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5G-NR POSITIONING REFERENCE SIGNAL REALIZATION IN 5G OPEN AIR INTERFACE PLATFORM

Master Thesis
192570 IVEM

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PhD

Tallinn 2021

TALLINNA TEHNIKAÜLIKOOL
Infotehnoloogia teaduskond

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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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01.02.2021

Abstract

The aim of this master's thesis is to create a test station based on 5G-NR technology, which generates a positioning reference signal in accordance with 3GPP (Third Generation Partnership Project) standards and transmit the signal to the radio ether. In this project is used the open source 5G-NR development platform - Open Air Interface (OAI). Which is created by the Open-Air Interface Software Alliance group.

The work provides an overview of the history and development of positioning systems based on radio signals. Innovative use cases that require 5G-NR support for positioning are also listed. The work introduces 3GPP standards related to positioning. The positioning principles used in the 5G-NR radio network are described and their use cases are explained. The paper provides a comprehensive overview of 5G-NR positioning reference signal generation and its integration with the OAI platform.

The result of this job creates a possibility to transmit real PRS signals in a 5G Stand-Alone (SA) network.

This thesis is written in English and contains 92 pages of text, 7 chapters, 56 figures and 11 tables.

Annotatsioon

5G-NR Positsioneerimise tugisignaali realiseerimine 5G Open Air Interface platvormil

Käesoleva magistritöö eesmärk on luua 5G-NR tehnoloogial põhinev testjaam, millega genereeritakse 3GPP (*Kolmanda põlvkonna partnerlusprojekt*) standarditele vastav positsioneerimise tugisignaal ja saadetakse raadioeetrisse. Töös kasutatakse *Open Air Interface Software Alliance* grupi poolt loodud 5G-NR platvormi *Open Air Interface* (OAI – vabaõhuliides). OAI näol on tegemist on vabavara platvormiga mis töötab operatsioonisüsteem Linux keskkonnas.

Töös antakse ülevaade raadiosignaalidel põhinevatel positsioneerimissüsteemide ajaloost ja arengust. Samuti on loetletud innovaatilisi kasutusjuhtumeid, mis vajavad positsioneerimiseks 5G-NR tuge. Tutvustatakse positsioneerimisega seotud 3GPP standardeid. Kirjeldatakse 5G-NR raadiovõrgus kasutatud positsioneerimise põhimõtteid ning selgitatakse nende kasutusjuhtumeid. Töös antakse põhjalik ülevaade 5G-NR positsioneerimise tugisignaali genereerimisest ja selle integreerimisest OAI platvormiga.

Lõputöö on kirjutatud ingliese keeles ning sisaldab teksti 92 leheküljel, 7 peatükki, 56 joonist, 11 tabelit.

List of abbreviations and terms

3GPP	Third Generation Partnership Project
5G	Fifth Generation of Mobile Communication Systems
5GPP	Fifth Generation Partnership Project
AMF	Access and Mobility Management
ARNS	Aviation Radio Navigation Service
BPSK	Binary Phase Shift Keying
CBC	Cloud Based Core
CP	Cyclic Prefix
D2D	Device to Device communication
DFT	Discrete Fourier Transform
EUTRAN	Evolved Universal Terrestrial Radio Access Network
eNB	EUTRAN Node B
FDD	Frequency Division Duplexing
GI	Guard Interval
gNB	New Radio Node B
IIoT	Industrial Internet of Things
IMT	International Mobile Telecommunications
IoT	Internet of Things
ISI	Inter Symbol Interference
GNSS	Global Navigation Satellite System
GPSDO	GPS Disciplined Oscillator
LMF	Location Management Function
LoS	Line of Sight
LPP	LTE Positioning Protocol
LTE	Long Term Evolution
MEO	Medium Earth Orbit

MIMO	Multiple Input Multiple Output
NB-IoT	Narrowband Internet of Things
NLoS	Non-Line of Sight
NG	New Generation
NGC	Next Generation Core
NR	New Radio
NRPPa	NR Positioning Protocol A
NR PRS	New Radio Positioning Reference Signal
OFDM	Orthogonal Frequency Division Multiplexing (User Allocation Only in Time Domain)
OFDMA	Orthogonal Frequency Division Multiple Access (User Allocation both in Time and Frequency Domain)
OTDOA	Observed TDOA
PBCH	Physical Broadcast Channel
PCF	Policy Control Function
PPS	Pulse Per Second
PRS	Positioning Reference Signal
PSS	Primary Synchronization Signal
RAN	Radio Access Network
RB	Resource Block
RE	Resource Element
RG	Resource Grid
RMC	Reference measurement channel
RNSS	Radio Navigation Satellite Service
RSTD	Reference Signal Time Difference Measurement
SAR	Search and Rescue
SC-FDMA	Single-Carrier Frequency Division Multiple Access
SMF	Session Management Function
SPL	Spatial Length
SRS	Sounding Reference Signal
SSB	Synchronization Signal and PBCH Block
SSS	Secondary Synchronization Signal
TDD	Time Division Duplexing
TDOA	Time Differential of Arrival

TOA	Time of Arrival
TOT	Time of Transmitted
TSG	Technical Specification Group
TUT	Tallinn University of Technology
UE	User Equipment
UPF	User Plane Function
UTC	Universal Time Coordinated
V2V	Vehicle to Vehicle communication
V2X	Vehicle to X communication
VLF	Very low Frequency

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1 Introduction

5G-NR (Fifth Generation New Radio) is a new generation mobile network that opens the door to many new technological solutions, some of which have so far even been considered utopian or impractical. One very important feature of the 5G-NR mobile network is the ability to accurately position user equipment. The desired positioning accuracy can be achieved thanks to a dedicated 5G-NR Positioning Reference Signal (PRS), involving different algorithms for both signal application and result evaluation. In order to check the results of the simulations and to improve the accuracy of the algorithms, it is necessary to perform measurements with the 5G-NR positioning reference signal in real conditions - in the city, in buildings, on the streets, etc.

The aim of this thesis is to create the 5G-NR test bed, which generates and transmits positioning reference signals. Thus allows measurements to be made in real conditions.

The test station is created using the 5G-NR Open Air Interface (OAI) which is created by the Open Air Interface Software Alliance group. OAI is an SDR-based (Software Defined Radio) 5G-NR base station (BS) and user equipment (UE).

The work includes the following stages:

- Getting to know the goals and technology of 5G-NR. What are the main directions in the development of 5G technology. Get acquainted with the network structure. Familiarize in detail with the 5G-NR radio layer and physical procedures.
  Familiarize yourself with the standards covering 5G positioning.
- Investigate information from similar projects. Explain the historical background of positioning, which have been the main problems. How has the 5G-NR PRS signal been previously implemented on an OAI or some other platform basis.
- Explain 5G positioning techniques – Time-, angle measurement-based techniques.

- Gather information about OAI software. How the physical layer is implemented, how it works.
- Implement and integrate PRS generator with OAI physical procedures.
- Provide results, radio measurements, and software debug log extracts.

Positioning has historically been associated with the need for navigation. The word navigation comes from the Latin word *"Navigatio"*- sailing, in other words, the sailors needed a guide to determine the course. Navigation is usually based on known signs, a situation is described, for example lighthouses on the nautical map, and so on to modern high-precision navigation instruments. In a more general sense, navigating is finding the path to your desired location. Not only humans need navigation, but also animals and birds. It is a wonder how well animals can do this, such as migratory birds, ants, fish, bats or dolphins. The first step in navigation is to find out your location in space – the positioning [28].

An example of positioning from nature: Bats and dolphins can generate ultrasonic pulses and hear the sound echoes. Echoes occur when wave propagation environment changes. Objects in propagation environment have different propagation properties, part of the transmitted signal reflects back from objects. Magnitude of reflection depends on scale of this change. Those animals are basically able to measure the forward - back propagation time of sound waves - Round Trip Time (RTT). The transmitted signal returns back at different time from objects located at different distances and allows to form a complete image of environment, similar to vision. This type of imaging is also called echo location.

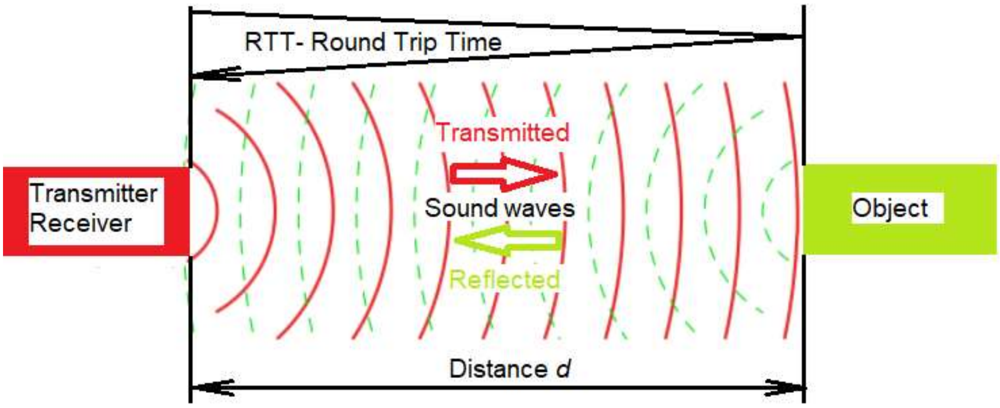


Figure 1 Soundwave Round Trip Time during on distance *d*

RTT measurement is also one possible method used in electronic positioning. Both sound and electromagnetic waves can be used. This thesis deals with positioning based on electromagnetic waves.

What all navigation instruments have in common is that some parameters must be measured for positioning. In earlier times, when electronic positioning devices had not yet been invented, device known as - sextant was used for positioning. Precondition to use sextant is that the visible objects with known positions must exist. Sextant measures the angular distance between two visible objects. Sextant allows to determine the position, mostly according to celestial bodies. Of course, it can be used today, probably in an emergency when no other means are available.

Returning to electronic positioning systems history, the first radio-based systems were introduced as early as the 1940 -s LORAN and DECCA. These systems were also used in World War II. Both systems used a network of ground-based radio stations. It was possible to position ship or aircraft based on the signals sent by the base stations. The hyperbolic positioning method known as TDOA was used, which is discussed in Chapter 3.2.3.

In 1956, F. Winterberg proposed testing the theory of general relativity using precise atomic clocks placed on orbiting satellites. The idea to create today's Global Positioning System (GPS) dates back to 1957, after the Soviet Union launched the first satellite, Sputnik. In connection with Sputnik, another positioning system was started - TRANSIT. The frequency and strength of the radio signal sent by satellite changed higher and lower due to the Doppler effect as the satellite moved closer or moved away. If the position of Sputnik in orbit is known, the radio frequency shift due to the Doppler effect allows the receiver's position on Earth to be estimated. TRANSIT was successfully tested in 1960 by the US Navy and it was the first satellite - based radio navigation system. TRANSIT constellation consisted of five satellites.

F. Winterberg's idea to install accurate clocks on satellites came true in 1967 with the launch of the Timation 1 satellite and Timation 2 in 1969. The use of an accurate atomic clock on a satellite has been implemented today in a satellite-based radio navigation system.

Definitely worth mentioning the OMEGA radio navigation system - 1970. OMEGA is the world's first international navigation system. OMEGA uses eight ground-based transmit stations, hyperbolic positioning method like earlier LORAN and DECCA. OMEGA is interesting system because it used Very Low Frequency (VLF) radio band $f = 10 - 14$ kHz. Each base station transmits pulse signals in three frequency f (10,2; 11,33; 13,6 kHz). Fourth frequency is unique for each base station. The system was managed by the United States Coast Guard in partnership with Argentina, Norway, Liberia, France, Japan and Australia. Omega was shut down permanently on 30 September 1997 due to success of GPS and declined use of the Omega during the 1990s [29] [30].

Coming to modern satellite positioning, it makes sense to talk about GNSS.

The GNSS - Global Navigation Satellite System the is general term of any satellite-based navigation system that has global coverage area. Device can use signals of one or many GNSS systems, to estimate its position. When measuring the signals of satellites of different systems, the results can be obtained faster and they can also be more accurate. Firstly, because the number of satellites in Line of Sight (LoS) is higher. At least 4 satellites must be visible for positioning. Second, by relying on the time signal of different systems, the time accuracy can be improved. GNSS includes 4 positioning system satellites, so that 8 to 10 satellites are visible at a time:

- GPS – Global Positioning System. Development of this system began in the 1970s in the United States, mainly for military purposes, but is also very important in nautical and aerial navigation. This system has 24 satellites on the orbits. As previously mentioned, GPS was introduced to civilian use in 1990 and thus became an international positioning system. GPS essentially replaced the terrestrial system OMEGA because it was more practical, more accurate and convenient to use.

- GLONASS – This system belongs to Russian Federation and the abbreviation comes from the Russian language (ГЛОбальная НАвигационная Спутниковая Система – Global Positioning System). This system has also 24 satellites on the orbit.

- Galileo – This system belongs to European Union and it has 27 satellites on the orbit.

- Bei-Dou – belongs to Republic of China, it has 30 satellites on the orbit.

All satellites using specific radio frequencies with CDMA (Code Division Multiple Access). Very briefly, CDMA allows devices to access the same frequency band at the same time, the receivers are able to distinguish the signal of each transmitter (satellite) on the basis of a code specific to each transmitter.
f_{L1} = 1575,41 MHz, f_{L2} = 1227,6 MHz, f_{L3} = 207,2420 - 1201,7430 MHz, f_{L5} = 1176,45 MHz;

Overview of GNSS radiofrequency allocations:

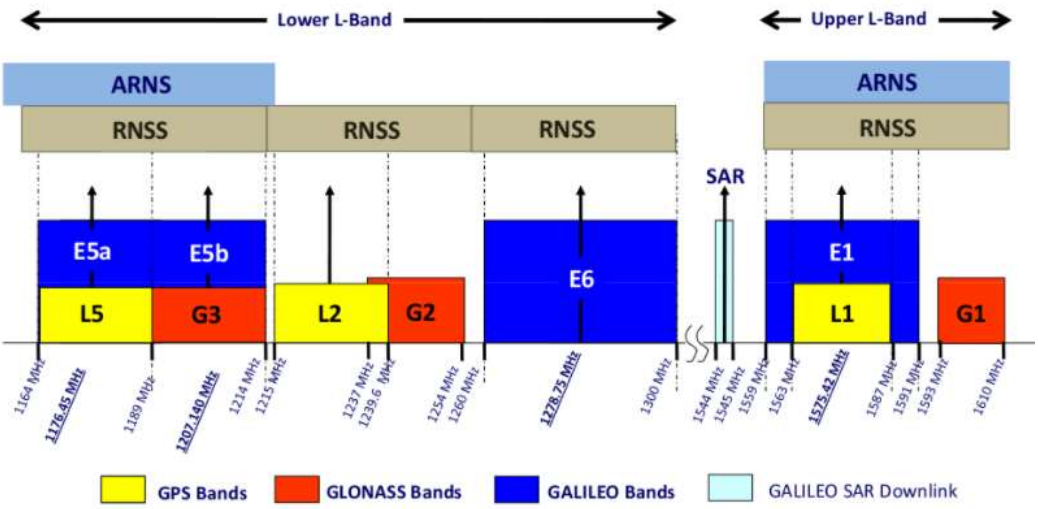


Figure 2 GNSS navigation frequency bands and -allocations [31]

ARNS – Aviation Radio Navigation Service;

RNSS – Radio Navigation Satellite Service;

SAR Downlink – Search and Rescue Downlink;

Galileo satellites receive emergency distress signals from radio beacons on frequency f = 406 MHz, this is the UL (Uplink) frequency. This SAR service has also source positioning functionality, so the received emergency signals with their parameters are returned to the ground via SAR-DL channel f = 1544 – 1545 MHz.

The satellites in the positioning system orbit at an approximate altitude of 20,000 km – MEO (Medium Earth Orbit - 5000 – 20000 km). The received satellite signal strength is very weak, so satellite signals may not be available everywhere. Many nowadays systems, such as self-driving cars, emergency beacons, or indoor systems, like warehouse and luggage robots, etc. expect precise positioning regardless the presence of a GNSS signal. In most of indoor cases, the lack of GNSS signal is inevitable, it is related by the fact that a large part of the signal is attenuated by passing through the walls of buildings. Second, in a populated area, the accuracy of positioning due to a multi-path radio signal propagation - the signals reflected from the buildings travel a different length of propagation path.

How to solve this GNSS availability and accuracy problem? The one possible answer is that there must be an alternative way of positioning, for example Mobile network-based positioning. The main problem with mobile network-based positioning has been positioning accuracy – it is many times smaller than achievable by satellite navigation methods.

As a precursor to 5G-NR (Fifth Generation New Radio) positioning, was introduced positioning capability in 3GPP LTE standard release 9 (4G technology) with accuracy of 50 m, which is still smaller than achievable by satellite navigation methods [3].

The development of 5G-NR also includes the positioning of UE (User Equipment) devices. It expands also to the IoT (Internet of Things) devices in 5G-NR network. Introduction of dedicated positioning reference signal PRS for 5G-NR in 3GPP release 16 opened the possibility of accurate mobile positioning [14].

Numerous simulations by different counterparts have been done and summary given in 3GPP TR38.855 [14] indicated that accuracies in order of few meters are achievable. This accuracy is similar in magnitude to that achieved with general purpose satellite navigation receivers. Minimum performance targets for positioning on release 16 [14] for regulatory use cases are less than 50 m in horizontal plane and less than 5 m in vertical one for 80% of user equipment UE. Starting point for commercial use cases in same release is from horizontal positioning error less than 3 m in indoor- and less than 10 m in outdoor development scenarios. Vertical positioning error must be less than three meters for both scenarios.

Target requirements in release 17 are stricter. For commercial use cases horizontal positioning accuracy must be better than 1 m and vertical accuracy less than 3 m for 90% of UEs. Target positioning requirements for Industrial IoT (IIoT) use cases are less than 0.2 m for horizontal- and less than one meter for vertical positioning accuracy for 90% of UEs [32]. Release 18 performance requirements are up to 0.2 m relative vertical- and horizontal accuracy with 95% confidence level [33].

The assumed positioning in the 5G-NR network is with accuracy up to 0.5 m [3].

However, all device positioning methods require at least two operations:

1) Signal measurements.
2) Position estimate computations.

Optionally is possible to estimate UE velocity [2].

Both techniques of the above two tasks must be carefully considered, to achieve desirable accuracy. There is also large ranging error in urban conditions. There are developed complicated estimation algorithms to improve ranging accuracy. This thesis project is concentrated to dedicated radio signal generation which in 5G-NR networks called NR Positioning Reference Signal (NR PRS).

1.1 Use cases of 5G-NR technology

Coming to the ITU 5G concept, it is divided into three main types of communications:

- Enhanced Mobile Broadband (eMBB) - high data rate services

  Increasing data transfer volumes require faster and higher-capacity network connections than 4G - Long Term Evolution (LTE) connection can provide. The 5G-NR network must cover all these needs.

- Massive Internet of Things, massive Machine Type Communications (mMTC)

  Massive IoT must cover the growing need for IoT devices – up to 10^6 device/km^2 can communicate with each other and provide access to databases and servers. This allows more automation in every area of life.

- Up to 1ms Ultra-Reliable Low-Latency Communication (URLLC) - Ultra-Reliable low-latency services.

  These services offer significant energy savings due to shorter connection time. Creates a completely new use in time-critical systems like remote control of vehicles, telemedicine etc.

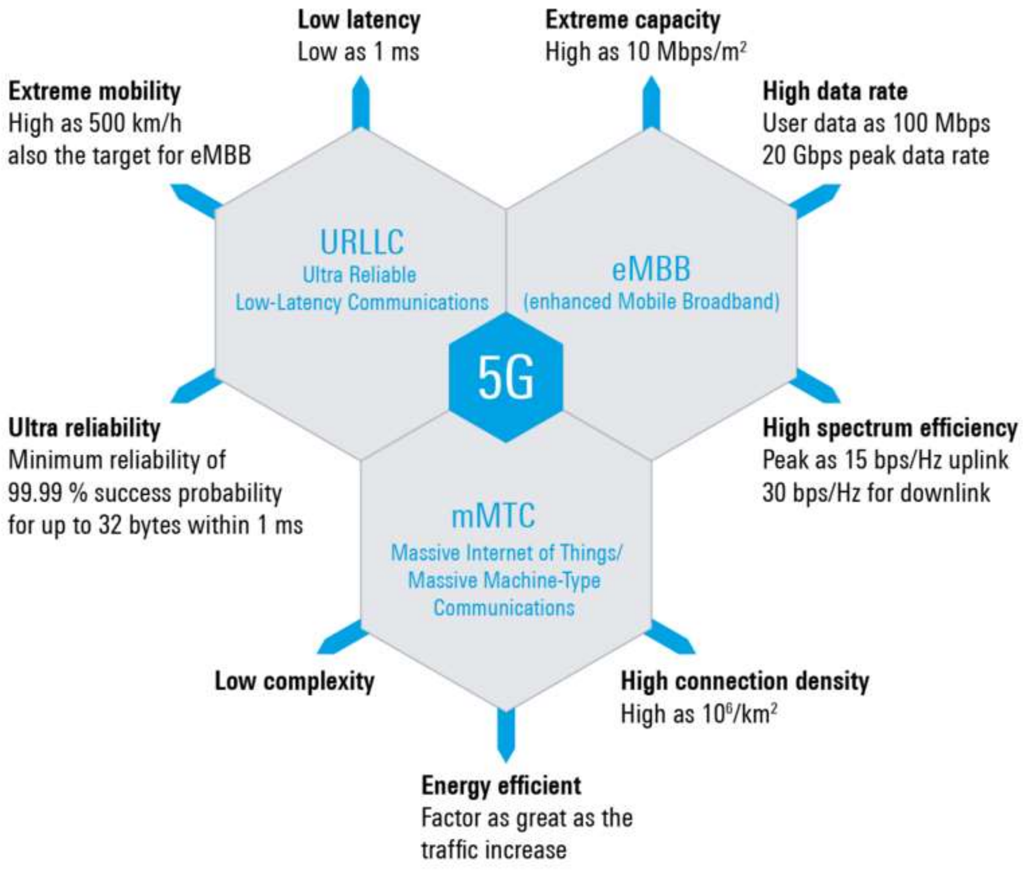


Figure 3 ITU vision for IMT-2020 and beyond [1]

Some completely new features that require a location service:

- Most important use case related to this thesis topic is possibility of positioning UE -s regardless of the presence of GNSS service availability;
- Vehicle to Vehicle communication (V2V) or Vehicle to everything (V2X) communication for example smart pedestrian crossing. This option in nowadays traffic is important improvement, it can save human lives in the future. Self-driving cars safety, truck trains with one driver, …;

- Tracking of goods in transport, tracking of location, conditions (temperature, humidity, etc. for example on food products);
- Smart agriculture solutions due to IoT over 5G communication network;
- Medical monitoring of the patient, also monitoring of portable medical equipment in hospitals;
- Virtual reality over 5G network;
- Smart city solutions are more realistic.

Some new features, which does not need UE positioning service, but still must be mentioned:

- Broadcasting of television signals over a 5G NR network. This will free up future frequency resources, also allows television signals to be broadcasted via the 5G satellite network;
- Ensuring network coverage in cross-border and sparsely populated areas via satellite;
- 5G devices are able receive and retranslate/retransmit signals from other user devices, thus providing a network connection in an area where there is no signal. This functionality is very important in an emergency situation – sidelink based mobile ad hoc NETworks – MANET networks (device coworking).

This list will certainly continue, and the availability of an online resource will create further new uses for UE and measurements or a location estimation from the UE also.

1.2 Brief overview of standards in NR positioning

- TS 37.355 The document contains the definition of the LTE Positioning Protocol (LPP) for the radio access technologies E-UTRA/LTE and NR [39].
- TS 38.133 NR; Requirements for support of radio resource management. These requirements include requirements on measurements in NR and the UE as well

as requirements on node dynamical behaviour and interaction, in terms of delay and response characteristics [40].

