OAIBOX™ 5G LAB Manual

This is a living document. Updates will be published online

Acronyms

5G CN	5G Core Network
AF	Application Function
AMF	Access and Mobility Management Function
APN	Access Point Name
AUSF	Authentication Server Function
BLER	Block Error Rate
CBRA	Contention-based Random Access
CFRA	Contention-free Random Access
CN	Core Network
CP	Cyclic Prefix
CQI	Channel Quality Indicator
CSI	Channel State Information
CU	Central Unit
DMRS	Demodulation Reference Signal
DN	Data Network
DU	Distributed Unit
EPC	Evolved Packet Core
FR1	Frequency Range 1
FR2	Frequency Range 2
gNB	gNodeB
IP	Internet Protocol
KPI	Key Performance Indicator
LTE	Long Term Evolution
LoS	Line-of-Sight
MCC	Mobile Country Code
MNC	Mobile Network Code
MNO	Mobile Network Operator
MCS	Modulation and Coding Scheme
N3	A 5G interface between the (R)AN and the UPF
NEF	Network Exposure Function
NGAP	NG Application Protocol
NG	A 5G NR interface located between 5G RAN and 5G Core Network
NI	A brand formerly known as National Instruments. NI currently belongs to Emerson.
NR	New Radio
NRF	Network Repository Function
NSSF	Network Slide Selection Function
OAI	OpenAirInterface™
PCF	Policy Control Function
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Data Shared Channel
PHY	Physical Layer

PRACH	Physical Random Access Channel
PUSCH	Physical Uplink Shared Channel
PUCCH	Physical Uplink Control Channel
RAN	Radio Access Network
RB	Resource Block
RRC	Radio Resource Control
RSRP	Reference Signal Received Power
RSSI	Received Signal Strength Indicator
SA	Standalone
SCS	Sub-Carrier Spacing
SDAP	Service Data Adaptation Protocol
SDR	Software Defined Radio
SINR	Signal to Interference plus Noise Ratio
SMF	Session Management Function
SNR	Signal-to-noise ratio
SRS	Sounding Reference Signal
SS	Synchronization Signal
SSS	Secondary Synchronization Signal
TB	Transport Block
TDD	Time-Division Duplex
UCI	Uplink Control Information
UDM	Unified Data Management
UE	User Equipment
UPF	User Plane Function
USRP	Universal Software Radio Peripheral

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Introduction

Preface

Historically, practical experimentation with cellular networks has been exclusively reserved for network vendors and telecommunication operators. This is primarily due to high equipment costs and licensing constraints. In recent years, the state of play has been changing with the advent of open-source 3GPP protocol stacks based on increasingly more affordable *Software-Defined Radio* (SDR) systems.

In this context, the *OpenAirInterface™* (OAI) project emerges as the leading open-source initiative that provides a 3GPP standard-compliant *Standalone* (SA) architecture implementation of a 5G System composed by the *5G core network* (5G CN), a 5G base station/*gNodeB* (gNB) and the *User Equipment* (UE). This 5G system runs on general-purpose x86 computing platforms along with off-the-shelf SDR hardware platforms.

The OAI is an open-source project established by EURECOM, managed by the OAI Software Alliance (openairinterface.org), and welcomes contributions to anyone who signs the license agreement.

- The OAI software stack is used by many different R&D teams worldwide.
- Apart from being an ideal platform for 5G and 6G collaborative research, we believe that OAI has a strong potential for educating graduate students and training wireless engineers on the practical aspects of 5G cellular networks.
- The OAI code is free for download and use. However, due to its open-source nature and flexibility, it is not meant to be used directly by graduate students in teaching Labs.
- With the OAIBOX™ product line, Allbesmart offers a plug-and-play solution that works as an abstraction layer of open-source complexities, contributing towards the adoption of OAI in teaching labs and training centres.
- The OAIBOX™ product was inspired by our experience as developers, key contributors, and testers of the 5G OAI full stack.
- The OAIBOX™ Dashboard is a web-based platform with pre-defined and easy-to-use 5G configurations, accessible through intuitive menus to facilitate hands-on experiments of 5G use cases.
- End-to-end test results can be measured against *Key Performance Indicators* (KPIs) shown in real-time plots that can be stored for further analysis and discussion.
- This manual includes several 5G Lab exercises to be replicated by students/researchers, addressing many different aspects of the 5G protocol stack.
- For each exercise, a Pre-Lab section summarises the most important background of the 3GPP NR standard, including key references to the *Technical Specification* (TS) required to understand the outcome of each step-by-step experiment.
- For some Labs, we also explain how to change the 5G configuration in the OAI code base, preparing students and future researchers for advanced uses of OAI beyond the pre-defined 5G lab exercises in the 5G Lab Manual.

