are ready to use.

4.3 Physical Layer Test

In this section, the simulation and the tests for 5G NR are explained. The RF simulator part presents the computer simulation to test the physical layer for 5G NR. On the other hand, the Physical Test Setup part explains the details for real-time physical layer test for 5G NR with USRP devices.

4.3.1 RF Simulator

RF simulator is an OAI feature that helps to test the OAI without any RF board since it imitates one. This simulator creates a non-real-time simulation that allows us to use a network interface to connect UE and related base station, gNB. Moreover, we can check signal processing algorithms and protocol implementations with this tool. The aim of the simulation is to test the physical layer of 5G NR and its protocol.

To run the RF simulator, the configuration in [42] is applied. These configurations are making the executables ready for the physical layer simulation. After this point, with separate terminal windows in the same computer, the simulation can be run. To run the 5G NR PHY layer simulation, the following commands should be applied with the dedicated setup explained in clause 4.2. The commands that specify the necessary configurations for both gNB and UE are :

- For gNB: `$ sudo RFSIMULATOR=enb ./nr-softmodem -O ../../../../targets/PROJECTS/GENERIC-LTE-EPC/CONF/gnb.band78.tm1.106PRB.usrpn300.conf --parallel-config PARALLEL_SINGLE_THREAD --rfsim --noS1 --phy-tes`
- For UE: `$ sudo RFSIMULATOR=127.0.0.1 ./nr-uesoftmodem --rfsim --noS1 --nokrnmod 1 --phy-test`

Running the command for gNB in a terminal is checking the source codes of the physical layer for gNB and establishing a virtual network to be connected by a UE. When the system is ready to broadcast, it is searching for virtual UEs.

Running the UE scenario command on another terminal configures virtual user equipment which checks the physical layer codes as for gNB and tries to connect to a virtual base station. When the UE is ready to connect, it is searching for a base station.

to connect a UE with a base station and check their physical layer protocol such as synchronization, and uplink protocols.

This test is quite similar to the previous RF simulator but in real-time. One USRP with one computer has gNB with the nr-softmodem executable running and the other USRP with its computer has UE configurations with nr-uesoftmodem running.

To run UE in one USRP, the command applied to the terminal is “\$ sudo ./nr-uesoftmodem -E --phy-test”. This command will start the process of configuring the parameters for UE and will check the signals to synchronize the UE with a gNB.

When all the configurations for initializing the OAI platform and initializing the UE is done, the software will run the synchronization thread continuously. In this thread, UE is first looking for Primary Synchronization Signal’s (PSS) position. Then, it looks for Secondary Synchronization Signal (SSS) and finally Physical Broadcast Channel.

In Figure 26, the phase that UE is looking for synchronization can be seen. The green light represents that the device is in receiving mode.

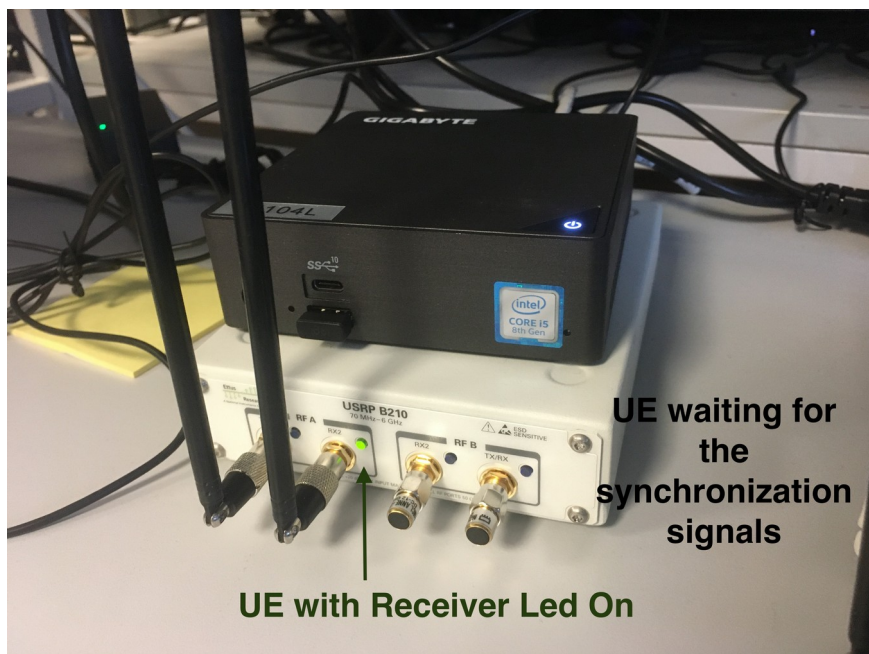


Figure 26. A UE looking for synchronization signals from the gNB.

An example of synchronization establishing moment can be seen in Figure 27. The screenshot of the terminal window shows that the software is looking for signals to