- TS 38.211 NR; Physical channels and modulation. The document describes the physical channels and signals for 5G-NR [4].
- TS 38.214 NR; Physical layer procedures for data. The document specifies and establishes the characteristics of the physicals layer procedures of data channels for 5G-NR [41].
- TS 38.215 NR; Physical layer measurements. The document describes the physical layer measurements for NR – including the TDOA measurement (Time Differential of Arrival) [42].
- TS 38.305 Stage 2 functional specification of User Equipment (UE) positioning in NG-RAN. The document specifies the stage 2 of the UE Positioning function of NG-RAN which provides the mechanisms to support or assist the calculation of the geographical position of a UE [43].
- TS 38.455 NR Positioning Protocol A (NRPPa). The document specifies the control plane radio network layer signalling procedures between a NG-RAN node and the LMF. NRPPa supports the concerned functions by signalling procedures defined in this document [44].
- TR 21.905 Vocabulary for 3GPP Specifications. The purpose of this report is to identify specialist technical terms used within the 3GPP project for the purposes of specifying service requirements [38].

1.3 Problem description

Several 5G-NR functionalities need very accurate UE device positioning data, like massive MIMO, propagation path or noise beam cancelling, D2D or V2V communication smooth handover operation, emergency call positioning etc. In some cases, positioning accuracy is very important.

Positioning method and algorithm in 5G-NR is based on 5G-NR PRS signal measurements and analysis. Significant weight is placed to difference of signal arrival time measurement (TDOA) and radio propagation channel delay estimations. Positioning must be available in both cases: when there is LoS view and when there is not Line of Sight (LoS) view between 5G-NR node (gNB) and the UE device. In case there is not direct signal received from gNB (NLoS), then only reflected or refracted signals are received by UE and actual signal propagation delay does not accurately reflect the distance between the UE and the gNB. Reflected signal path and actual direct path variations causes a major accuracy error in UE positioning process. When performing positioning accuracy measurements, it is necessary to create and analyze such scenarios. The 5G-NR Open Air Interface (OAI) can be used as a platform for this testing purposes.

2 The state of the art

The transition to a new generation of mobile communications - 5G technology - is currently relevant in worldwide. As the non-standalone mode based on 5G-NR technology is well suited for the transition period, there are more implementation and experiment result publications released to the worldwide.

First of all, the Open Air Software Alliance group has made a great contribution to the development of 5G-NR [18]. The 13 members have created an excellent launch pad for 5G NR development and measurements based on hardware and Open Air Interface.

It is known that at least one positioning project has been created on the basis of OAI NB-IoT, using LTE PRS, not NR-PRS signal [19].

Other OAI based projects, which are not related with positioning in 5G-NR:

- Build OAI LTE eNB & EPC; BMW-lab group [20] (1 year old).
    1. Implemented LTE base station and used Huawei Android smartphone for communication speed test with radio signal measurements.
    2. LTE with Nokia EPC (Evolved Packet Core).
    3. NB-IoT and nfapi tests.

- Connect UE with OAI gNB (USRP B210) (2years old) [21].
    1. Build and configure OAI gNB.
    2. UE Configuration and User registration on HSS (Home Subsscrier Server) database.

- Open Cells Project. Using OAI and Lime SDR (Software Defined Radio) [22].
    1. RF simulations, 1 eNB- 2 UEs.
    2. eNB +EPC in OAI and USRP (Universal Software Radio Peripheral).

Patent: US2020021946A1 (16.01.2020) [23].

Systems and methods for PRS muting in a Fifth-Generation wireless networks.

- Methods and techniques are described for supporting location services for a user equipment (UE) in a Fifth-Generation wireless network in which a Base Station, such as a gNB or NG-eNB, broadcasts a Positioning Reference Signal (PRS) in a plurality of different directions and at a plurality of different times.

Master thesis research project, not related with OAI:

“System Level Study of 5G Indoor Industrial Positioning” [27].

> This project is investigating DL-TDOA based positioning accuracy, radio channel estimations, positioning estimations, -simulations, LoS detection.

Significant 5G-NR cornerstones are sure to be highlighted by Huawei, Ericsson, LG-Electronics, Qualcomm, Nokia and others ... developments by that have made a great contribution to 3GPP. The 3GPP standard describes the principle and parameters of 5G PRS signal generation quite well. This has created a good starting position. It is known that most studies related to NR positioning are based on mathematical simulations.

There are many issues not solved yet in NR positioning process:

- Ericsson report DL-PRS Resources in the assistance data are sorted in a decreasing order of measurement priority [8].
- R1-2005681 Remaining issues on DL PRS and measurements for NR ... SRS transmission and PRS processing priority for NR positioning LG Electronics [9].

Measurements with real NR PRS signals are required to confirm estimations and simulations.

2.1 5G-NR network core

In chapter 1.1 - 5G-NR use cases were introduced as ITU vision of NR three goals. These are ultra-reliable low-latency services, high data rate services, massive-IOT and machine communications. It is definitely worth mentioning that one of the key words in achieving these three main goals is Software-Defined Network

(SDN). In short, the 5G core network consists of many services that are implemented in software and enable the provision of the service to all cloud service providers. In the Figure 4 is depicted basic structure of future - Next Generation Core network (NGC) or Cloud Based Core (CBC), S1 and X2 are signalling paths – communication establishing, grey lines are payload paths – packet data communication:

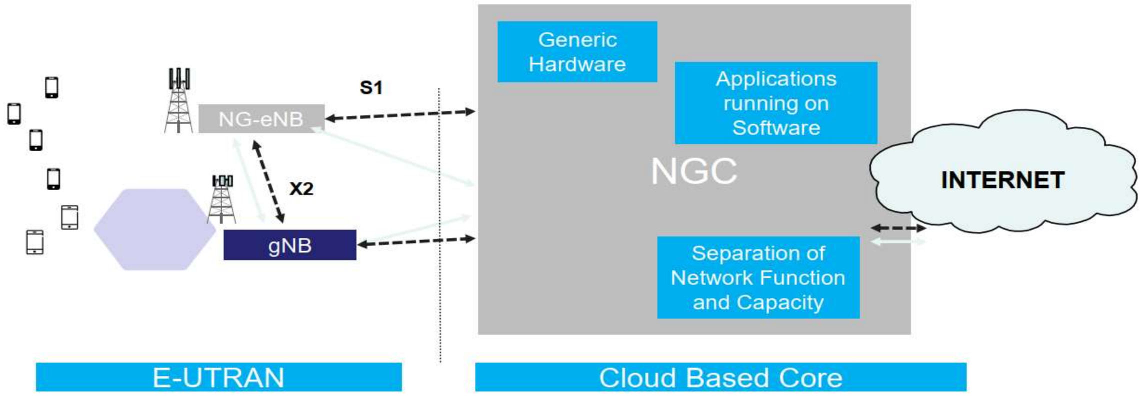


Figure 4 5G Next Generation Cloud Based Core network structure [10]

The Second keyword is Edge computing. It allows data processing and calculations to be performed closer to the UE -s. Edge computing also reduces data communications over network resources.

Knowing the location of the UE, it is possible to communicate with the nearest base station, which is important to achieve the best data connection quality and low latency services. As described in Figure 4 above, NGC - network consists of functions running in software (Software Defined Network – SDN). Location Management Function (LMF), which is managing device positioning, but there are also other functions related to positioning in Figure 5. Positioning Signals are handled separately in chapter 2.2.

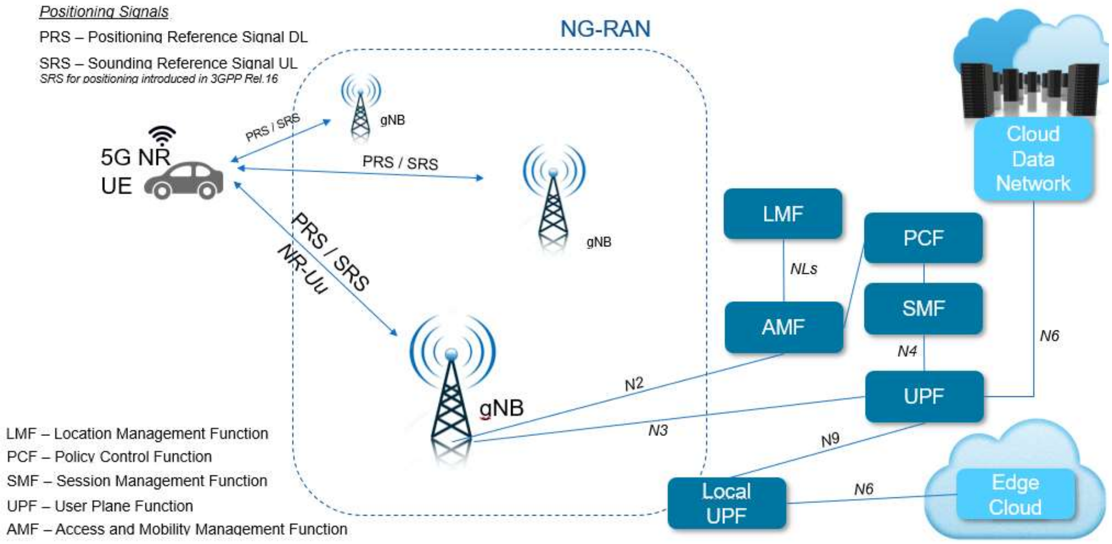


Figure 5 Positioning related functions and services in the 5G-NR network [24]

The LMF manages location-, positioning- and support services for target UE, also delivering location assistant data to the UE. The LMF combines all received positioning results and determines a single location estimate for the target UE.

The Access and Mobility Management Function (AMF) is responsible for handling connection and mobility management tasks between UE and network. AMF receives all connections and session related information from UE. The AMF implements the ciphering and integrity protection algorithms as well.

The Policy Control Function (PCF) provides policy rules. This function supports the unified policy framework that governs network behaviour. It stays between AMF and SMF (Session Management Function).

The SMF is one of the control plane network functions, it is responsible of session establishment, modify and release.

The User Plane Function (UPF) is responsible of user and control plane data separation, packets routing and forwarding, policy enforcement and data buffering.

2.2 Positioning in 5G-NR network

2.2.1 Signalling scheme

Signalling means the transmission of control signals in a communication network. Figure 6 shows step by step signalling in case of positioning request.

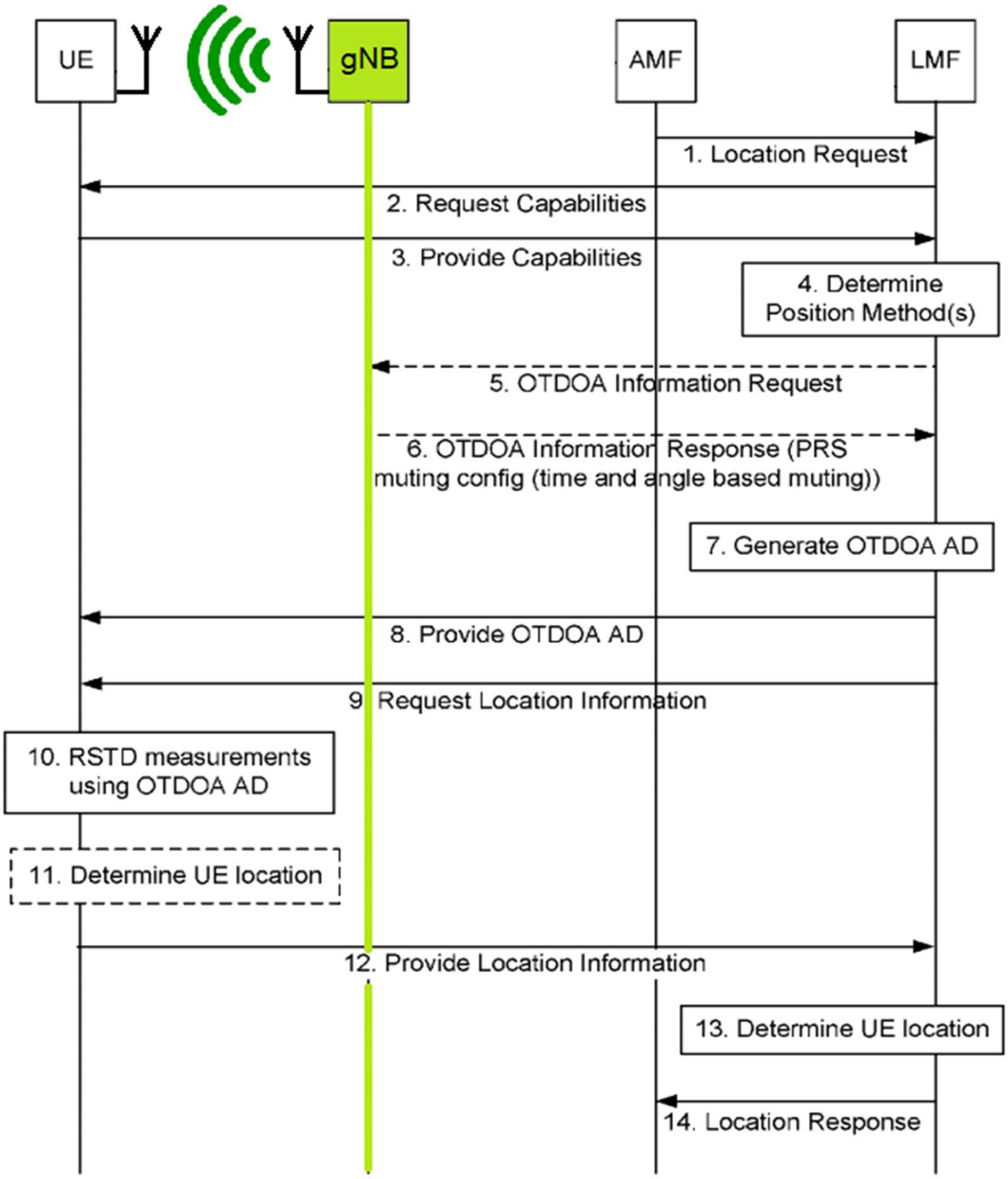


Figure 6 Signalling sequence flow for UE positioning in 5G-NR [23]

Positioning in 5G-NR network starts with Access and Mobility Management Function (AMF) request to the Location Management Function (LMF) - step nr 1 in Figure 6, there is no PRS resources generated to the radio ether yet. LMF considering capabilities according to the UE response (steps 2 and 3). According to the capabilities of gNB -s nearby to the UE, the LMF will choose optimal or settings for PRS resource generation (steps 5, 6). Now the LMF sets up the UE and network nodes (gNB -s) for positioning (steps 7, 8 and 9). When positioning is succeeded or not, the UE transmits response to the LMF (steps 10, 11, 12 and 13). Now the LMF responds to the AMF request (step 14).

2.2.2 Overview of positioning capabilities

According to the standard 3GPP TS 38.215 (Physical layer measurements), the 5G-NR positioning technique involves TDOA- and signal arrival angle measurement, also Round-Trip Time (RTT) measurement can be used. Positioning Reference Signals can be transmitted to the different sectors so that the angle measurement can also be performed. The division of such a radio resource into sectors and phase measurement is possible thanks to the beam forming technology. In terms of positioning, this increases accuracy. The accuracy of angle measurement is related of antenna array configuration. Antenna array configuration and physical dimensions are also directly related of used frequency band. The Figure 7 describes the antenna configurations and which antenna needs to be used to obtain the desired beamforming (4T4R means that there are 4 transmitter and 4 receiver antennas).

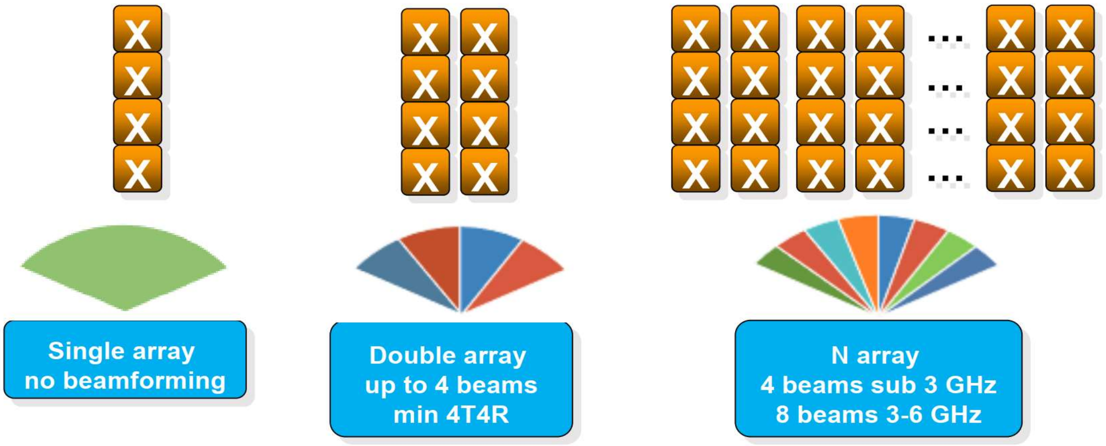


Figure 7 Antenna arrays used in 5G NR gNB -s [1]

The following Figure 8 illustrates well 5G-NR positioning solutions. There are shown DL based positioning resources (DL-PRS), DLPRS set when beamforming is used, DL and UL based positioning method. When UE receives DL-PRS, then UE replies to the gNB with UL-SRS (Sounding Reference Signal), RTT will be measured on gNB side. NR positioning solutions are described in document “Study on NR positioning support” - 3GPP TS 38.855 v16 [14].

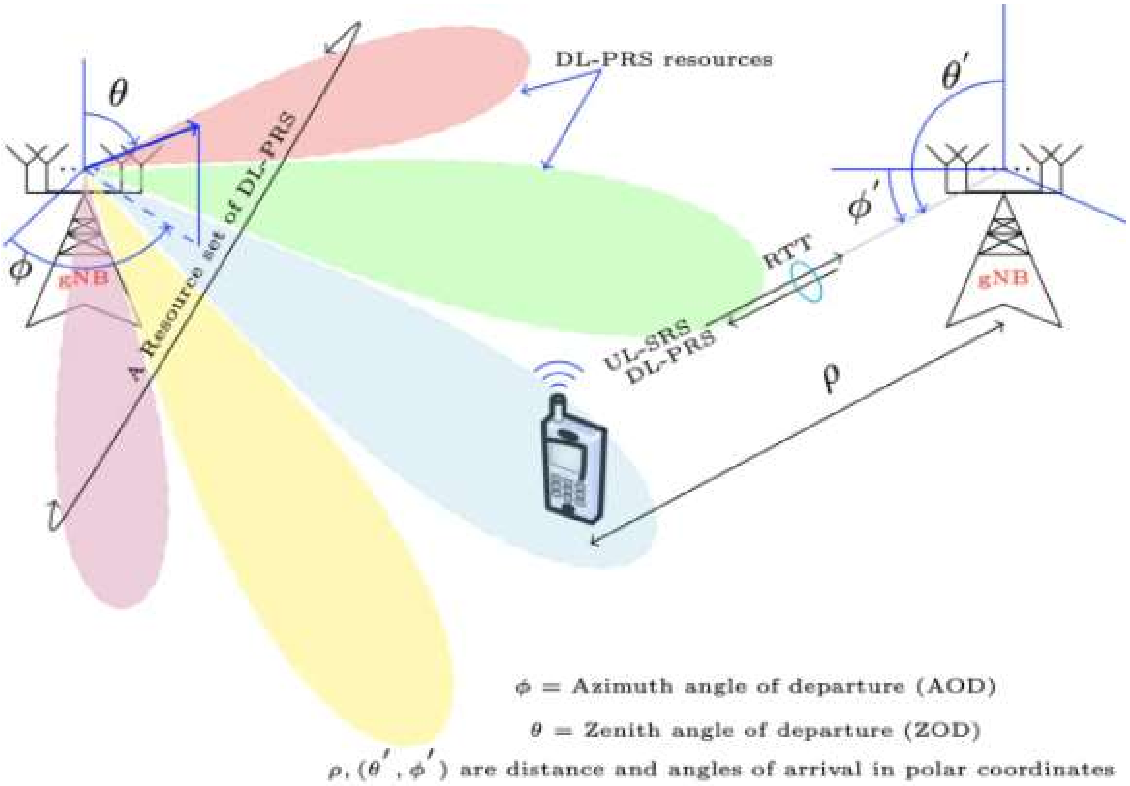


Figure 8 Positioning signal resources in 5G-NR [5]

In Figure 8 ϕ is azimuthal angle (AoD) and θ is elevation- or Zenith angle of Departure (ZoD). These principals were also mentioned in chapter “*Positioning methods in NG Radio Access Network*”.

2.2.3 5G-NR PRS signal

Dedicated 5G-NR PR-Signals were introduced in 3GPP release 16 in 2018 [45]. 5G-NR technology allows more Base Stations (BS) to use the same frequency band. PRS is specifically designed to deliver the highest possible levels of accuracy, coverage, interference avoidance and suppression. The PRS sequences in 5G-NR are based on Gold sequences (Gold sequences are explained more detail in capture 3.5) In the following Figure 9 is a part of Resource Grid (RG) or an example RG (with reduced dimensions), which illustrates how different BS PR-Signals can be mapped, there are used different first symbol offsets of the downlink PRS $l_{\text{start}}^{\text{PRS}}$ (it is explained in chapter 2.2.5 DL PRS mapping)..

In Figure 9 are shown subcarriers within single Resource Block (RB). For better resolution - that is, the ability to distinguish between individual paths in the case of multipath propagation - the larger frequency band - or more resource blocks can be used. To achieve greater distance of receivable signal, the signals are orthogonal (Gold codes) and these are located in the resource network at different frequencies and at different locations in time. Additionally, the signals of neighbouring stations can be muted while the PRS signal is being sent from a distance in order to further suppress possible interference. The base station can also increase the signal power of the PRS (signal boosting). The distance of PRS signals in frequency domain are defined as Comb size $K_{comb}^{PRS} \in \{2,4,6,12\}$, it depends on use cases, the larger the step, the bigger number of base stations that can transmit the signal simultaneously without interfering with each other. At the same time, their signal power remains lower. In Figure 9 - the signals repeat in every sixth subcarrier, transmission comb size – 6. For comb-N PRS, N symbols can be combined to cover all the subcarriers in the frequency domain, the condition is that PRS resources must not overlap NR synchronization signal blocks.

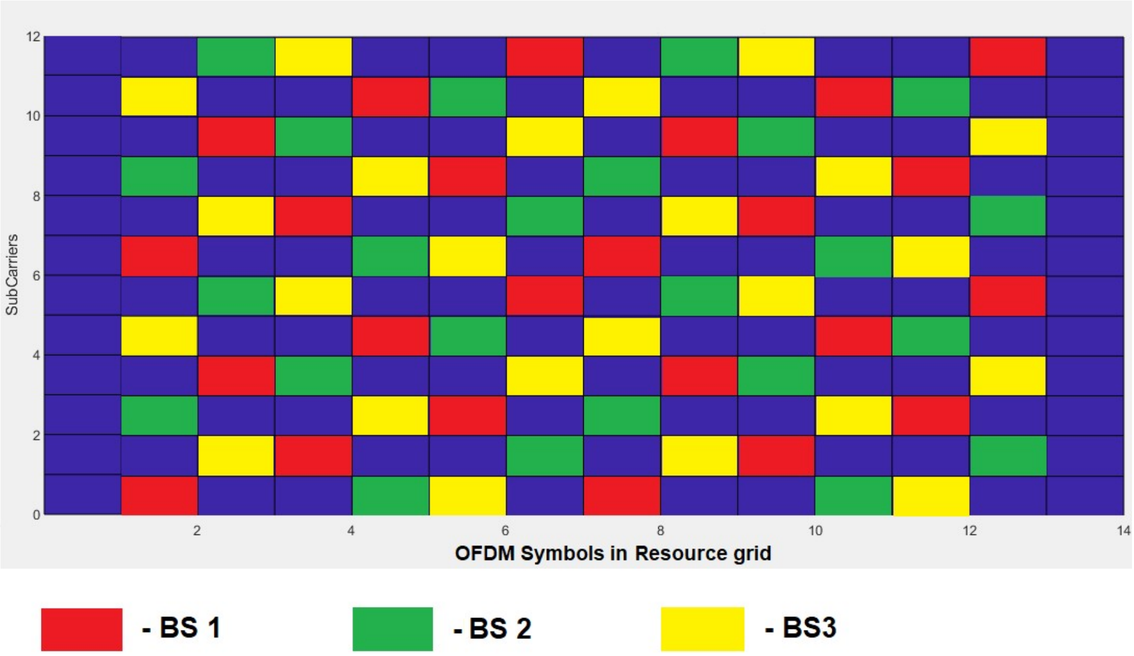


Figure 9 5G-NR DL - PRS signals shown in Resource Grid

PR-Signals are QPSK modulated, where are four phase values as it is shown in Figure 10. This is the common modulation scheme for LTE physical layer synchronization signals as well.