Wireless networks have been taught in the past based on theoretical models and reliance on simulation tools constructed under simplifying assumptions and usually addressing a single protocol layer.

We believe that the OAIBOX™, with its full 5G stack and over-the-air transmission, is a transformative approach to teaching practical aspects of cellular networks, preparing students for the global standard adopted by the industry.

Thank you for supporting us in acquiring the OAIBOX™ and for providing valuable feedback. This motivates us to invest further in new features and training material.

1 Introduction

1.1 OAIBOX™ overview

OAIBOX™ is a 5G end-to-end testing solution (CN5G + gNB + UE) for research, experimentation and education based on *OpenAirInterface™* (OAI), the leading **open source** 5G base station and Core Network software suite. The OAIBOX™ includes an open-source OAI distribution tested and optimised for the selected OAIBOX™ HW configuration. OAIBOX™ is a plug-and-play computer platform that integrates with NI *Universal Software Radio Peripheral* (USRP) Software-Defined-Radios, a 5G UE Quectel RM500Q-GL and an already programmed SIM card for over-the-air transmission.

The solution comes with this 5G Lab Manual that provides an overview of different aspects of the 3GPP 5G NR protocol stack, including step-by-step exercises to be replicated by students and wireless engineers. A cloud-based Dashboard allows real-time 5G network monitoring and management.

Being open source, users can change the code to implement and validate advanced 5G algorithms, which makes OAIBOX™ the ideal solution for 5G research and education.

There are currently four OAIBOX models (https://www.oaibox.com/#products). This manual refers to the OAIBOX™40 and the OAIBOX™ MAX.

1.1.1 OAIBOX™ 40 features and datasheet

The OAIBOX™ 40 model includes a *Software Defined Radio* (SDR) with bandwidth up to 40 MHz inside the box.

The OAIBOX™ 40 includes access to both the OAIBOX™ Dashboard and the 5G Lab Manual, a 5G ready UE with a pre-programmed 5G SIM card (section 1.2.3) and technical support, as summarized by Figure 1-1.

The RF cable kit may be included in your order, to allow over-the-cable connection between the OAIBOX™ 40 and the UE (see section 1.2.6).

The OAIBOX™ 40 main features are summarized below, whilst its datasheet can be found on Table 1-1:

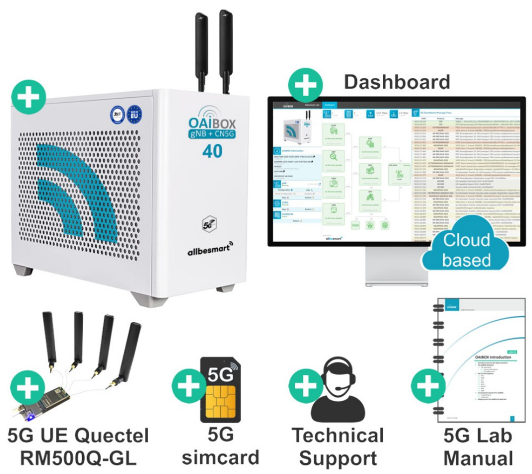


Figure 1-1: OAIBOX™ 40 solution – what is in the box

- Out-of-the-box 5G end-to-end solution.
- Integrated with 5G core and FR1 RAN.
- Interoperable with major 5G modems.
- Intuitive web-based *Graphical User Interface* (GUI) for network managing and monitoring.
- Real-time network KPIs plots with exportable collected data in *JavaScript Object Notation* (JSON) format.
- New features and capabilities are provided throughout the lifetime of the product as we develop and release them.
- The SDR card is inside the box.
- Free access to the open-source OAI 5G stack.