synchronize itself continuously, and when it is found, the synchronization process is handled. In the end, decoding MIB proves that the data sent from gNB is decoded in UE which shows that synchronization signals, broadcast channel, control channel and the shared channel is working.

```

dragon@dragon-GB-BR15-H-8250: ~/openairinterface5g/cmake_targets/ran_build/build
File Edit View Search Terminal Help
[PHY] [SCHED][UE] Check absolute frequency DL 3619080000.000000, UL 3619080000.000000 (RF ca
rd 0, oai_exit 0, channel 0, rx_num_channels 1)
[PHY] Starting sync detection
[PHY] [UE thread Synch] Running Initial Synch (mode 0)
[PHY] [UE] nr_synchro_time: Sync source = 0, Peak found at pos 26036, val = 3635314 (65 dB)
avg 61 dB, ffo 0.000000
PSS execution duration 450262 microseconds
[PHY] [UE0] Initial sync : Estimated PSS position -1, Nid2 0
[PHY] sync_pos -1 ssb_offset 460691
[PHY] TDD Normal prefix: SSS error condition: sync_pos -1
[PHY] [UE] nr_synchro_time: Sync source = 2, Peak found at pos 1809
avg 61 dB, ffo 0.000000
PSS execution duration 446802 microseconds
[PHY] [UE0] Initial sync : Estimated PSS position -1, Nid2 2
[PHY] sync_pos -1 ssb_offset 460691
[PHY] TDD Normal prefix: SSS error condition: sync_pos -1
[PHY] [UE0] Initial sync : Estimated power: 0 dB
[PHY] [SCHED][UE] Check absolute frequency DL 3619080000.000000, 3619080000.000000 (RF ca
rd 0, oai_exit 0, channel 0, rx_num_channels 1)
[PHY] Starting sync detection
[PHY] [UE thread Synch] Running Initial Synch (mode 0)
[PHY] [UE] nr_synchro_time: Sync source = 0, Peak found at pos 3016, val = 1037654900 (90
dB) avg 62 dB, ffo 0.000000
PSS execution duration 449659 microseconds
[PHY] [UE0] Initial sync : Estimated PSS position 304416, Nid2 0
[PHY] sync_pos 304416 ssb_offset 304308
[PHY] Calling sss detection (normal CP)
Nid2 0 Nid1 0 tot_metric 31344, phase_max 5
[PHY] [UE0] Initial sync: starting PBCH detection (rx_offset 0)
[MAC] [L2][MAC] decode mib
[PHY] [UE0] Initial sync: pbch decoded sucessfully
[PHY] TDD Normal prefix: CellId 0 metric 31344, phase 5, pbch 0
[PHY] [UE0] In synch, rx_offset 300996 samples
[PHY] [UE 0] RRC Measurements => rssi -inf dBm (dig -inf dB, gain 1
dBm/RE, rsrq -inf dB
[PHY] HW: Configuring channel 0 (rf_chain 0): setting tx_gain 20.
tx_freq 3619080000.000000 Hz, rx_freq 3619080000.000000 Hz
[PHY] HW: Configuring channel 1 (rf_chain 0): setting tx_gain 20.
tx_freq 0.000000 Hz, rx_freq 0.000000 Hz
[PHY] HW: Configuring channel 2 (rf_chain 0): setting tx_gain 20.
tx_freq 0.000000 Hz, rx_freq 0.000000 Hz
[PHY] HW: Configuring channel 3 (rf_chain 0): setting tx_gain 20.
tx_freq 0.000000 Hz, rx_freq 0.000000 Hz
[PHY] Got synch: hw_slot_offset 26, carrier off 0 Hz, rxgain 110.
0 Hz, UL 3619080000.000000 Hz)
Setting USRP TX Freq 3619080000.000000, RX Freq 3619080000.000000
[PHY] Resynchronizing RX by 300996 samples (mode = 0)
[MAC] [L2][MAC] decode mib
LLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLLL[MAC] [L2][MAC] decode mib
=====
[PHY] Harq round stats for Downlink: 1/2/0/0 DLSCH errors: 0
=====
[MAC] [L2][MAC] decode mib
[MAC] [L2][MAC] decode mib
[MAC] [L2][MAC] decode mib
[MAC] [L2][MAC] decode mib
[MAC] [L2][MAC] decode mib
[MAC] [L2][MAC] decode mib
[MAC] [L2][MAC] decode mib

```

UE synchronization thread is looking for synchronization signals

UE found the synchronization signals and synchronized with gNB

Decoding of MIB repeatedly

Figure 27. NR UE log file which shows the synchronizing moment.

Moreover, when another UE is added to the system with a new computer and a USRP while one UE is already synchronized and connected to the base station, the new UE can also be synchronized and connected to the same base station.