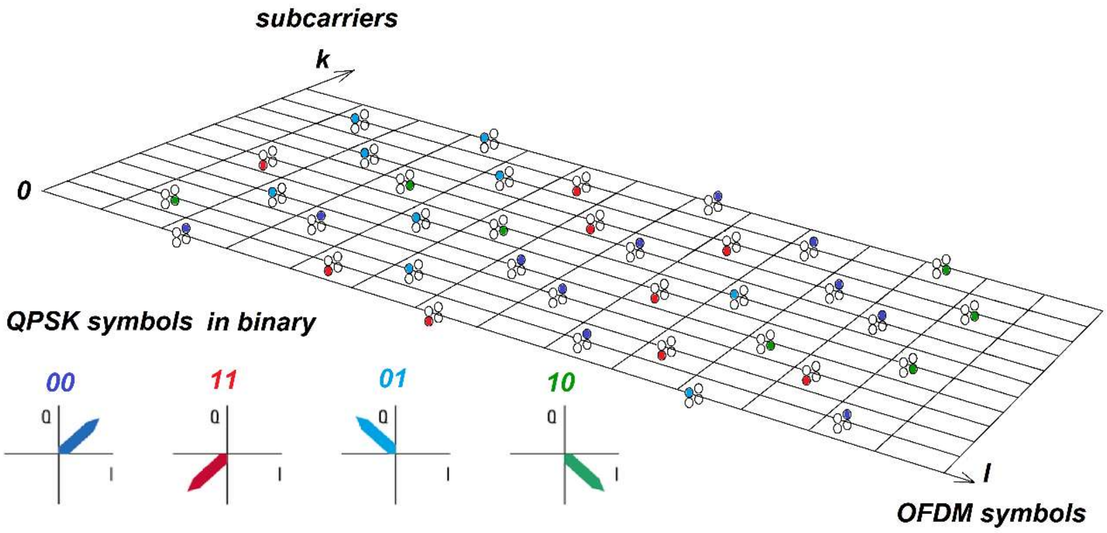


Figure 10 QPSK modulated signal phasor representation [1]

2.2.4 DL PRS-generation

DL PRS signal generation is described in 3GPP standard 3GPP TS 38.211 7.4.1.7 [4]

$$r(n) = \frac{1}{\sqrt{2}}\left(1 - 2 \cdot c(2n)\right) + j\frac{1}{\sqrt{2}}\left(1 - 2 \cdot c(2n + 1)\right)$$

Where:

Complex DL PRS sequence - $r(n)$
Gold sequence - $c(n)$

Generic pseudo-random sequences are defined by a length-31 Gold sequence. The output sequence is defined by 3GPP TS 38.211 5.2.1 [4]

$$c(n) = [x_1(n + N_c) + x_2(n + N_c)]\mathrm{mod}2$$

$$x_1(n + 31) = [x_1(n + 3) + x_1(n)]\mathrm{mod}2$$

$$x_2(n + 31) = [x_2(n + 3) + x_2(n + 2) + x_2(n + 1) + x_2(n)]\mathrm{mod}2$$

Sequence length M_{PN}, where $n = 0,1, \ldots, M_{PN} - 1$; $N_c = 1600$.

The first m-sequence x_1 shall be initialized with $x_1(0) = 1; x_1(n) = 0; n = 1,2, \ldots ,30;$

The second m-sequence x_2 is initialized with initial seed c_{init}, value depending on the application of the sequence:

$$c_{init} = \left[2^{22}\left\lfloor\frac{n_{ID,seq}^{PRS}}{1024}\right\rfloor + 2^{10}\left(N_{symb}^{slot}n_{s,f}^{\mu} + l + 1\right)\left[2\left(n_{ID,seq}^{PRS}\mathrm{mod}1024\right) + 1\right] + \right.$$
$$\left. +\left(n_{ID,seq}^{PRS}\mathrm{mod}1024\right)\right]\mathrm{mod}2^{31}.$$

Where $n_{ID,seq}^{PRS}$ is DL PRS sequence ID $\in \{0,1,\dots,4095\}$ is given by the higher-layer parameter *dl-PRS-SequenceID*; N_{symb}^{slot} is the number of OFDM symbols per slot; $n_{s,f}^{\mu}$ is the slot number; l is the OFDM symbol within the slot to which the sequence is mapped [4] capture 7.4.1.7.2.

Gold sequence generation and Modul operation is also handled in capture 3.5.

2.2.5 DL PRS mapping

For each downlink PRS resource configured, the UE shall assume the sequence $r(m)$ is scaled with a factor β_{PRS} and mapped to resources elements $(k,l)_{p,\mu}$ according to

$$\begin{aligned}
&a_{k,l}^{(p,\mu)} = \beta_{\mathrm{PRS}}\, r(m)\\
&m = 0, 1, \dots\\
&k = mK_{\mathrm{comb}}^{\mathrm{PRS}} + \left(\left(k_{\mathrm{offset}}^{\mathrm{PRS}} + k'\right) \bmod K_{\mathrm{comb}}^{\mathrm{PRS}}\right)\\
&l = l_{\mathrm{start}}^{\mathrm{PRS}}, l_{\mathrm{start}}^{\mathrm{PRS}} + 1, \dots, l_{\mathrm{start}}^{\mathrm{PRS}} + L_{\mathrm{PRS}} - 1
\end{aligned}$$

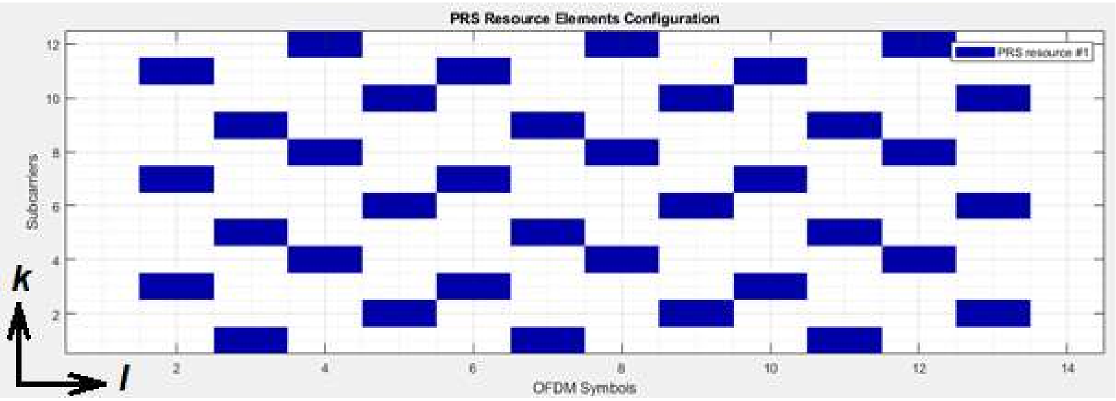


Figure 11 PRS in one Resource Block, 12 symbols, CombSize = 4

Where k and l marking Resource Element (RE) placement on Resource Block (RB), similar like on coordinate plain, Figure 22 and Figure 11 explains how k and l placed on RG. $l_{\text{start}}^{\text{PRS}}$ is the first symbol of the downlink PRS within a slot and given by the higher-layer parameter *dl-PRS-ResourceSymbolOffset*;
L_{PRS} is the size of the downlink PRS resource (offset from $l_{\text{start}}^{\text{PRS}}$). $L_{\text{PRS}} \in \{2,4,6,12\}$ is given by the higher-layer parameter *dl-PRS-NumSymbols*;

The comb size $K_{comb}^{PRS} \in \{2,4,6,12\}$ is given by the higher-layer parameter *dl-PRS-CombSizeN*, such that the combination {L_{PRS}, K_{comb}^{PRS}" } is one of {2, 2},{4, 2}, {6, 2}, {12, 2}, {4, 4}, {12, 4}, {6, 6}, {12, 6} and {12, 12};

The resource-element offset $k_{\text{offset}}^{\text{PRS}} \in \left\{0,1,\ldots,K_{\text{comb}}^{\text{PRS}}-1\right\}$ is obtained from the higher-layer parameter *dl-PRS-CombSizeN* and *ReOffset*;

The quantity k' is given by Table 7.4.1.7.3-1 in [4].

The reference point for $k = 0$ is the location of the point *A* of the positioning frequency layer, in which the downlink PRS resource is configured where point *A* is given by the higher-layer parameter *dl-PRS-PointA*, wich is also defined as absolute frequency of the reference resource block for DL PRS. Its lowest subcarrier. A single Point A for DL PRS resource allocation is provided per positioning frequency layer. All DL PRS resources belonging to the same DL PRS resource set have common Point A [37].

Table 1 The frequency offset k' as a function of l-l_$l_{\text{start}}^{\text{PRS}}$ (Table 7.4.1.7.3-1 [4])

$K_{\text{comb}}^{\text{PRS}}$	**Symbol number within the downlink PRS resource $l - l_{\text{start}}^{\text{PRS}}$**											
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
2	0	1	0	1	0	1	0	1	0	1	0	1
4	0	2	1	3	0	2	1	3	0	2	1	3
6	0	3	1	4	2	5	0	3	1	4	2	5
12	0	6	3	9	1	7	4	10	2	8	5	11

3 Overview of positioning methods and 5G-NR physical layer

There are several standard UE positioning methods which all will not covered in this chapter. Good results have been shown by Observed Time Differential of Arrival (OTDOA), Angle of Arrival (AoA) and Angle of Departure (AoD) based positioning principles. Support for Radio Beam Forming (BF) is also one of 5G-NR advantages. To implement BF functionality, the location information of UE is required. Beamforming in 5G is based on two fundamental physical resources: SS/PBCH blocks (Synchronization Signal / Physical Broadcast Channel) and the capability to configure CSI-RS (Channel State Information Reference Signals), so this is solved independently and not handled in detail in this thesis [1].

3.1 Positioning methods in NG Radio Access Network

5G networks transmits regularly SSB block for synchronization and broadcast purposes. It is possible to assign separate index to sequential SSB blocks – Figure 12. Due to BF each block with separate index can be transmit in some defined direction. Measurement of powers of those blocks enables to estimate direction from gNB to UE.

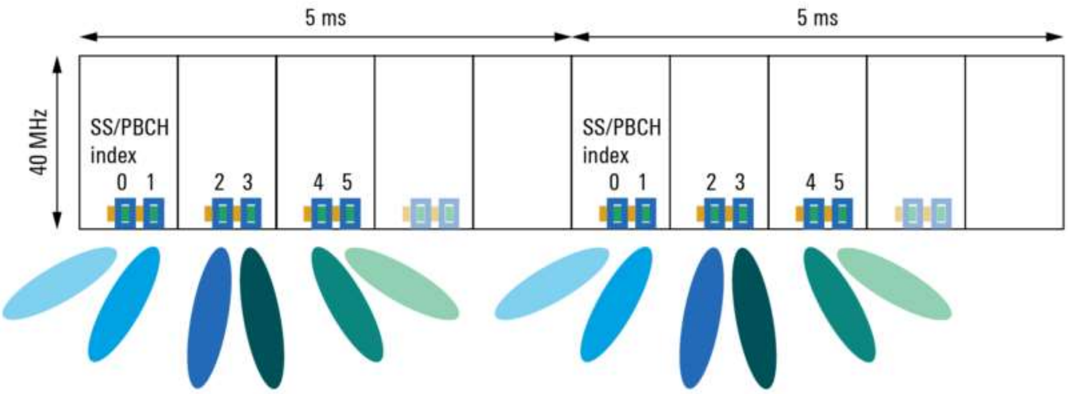


Figure 12 The principle of SSB indexing when used BF [1]

Knowing directions from two or more gNB -s allows to estimate position of UE, the method is known as triangulation. In Figure 13 triangulation example are network nodes with known coordinates $P_1(x_1, y_1)$, $P_2(x_2, y_2)$, known azimuths φ_1, φ_2 and $P_0(x_0, y_0)$ with unknown coordinates.

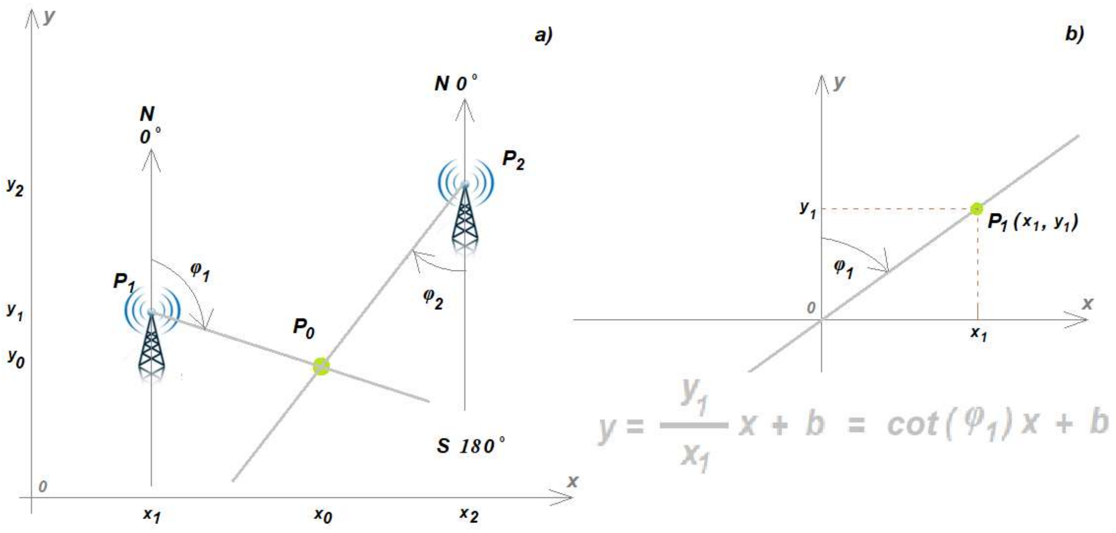


Figure 13 Triangulation example a); Parametric straight line equation b)

P_0 is common point of two straight line in Figure 13. To determine the coordinates of the point *P_0* (UE), a system of linear equations must be solved:

$$\begin{cases} y_0 = y_1 + cot\ (\varphi_1\ )x_0 + x_1 \\ y_0 = y_2 + cot\ (\varphi_2\ )x_0 + x_2 \end{cases}$$

Positioning is based on the observation, which are classified by position calculation:

a) UE based – position calculations are made in UE

b) UE assisted – position calculations are made in Network side used UE measurements (observations)

c) Network based – position calculations are made in Network based on UE generated signal measurements in Network side

d) Network assisted – Signal measurements made by UE position estimation is made using Network assistance.

Table 2 Positioning methods by classification [3]

Method	UE - based	UE-assisted, LMF-based	NG-RAN node assisted
A-GNSS	Yes	Yes	No
OTDOA (note1, note 2)	No	Yes	No
E-CID (note 3, note 4)	No	Yes	Yes

n1 - This includes TBS positioning based on PRS signals

n2 - In this version of the specification only OTDOA based on LTE signals is supported

n3 - In this version of the specification only E-CID based on LTE signals is supported

n4 - This includes Cell-ID for NR method

Location Management Function (LMF) is 5G core network entity to support location determination for UE and measurements or a location estimation from the UE also.

3.2 Time measurement-based positioning methods

3.2.1 Time of Arrival based positioning method

Location estimate of UE can be calculated using measured time of arrival (TOA) of the received PSR signals from different network nodes. It is important that network nodes and UE device are time synchronized. Signal time of transmitted (TOT) from network node is known, this is the time when signal transmission was started. TOA is measured in UE. When signal TOT and TOA are both known, then it is easy to calculate radio signal Time of Flight (TOF):

$TOF = TOA - TOT$;

Knowing the radio signal TOF and the radio wave propagation speed, then the radio wave travelled distance d between network node and UE can be calculated as:

$d = TOF \cdot c$;

Where c is electromagnetic wave propagation speed in vacuum. In the air environment the electromagnetic wave propagation speed v_{air} is very close to the propagation speed in vacuum - c. As we know that the light is also electromagnetic wave. The refractive index of air for visible light is about 1.0003, so the speed of light in air is about 90 km/s slower than c:

$c = 2{,}99792458 \cdot 10^8$ m/s; $v_{air} = 2{,}99702458 \cdot 10^8$ m/s;

In calculations generally $v_{air} \approx c$ [34];

For each calculated distance, it can be assumed that the UE is on a circle with radius d_i with respect to network node – d_1 … d_3 in Figure 14. In this case we expect that radio waves travelling in a straight line from BS to the UE (P_i to the P_0).

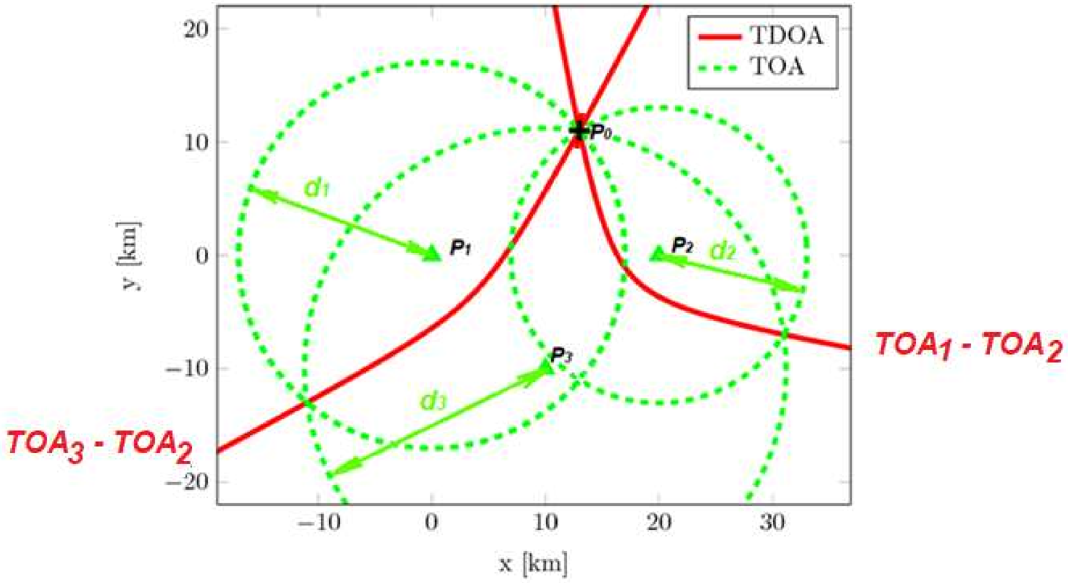


Figure 14 Principle and relations of trilateration- (TOA – green colour), and multilateration (TDOA – red colour) positioning method [46]

At least three measurements are needed for two-dimensional (2D) position estimation and at least four measurements for 3D position estimation. Estimation based on three TOA measurements is called trilateration method. Trilateration method 2D case is illustrated in the Figure 14.

The coordinates of Points $\{P_1, P_2, P_3\}$ are known, P_0 coordinates are unknown. There may be more points with known coordinates $\{P_1, P_2, P_3, \ldots, P_i\}$, It will increase positioning accuracy as well.

In Figure 15 are graphically explained Euclidean distances between known- and unknown points. These distances as sections between points P_0 and P_i:

$$d_i(P_i, P_0)^2 = (P_{0x} - P_{ix})^2 + (P_{0y} - P_{iy})^2$$

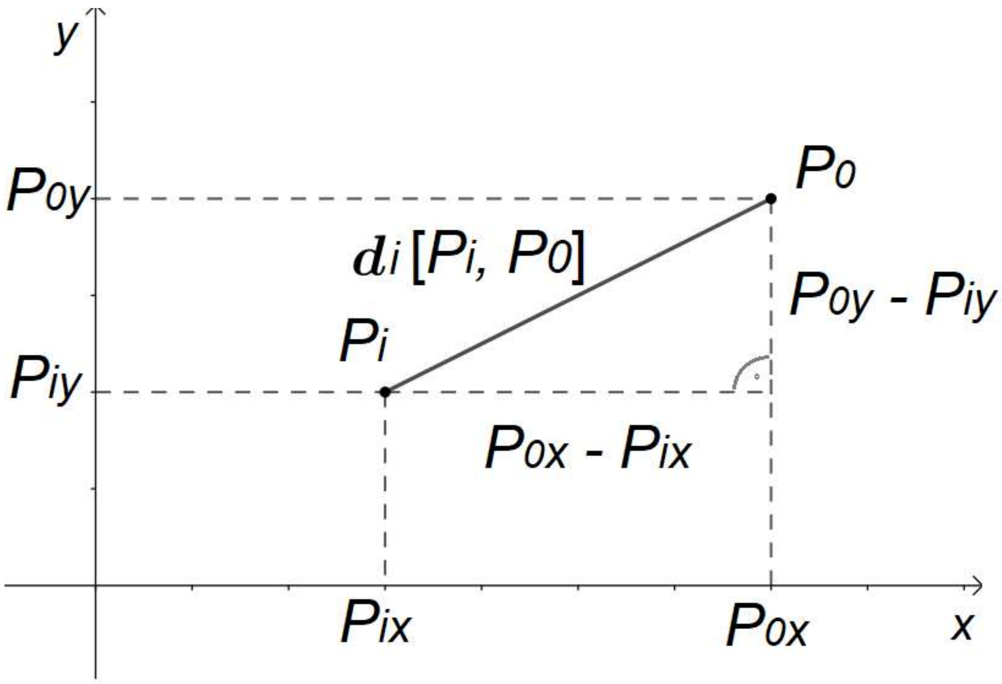


Figure 15 Euclidean distance di [Pi, P0] in case of 2D space

Distances between known and unknown points Pi and P0 in Figure 15 is as follows:

d_1 = [P_1, P_0]; d_2 = [P_2, P_0]; d_3 = [P_3, P_0];

The disadvantage of the TOA method is that accurate synchronization of the UE time is difficult and not always feasible.

3.2.2 Round Trip Time measurement

As an alternative method to TOA is to measure round trip time. RTT method was briefly described also in page 16 and 32. RTT method does not require time synchronization in -UE device side like it is in case of TOA method. The UE device receives the signal and sends back to the network node. The distance calculation considers the forward – back TOF (round trip) and the process time in the UE. Figure 16 illustrates RTT measurement procedure.