Table 1-1: OAIBOX™ 40 data sheet

Technology	5G NR SA
Frequency bands	any 3GPP FR1 band up to 6GHz (defaults Bands 41, 77 and 78)
Channel bandwidth	up to 40 MHz (default bands 20 MHz and 40 MHz)
Max. throughput	150 Mbps
Standards	3GPP Rel. 15/16 (aligned with OAI roadmap)
Antennae	SISO
Max. UEs	16 (OAIBOX™ comes with 1 UE)
Max. gNB EIRP	10 dBm (10 mW)
Duplex mode	TDD with configurable slot structure (FDD is possible with customization)
Range	Up to 150 m (LoS)
Power consumption	<150 W
Power supply	110 V and 220 V
Operating temp	-10º C to 40ºC
SDR card	NI USRP B200 [1]
Sampling Rate	46.08 Msps on the internal USRP
Weight	7.5 Kg
Dimensions	185mm x 292mm x 376 mm
RF Cable kit	Optional RF cables to avoid over-the-air transmission
Dashboard	Access to all features of the OAIBOX™ Dashboard Premium
UE	5G UE Quectel RM500Q + SIM, iPhone14 Pro + SIM (optional), Google Pixel 7 + SIM (optional)

1.1.2 OAIBOX™ MAX features and datasheet

The OAIBOX™ MAX model, see Figure 1-2, does not include an SDR, which must be bought separately. it can be any *National Instruments* (NI) USRP, such as the B200, B210, N300, N310, X310, or the X410.

These USRPs can go up to 100 MHz bandwidth and can support up to MIMO 2x2 .

The OAIBOX™ MAX brings a 10 Gbit *Network Interface Card* (NIC) and a SD card filesystem for your USRP.

Users of the OAIBOX™ MAX may also find useful to include a RF cable kit in their order, to allow over-the-cable connection between the OAIBOX™ MAX and the UE (see section 1.2.6).

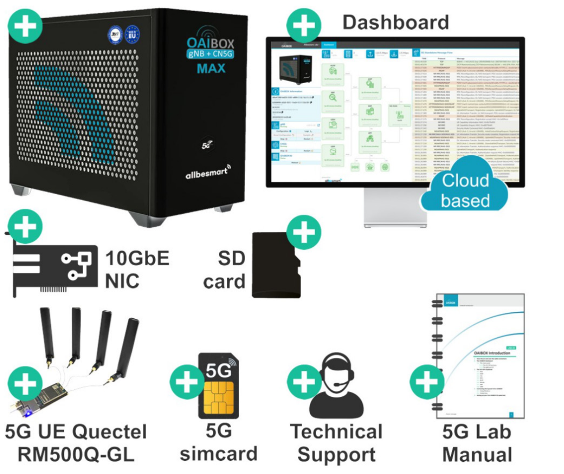


Figure 1-2: OAIBOX™ MAX solution – what is in the box

The OAIBOX™ MAX main features are summarized below. Its datasheet can be found on Table 1-2:

- Out-of-the-box 5G end-to-end solution.
- Integrated with 5G core and FR1 RAN.
- Interoperable with major 5G modems.
- Intuitive web-based GUI for network managing and monitoring.
- Real-time network KPIs plots with exportable collected data in JSON format.
- Supported external SDR cards NI USRP B200, B210, N300, N310, X310, X410.
- Free access to the open-source OAI 5G stack.