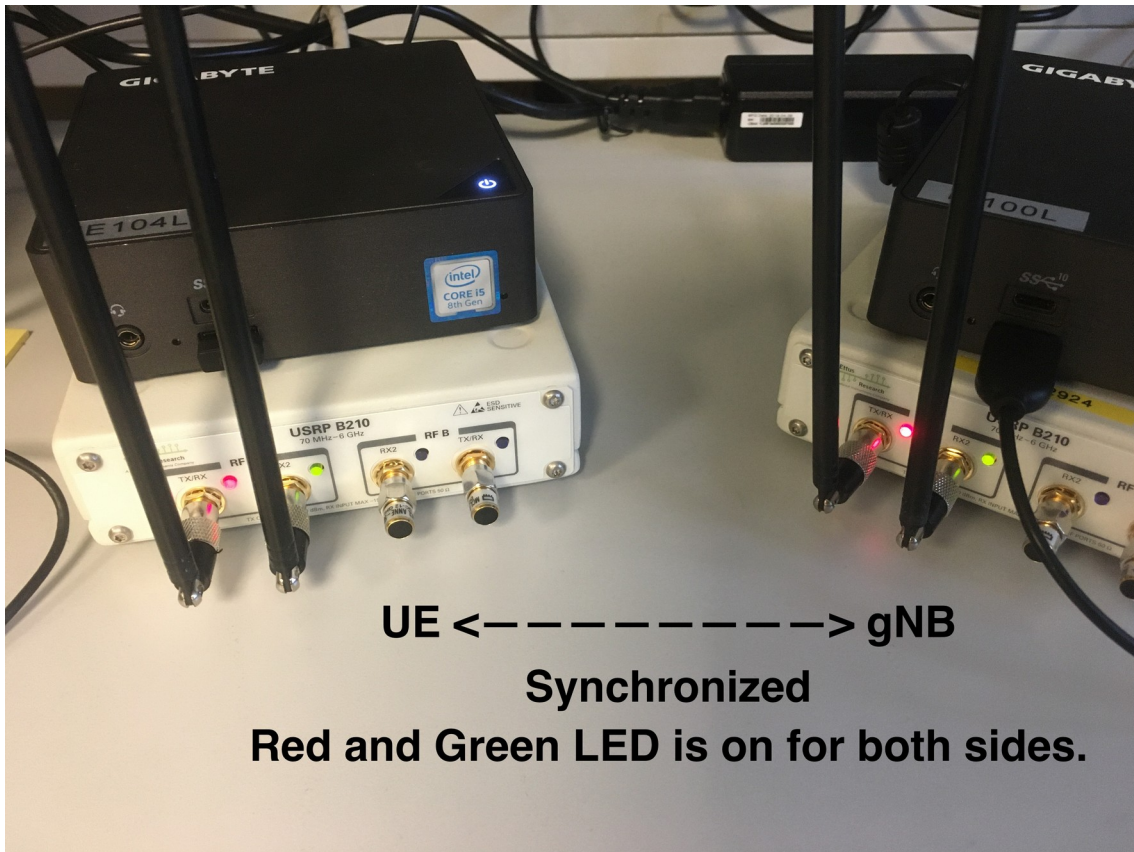


Figure 29. Physical layer connection between UE and gNB is established.

Physical layer test results are showing that the signals and the channels in the PHY layer for 5G NR are working properly. Since the signals and channels for sidelink are created by taking 5G NR codes as a reference and applying the sidelink standards on it, the 5G NR test is an important step.

These RF simulations and physical layer tests are sufficient enough to build up the sidelink feature on the existing UE software which is explained in the following chapter.

5 5G New Radio Sidelink Testbed

In this part of the thesis, the process of sidelink development is explained in detail. First, the main plan for the development of the sidelink physical layer with the working flow of OAI software is explained. Then, the development phase of the 5G NR Sidelink is explained with graphs for the embedded system. At the end of the chapter, the final status of the development process and possible future moves are studied.

5.1 Roadmap for Development

Since sidelink development on 5G NR is a very recent topic, there is no open-source real-time development, even there is no open-source simulation tool with 5G NR Sidelink with the latest release (Release 16) until this time. That is why, before starting the programming side of it, the OAI software should be examined in a way that developing sidelink on it can be possible.

OAI is supporting LTE, LTE-Sidelink and 5G NR soft modem development codes in which all have PHY layer development. To create a 5G sidelink soft modem from these codes, the differences between LTE and LTE-Sidelink, 5G NR and LTE were checked. Moreover, the way that OAI creates executables such as soft modems should have been understood to implement 5G Sidelink in the same way that OAI implements for the 5G NR or LTE. In the following subchapter, details about the investigation of OAI 5G NR codes and LTE-Sidelink codes are explained.

After having an overall understanding of the concept, the development has started. During the development, LTE-Sidelink codes are the main reference although the development is going on top of 5G NR codes. In other words, for the main function that combines all the initializing process of the OAI, the sidelink communication, and threads that control the transmitting and receiving signals, LTE-Sidelink code is the main reference. On the other hand, for generating signals and channels such as PSSS, SSSS, PSBCH, etc., the 5G NR code is leading the development.

Besides these, the main idea is developing the 5G Sidelink step by step since it can be very complicated if the task is tried to be handled at once. Therefore, the first focus is having 2 UEs synchronized without the help of the base station (out of coverage scenario). Under the synchronization, the task was mainly creating Synchronization Signals Block (SSB) which includes PSSS, SSSS and PSBCH with its DMRS and running these source code files inside the main function that initializes the OAI and running the threads that allow communication. In subchapter 4.3, the development of these steps is explained.

5.2 Embedded Flow in OAI for UE SoftModem

The embedded system of the OAI soft modems is ramified, therefore; an additional tool is used to understand which of the files are included under the main function, and which files are called by the main function. This tool is called Doxygen which helps developers who try to use someone else's code and make changes to it. An example of a graph diagram that Doxygen provides for the main function of `nr-uesoftmodem` can be seen in Figure 30.

5.2.1 Overall Explanation of the Flow Chart

This part of the thesis is giving an overview of how the setup is handled by the OAI soft modem. It can be beneficial for the new users of OAI to understand the coding structure. This part is studying the main function of the source files for the UE soft modem in OAI software.

First of all, the necessary functions are called by the main function to initialize the OAI system and getting options from the user to specify which kind of scenario is going to be handled. For example, starting the background system, initializing logging, getting command-line options from the user, setting the CPU frequency, initializing the user equipment, and initializing the transmitting and receiving parameters for transmission are some of the tasks that the main function handles at the beginning of the executable. The functions that handle the tasks above in the `nr-uesoftmodem` executable before initializing the UE variables can be seen on the top side of Figure 30.