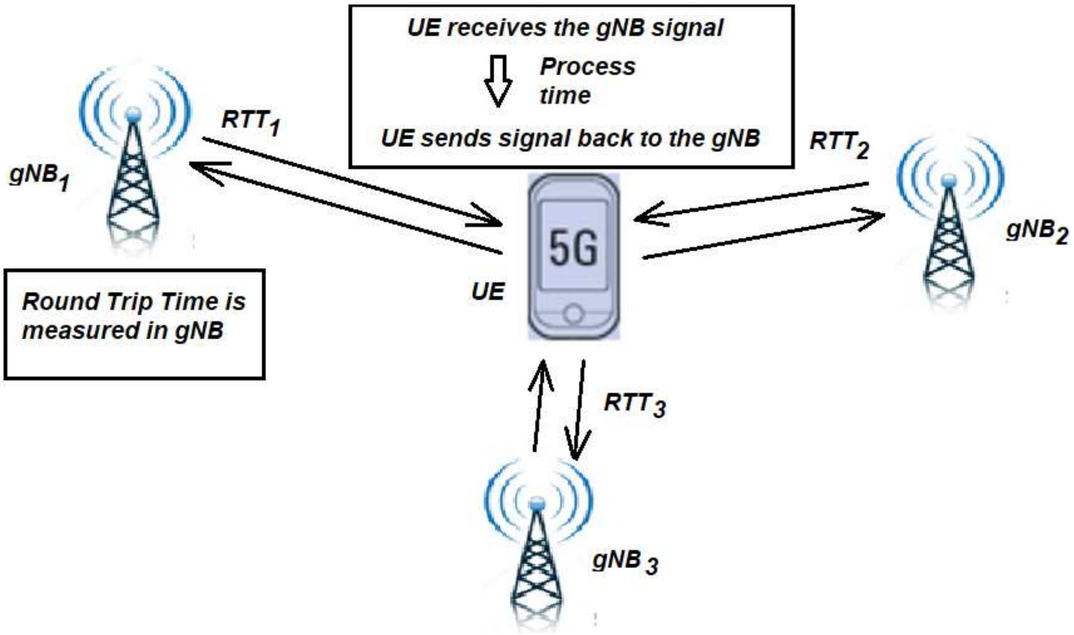


Figure 16 Round Trip Time measurement procedure

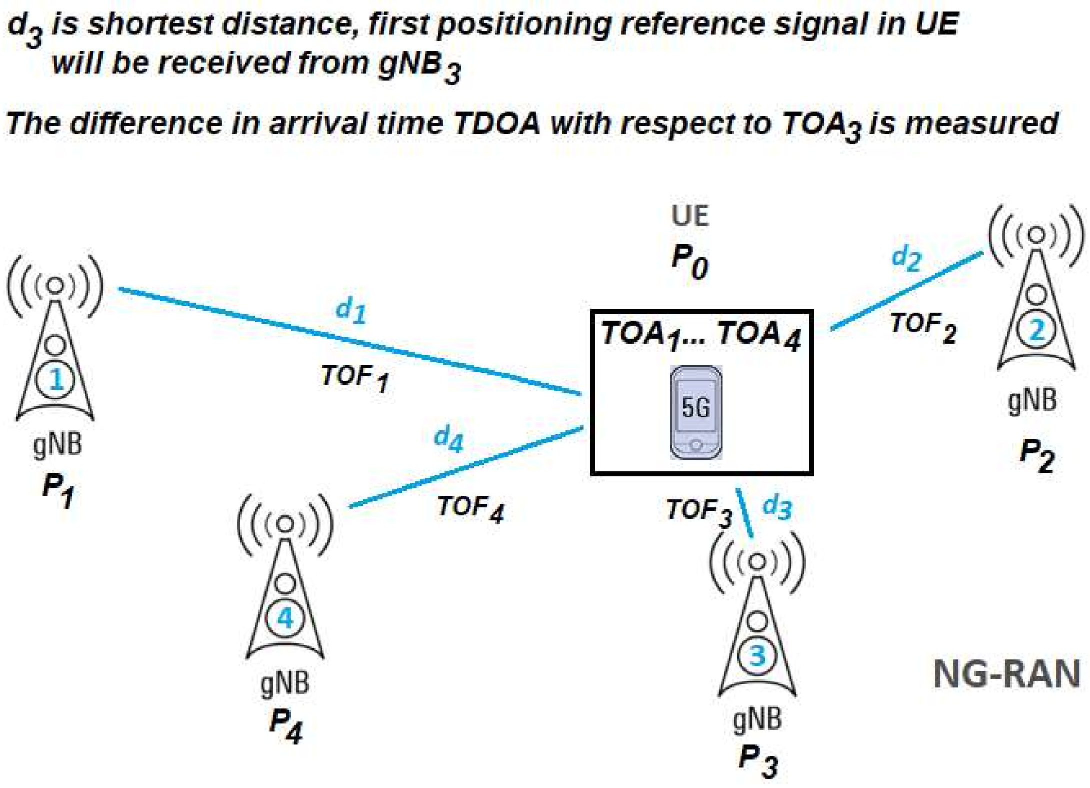
3.2.3 Time Differential of Arrival method

Signal arrival time difference measurement also does not need UE device time synchronization with network nodes – gNB -s. It is important that gNB -s are time synchronized and they are sending PRS instantaneously. TDOA is known as multilateration or hyperbolic positioning method as it is illustrated in Figure 14 with red lines. Distance - d_2 between point P_0 and P_2 is shortest signal path, so all differences are also represented relative to P_2:

$\Delta t_{32} = TOA_3 - TOA_2$; $\Delta t_{12} = TOA_1 - TOA_2$;
$\Delta d_{32} = d_3 - d_2 = c \cdot \Delta t_{32}$; $\Delta d_{12} = d_1 - d_2 = c \cdot \Delta t_{12}$.

Where c is radio wave propagation speed in vacuum (explained in page 38).

TDOA principle is also illustrated in Figure 17, the shortest signal path is d_3, hence the TDOA -s are represented relative to P_3. P_1 … P_3 are transmitter positions – Anchor nodes which have usually fixed position in mobile networks, in 5G-NR networks they are called gNB -s (NR node B). P_0 is estimated receiver position. Distances d_1 … d_3.


d_3 is shortest distance, first positioning reference signal in UE will be received from gNB $_3$

The difference in arrival time TDOA with respect to TOA_3 is measured

Figure 17 TDOA based positioning principle

In 5G – NR is used term like OTDOA – Observed TDOA.

OTDOA is UE - assisted method based on Reference Signal Time Difference. Network nodes sending out synchronous and dedicated Positioning Reference Signal (PRS). This dedicated signal generation is the main topic of this thesis. The NR – PRS signal is described in chapter 2.2.3.

3.3 Effect of Network Node time synchronization on positioning accuracy

In case of TDOA method, the positioning reference signals must be transmitted simultaneously from network nodes or the delay between the signals must be known. In case of TOA, the network nodes and UE must be precisely time synchronized. The synchronization time error can be viewed as the Spatial Length SPL of the radio wave, which is added to the distance estimation during positioning. This is the distance that radio waves can travel in error time is illustrated in Figure 18.

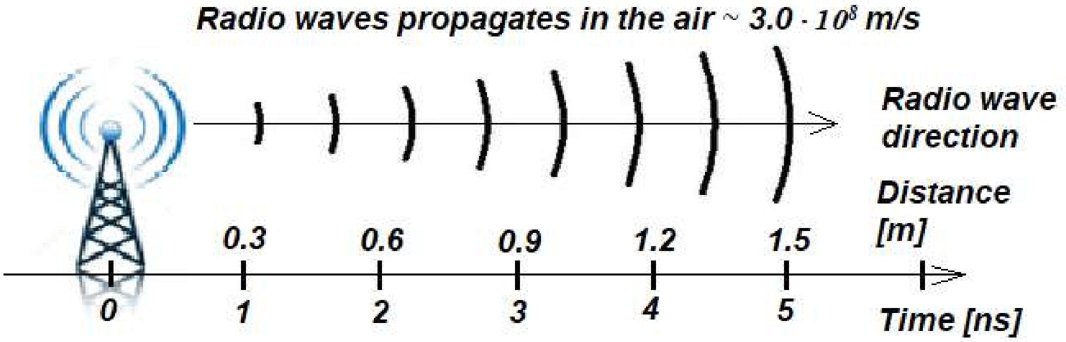


Figure 18 The length of the path at which the radio waves reach the error time caused by the synchronization error

The accuracy of the clock is evaluated according to the Network Time Protocol (NTP) Stratum level. The reference clock time is Universal Time Coordinated (UTC). UTC is world time on zero meridian. UTC time is considered as NTP Stratum level 0 and it is also the time of the atomic clock in England. NTP Stratum level tree is hierarchical tree, shown in Figure 19. The accuracy of the clock time as it is in Table 3.

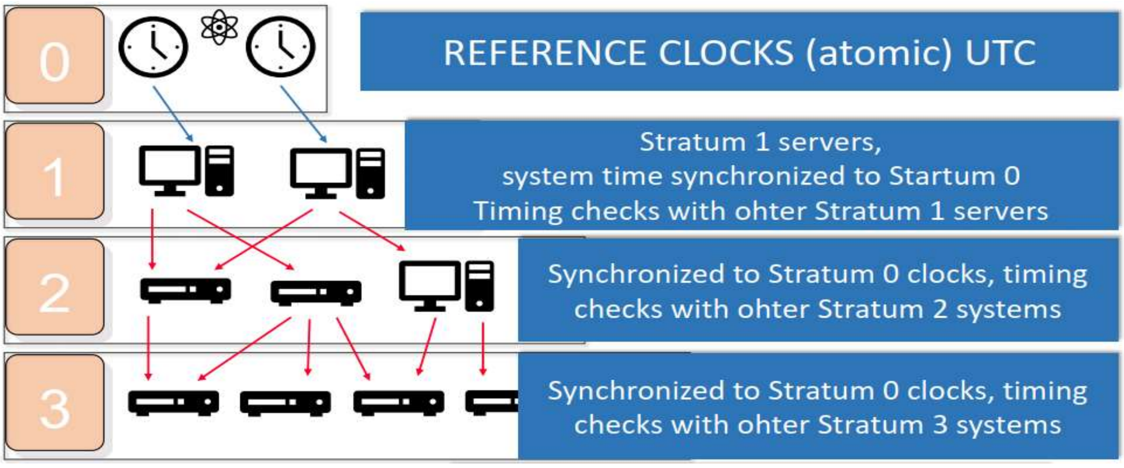


Figure 19 NTP Stratum level hierarchical tree

Table 3 Accuracy of NTP Stratum levels

Level	Free-Run Accuracy [s]	Adjusted Range or Accuracy [s]	Holdover Accuracy 24h [s]	Time to Fist Frame Slip	Clock Type
Stratum - 1	1,0E-11	1,0E-11	N/A	72 days	Cesium or GPS
Stratum - 2	1,6E-8	1,6E-8	1E-10	7 days	Rubidium
Stratum – 3E	4,6E-6	1,0E-6	0,00000001	3,5 hours	Precision quartz
Stratum - 3	4,6E-6	1,0E-6	3,7E-7	6 min	Transport frame
Stratum - 4	3,2E-5	3,2E-5	N/A	4 sec	Customer premises clock

According to the table 3, GPS is classified as Stratum level 1. GPS controlled digital oscillators are classified hence Stratum level 2.

Stratum level 2 free run accuracy is t_acc = 16 ns which means in spatial length *SPL* = ±4,8 m. Short term drift t_drift = 0,1 nsec, in spatial length *SPL* = ±0,03 m. *The SPL* indicates the distance that radio waves propagate in the propagation environment during this time *t_acc* or *t_drift.* (t_acc can be considered as a standard deviation of a random value)

Thus, uncertainty is already prescribed when measuring TDOA principle, but this can be improved by using additional methods and estimations.

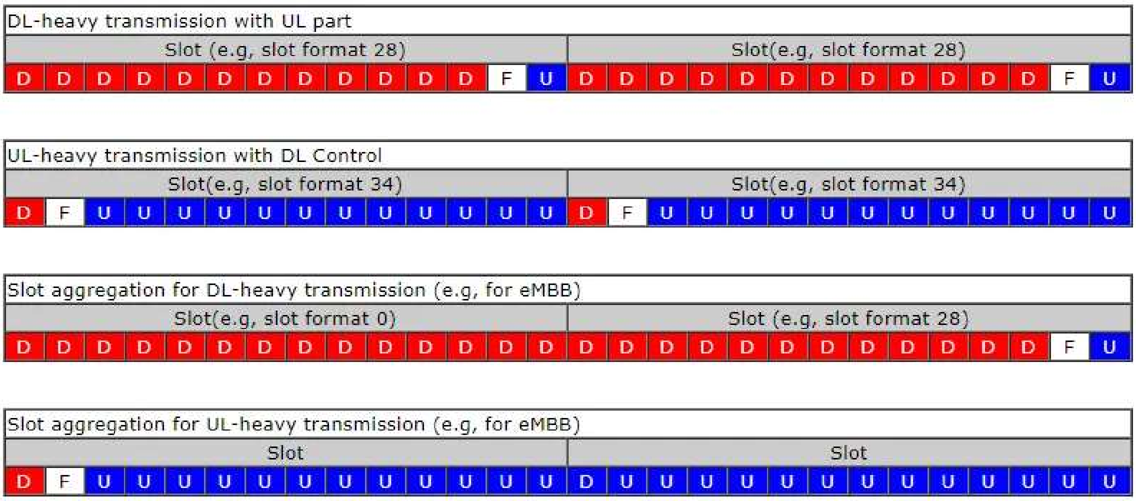
3.4 5G-NR Physical Layer PHY allocation and radio frame overview

3.4.1 Radio Resource allocation – duplexing techniques

There are two duplexing techniques used in 5G-NR, Time Division Duplex (TDD) and Frequency Division Duplex (FDD). FDD technique uses two carrier frequencies f_c. One is for Uplink (UL) and one is for Downlink (DL). TDD technique uses same frequency f_c for UL and DL. Both techniques have advantages and disadvantages. When one or the other technique is more suitable is shown in Table 4Table 4.

Table 4 TDD and FDD advantages and disadvantages [35]

Feature	5G FDD	5G TDD
Application	FDD version is used where both uplink and downlink data rates are symmetrical.	TDD version is used where both uplink and downlink data rates are asymmetrical.
Frame structure	FDD frame structure type is used.	TDD frame structure type is used.
Interference with neighbouring Base Stations	Less	More
Deployment type	Not suitable for very dense environments.	It is used in very dense deployments with low-power nodes.
Frequency bands	It is preferable for lower frequency bands.	It is preferable for higher frequency bands usually above 10 GHz.
Channel response	Downlink and uplink channel responses would not match perfectly due to different frequency bands used in both these directions.	It matches and hence TDD delivers better performance in MIMO/Beamforming algorithms compare to FDD.



DL-heavy transmission with UL part
Slot (e.g, slot format 28) | Slot(e.g, slot format 28)
D D D D D D D D D D D D F U D D D D D D D D D D D D F U

UL-heavy transmission with DL Control
Slot(e.g, slot format 34) | Slot(e.g, slot format 34)
D F U U U U U U U U U U U U D F U U U U U U U U U U U U

Slot aggregation for DL-heavy transmission (e.g, for eMBB)
Slot(e.g, slot format 0) | Slot (e.g, slot format 28)
D D D D D D D D D D D D D D D D D D D D D D D D D D F U

Slot aggregation for UL-heavy transmission (e.g, for eMBB)
Slot | Slot
D F U U U U U U U U U U U U D U U U U U U U U U U U U U

Figure 20 5G-NR flexible radio resource allocations, symbols: D – DL; U – UL; F – Flexible [36]

In current project used TDD duplexing technique. TDD allows to use radio resources very flexible and smartly depending on Downlink (DL) and Uplink (UL), resource needs. Of course, different DL/UL resource allocations (configuration – slot format) cannot be used on the same radio channel at the same time. It is flexible as shown in the Figure 20, these are quite extreme situations.

Slot formats are defined in 3GPP standard 38.213 table 11.1.1 – NR Physical layer procedures for control [11].

3.4.2 General overview of 5G-NR Radio frame structure

5G-NR radio frame structure is illustrated in Figure 21. Resource Element (RE) is a smallest part in Resource Grid (RG), RE is Resource Element, RE is a part of subcarrier in one OFDM symbol. According to the 3GPP standard TS 38.211 [4], in case of Normal Cyclic Prefix (CP = Normal), in Table 5 are default relations between the Numerology μ, Number of slots in subframe $N_{slot}^{subframe,\mu}$, Number of slots in frame $N_{slot}^{frame,\mu}$, and Number of symbols within a slot N_{symb}^{slot}.

Table 5 Frame parameters according to Numerology, CP = NORMAL

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

5G-NR Resource element indexing and one subframe resource grid is explained more detail in Figure 22

Symbols used in Figure 22:

$\bar{l}$ – OFDM symbol number in subframe, k - subcarrier number, l - OFDM symbol number in slot, N_{RB}^{μ} – number of RB -s in RG, N_{SC}^{RB} – number of subcarriers in RB, $N_{symb}^{subframe}$ – number of OFDM symbols in subframe.

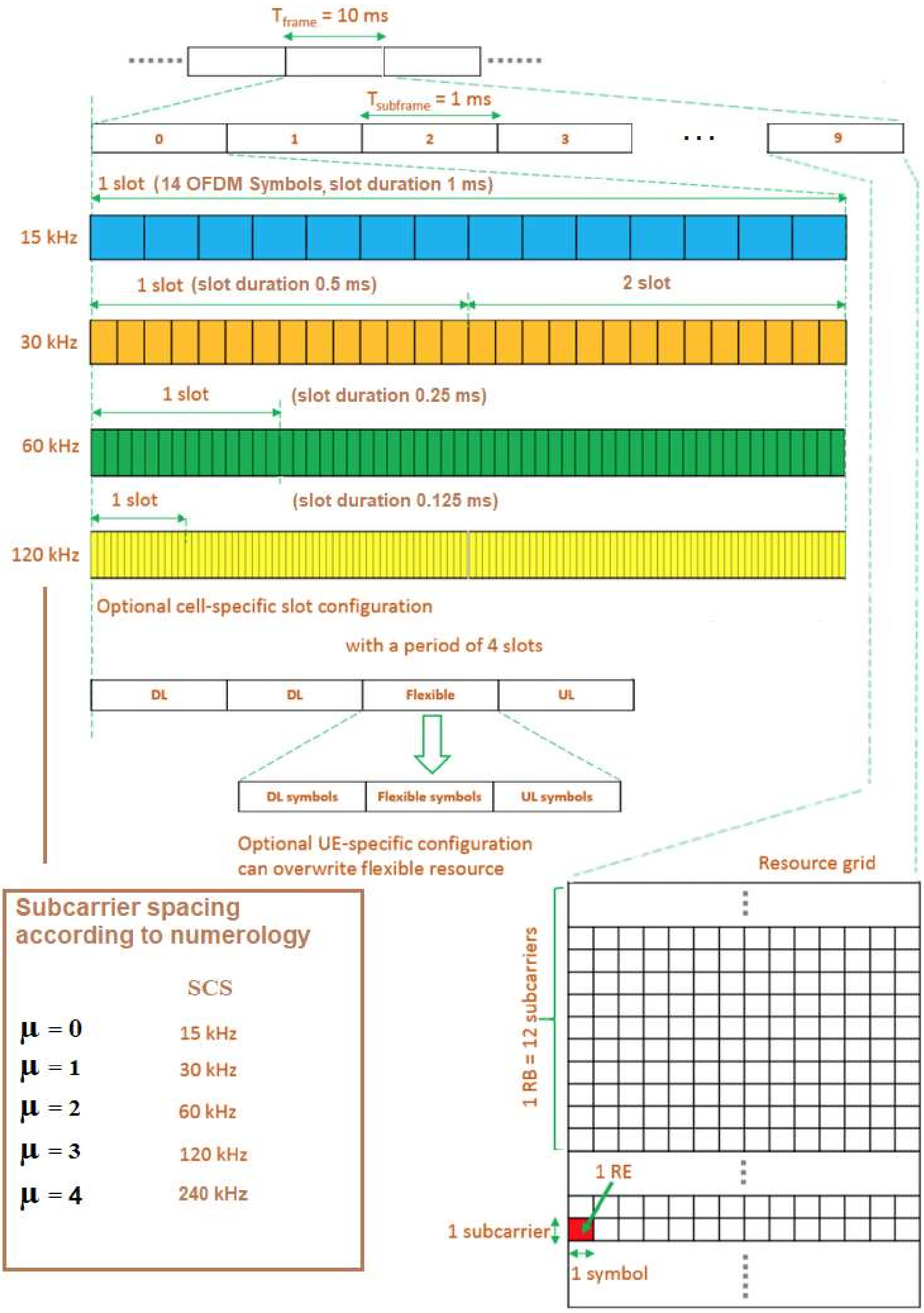


Figure 21 General overview of 5G-NR Radio frame structure [12]

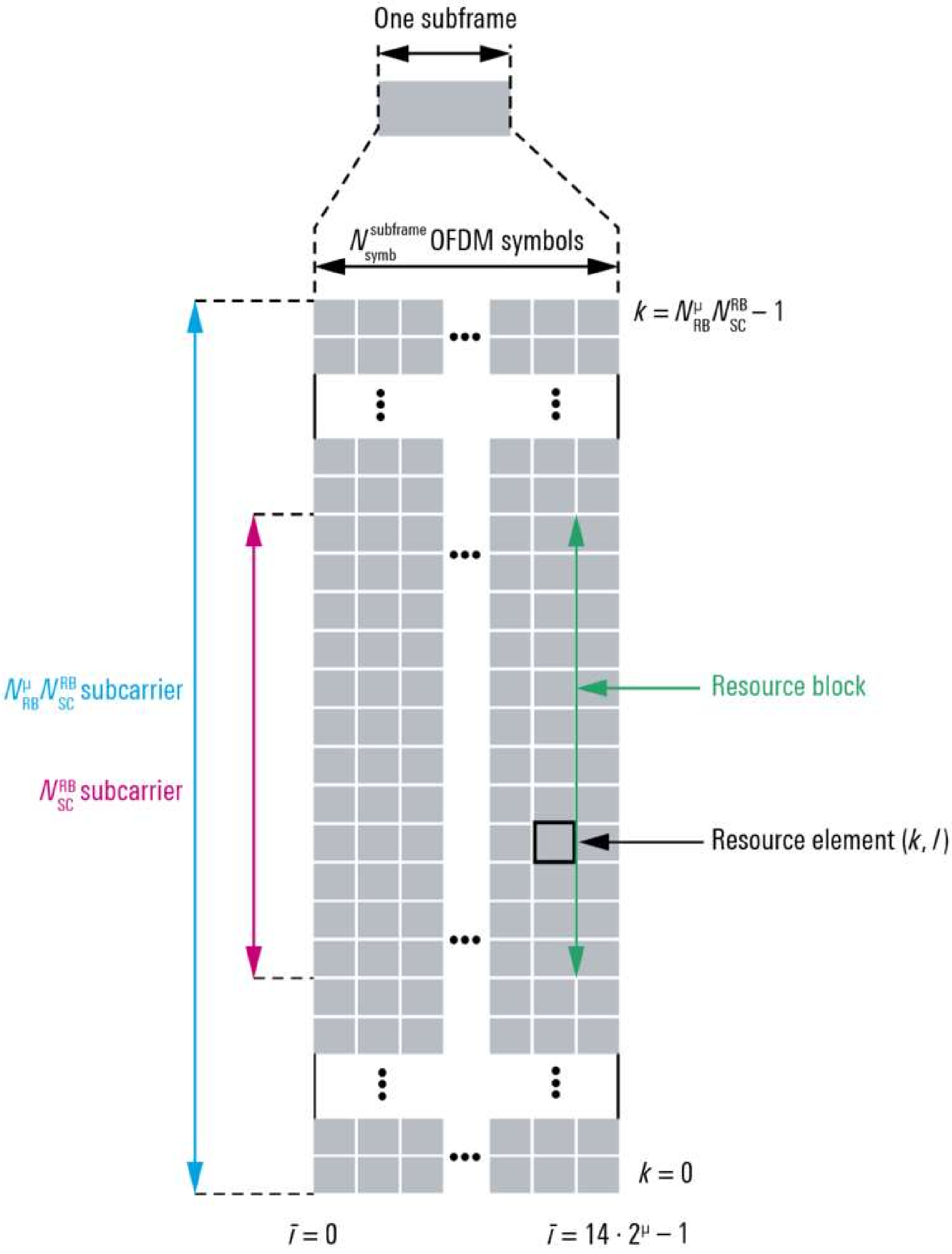


Figure 22 5G-NR Resource Block and Resource elements

The main reason why CP is needed between OFDM symbols is the fact that if the radio signal reaches the device over the multiple paths with different lengths. There will inevitably be a delay between the signal received directly and the signal that has travelled a long way. Multipath propagation can cause unwanted overlap between the symbols, this is called Inter Symbol Interference (ISI). To avoid ISI, the Guard Interval (GI) is added between symbols. Very common method is rotate the copy of symbol tail to the symbol head. The idea is that the beginning and end of the symbol are identical throughout the GI. It allows receiver to detect where the symbol starts in time domain. It is very complicated task, but using CP instead of empty GI, makes it much easier. The symbol start detector just cross-correlates the input signal samples with the delayed signal samples by the duration *T* of the symbol.