Table 1-2: OAIBOX™ MAX data sheet

Technology	5G NR SA
Frequency bands	any 3GPP FR1 band up to 6GHz (defaults Bands 41, 77 and 78)
Channel bandwidth	up to 100 MHz
Max. throughput	800 Mbps
Standards	3GPP Rel. 15/16 (aligned with OAI roadmap)
Antennae	MIMO, external SMA connector
Max. UEs	16 (OAIBOX™ comes with 1 UE)
Max. gNB EIRP	10 dBm (10 mW)
Duplex mode	TDD with configurable slot structure (FDD is possible with customization)
Range	Up to 150 m (LoS) with external directive antenna (optional)
Power consumption	<150 W
Power supply	110 V and 220 V
Operating temp	-10º C to 40ºC
SDR card	External NI USRP B200 / B210 [1]/ N300 / N310 / X310 / X410
Sampling Rate	46.08 Msps on the internal USRP.
Weight	7 Kg
Dimensions	185mm x 292mm x 376 mm
RF Cable kit	Optional RF cables to avoid over-the-air transmission
Dashboard	Access to all features of the OAIBOX™ Dashboard Premium
UE	5G UE Quectel RM500Q + SIM, iPhone 14 Pro + SIM (optional), Google Pixel 7 + SIM (optional)

New features and capabilities are provided throughout the lifetime of the product as we develop and release them.

1.1.3 RF spectrum for testing

OAIBOX™ operates in any 3GPP TDD Band from Frequency Range 1 (below 6GHz). The gNB transmitted power is limited to 10 dBm. OAIBOX™ allows the configuration of the central frequency to avoid bands being used by local Mobile Network Operators.

If you don't have a trial license you can use an RF cable kit to perform 5G testing with no over-the-air transmission (the cable kit is optional). Alternatively, you can use a Faraday cage.

1.1.4 OAIBOX™ software architecture

The OAIBOX™ provides a monolithic deployment of OAI gNB corresponding to a single gNB (CU+DU) program on a single host running the whole 5G NR RAN stack and the 5G CN.

The OAIBOX™ 40 software reference architecture is shown in Figure 1-3. The end-to-end 5G test system combines software from Quectel, NI, OAI and Allbesmart. The OAIBOX™ MAX has a similar architecture with an additional interface between OAI L1 and the NI USRP through a 10 Gbit ethernet card that comes with the solution.

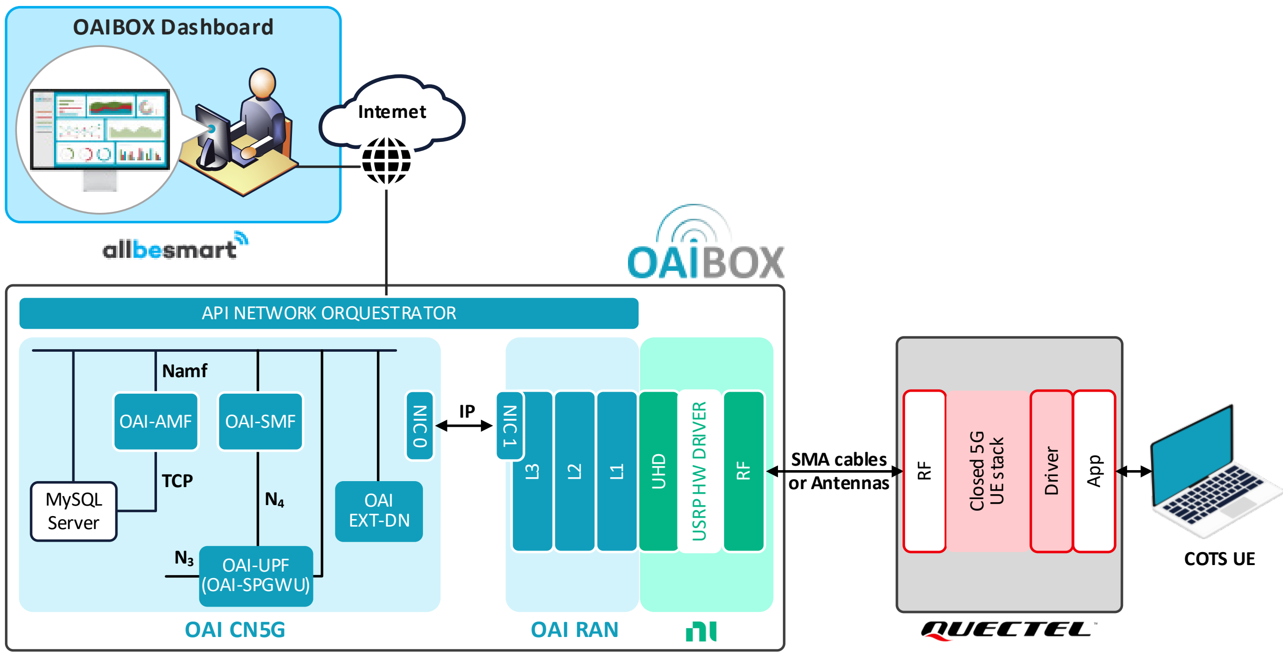


Figure 1-3:OAIBOX™ 40 software reference architecture.