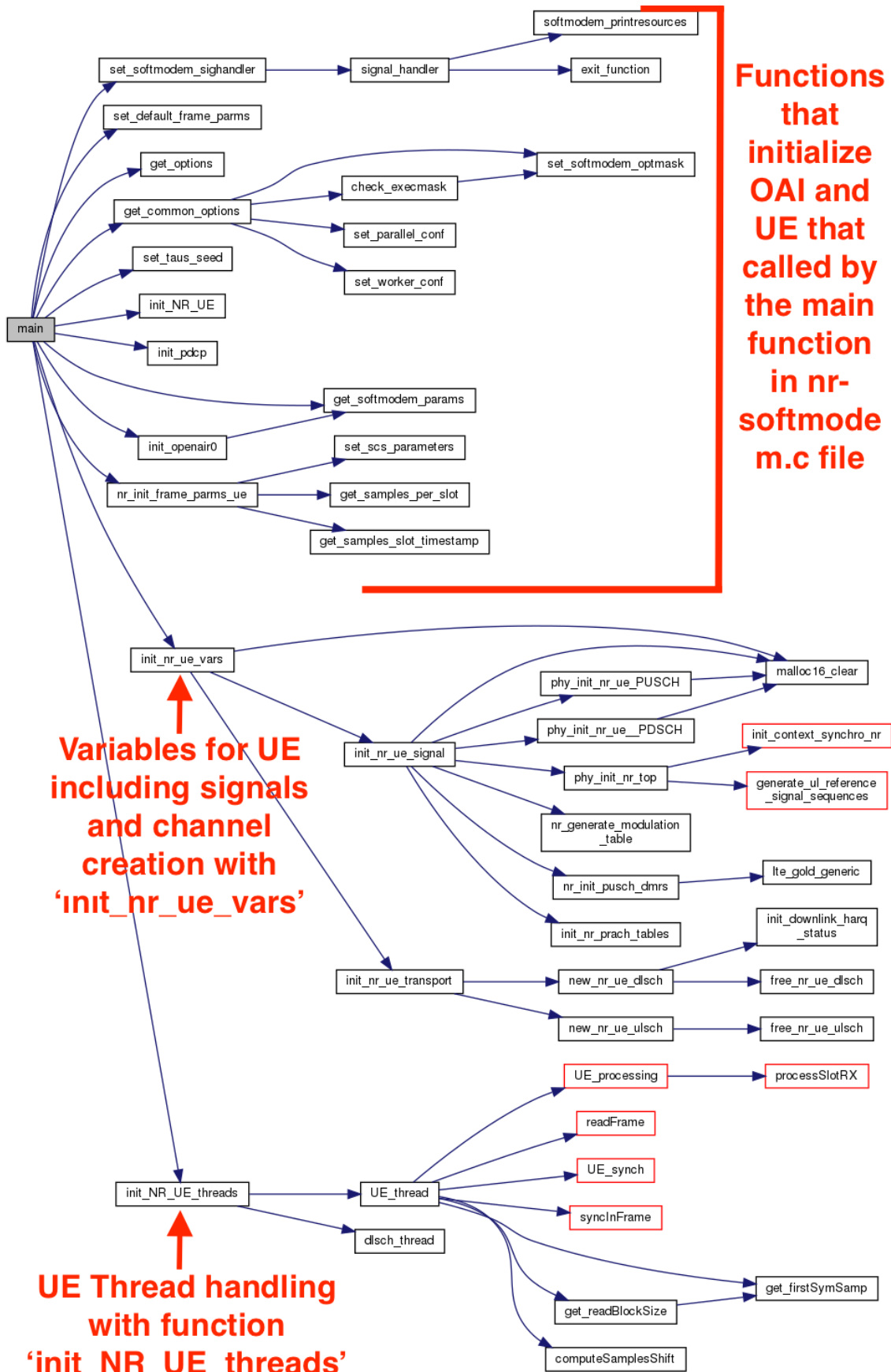


Figure 30. Functions that are called by the main function in nr-softmodem.c file

When the configurations are done, OAI starts the operations for the desired scenario. For example, if the user wants to have sidelink communication without the assistance of the base station, some functions are being called in the main function, which are initializing UE frame parameters and variables. Figure 31 shows the functions under initializing the variables. These variables are separated into two categories which are signal and transport. The signal part is responsible for generating sequences for the signals which includes configuration of DMRS and generation of PSS and SSS. The generation of these signals, their allocations on the resource grid, etc. are based on the 3GPP standardizations. On the other side of the initializing variables, the transport part handles the decoding shared channels for uplink and downlink.

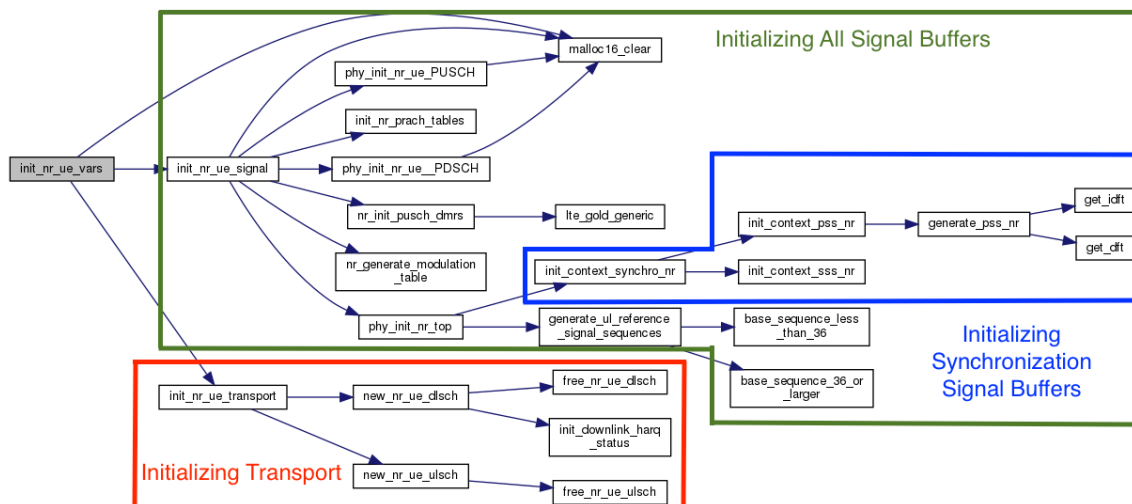


Figure 31. Function tree for initializing UE variables

As a final part of the executable, the main function activates threads which are UE thread and DLSCCH thread. UE thread is responsible mainly for UE processing and UE synchronization.