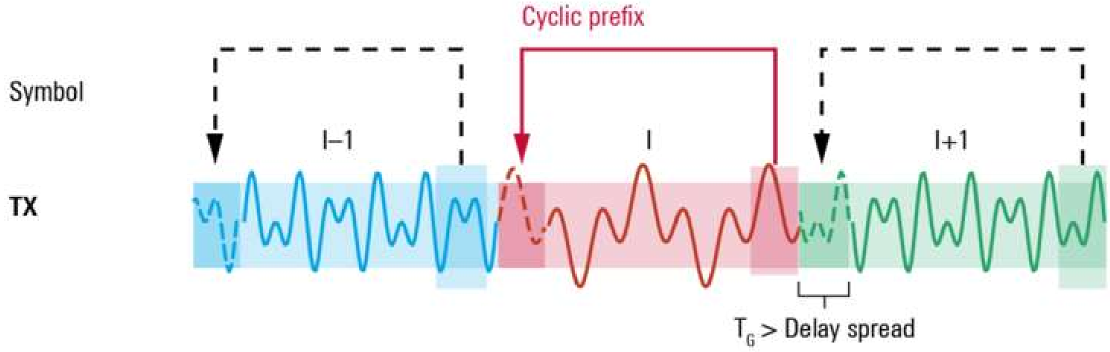


Figure 23 Principle of NR CP, the part of samples from symbol end copied to the symbol beginning [1]

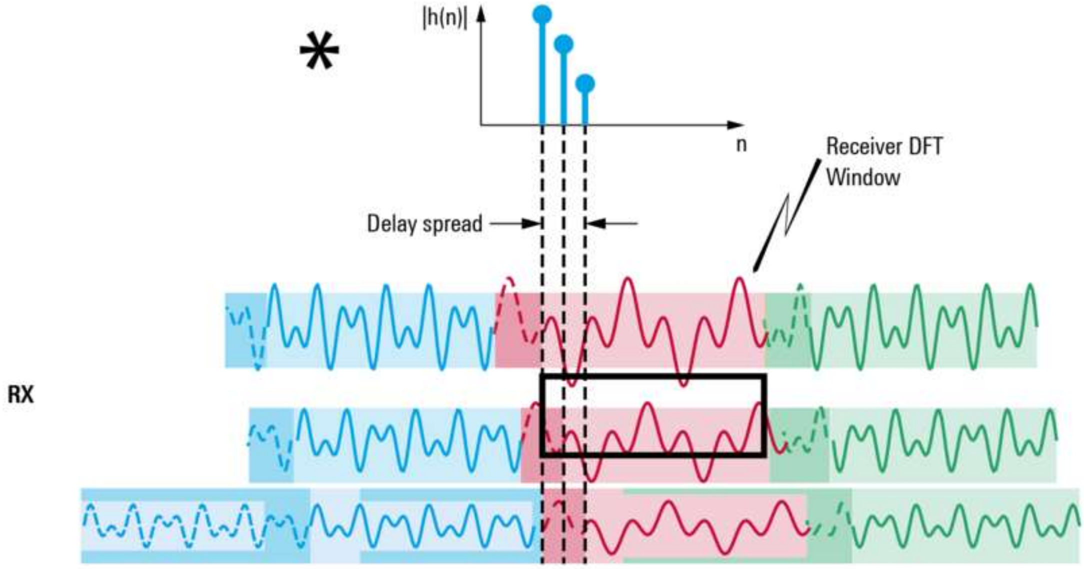


Figure 24 OFDM symbol reception on receiver side when CP is used Impulse response |h(n)| in DFT (Discrete Fourier Transform) window depending on delay spread [1] [25]

Figure 24 illustrates OFDM symbol reception on receiver side when CP is used.

CP option “Normal” or “Extended” is available for numerology μ = 2 (NR and NG-RAN Overall description 3GPP TS 38.300 table 5.1.1 [13]), CP duration depends on OFDM symbol duration. OFDM symbol- and CP durations are listed in following table:

Table 6 Duration of CP according to numerology

Parameter / Numerlogy (μ)	0	1	2	3	4
Subcarrier Spacing (KHz)	15	30	60	120	240
OFDM Symbol Duration (μs)	66,67	33,33	16,67	8,33	4,17
Cyclic Prefix Duration (μs)	4,69	2,34	1,17	0,57	0,29
OFDM Symbol including CP (μs)	71,35	35,68	17,84	8,92	4,46
CP “Normal” - N, “Extended”- E	N	N	N / E	N	N

3.5 Gold Codes

Gold codes – Gold sequences are binary codes named after Robert Gold and they are widely used in telecommunication for Code Division Multiple Access (CDMA), also in Global Positioning System (GPS). Gold codes are pseudo random codes which have very small cross correlations with all other codes in order. It allows to use same frequency band more efficiency in same time.

3.5.1 M-sequence

Signals can be classified as deterministic and random. Deterministic signals are completely defined by one or more variables. The sequence of the random signal is not known. Random signals are described by statistics or probability. The random signal of natural origin is for example, thermal noise in an electrical conductor. In ideal the random signal does not repeat, it is unique. Thus, the cross-correlation between two random signals is very small. M-sequence have property which is similar to the thermal noise. If it is desired to generate a signal that does not seem to repeat, a M-sequence can be used. Sufficient complexity and length M-sequence has properties close to random binary sequence, but it is actually still deterministic – pseudo-random sequence. Of all pseudo-random signals, a good property is that they can be generated in a determined manner and this makes frequency hopping and spread spectrum communication possible, because an identical copy of the pseudo-random signal generated by the transmitter can also be generated by the receiver.

Frequency hopping is widely used in military communication, if the enemy does not know how the sequence changes, he cannot eavesdrop on the communication, at least not in real time. Frequency hopping is also used in Bluetooth and mobile communication, it helps prevent complete data loss, or loss of availability, for example, if part of the radio channel is disturbed. The energy of the spread spectrum signal is spread over a wide frequency band and is difficult to distinguish from noise, which is why it is widely used in military technology, such as radars. The enemy does not understand that he is in the radar surveillance area, he cannot detect the radar signal from the radio ether. Another good feature of a spread spectrum signal is noise immunity, for example, narrowband noise generally does not interfere with spread spectrum communication. In Figure 25 is the example M-sequence. The sequence is generated with a 3 bit shift register. This M-sequence repeats in every 7 symbols. The longer the D trigger chain, the longer the repetition interval.

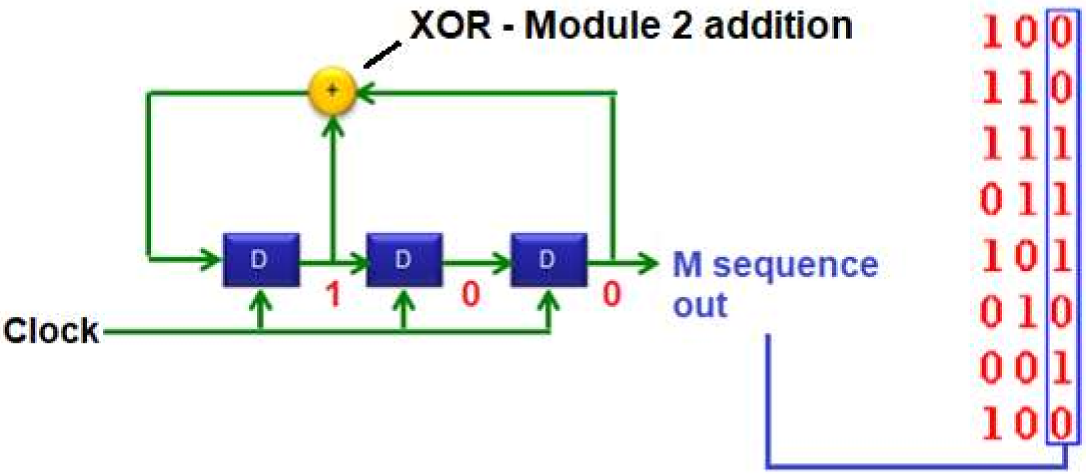


Figure 25 D-Trigger-based M - sequence generator principle $G = 1 + x + x^3$ [15]

Modul operation in computer programming is simple division with residue, known in mathematics.

For example:

10 mod 7 is 3, because 10 : 7 = 1, remainder 3;

10 mod 10 is 0, because 10 : 10 = 1, reminder 0;

2 mod 10 is 2, because 2 : 10 = 0, reminder 2; And so on

In a binary number system, the order value can only be 0 or 1. For Bitwise operation must be at least two arguments x_0 and x_1 in Table 7:

Table 7 Module 2 addition and XOR Truth table compared

Argument values		Mod 2 addition (⊕)	XOR
x_1	x_0	$y = (x_1 + x_0) / 2$	y
0	0	0	0
0	1	1	1
1	0	1	1
1	1	0	0

OR operation is also called as logical addition, hence the symbol "+" indicates the OR operation in Table 7. Widely used Module 2 addition symbol in diagrams is ⊕.

The D – trigger (Delay) is transparent with a high clock cycle. The output changes at "HIGH" Clock Signal (Clock) level, transitions of D trigger are in Table 8.

Table 8 D trigger transition table

Clock	D	Qt	Qt+1	Clock	D	Qt	Qt+1
0	0	0	0	1	0	0	0
0	1	0	0	1	1	0	1
0	0	1	0	1	0	1	0
0	1	1	0	1	1	1	1

In general, it can be said that trigger D holds the state of the output until the next clock cycle, so it works as memory during one clock cycle.

The M-sequence generator is fully feasible as a hardware solution, using XOR Gates and D triggers, they are very fast, but it is all feasible in software as is the case with OAI

Since the M sequence has the characteristics of a random signal, its frequency spectrum is also similar to that of a random binary signal – Figure 26.

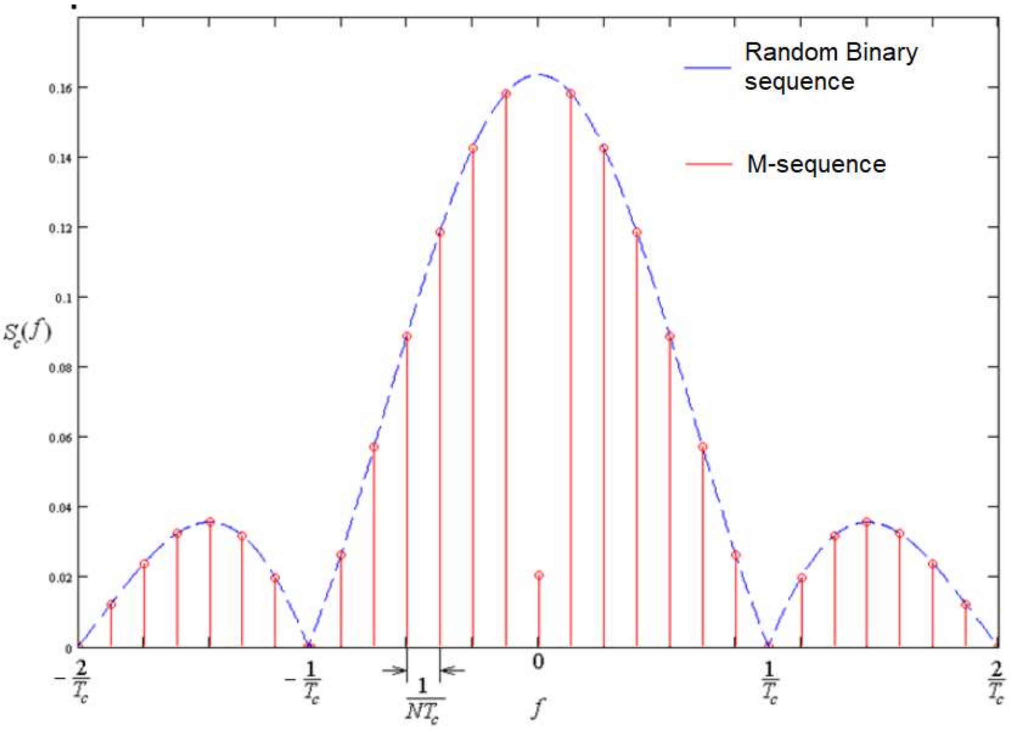


Figure 26 Frequency spectrum diagram of M – sequence

3.5.2 Gold sequence

Gold sequences are generated from two pseudo random M sequences. Module 2 addition used to add two M-sequences.

M-sequence generators in Figure 27, based also on D triggers and feedback loops via module 2 adders, like was described in previous chapter 3.5.1, usually realized in hardware-based solutions, depends on use cases. In this thesis project it is running in software, because it is more flexible, changes are easy to make, but it requires part of the computer performance. The figure of the hardware generator clearly explains well the principle of generating the Gold sequence.

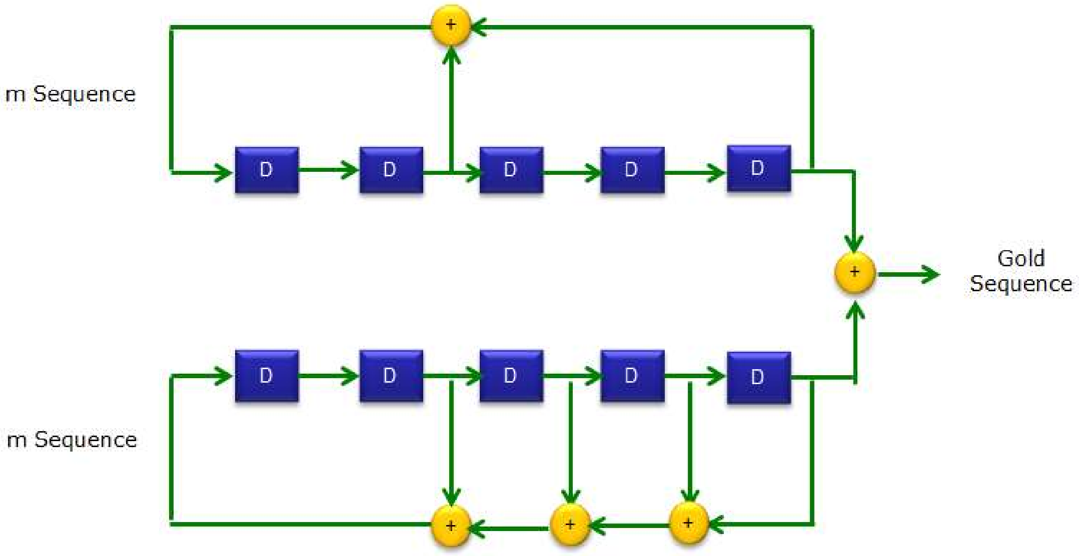


Figure 27 Gold code generation principle, generator polynomials G1 = $1 + x^2 + x^5$, G2 = $1 + x^2 + x^3 + x^4 + x^5$ [15]

Gold code autocorrelation and cross correlation comparison in Figure 28, the result is more similar to the random sequence. Red line in comparison example is Gold code autocorrelation result. Gold code cross-correlation with other code in the sequence (green line) gives the result which is similar to random signal cross-correlation (blue line).

Sequence 1 = {0 1 1 0 1 0 0 0 1 1 0 0 1 0 0 1 0 1 0 0 0 1 0 0 0 1 1 0 1 1 1 0 1 0 1 0}

Sequence 2 = {0 1 0 0 1 0 0 0 0 0 1 0 1 1 0 0 1 1 0 0 0 0 0 1 1 1 0 0 0 1 1 1 0 1 1 0}

Random sequences used in this example:

Sequence 1 = {0 1 1 0 0 0 1 10 1 1 0 1 0 1 0 0 0 0 1 0 1 0 0 0 1 0 0 0 1 0 1 0 1 0 1}

Sequence 2 = {0 0 0 1 1 1 0 1 1 1 1 1 0 1 0 0 1 0 0 1 1 0 1 0 1 1 0 1 1 1 1 0 0 0 1 1}

These Gold sequences are generated using 5G PRS Gold sequence generator.

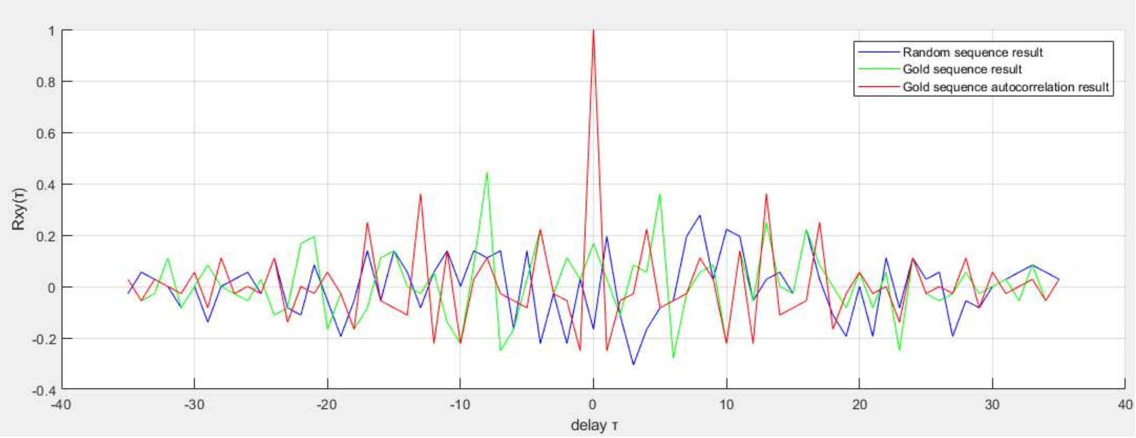


Figure 28 Gold- and random sequence cross correlation compared with same Gold sequence autocorrelation

4 Testbed Development of 5G NR PRS

Focus on this task is PRS resource generation in network node – gNB and transmit it to the air (radio ether), create testbed for positioning accuracy measurements and experiments in Open Air Interface platform (OAI). All PRS configuration settings can be selected manually, so without LMF support. A PRS resource is set of resource blocks filled with a prs signal in one slot. In Figure 29 are shown Two PRS resources with repetition.

The integration stages of PRS signal generator to the OAI project shortly:

- PRS simulations in Matlab

- Familiarization with OAI procedures and program structure
- Create PRS parameter objects, which would be configurable from core network side for 5G NR flexibility
- Generate NR PRS signal in C language according to the standard 3GPP TS 38.211 chapter 7.4.1.7 [4].
- Integrate NR-PRS signal generator to the OAI.
- Map OFDM symbols with generated NR PRS resources to the Physical Downlink Resource Blocks (PHY DL RB -s) according to the standard 3GPP TS 38.211 chapter 7.4.1.7 [4].

4.1 5G-NR Positioning Reference Signal simulation in Matlab

Graphical visualization is indisputably the best way to understand what is happening in NR radio frame and PHY RB -s (Physical Resource Blocks). PRS signal visualization capability is available in new Matlab version 2021 5G-NR toolbox.

Matlab signal parameter variables and short description:

In Matlab simulation is used same parameters which are used in OAI implementation. This allows to compare the simulation results with OAI implementation.

For PRS signal generation is required to define multiple signal- and system related parameters. There are many predefined and initialized objects in Matlab 5G toolbox. Before PRS signal generation, radio resource parameters must be defined first. For example N_{RB} -s (Number of Resource Blocks), *SCS* (Subcarrier Spacing), … etc. In general the *SCS* and Slot configurations together called as Numerology μ – it is handled more detail in capture 1.6.2 In 5G-NR OAI project the Numerology configuration is set to
$\mu = 1$ (project variable „*mu*")

It is very common to use universally understood or standard variable names, for this reason, also the standard variable names are used in this project.

In Matlab 5G toolbox is object *„nrCarrierConfig"*:

Table 9 Carrier configuration parameters and values used in simulation and OAI [16]

Parameter	**Short description**	**Value used in project**
NCellID	Physical layer cell identity	0
SubcarrierSpacing	Subcarrier spacing in kHz	30
CyclicPrefix	Cyclic prefix length	'Normal'
NSizeGrid	Number of RBs in carrier resource grid	106
NStartGrid	Start of carrier resource grid relative to CRB 0	0
NSlot	Slot number	0
NFrame	System frame number	0
SymbolsPerSlot	Number of OFDM symbols per slot N_{symb}^{slot}	14
SlotsPerSubframe	Number of slots per 1 ms subframe $N_{slot}^{subframe,\mu}$	2
SlotsPerFrame	Number of slots per 10 ms frame $N_{slot}^{frame,\mu}$	20

Creating carrier configuration object in Matlab: *carrier = nrCarrierConfig;*

Object for PRS „*nrPRSConfig*", which includes 15 predefined PRS signal parameters. In Table 10 are described the list of „*nrPRSConfig"* parameters used in simulation.

Table 10 NR PRS configuration parameters and values used in simulation [17]

Parameter	**Short description**	**Value used in project**
PRSResourceSetPeriod	PRS resource set slot periodicity and slot offset	[10 3]
PRSResourceOffset	Slot offset of each PRS resource	[1 4]
PRSResourceRepetition	PRS resource repetition factor	2
PRSResourceTimeGap	Slot offset between two consecutive repeated instances of a PRS resource	2
MutingPattern1	Muting bit pattern option-1	[ ] not defined
MutingBitRepetition	Muting bit repetition factor	1
MutingPattern2	Muting bit pattern option-2	[ ] not defined
NumPRSSymbols	Number of consecutive OFDM symbols allocated for each PRS resource	12
SymbolStart	Starting OFDM symbol of each PRS resource in slot	1
NumRB	Number of PRBs allocated for all PRS resources	106
RBOffset	Starting PRB index of all PRS resources relative to carrier resource grid	0
CombSize	Comb size of all PRS resources	4
REOffset	Starting RE offset in first PRS OFDM symbol of each PRS resource	2
NPRSID	Sequence identity of each PRS resource	0
FrequencyOffsetTable	Frequency offsets table (Table 7.4.1.7.3-1 [4]))	4 x 13 table

Creating PRS configuration object in Matlab: *prs = nrPRSConfig;*

If PR-Signals need to be received from a distant neighbouring base station, the propagation time is longer, thus, there must also be a longer time period between PRS signals, therefore the PRS resource period - *PRSResourceSetPeriod* is configurable. The nominal value of *PRSResourceSetPeriod* must equal 2^{μ} multiplied by one of the values in the set:

{4, 5, 8, 10, 16, 20, 32, 40, 64, 80, 160, 320, 640, 1280, 2560, 5120, 10,240} [4].

In Figure 29 is shown generated PRS signals with resource repetition. PRS resource repetition allows to increase positioning accuracy, because averaging multiple measurements can reduce the random error. All parameters in simulation have been selected as used in 5G-NR OAI, it gives good overview, when and at which slot the signal must be generated in the OAI PHY procedure cycle. For comparison of signals without symbol repetition is Figure 30, OFDM symbols by the slot order are shown in Figure 31. It is possible to repeat PRS resource up to 32 times during one sequence, depending on PRS resource set periodicity.