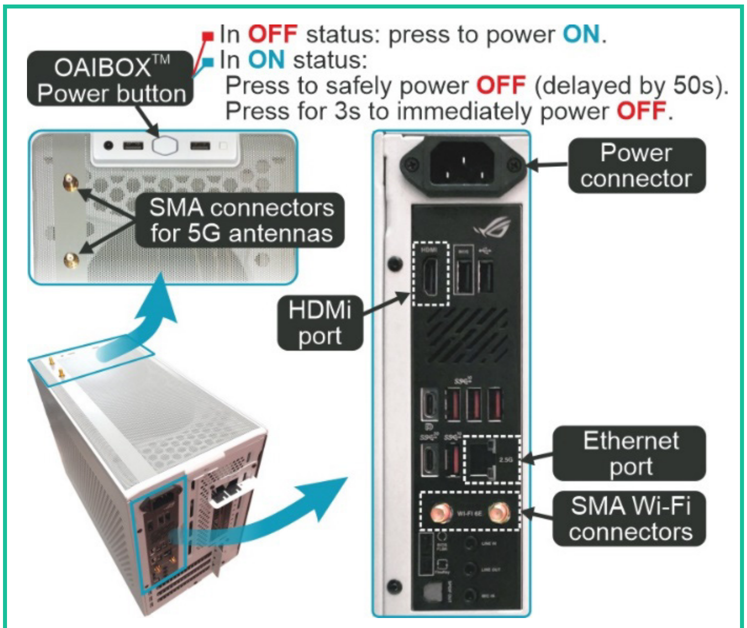
1.2 Setup Guide

All OAIBOX™ products include dedicated support, including a "BRING-UP SESSION", where our team discusses and addresses any issues or challenges encountered during the initial stages of setting up the OAIBOX™. This session aims to ensure that the OAIBOX™ is properly set up and functioning as expected.

It is highly recommended that the actions described in the next subsections are taken once you have received your OAIBOX™, and before the bring-up session.

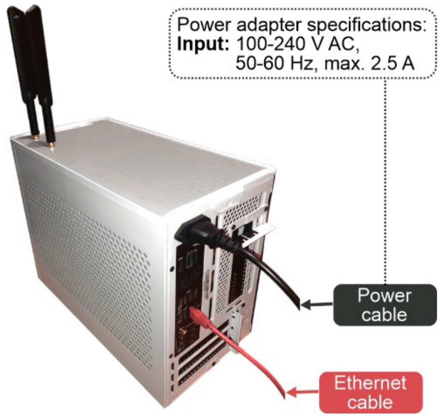
1.2.1 OAIBOX™ 40 quick setup guide

Step 1. Take the OAIBOX™ from the packaging box and place it on a flat surface



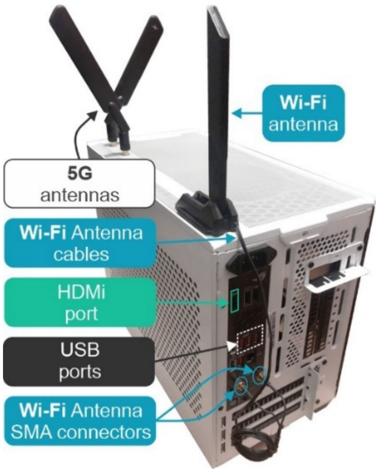
Step 2. Take note of the following OAIBOX™ ports and connectors

Step 3. Assemble the **5G antennas** directly on the **SMA connectors** (in no specific order)



Step 4. Connect the **power** and **network** cables (Internet access is required)