UE processing part of the thread includes physical layer procedures for transmitter and receiver which contain procedures of the control channel and shared channel for uplink and downlink, physical broadcast channel, transmission related measurement functions, and slot selection, etc.

On the synchronization side of the UE, functions for generation and detection of synchronization signals, detection of PBCH, channel estimation, etc. are running continuously under this thread until the UE finds a connection with a synchronization

These threads are running the executables in real-time while establishing communication with RF boards such as USRP.

Although the function flow is based on nr-uesoftmodem, in the other soft modems such as lte-uesoftmodem, the structure of the executable is mostly the same with different ordering in the function flow.

Moreover, in the case of sidelink transmission, the UE soft modem has extra threads for synchronization and the sidelink process which are independent of the UE thread that handles Uu-link communication.

5.3 Software Development

In this part of the thesis, the progress of the development for synchronization is studied. The overall structure of the development plan can be seen in Figure 33.

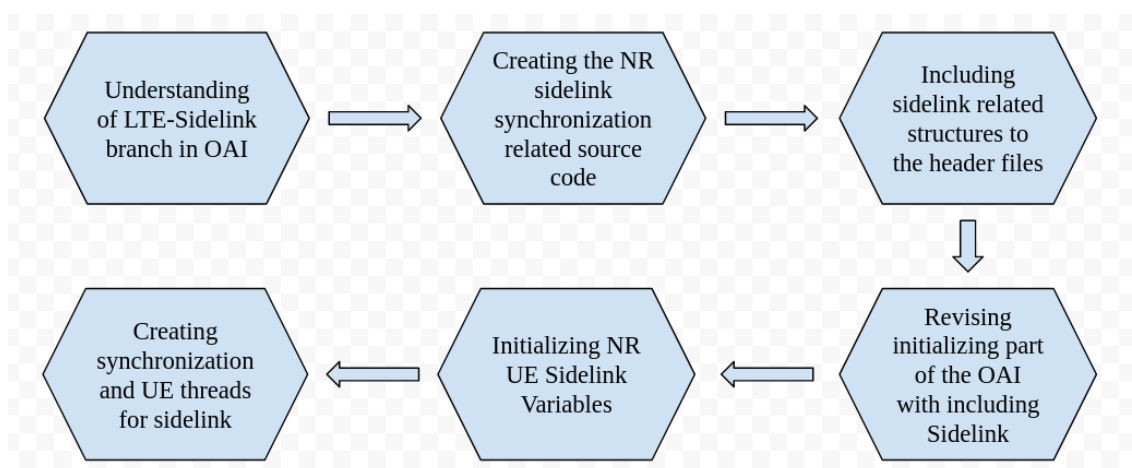


Figure 33. Road map of the development for 5G NR Sidelink.

The development is based on nr-uesoftmodem, however, D2D communication in LTE is the main reference to build up the sidelink on 5G NR since LTE-sidelink codes under lte-uesoftmodem are reliable. This is why understanding the LTE-sidelink branch is very important.

As a second step, creating the source files for synchronization such as PSSS and SSSS generation, SSB (Synchronization Signals Block) and PSBCH creation and parameters, etc. This step is basically applying the 3GPP standards to the code. For this process, the source files supported by OAI for 5G NR development are used. Since the differences

for PSS and SSS between 5G NR and 5G NR Sidelink are very few as mentioned in this thesis at clause 2.3.3, editing the source code for PSSS and SSSS is not that challenging. On the other hand, SSB block is quite different in 5G NR Sidelink than 5G NR referring to the same clause. These source files needed to be created in the beginning since, over the development, these files are going to be used inside the initializing functions and threads. Also, the creation of the source code for the synchronization signals is independent of the OAI soft modem structure.

The next step of the development is defining all the structures, pointers, integers used inside the sidelink communication. To achieve this task, LTE-sidelink code is debugged line by line to find pointers, flags, structures, etc. Most of them are defined under the definitions file (`defs_ue.h`), therefore, finding sidelink related definitions in this header file and adding them in the 5G NR definitions file (`defs_nr_ue.h`) would clear up the task.

After adding these definitions, the main function (inside `nr-uesoftmodem.c` file) enhancement can be started with some changes for initializing the OAI. Some of the changes are including more command-line options from the user to understand if the user wants the device as a synchronization reference or a relay UE, adding additional flags to control future functions conditions, etc. Until this part, the functions that the main function calls at the top side of Figure 30 remain almost the same with some small changes inside the code.

Since the source files for PSSS, SSSS and PSBCH are already updated for sidelink, initializing 5G NR UE variables can be the next step to proceed. Figure 34 is the updated version of Figure 31. In the following figure, the new functions that initialize UE signal calls are added to handle which have extra SL (Sidelink) at the end of the function names.