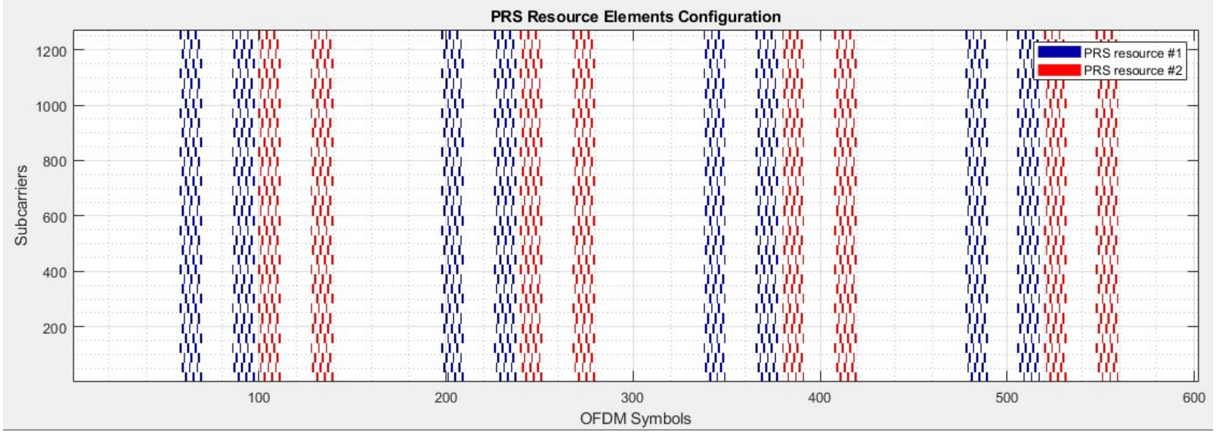


Figure 29 Generated PRS signals with OFDM symbols repetition

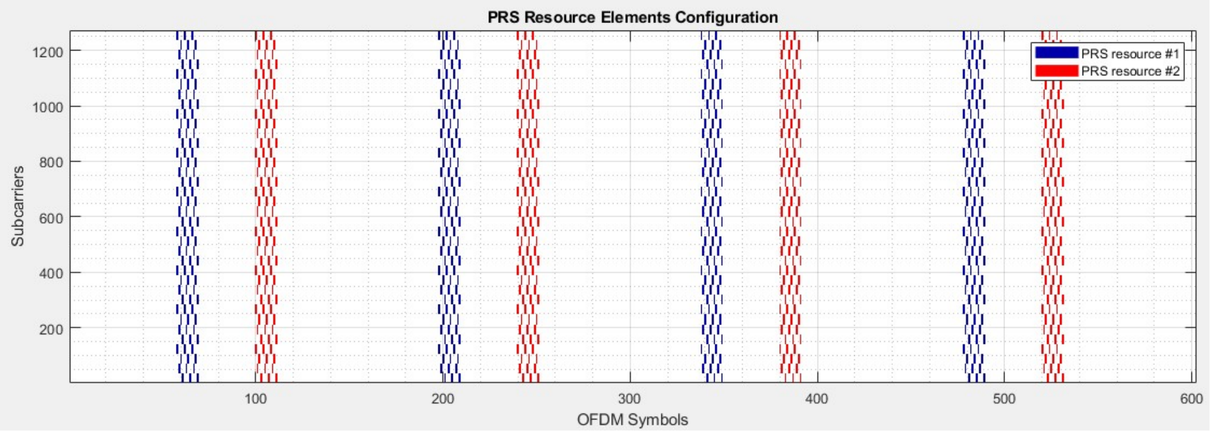


Figure 30 Generated PRS signals without OFDM symbols repetition

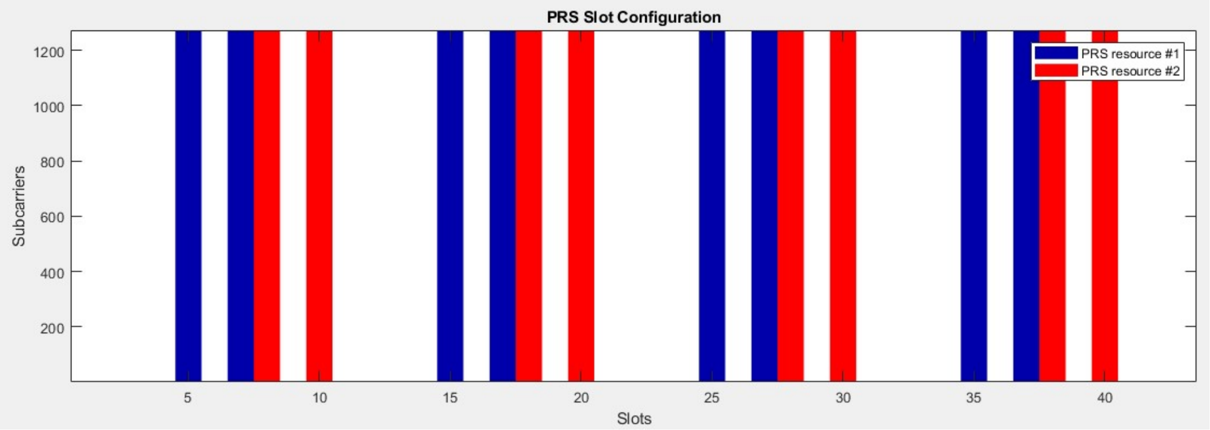


Figure 31 Generated PRS OFDM symbols by the slot order

4.2 Setting up hardware

Two Mini PCs have been used to run 5G OAI - Gigabyte BRi5 – 8250. Installed Ubuntu version 18.04.5 LTS

Two Ettus USRP B210 are used to access the radio network (USRP - Universal Software Radio Peripheral, RRU – Remote Radio Unit)

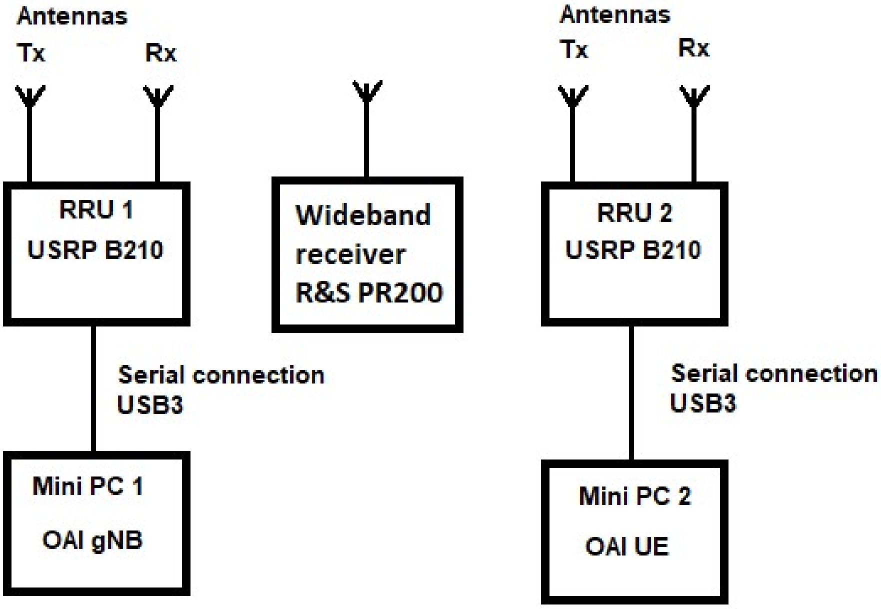


Figure 32 5G OAI and RRU connection diagram, wideband receiver for signal measurements

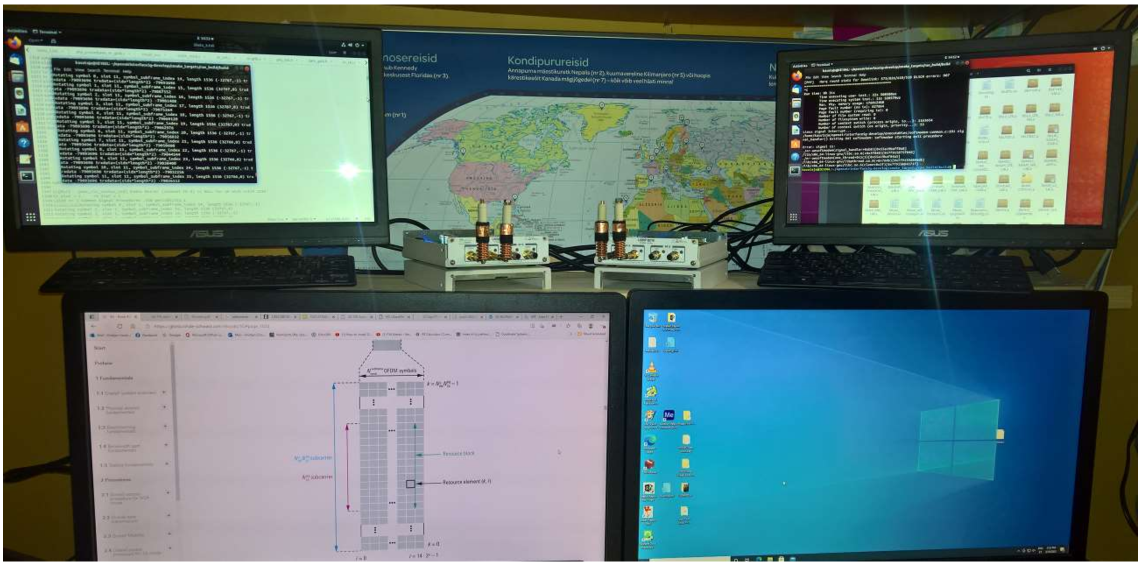


Figure 33 Radio hardware (RRU) Ettus USRP B210

Figure 34 Gigabyte Mini PC -s for 5G OAI

The GPSDO (GPS Disciplined Oscillator) module is optional USRP accessory, which allows to synchronize multiple devices using GPS clock signal without any additional reference resources. It is also used in current setup – Figure 35. GPS antennas must be placed outdoor to receive satellite signals, but if it is not possible, then alternatively external reference sources are used. This option must be added as a command line parameter, when staring NR-softmodem:

--*clock*: tells hardware to use a clock reference (*0*: internal, *1*: external, *2*: gpsdo)

The PPS signal – Pulse Per Second. It is accurate *t* = 1 sec pulse signal. GPSDO generates also *f* = 10 MHz frequency reference, same as REF IN in Figure 35

Figure 35 Synchronization capabilities on USRP B 210

Dimensions of antennas used in the project:

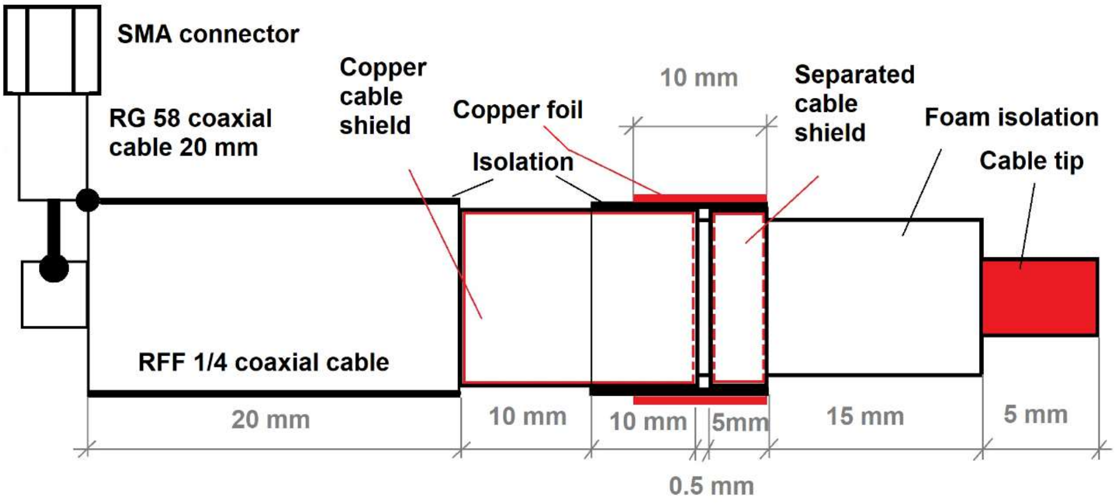


Figure 36 Handmade f = 3619 MHz antenna dimensions

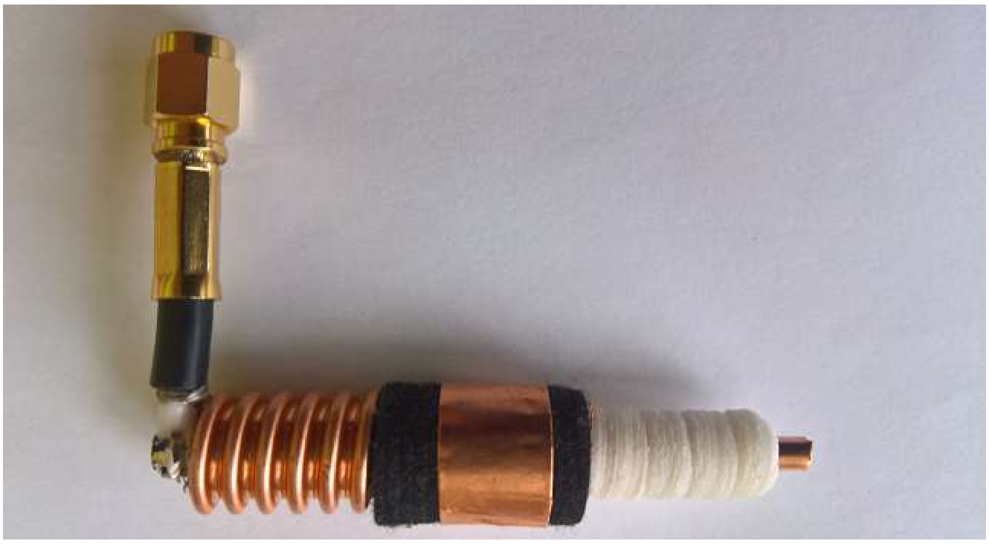


Figure 37 Photo of used antenna

M : 3.6192 GHz
Ref: -1 dB
Att: 10 dB
48.6 + j3.26 Ω
1.4e+02 pH
SWT: 1 s
FSH-Z2: Smith Chart
M: 3.6192 GHz
Center: 3.619 GHz
Span: 2 MHz

Figure 38 Antenna tuning result at f = 3619 MHz Z = 48.6 + j 3.26Ω

The antennas are tuned to the center-frequency defined in the OAI, *f* = 3619,2 MHz.

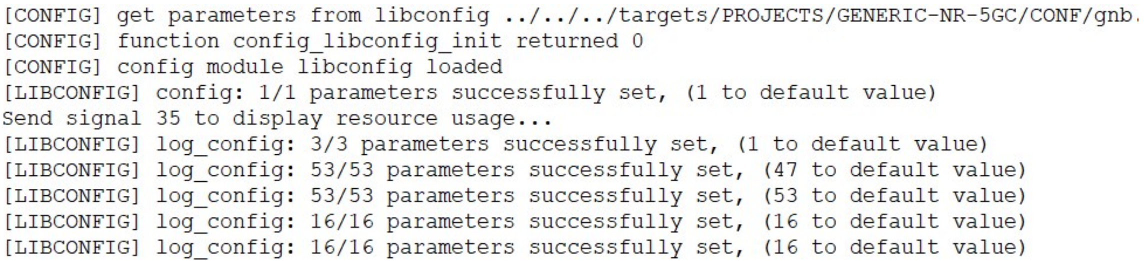
This is in NR operating band n78. The table of NR radio channels is included in Appendix 2.

4.3 Parameters and settings used in OAI

This chapter investigates working principles of current OAI software.

When the “nr_softmodem” program starts, the first steps are parameter initializations and loading configurations from configuration file:

~/targets/PROJECTS/GENERIC-NR-5GC/CONF/gnb.sa.band78.fr1.106PRB.usrpb210.conf



```
[CONFIG] get parameters from libconfig ../../../targets/PROJECTS/GENERIC-NR-5GC/CONF/gnb.
[CONFIG] function config_libconfig_init returned 0
[CONFIG] config module libconfig loaded
[LIBCONFIG] config: 1/1 parameters successfully set, (1 to default value)
Send signal 35 to display resource usage...
[LIBCONFIG] log_config: 3/3 parameters successfully set, (1 to default value)
[LIBCONFIG] log_config: 53/53 parameters successfully set, (47 to default value)
[LIBCONFIG] log_config: 53/53 parameters successfully set, (53 to default value)
[LIBCONFIG] log_config: 16/16 parameters successfully set, (16 to default value)
[LIBCONFIG] log_config: 16/16 parameters successfully set, (16 to default value)
```

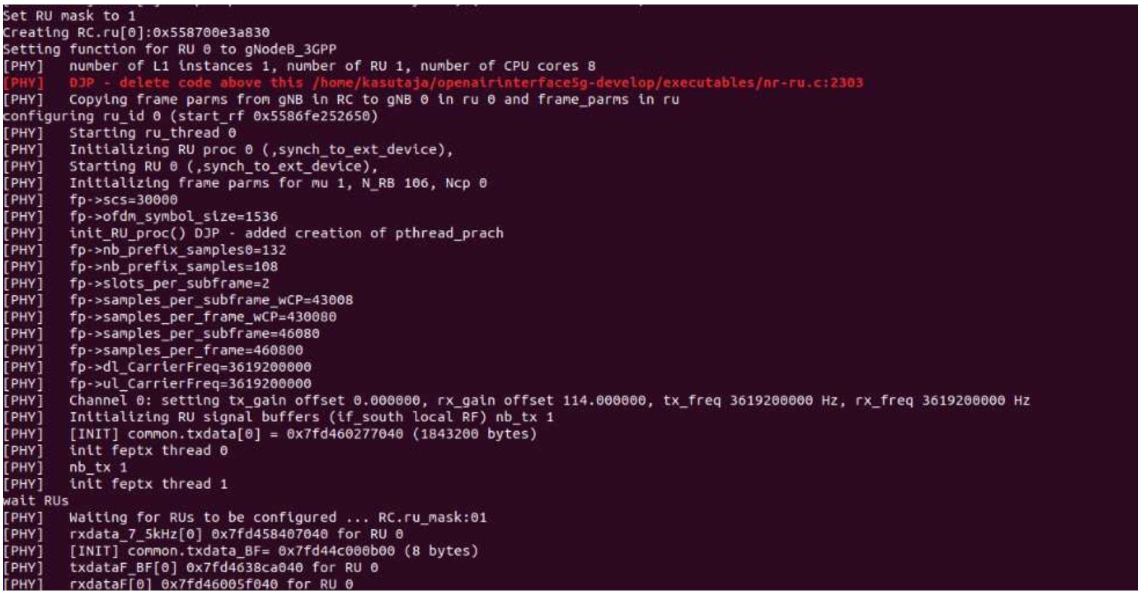
Figure 39 NR_softmodem startup initialization and configuration

In Figure 39 is screenshot of the [CONFIG] and [LIBCONFIG] procedure.

Most of important parameters and initialization values are listed in the startup screen, a short part of startup screen is shown in Figure 40.

Typedefs – type definitions are mostly in “defs_nr_common.h”, and in “defs_nr.h”, but as it was mentioned they are also in other header files. The top-level parameter structure *“PHY_VARS_gNB”* is defined in header file “defs_gNB.h” and it includes frame parameter structure “*NR_DL_FRAME_PARMS frame_parms*”, which is defined in header file “defs_nr_common.h”.

In parameter initialization phase, some parameters will be initialized from file “parms.c”. Parameters which are loaded in [LIBCONFIG] phase are initialized from “*RC.gNB*” structure, this abbreviation means - Resource Config.



```
Set RU mask to 1
Creating RC.ru[0]:0x558700e3a830
Setting function for RU 0 to gNodeB_3GPP
[PHY]   number of L1 instances 1, number of RU 1, number of CPU cores 8
[PHY]   DJP - delete code above this /home/kasutaja/openairinterface5g-develop/executables/nr-ru.c:2303
[PHY]   Copying frame parms from gNB in RC to gNB 0 in ru 0 and frame_parms in ru
configuring ru_id 0 (start_rf 0x5586fe252650)
[PHY]   Starting ru_thread 0
[PHY]   Initializing RU proc 0 (,synch_to_ext_device),
[PHY]   Starting RU 0 (,synch_to_ext_device),
[PHY]   Initializing frame parms for mu 1, N_RB 106, Ncp 0
[PHY]   fp->scs=30000
[PHY]   fp->ofdm_symbol_size=1536
[PHY]   init_RU_proc() DJP - added creation of pthread_prach
[PHY]   fp->nb_prefix_samples0=132
[PHY]   fp->nb_prefix_samples=108
[PHY]   fp->slots_per_subframe=2
[PHY]   fp->samples_per_subframe_wCP=43008
[PHY]   fp->samples_per_frame_wCP=430080
[PHY]   fp->samples_per_subframe=46080
[PHY]   fp->samples_per_frame=460800
[PHY]   fp->dl_CarrierFreq=3619200000
[PHY]   fp->ul_CarrierFreq=3619200000
[PHY]   Channel 0: setting tx_gain offset 0.000000, rx_gain offset 114.000000, tx_freq 3619200000 Hz, rx_freq 3619200000 Hz
[PHY]   Initializing RU signal buffers (if_south local RF) nb_tx 1
[PHY]   [INIT] common.txdata[0] = 0x7fd460277040 (1843200 bytes)
[PHY]   init feptx thread 0
[PHY]   nb_tx 1
[PHY]   init feptx thread 1
wait RUs
[PHY]   Waiting for RUs to be configured ... RC.ru_mask:01
[PHY]   rxdata_7_5kHz[0] 0x7fd458407040 for RU 0
[PHY]   [INIT] common.txdata_BF= 0x7fd44c000b00 (8 bytes)
[PHY]   txdataF_BF[0] 0x7fd4638ca040 for RU 0
[PHY]   rxdataF[0] 0x7fd46005f040 for RU 0
```

Figure 40 gNB startup initialization “mu” == µ

4.4 Investigation of PSS and SSS generators

PSS and SSS signals are mapped to the “*txdataF”* two-dimensional array, but if there is used only 1 antenna port, then only one data vector is used. The “*txdataF”* is declared in top level structure “*PHY_VARS_gNB->common_vars”.*

The generated PSS sequence is in following format:

d_pss = [23170; -23170; -23170; 23170; -23170; -23170; -23170; -23170; 23170; ……]

This form is obtained from binary sequence as follows:

`d_pss[i] = (1 - 2*x[m]) * 23170;`

The zeros in the generated binary sequence are positive and ones are negative.

In 3GPP 38.211 it is given *x(6) x(5) x(4) x(3) x(2) x(1) x(0) =* {1, 1 ,1 ,0 ,1 ,1 ,0};

PSS sequence initial value in OAI “pss.c”:

x_initial = {0, 1, 1, 0, 1, 1, 1}; - so there is used big endian order.

PSS and SSS signals in 5G-NR are BPSK (Binary Phase Shift Keying) modulated, so they have two phase values shown in Figure 41.

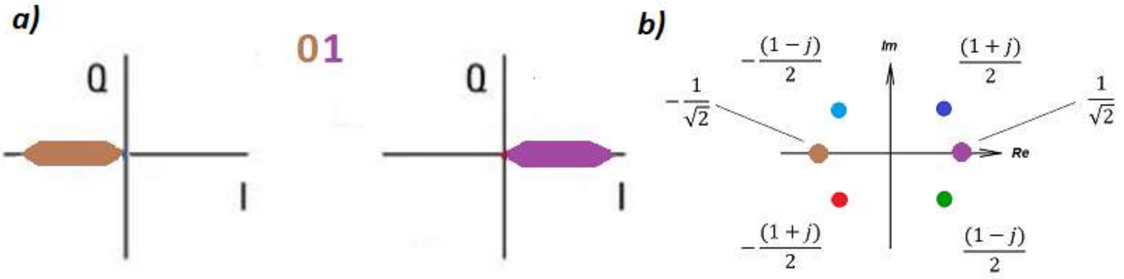


Figure 41 BPSK modulation phasor diagram *a)* BPSK and QPSK signal constellation with mapping values *b)*

Hence the *d_pss* and *d_sss* vectors have only two possible combinations of complex values { 23170 + j0; -23170 + j0 }.

PSS writing to the output array *txdataF* (copy from OAI source code “nr_pss.c”):

```
  a = amp; // amplification a = 512

    // PSS occupies a predefined position (subcarriers 56-182, symbol 0)
within the SSB block starting from

k = frame_parms->first_carrier_offset + frame_parms->ssb_start_subcarrier +
56; //and
    if (k>= frame_parms->ofdm_symbol_size) k-=frame_parms->ofdm_symbol_size;
    l = ssb_start_symbol;

    for (m = 0; m < NR_PSS_LENGTH; m++) {
      ((int16_t*)txdataF)[2*(l*frame_parms->ofdm_symbol_size + k)] = (a *
d_pss[m]) >> 15;
      k++;

    if (k >= frame_parms->ofdm_symbol_size) k-=frame_parms->ofdm_symbol_size;
```

PSS sequence is written to the output array consist of {-363; 363}

$$\pm\frac{a}{\sqrt{2}} = \pm\frac{512}{\sqrt{2}} = \pm 363$$

Value 363 is directly suitable for BPSK modulation (where *a* is amplification value). It is not necessary to implement a separate function for modulation.

The PSS sequence is placed to the output array over one index, imaginary part values are not written, they are zeros.

The size of each OFDM symbol in this project is “*ofdm_symbol_size* = 1536”. The PSS data is written to the *txdataF* array according to the following scheme in Figure 42

OFDM Symbol 0	OFDM Symbol 1	OFDM Symbol 2	OFDM Symbol 3	OFDM Symbol 4	....	End of slot

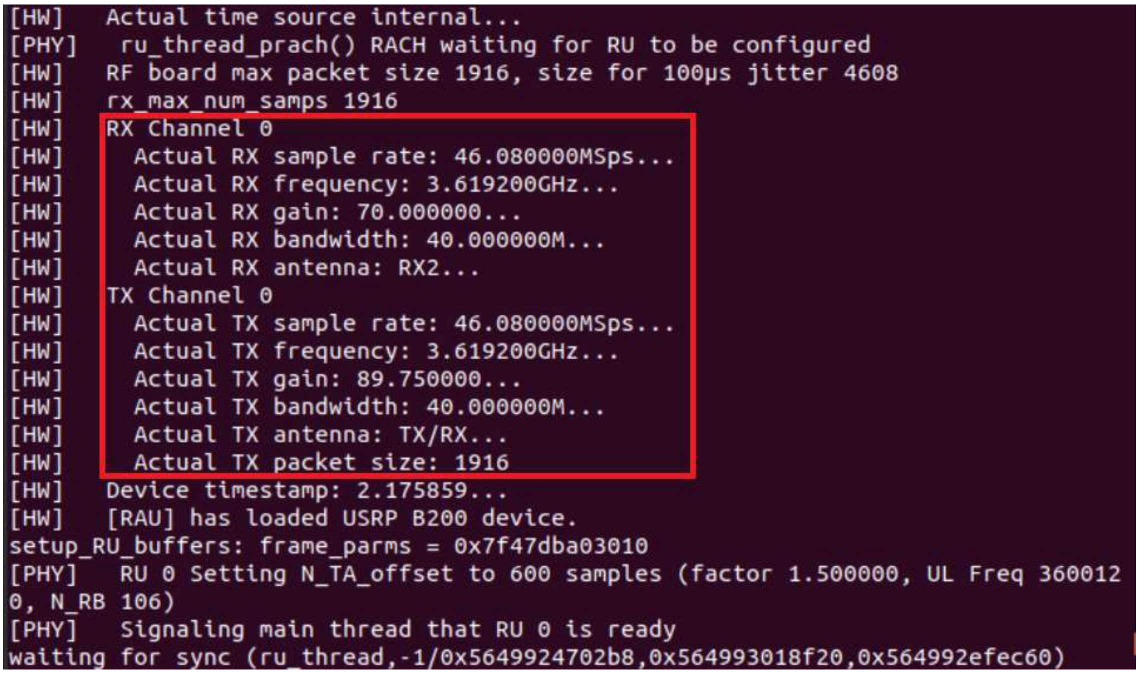
Figure 42 Data mapping to the OAI *txdataF* array

Complex numbers Real and Imaginary part placed in a row and used data type is integer, so the array size is doubled.

To understand, where this number 1536 comes from, you need to go back to the chapter on OFDM numerology – 3.4.2 – Figure 21.

Subcarrier spacing by $\mu = 1$ is $SCS = 30$ kHz, $OFDM\_symbol\_duration = \frac{1}{SCS}$.

Actual TX sample rate is 46.080000 MSps (Mega Samples per second)



```
[HW]   Actual time source internal...
[PHY]   ru_thread_prach() RACH waiting for RU to be configured
[HW]   RF board max packet size 1916, size for 100µs jitter 4608
[HW]   rx_max_num_samps 1916
[HW]   RX Channel 0
[HW]     Actual RX sample rate: 46.080000MSps...
[HW]     Actual RX frequency: 3.619200GHz...
[HW]     Actual RX gain: 70.000000...
[HW]     Actual RX bandwidth: 40.000000M...
[HW]     Actual RX antenna: RX2...
[HW]   TX Channel 0
[HW]     Actual TX sample rate: 46.080000MSps...
[HW]     Actual TX frequency: 3.619200GHz...
[HW]     Actual TX gain: 89.750000...
[HW]     Actual TX bandwidth: 40.000000M...
[HW]     Actual TX antenna: TX/RX...
[HW]     Actual TX packet size: 1916
[HW]   Device timestamp: 2.175859...
[HW]   [RAU] has loaded USRP B200 device.
setup_RU_buffers: frame_parms = 0x7f47dba03010
[PHY]   RU 0 Setting N_TA_offset to 600 samples (factor 1.500000, UL Freq 360012
0, N_RB 106)
[PHY]   Signaling main thread that RU 0 is ready
waiting for sync (ru_thread,-1/0x5649924702b8,0x564993018f20,0x564992efec60)
```

Figure 43 USRP TX channel parameters

The OFDM symbol size must be equal to the size of the FFT window, even though the number of subcarriers is 106 · 12 = 1272.

$$ofdm\_symbol\_size = \text{FFT size} = \frac{Sampling\ rate}{SCS} = \frac{46{,}08 \cdot 10^6}{30 \cdot 10^3} = 1536$$

Table 11 pss.c and sss.c parameters

	l = ssb_start_symbol	*first_carrier_offset*	Starting at index	*ssb_start_subcarrier*
pss	2	900	9088	516
sss	2 + 2 = 4	900	15232	516

These offset values are given from Absolute frequency point A.

Absolute frequency point A is the common reference point in the frequency domain for all resource grids. All resources in frequency domain have offset values from this point.

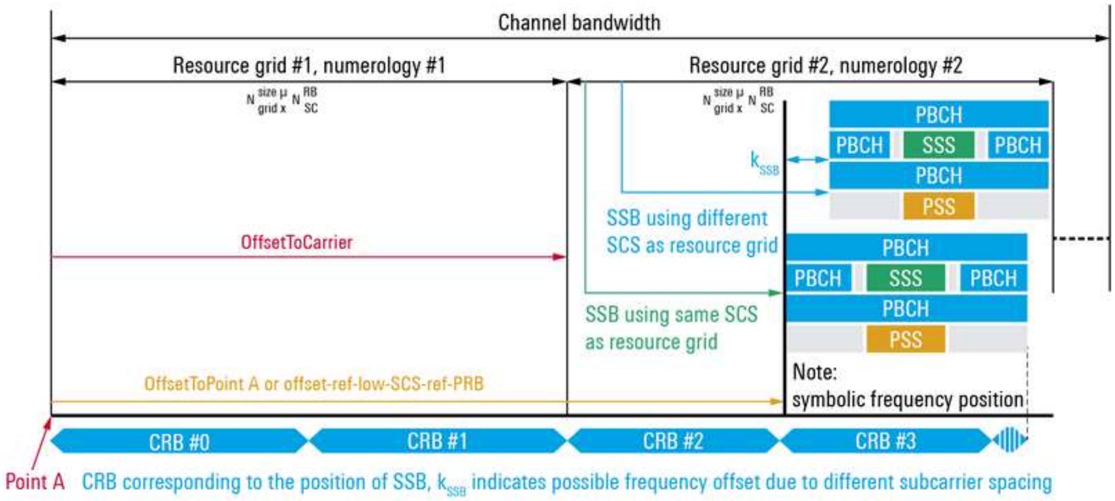


Figure 44 Offsets to Absolute frequency point A [1]

Carrier and resource offsets in OAI project are set in file “nr_params.c”

```
first_carrier_offset = ofdm_symbol_size - (N_RB_DL * 12 / 2) = 1536 – 106 · 6
= 900
```

```
ssb_start_subcarrier = (12 * config->ssb_table.ssb_offset_point_a + sco) =
516
```

The quantity *Kssb* is the *subcarrier offset* *"sco"* from subcarrier 0.

During the PSS symbol writing (mapping) to the *txdataF* array, the lowest index value is 6144 and the highest index value is 9214, mapping is started at index 9088. PSS mapping order is illustrated in Figure 45.

"d_pss" indexes are circular shifted over *index* = 9088;

"*d_sss*" indexes are circular shifted over *index* = 15232;

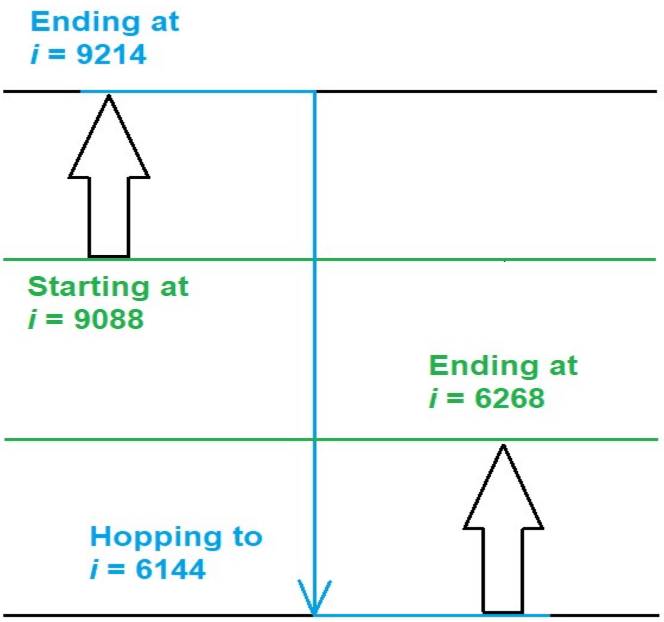


Figure 45 PSS signal mapping indexing order

PSS mapping starting at value $k = first\_carrier\_offset + ssb\_start\_subcarrier + 56 = 1472$

Index shift beginning at 9214 when $k = 1535$, it follows from PSS index calculation:

$$Index = 2(l \cdot ofdm\_symbol\ size + k) = 2(2 \cdot 1536 + 1535) = 9214$$

PSS is located in OFDM symbol 2; $l = 2$.

From the PSS mapping scheme, it can be concluded that the *k* value 0 and 1535 are in the center of the OFDM symbol as it is shown in Figure 46:

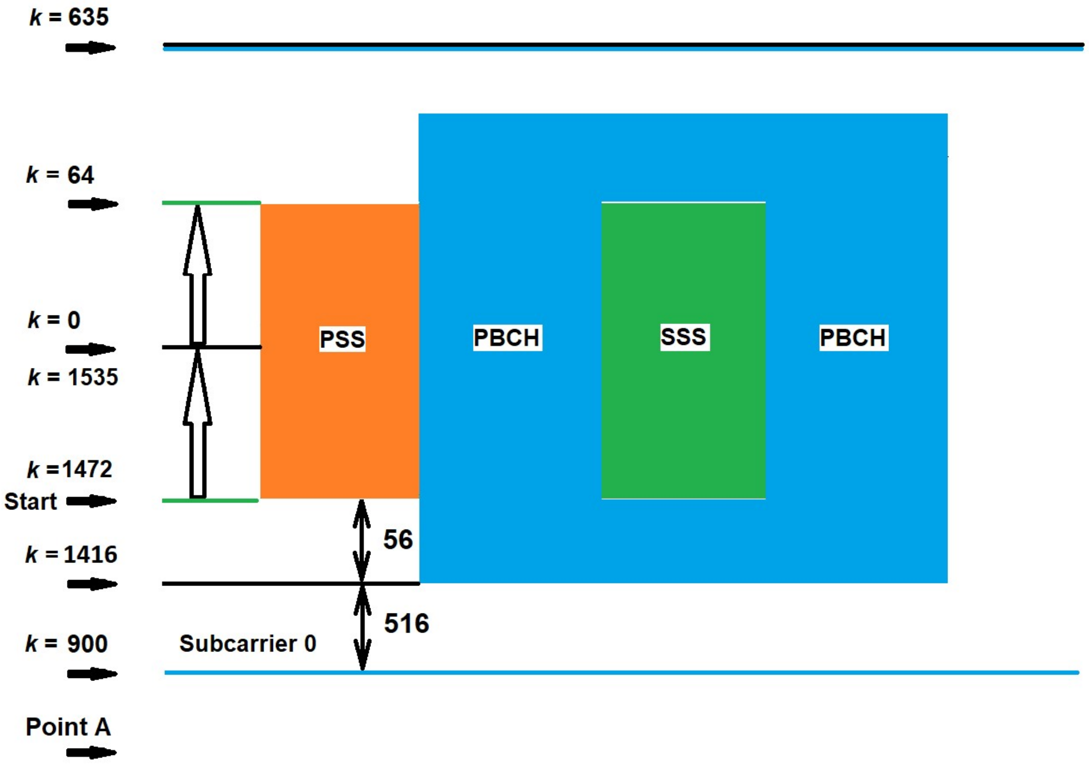


Figure 46 PSS and SSS mapping scheme to the one OFDM symbol

This scheme will also be used for PRS mapping.

4.5 5G-NR PRS generation in C programming language

A simplified flow diagram of the PRS generator is shown in Figure 47. M-sequence *x1* is same for all OFDM symbols, it is generated once, when the program starts. M-sequence *x2* and Gold-sequences are different for each OFDM symbol and they will be generated separately. The Gold sequence is calculated in parts - a total of 5 parts, because part 1, 3, and 4 does not change with same PRS sequence ID value. They are also calculated once. Partial calculation also simplifies the debugging process in development phase. The printout of the generated signal - Figure 48 can be compared to that simulated in Matlab - Figure 11 (printout is in vertically mirrored view).

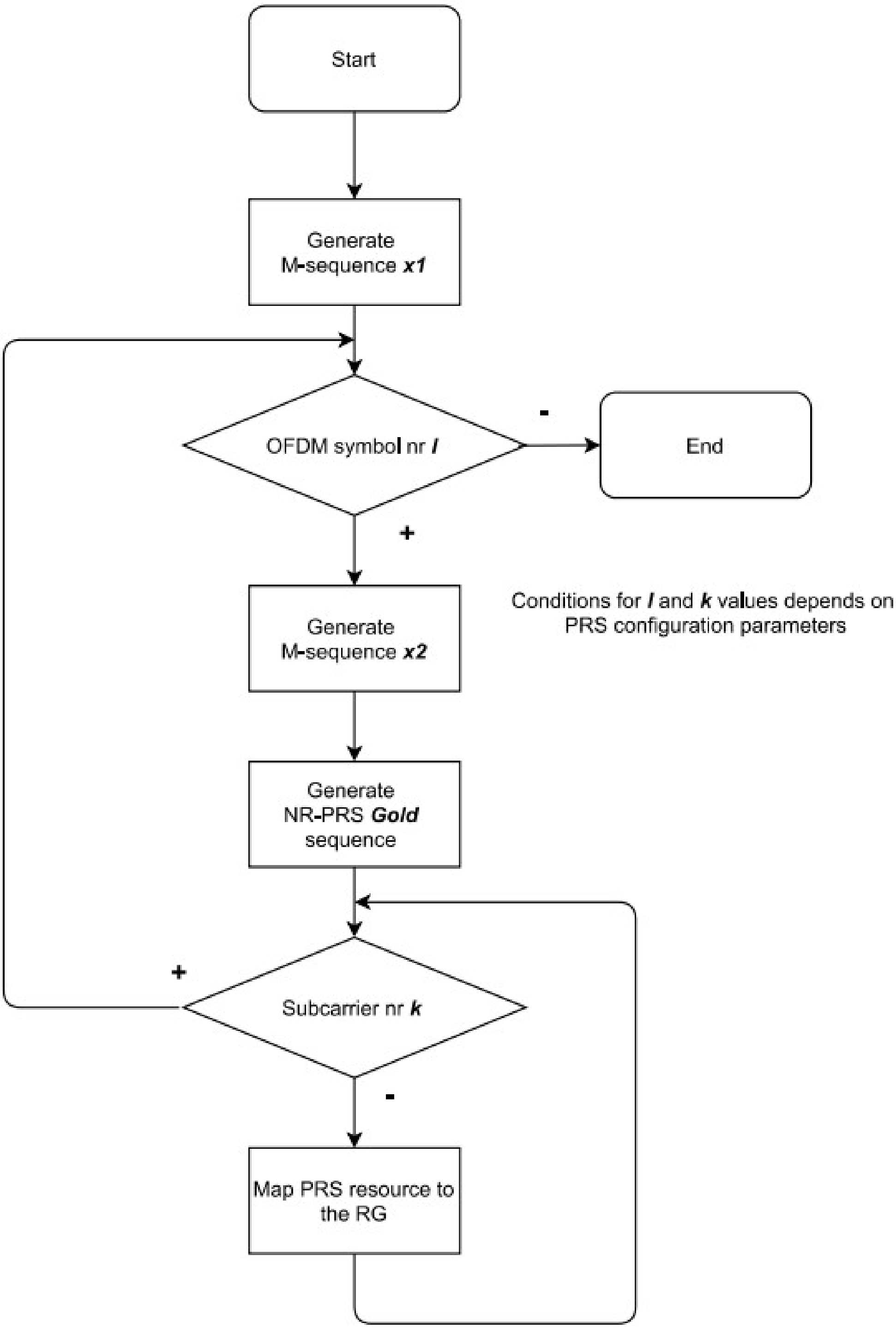
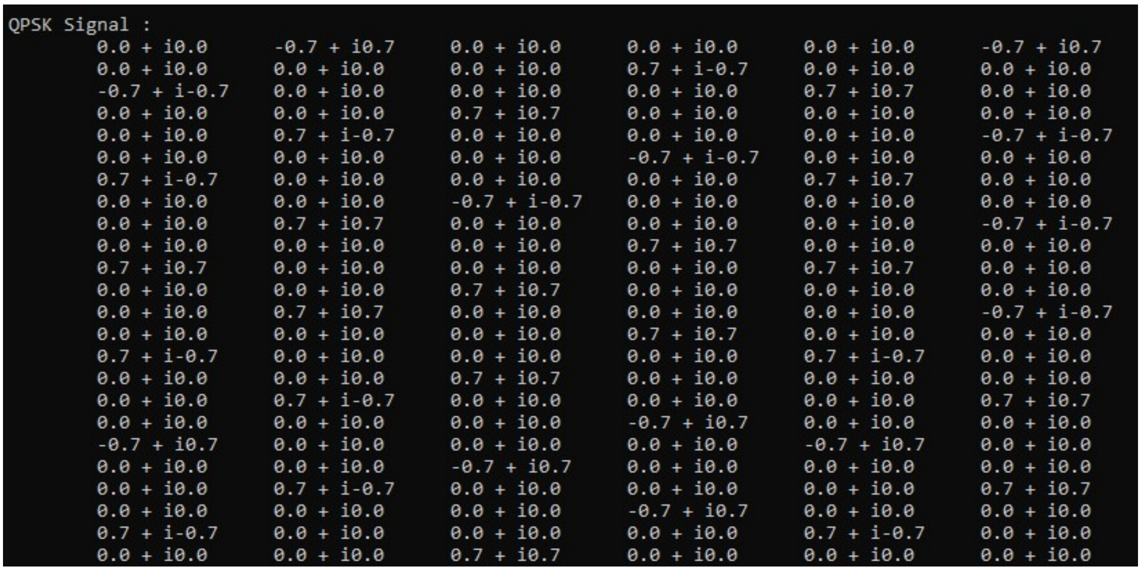


Figure 47 NR-PRS generator flow diagram



```
QPSK Signal :
        0.0 + i0.0      -0.7 + i0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i0.7
        0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i-0.7     0.0 + i0.0      0.0 + i0.0
        -0.7 + i-0.7    0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0
        0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0      0.0 + i0.0
        0.0 + i0.0      0.7 + i-0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i-0.7
        0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i-0.7    0.0 + i0.0      0.0 + i0.0
        0.7 + i-0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0
        0.0 + i0.0      0.0 + i0.0      -0.7 + i-0.7    0.0 + i0.0      0.0 + i0.0      0.0 + i0.0
        0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i-0.7
        0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0
        0.7 + i0.7      0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0
        0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0      0.0 + i0.0
        0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i-0.7
        0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0
        0.7 + i-0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i-0.7     0.0 + i0.0
        0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0      0.0 + i0.0
        0.0 + i0.0      0.7 + i-0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i0.7
        0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i0.7     0.0 + i0.0      0.0 + i0.0
        -0.7 + i0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i0.7     0.0 + i0.0
        0.0 + i0.0      0.0 + i0.0      -0.7 + i0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0
        0.0 + i0.0      0.7 + i-0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i0.7
        0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      -0.7 + i0.7     0.0 + i0.0      0.0 + i0.0
        0.7 + i-0.7     0.0 + i0.0      0.0 + i0.0      0.0 + i0.0      0.7 + i-0.7     0.0 + i0.0
        0.0 + i0.0      0.0 + i0.0      0.7 + i0.7      0.0 + i0.0      0.0 + i0.0      0.0 + i0.0
```

Figure 48 Generated PRS in C programming language (included file prs.c)

4.6 5G-NR PRS generator integration to the OAI

The first step is to create a PRS parameter structure and integrate it with the top-level parameter structure *“PHY_VARS_gNB”*.

PRS parameter structure created in header file *~/openair1/PHY/defs_gNB.h* :

NR_DL_PRS_PARMS prs_parms;

Structure “*prs_parms*” with initialization values added to the appendix 1.

Parameters created in header file *~/openair1/PHY/defs_nr_common.h* :

```
#define MAX_PRS_N_RB 106 //Maximum number of PRB -s allocated for PRS
#define MAX_NR_PRS_LENGTH 2872 //(1600 + 24*PRS_N_RB/PRS_TRANSMISSION_COMB)
#define MAX_PRS_GOLD_LENGTH 1272 //(PRS_N_RB * 24 / PRS_TRANSMISSION_COMB)
#define PRS_N_SLOTS 1 // Number of slots
#define PRS_LEN_X2INIT 26 //M sequence X2INIT length

typedef struct NR_DL_PRS_PARMS NR_DL_PRS_PARMS; // for PRS parameters
```

Generating a PRS signal is quite resource-demanding for a micro-PC. In process flow chart Figure 49 are shown conditions and steps that should be performed when adding a

PRS resource to OAI physical procedures. In current project is not yet implemented the PRS sequence ID comparison with the previous value. Currently, the goal was to generate a PRS resource and transmit it to the air. To improve OAI performance, a PRS resource table is generated, and with the same sequence ID, the signal can be mapped from the table. The PRS table in current project is declared and initialized in function "*phy_procedures_nr_gNB.c* ".

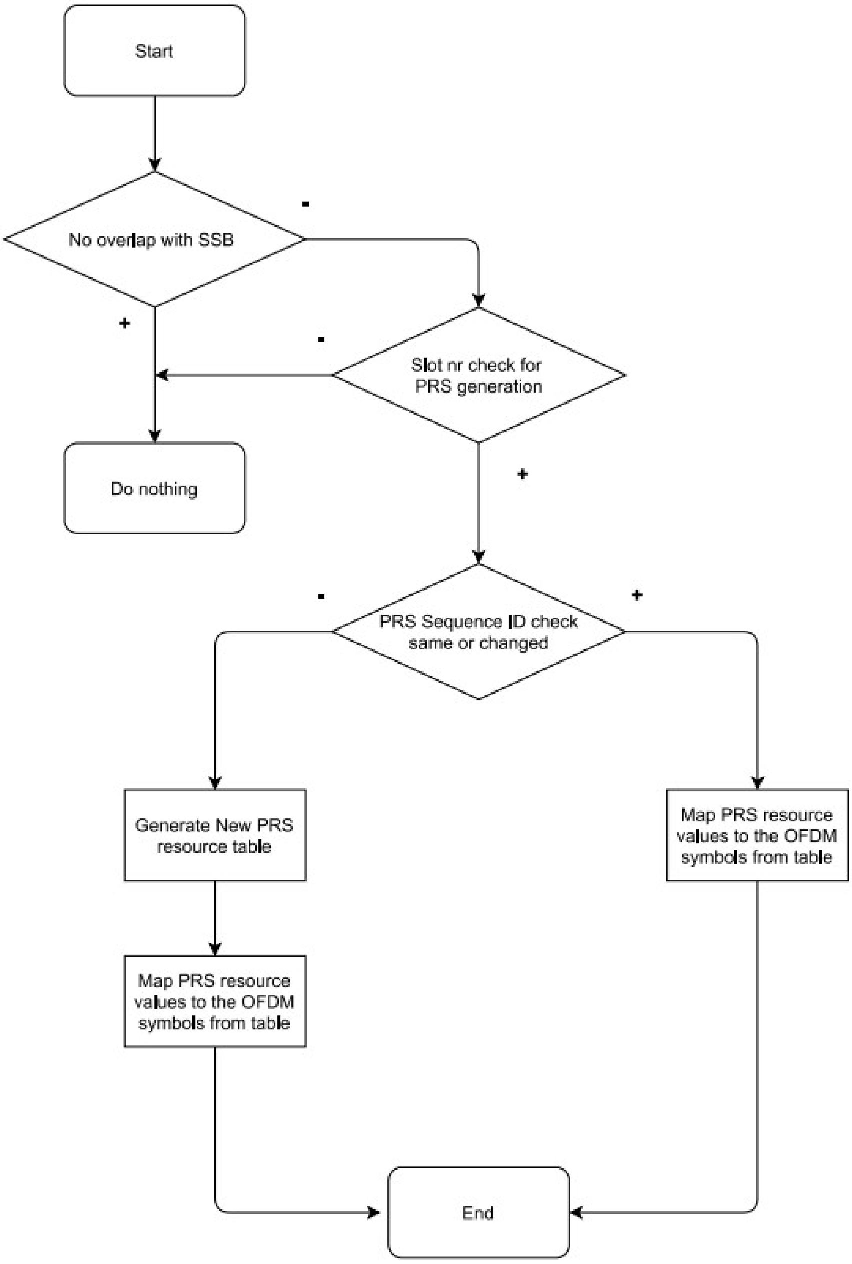


Figure 49 PRS generation scheduling task in NR physical procedures function

PRS parameter initialization and declarations in “*phy_procedures_nr_gNB.c* “:

```
uint8_t prs_in_progress = 1;
static uint8_t generate_new_prs_seq = 1;
static uint8_t prs_init_flag = 0;
if(!(prs_init_flag)){
      get_nr_prs_parameters(prs_parms); //Init PRS parameters
      prs_init_flag = 1;
}
//NR PRS sequence related declarations
uint16_t prs_tab_len = prs_parms->prs_num_of_rb * 12/prs_parms->prs_comb_size
;
static int16_t prs_table[12][2*12*MAX_PRS_N_RB/2]; //max table length
```

Function “*get_nr_prs_parameters”* is implemented in file “*nr_parms.c*”.