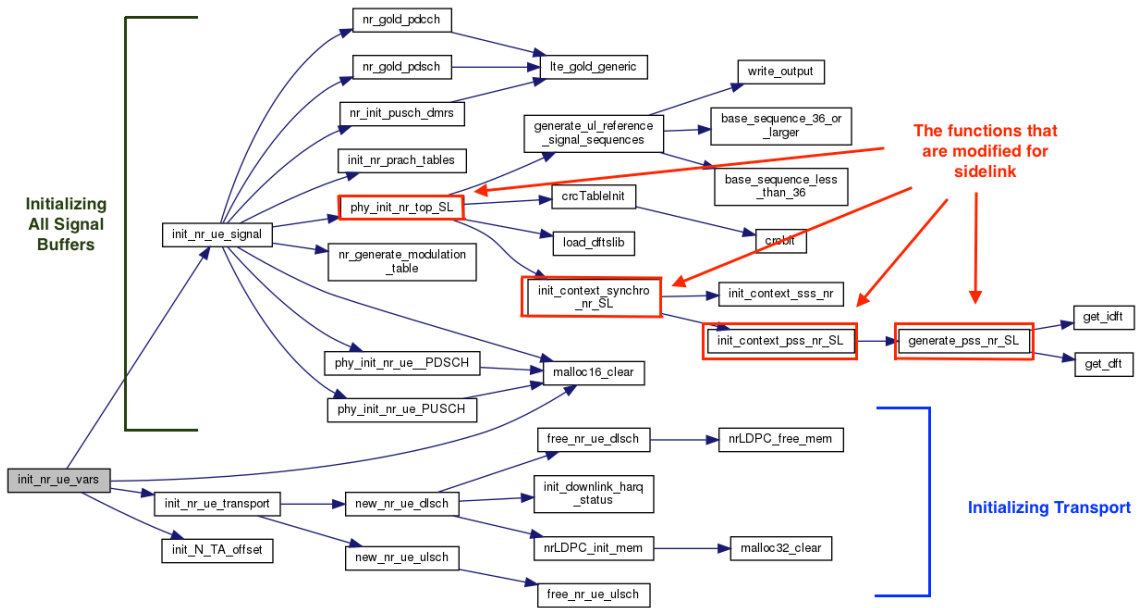


Figure 34. Function tree for initializing UE variables for NR Sidelink

As a final step of developing synchronization, the threads which control the synchronization process in real-time should be handled. LTE-sidelink threads are taken as a reference for handling synchronization and added to 5G NR code with changing inside variables as they match up with 5G NR variables. The tree for the main function that calls for all the threads can be seen in Figure 35.

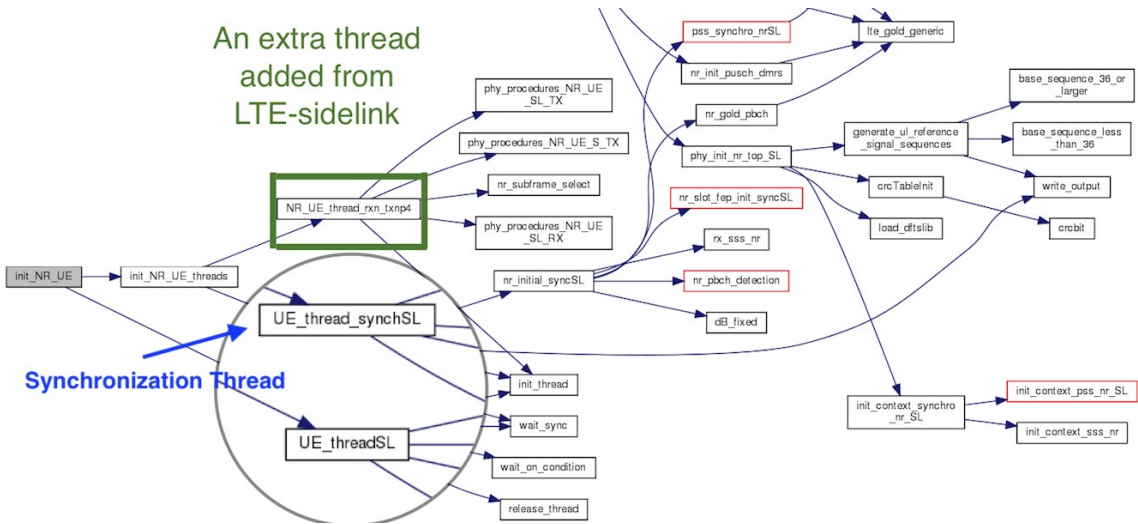


Figure 35. UE initializing flow including 3 main threads that responsible for the synchronization. These threads start running when the main function completes all of its functions. They are controlling the flags to understand the state of the synchronization.

5.4 Current Situation and Possible Plans for the Development

At the end of the development, when the executable is running, the log file gives the same outputs as the working LTE-sidelink until the threads are called. When the threads start, the executable exits since both threads are trying to use the receiver at the same time. In order to solve this issue, debugging is necessary, however, multi-thread debugging can take so much time. If the sidelink synchronization is established with solving thread issues, other channels such as PSCCH and PSSCH will be added.

Besides that, the development process on OAI takes lots of time without any guidance. Since OAI software is very deep in terms of codes and architecture, it takes lots of time to understand the working principles of the functions. That is why the development of a non-existing feature on OAI might result unfinished as in my case. On the other hand, the usage of OAI in the application layer is simple in comparison to development since the tutorials that OAI supports on the web [41] is decent to complete a study.

6 Conclusion and Future Work

Sidelink communication has become a very important aspect with rapid growth in technology. It promises a huge potential on becoming autonomous in vehicular area. Moreover, V2X will provide safer and controllable transportation systems with fewer power consumptions. This study presented physical layer evaluation, development process on 5G NR Sidelink testbed, and throughput evaluation on 5G.

In Chapter 2, the sidelink standardization for physical layer enhancements from D2D through 5G Sidelink is presented. This chapter provides the necessary enhancements and differences in resource allocation in the physical layer. It is aimed to explain the overall release features and differences for the ones who are working on the physical layer protocol. Furthermore, already existing research papers and topic related standards are presented at the end of the chapter.

In Chapter 3, a simulator that evaluates the indicators which are data rate, latency and PER performances in 5G is studied. This study explains the use of MCS indexes in the simulator and the maximum transmission power effects on these indicators.