All PRS related function prototypes are declared in header file “*nr_transport_proto.h*”. For PRS generator and signal mapping function is created in new file “*nr_prs.c*”. The item is added to the cmake targets list “*CMakeList.txt*”.

Overlap with SSB is not allowed when generating PRS, so the first condition in Figure 49 would check whether SSB is generated in this slot.

NR_PRS_DEBUG can be defined in header file to debug a program.

A 5G_NR signal analyzer would be suitable for checking and analyzing the generated signal like it is shown in Figure 50, but our current situation does not allow the use of such hardware.

Ref Level 0.00 dBm
Freq 28.1 GHz
Mode Downlink, 100 MHz
Capture Time 20.1 ms
BWP/SS All
Att 0 dB
Frame Count 1 of 1(1)
Frame 1
YIG Bypass

Frame Results Selected	Mean
EVM PDSCH QPSK (%)	0.75
EVM PDSCH 16QAM (%)	
EVM PDSCH 64QAM (%)	
EVM PDSCH 256QAM (%)	
EVM All (%)	0.75
EVM Phys Channel (%)	0.75
EVM Phys Signal (%)	0.73
Frequency Error (Hz)	-2.57
Sampling Error (ppm)	0.50
Power (dBm)	-7.34

Figure 50 R&S FSVA3000 5G-NR signal analyser screen view

The R&S PR200 wideband receiver has been used to test the signal, measurement scheme is in Figure 32. Measurement period and resolution bandwidth of R&S PR200 does not allow to measure OFDM symbols with duration 33 μs and subcarrier spacing 30 kHz. Therefore, a special signal is generated for testing purposes, from which it can be concluded whether the 5G-NR resource grid is under control.

TEST can be defined in header file to generate special test signal.

There are generated signals to the desired subcarriers or a signal running diagonally across the frequency band. Test signal generator source code.

```
 #ifdef TEST
//k_test = 635;//900-sc 0, (0 and 1536)-center, 635- max sc //fco is 900
      if(slot_nr == 0) counter= counter + 100;

k_test = counter;

      if (k_test >= frame_parms->ofdm_symbol_size) k_test-=frame_parms-
>ofdm_symbol_size;

      if(k_test >= 635 && k_test < 900 && slot_nr== 0) counter = 900;


((int16_t*)txdataF)[(l*frame_parms->ofdm_symbol_size + k_test)<<1] = 256;

((int16_t*)txdataF)[((l*frame_parms->ofdm_symbol_size + k_test)<<1)+1] = 256;

#endif
```

First line in test signal generator source code generates signals to the desired subcarrier. In Figure 51 is generated test signal to the PSS and SSS start subcarrier, marked with M1, $k = 1472$.

In Figure 52 is generated test signal to the first subcarrier, marked with D2, $k = 900$.

In Figure 53 is generated test signal to the upper subcarrier, marked with D3, $k = 635$.

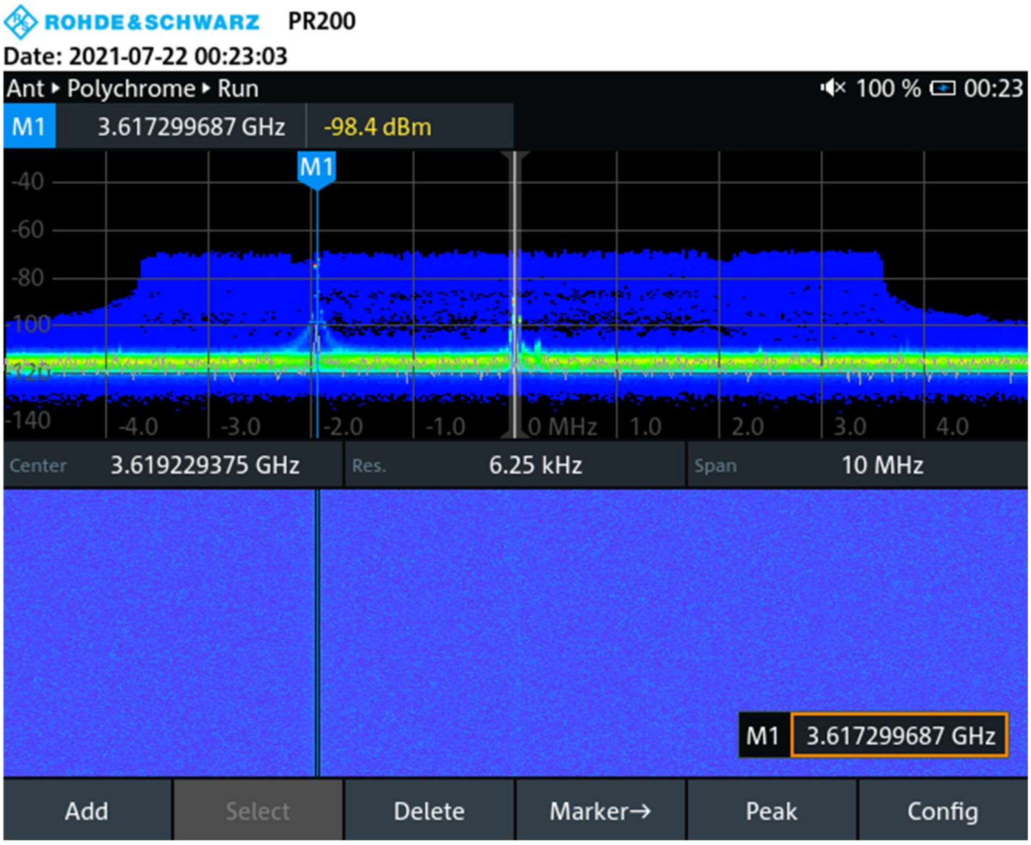


Figure 51 Test signal is generated to the PSS start subcarrier *k* = 1472

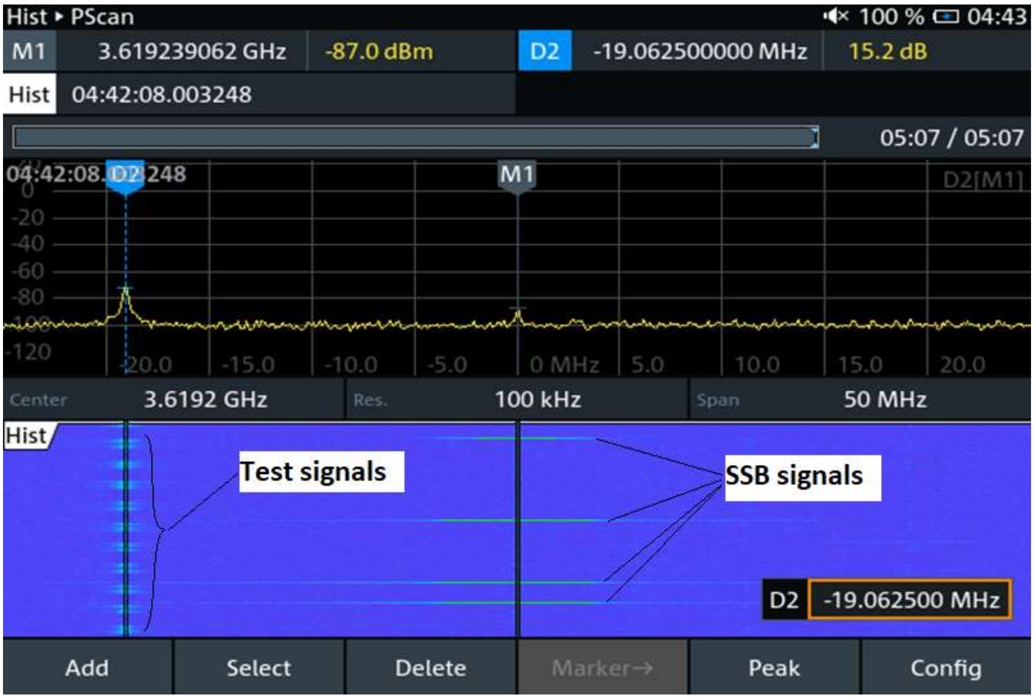
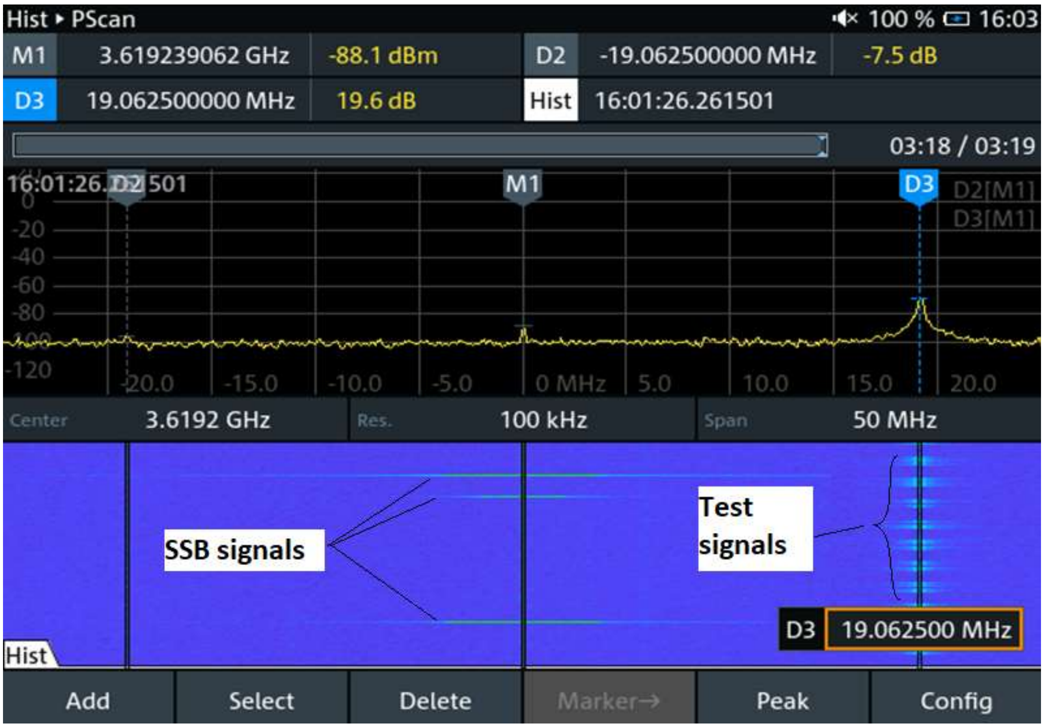


Figure 52 Test signal is generated to the first subcarrier *k* = 900



M1 3.619239062 GHz -88.1 dBm
D2 -19.062500000 MHz -7.5 dB
D3 19.062500000 MHz 19.6 dB
Hist 16:01:26.261501
Center 3.6192 GHz
Res. 100 kHz
Span 50 MHz
D3 19.062500 MHz

Figure 53 Test signal is generated to the upper subcarrier $k = 635$

5 Results

As a result of this work, the 5G-NR positioning reference signals are transmitted to the radio ether. Log file with generated NR PRS signal values is included with this thesis. Short sample is added in Appendix 3. Generating a PRS resource is a computationally intensive process. Regenerating the sequence for each PRS resource significantly affects micro-PC performance. Generating PRS sequence data into a table allows the use of larger PRS resources for positioning. If necessary, several tables can be generated and their data can be used alternately. Signal measurements are made over the radio, like it is shown in Figure 32.

In Figure 54 are generated only Synchronization Signal Blocks (SSB -s) with NR PRS and test signals. PRS resources are generated to the Tx slot nr 15. To check the actual slot nr, there is used debug line in PRS generator source code “*nr_prs.c*” – screenshot of result is in Appendix 4. The other signal generator functions are temporary commented out in OAI source code „*phy_procedures_nr_gNB.c*”. The other signals are commented out, because it helps better to understand where the PRS resources are located on the radio spectrum waterfall - Figure 54.

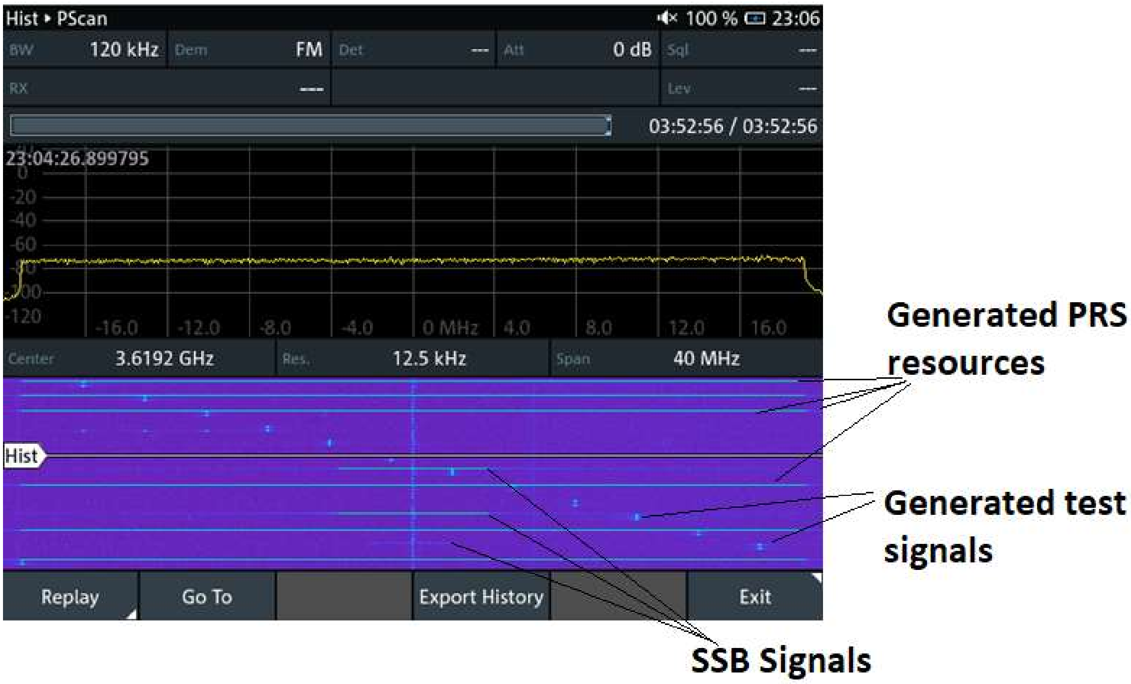

BW 120 kHz
Dem FM
Det ---
Att 0 dB
Sql ---
RX ---
Lev ---
03:52:56 / 03:52:56
23:04:26.899795
Center 3.6192 GHz
Res. 12.5 kHz
Span 40 MHz

Figure 54 Captured PRS resources in Tx slot nr 15 with test signal and SSB signals

In Figure 55 are captured PRS resources and SSB signals, all Tx slots are filled with PRS except the SSB occupied slots. This proves that the entire 5G-NR resource grid is beautifully under control.

Hist ▸ PScan 100 % 19:15

BW 120 kHz
Dem FM
Det ---
Att 13 dB
Sql ---
RX ---
Lev ---

02:15 / 02:18

19:12:56.723313

Center 3.6192 GHz
Res. 100 kHz
Span 40 MHz

Figure 55 Captured PRS resources – all Tx slots are filled except the SSB occupied slots.

Hist ▸ PScan 69 % 20:40

BW 120 kHz
Dem FM
Det ---
Att 0 dB
Sql ---
RX ---
Lev ---

31:46 / 31:46

20:40:10.869875

Center 3.6192 GHz
Res. 100 kHz
Span 40 MHz

Figure 56 Captured PRS resources, SSB and DCI signals.

DCI – Downlink Control Information.

The final captured signals are shown in Figure 56, positioning reference signals are generated to the Tx slots nr 15, all other signals are also enabled. No overlaps with SSB.

6 Conclusions

As a result of this project, using available hardware were developed an additional software, that allows now to generate PRS for future tests and measurements. At the same time, the first part of the positioning capability has been created for the 5G-NR Open Air Interface platform.

- Most challenging part of work was interfacing created software with existing OAI. As a result of this research, it was possible to create functions with a similar structure, which have been previously implemented in OAI. For example, the placement of PRS parameters in a top-level structure "*PHY_VARS_gNB*". This is especially important for real-time changes in PRS parameters.

- This is nice to have a 5G signal analyzer, which greatly simplifies the signal verification procedure. During this work, the methods of verifying and debugging with available devices were worked out:

    1. Special test signals were generated to the single desired subcarrier;

    2. To distinguish PRS on measurement instrument screen, all other 5G-NR physical signal generator function lines except SSB -s in OAI source code were commented out during PRS test;

    3. To check the values of important variables during PRS generation, file logging and OAI display were used.

  The result was verifiable with the existing measuring equipment. The use of a test signals in this work showed that the 5G-NR resource grid is under control.

7 Next steps to use the testbed

1. Improve LIBCONFIG initialization part. It is easier to change PRS parameters in configuration file. This improvement allows to change parameters without compiling each time after the changes are made.

2. If required to make measurements with multiple PRS sequences, then the sequence ID comparison must also be implemented. If PRS sequence ID changes, then the PRS table must be renewed.

3. Testbed tests with additional power amplifier. The use of a power amplifier for the transmission of PRS signals proves necessary if the distance of the device to be positioned is out of range of the test station.

4. Implement the other 5G-NR OAI-UE device to also receive transmitted PRS signals.

5. Implementing positioning algorithm based on those measurements. The positioning algorithm can be improved based on the measurement results repeated with each change to the algorithm.

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45. 3GPP Release 16 introduction. https://www.3gpp.org/release-16

46. Accuracy studies for TDOA and TOA localization. https://www.semanticscholar.org/paper/Accuracy-studies-for-TDOA-and-TOA-localization-Kaune/f7a0431addfba8c8db62f0cfb19940226d1ff7bc

47. Frequency bands used in 5G-NR https://www.etsi.org/deliver/etsi_ts/138100_138199/138104/15.03.00_60/ts_138104v150300p.pdf

Appendix 1 – PRS parameter structure and initial values

```
//prs_params = NULL;
prs_parms->t_prs_period = 10;    //resource set slot periodicity
prs_parms->t_prs_offset = 15;    //slot offset
prs_parms->prs_res_offset[1] = 1;       //it is two dimensional vector
prs_parms->prs_res_offset[2] = 4;
prs_parms->prs_res_repetition = 2;      //PRS resource repetition factor
prs_parms->prs_res_time_gap = 2; //slot offset between two repeated instances
prs_parms->prs_muting_pt_1 = 0;  //muting bit pattern option 1
prs_parms->prs_muting_bit_rep = 1;      //muting bit repetition factor
prs_parms->prs_muting_pt_2 = 0;  //muting bit pattern option 2
prs_parms->prs_num_of_symbols = 12;     //number of PRS symbols
prs_parms->prs_start_symbol = 0; //prs start symbol
prs_parms->prs_num_of_rb = 106;  //number of prb-s allocated for all PRS
resources
prs_parms->prs_rb_offset = 0;    //starting prb index of all prs resources
prs_parms->prs_comb_size = 4;    //prs comb size according to 38.211 7.4
prs_parms->prs_re_offset = 3;    //starting RE offset in first PRS OFDM
symbol of each PRS resource 2 ?
prs_parms->prs_seq_id = 134;            //Sequence identity of each PRS
resource
prs_parms->prs_fr_offs_table = 0;       //frequency offset table according to
38.211 tab 7.4.1.7.3-1
//
```

Appendix 2 – 5G-NR frequency bands

Frequency bands used in 5G-NR [47]

NR *operating band*	Uplink (UL) *operating band* BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) *operating band* BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n86	1710 MHz – 1780 MHz	N/A	SUL

Appendix 3 – Sample of generated PRS Gold sequence values

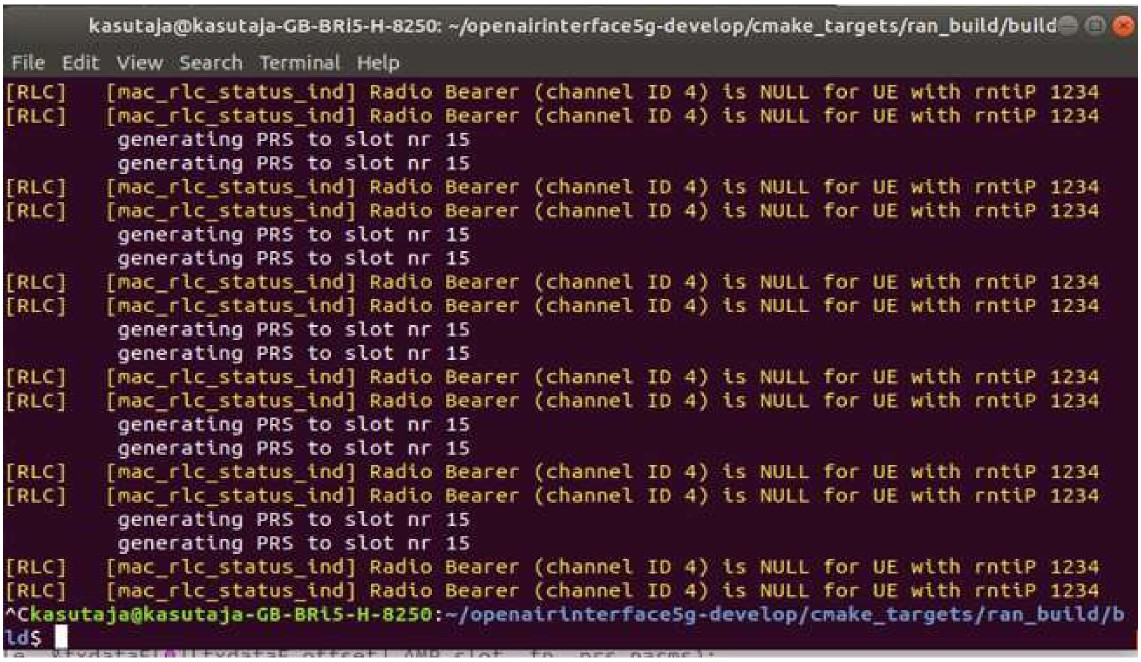
PRS parameters are initialized -- parameters are set in nr_parms.c

prs_len 318

prs_table

```
OFDM symbol nr 0
16384 -16384 -16384 -16384 -16384 16384 -16384 -16384 16384 -16384 16384 -
16384 16384 -16384 -16384 16384 16384 -16384 -16384 -16384 16384 -16384 -
16384 16384 ……
OFDM symbol nr 1
16384 16384 -16384 16384 -16384 16384 -16384 -16384 16384 -16384 16384 -16384
-16384 16384 -16384 16384 16384 -16384 16384 -16384 -16384 16384 -16384 16384
…..
```

Appendix 4 Checking the slot number when mapping PRS



```
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
          generating PRS to slot nr 15
          generating PRS to slot nr 15
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
          generating PRS to slot nr 15
          generating PRS to slot nr 15
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
          generating PRS to slot nr 15
          generating PRS to slot nr 15
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
          generating PRS to slot nr 15
          generating PRS to slot nr 15
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
          generating PRS to slot nr 15
          generating PRS to slot nr 15
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
[RLC]    [mac_rlc_status_ind] Radio Bearer (channel ID 4) is NULL for UE with rntiP 1234
^Ckasutaja@kasutaja-GB-BRi5-H-8250:~/openairinterface5g-develop/cmake_targets/ran_build/b
ld$ 
```

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I Kristjan Soodla

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