In the following chapters, in Chapter 4 and 5, a testbed development is presented. In Chapter 4, the testbed related information such as hardware, software, how to set up the testbed, etc. is explained. This chapter also includes the physical layer test for 5G in real-time and also in simulation. On the other hand, in Chapter 5, the development process for 5G Sidelink synchronization is explained. The roadmap for the process, the embedded system in OAI and development phases are explained in this chapter.

Although there is no solid result from the development, this thesis provides necessary developing information including sidelink standard explanation. Moreover, an overall explanation for OAI and its working principle is tried to be explained.

As a future work:

- Detailed study on OAI threads to understand where the problem occurs,
- Using MATLAB to develop 5G NR Sidelink,
- Another commercial software usage to evaluate on 5G NR Sidelink performance

are the possible choices to continue to work on.

References

- [1] F. Eckermann, M. Kahlert and C. Wietfeld, "Performance Analysis of C-V2X Mode 4 Communication Introducing an Open-Source C-V2X Simulator," 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019, pp. 1-5, doi: 10.1109/VTCFall.2019.8891534.
- [2] Kenney, J.B.. "Dedicated Short-Range Communications (DSRC) Standards in the United States." Proceedings of the IEEE 99 , no. 7 (2011): 1162 -1182.
- [3] S. Lien et al., "3GPP NR Sidelink Transmissions Toward 5G V2X," in IEEE Access, vol. 8, pp. 35368-35382, 2020, doi: 10.1109/ACCESS.2020.2973706.
- [4] Rohde & Schwarz, Device to Device Communication in LTE Whitepaper. [Online]. Available: https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_application/application_notes/1ma264/1MA264_0e_D2DComm.pdf. [Accessed 8 May 2021]
- [5] Nait Hamoud, Othmane & Kenaza, Tayeb & Challal, Yacine. (2018). Towards using multiple KGC for CL-PKC to secure D2D communications. 283-287. 10.1109/SaCoNeT.2018.8585671.
- [6] Höyhtyä, Marko & Apilo, Olli & Lasanen, Mika. (2018). Review of Latest Advances in 3GPP Standardization: D2D Communication in 5G Systems and Its Energy Consumption Models. Future Internet. 10. 10.3390/fi10010003.
- [7] Khandker S, Torres-Sospedra J, Ristaniemi T. Improving RF Fingerprinting Methods by Means of D2D Communication Protocol. Electronics. 2019; 8(1):97 [Online]. Available: <https://doi.org/10.3390/electronics8010097> [Accessed 8 May 2021]
- [8] 3GPP TS 23.303 V12.5.0, June 2015; Technical Specification Group Services and System Aspects; Proximity-based services
- [9] 3GPP TS 36.300 V12.6.0, June 2015; Technical Specification Group Radio AccessNetwork; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description
- [10] Techplayon, "PSS and SSS (LTE Synchronization)," [Online]. Available: <http://www.techplayon.com/pss-and-sss-lte-synchronization/>. [Accessed 8 May 2021]
- [11] MathWorks, "Synchronization Signals (PSS and SSS)," [Online]. Available: <https://www.mathworks.com/help/lte/ug/synchronization-signals-pss-and-sss.html>. [Accessed 8 May 2021]
- [12] Jung Y-A, Song H-K, You Y-H. Improved Joint Estimation of Set Information and Frequency Offset for LTE Device-to-Device Communications. Applied Sciences. 2020; 10(1):77. [Online]. Available: <https://doi.org/10.3390/app10010077>. [Accessed 8 May 2021]

- [13] 3GPP TS 36.331 V12.6.0, June 2015; Technical Specification Group RadioAccess Network; Evolved Universal Terrestrial Radio Access (E-UTRA); RadioResource Control (RRC)
- [14] MathWorks, 2021. [Online]. Available: https://www.mathworks.com/content/dam/mathworks/tag-team/Objects/d/90538_95058v00_LTE_Application_Note.pdf. [Accessed: 08- May- 2021].
- [15] MathWorks, "LTE Sidelink Resource Pools and PSCCH Period- MATLAB & Simulink", 2021. [Online]. Available: <https://www.mathworks.com/help/lte/ug/lte-sidelink-resource-pools-and-pscch-period.html#d123e15783> [Accessed: 08- May- 2021].
- [16] Noura, Hassan & Znaidi, Wassim. (2015). Security of Cooperative Intelligent Transport Systems: Standards, Threats Analysis and Cryptographic Countermeasures. Electronics. 4. 10.3390/electronics4030380.
- [17] Shashank Kumar Gupta, Jamil Yusuf Khan and Duy Trong Ngo (May 26th 2020). An LTE-Direct-Based Communication System for Safety Services in Vehicular Networks [Online First], IntechOpen, DOI: 10.5772/intechopen.91948. Available from: <https://www.intechopen.com/online-first/an-lte-direct-based-communication-system-for-safety-services-in-vehicular-networks>
- [18] MathWorks, "Release 14 V2X Sidelink PSCCH and PSSCH Throughput- MATLAB & Simulink", 2021. [Online]. Available: <https://www.mathworks.com/help/lte/ug/release-14-v2x-sidelink-psscch-throughput.html>. [Accessed: 08- May- 2021].
- [19] W. Anwar, N. Franchi and G. Fettweis, "Physical Layer Evaluation of V2X Communications Technologies: 5G NR-V2X, LTE-V2X, IEEE 802.11bd, and IEEE 802.11p," 2019 IEEE 90th Vehicular Technology Conference (VTC2019-Fall), 2019, pp. 1-7, doi: 10.1109/VTCFall.2019.8891313.
- [20] 3GPP, "TR37.985 Overall description of Radio Access Network (RAN) aspects for Vehicle-to-everything (V2X) based on LTE and NR (v16.0.0, Release 16)," 3GPP, Tech. Rep., Sept. 2020.
- [21] Nestor Bonjorn, Fotis Foukalas, Paul Pop. Enhanced 5G V2X Services using Sidelink Device-to-Device Communications. 17th Annual Mediterranean Ad Hoc Networking Workshop (Med-Hoc-Net 2018), Jun 2018, Capri Island, Italy. pp.116-122. (hal-01832538)
- [22] 3GPP. Enhancement of 3GPP Support for V2X Scenarios; Version 16.2.0; Technical Specification (TS) 22.186; 3rd Generation Partnership Project (3GPP), Valbonne, France, 2019
- [23] K. Ganesan, P. B. Mallick, J. Löhr, D. Karampatsis and A. Kunz, "5G V2X Architecture and Radio Aspects," 2019 IEEE Conference on Standards for Communications and Networking (CSCN), 2019, pp. 1-6, doi: 10.1109/CSCN.2019.8931319.
- [24] M. H. C. Garcia et al., "A Tutorial on 5G NR V2X Communications," in IEEE Communications Surveys & Tutorials, doi: 10.1109/COMST.2021.3057017.
- [25] 3GPP, "TS 38.211 NR; Physical channels and modulation (v16.0.0, Release 16)," 3GPP, Tech. Spec., March 2020.

- [26] "5G NR: Synchronization Signal/PBCH block (SSB)", Howltestuffworks.blogspot.com, 2021. [Online]. Available: <http://howltestuffworks.blogspot.com/2019/10/5g-nr-synchronization-signalpbch-block.html>. [Accessed: 08- May- 2021].
- [27] "3GPP", 3gpp.org, 2021. [Online]. Available: <https://www.3gpp.org/>. [Accessed: 08- May- 2021].
- [28] Z. Ghadialy, "3GPP Technical Specifications (TS) and Reports (TR) related to V2X", 3g4g.co.uk, 2021. [Online]. Available: https://www.3g4g.co.uk/V2X/v2x_0001_specifications.html. [Accessed: 08- May- 2021].
- [29] Abdel Hakeem, S.A., Hady, A.A. & Kim, H. 5G-V2X: standardization, architecture, use cases, network-slicing, and edge-computing. *Wireless Netw* 26, 6015–6041 (2020). [Online]. Available: <https://doi.org/10.1007/s11276-020-02419-8>. [Accessed: 08- May- 2021].
- [30] S. A. Ashraf, R. Blasco, H. Do, G. Fodor, C. Zhang and W. Sun, "Supporting Vehicle-to-Everything Services by 5G New Radio Release-16 Systems," in *IEEE Communications Standards Magazine*, vol. 4, no. 1, pp. 26-32, March 2020, doi: 10.1109/MCOMSTD.001.1900047.
- [31] S. Zheng, R. Zhao, L. Zhao, X. Ren, J. Hu and Y. Shi, "A Sequence-based Automatic Gain Control mechanism for the Physical Channels in NR-V2X," 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), 2020, pp. 1-5, doi: 10.1109/VTC2020-Spring48590.2020.9129025.
- [32] D. Leon Gonzalez, "Performance Analysis of the Cellular-V2X Mode 4", 2020. [Online]. Available: <http://hdl.handle.net/2117/328222>. [Accessed: 08- May- 2021].
- [33] "Understanding modulation and coding schemes", *Control Engineering*, 2021. [Online]. Available: <https://www.controleng.com/articles/understanding-modulation-and-coding-schemes/>. [Accessed: 08- May- 2021].
- [34] 3GPP, "TS 38.214 NR; Physical layer procedure for data (v16.3.0, Release 16)," 3GPP, Tech. Spec., September 2020
- [35] 3GPP, "TR 38.901 "Study on channel model for frequencies from 0.5 to 100 GHz (v16.1.0, Release 16)," 3GPP, Tech. Rep., Dec. 2019.
- [36] "OpenAirInterface – 5G software alliance for democratising wireless innovation", [Openairinterface.org](https://openairinterface.org), 2021. [Online]. Available: <https://openairinterface.org/>. [Accessed: 08- May- 2021].
- [37] "5G RAN – OpenAirInterface", [Openairinterface.org](https://openairinterface.org), 2021. [Online]. Available: <https://openairinterface.org/oai-5g-ran-project/>. [Accessed: 08- May- 2021].
- [38] "OAI Feature Set", [GitLab](https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/develop/doc/FEATURE_SET.md), 2021. [Online]. Available: https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/develop/doc/FEATURE_SET.md. [Accessed: 08- May- 2021].
- [39] "What is USRP | IGI Global", [Igi-global.com](https://www.igi-global.com/dictionary/usrp/70378), 2021. [Online]. Available: <https://www.igi-global.com/dictionary/usrp/70378>. [Accessed: 08- May- 2021].
- [40] Ettus, 2021. [Online]. Available: https://www.ettus.com/wp-content/uploads/2019/01/b200-b210_spec_sheet.pdf. [Accessed: 08- May- 2021].

- [41] "5g Nr Development and Setup · Wiki · oai / openairinterface5G", GitLab, 2021. [Online]. Available: <https://gitlab.eurecom.fr/oai/openairinterface5g/-/wikis/5g-nr-development-and-setup>. [Accessed: 08- May- 2021].
- [42] OpenAirInterFace, GitLab, 2021. [Online]. Available: <https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/develop/targets/ARCH/rfsimulator/README.md>. [Accessed: 08- May- 2021].

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