Step 5. *Optional* Assemble the Wi-Fi antenna

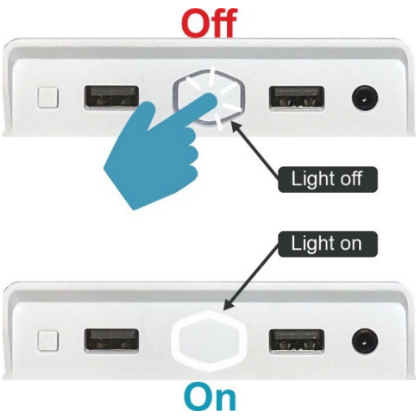


> To connect the OAIBOX™ to the Internet via a Wi-Fi connection, you will need to **temporarily** plug in a monitor, a mouse, and a keyboard.

1. Connect the monitor to the HDMi port.
2. Connect the mouse to a USB port.
3. Connect the keyboard to a USB port.
4. Turn **ON** the OAIBOX™ (see step **3.1**).
5. Use the Ubuntu GUI to configure your Wi-Fi connection.
6. Test the Internet connection.
7. You may unplug 1 2 and 3.

Step 6. *Optional* Configure the Wi-Fi connection to the Internet

Step 7. **Turn ON** the OAIBOX™ (in case you have not yet done it during the optional Step 6)

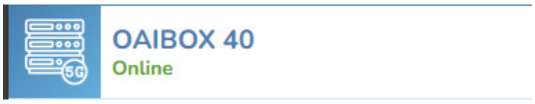


> Wait up to 5 minutes after powering ON the OAIBOX™ for the first time, to allow for BIOS self-check and the automatic OAIBOX™ registration to complete.

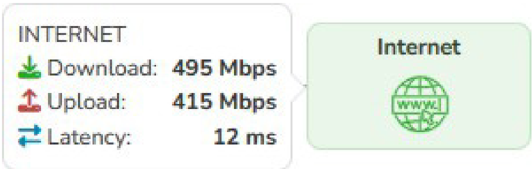
1. Using a **separate computer** (e.g., a laptop), access the following url: http://my.oaibox.com
2. Perform login or, create an account in case you don't have one. Use an **e-mail address** on the same domain (e.g., *@acme.com*) as the one specified in the OAIBOX™ order.

Step 8. Access your OAIBOX™ Dashboard (for additional information see section 1.3)

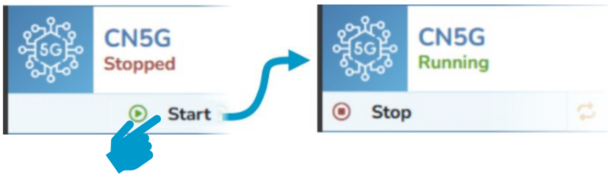
Step 9. Start the CN5G and gNB modules on the OAIBOX™ Dashboard



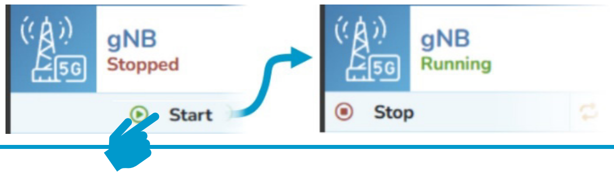
1. Verify your OAIBOX™ status.



2. Verify the Internet module is green and leave the mouse over it to check the OAIBOX™ Internet connection speed. A minimum of 150 Mbps is recommended for the OAIBOX™ 40.



3. Start the **CN5G** by clicking on "**Start**". Wait for all CN5G modules turn green (CN5G with label "**Running**").

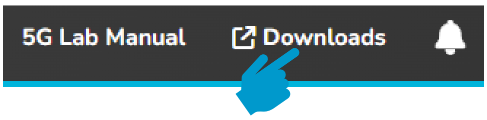


4. Start the **gNB** by clicking on "**Start**". Wait for the NG-RAN module to turn green (gNB with label "**Running**").

Step 10. Install the Quectel 5G UE and connect it to your computer/laptop using a USB cable

Do not connect the Quectel to your computer/ laptop before installing its drivers.

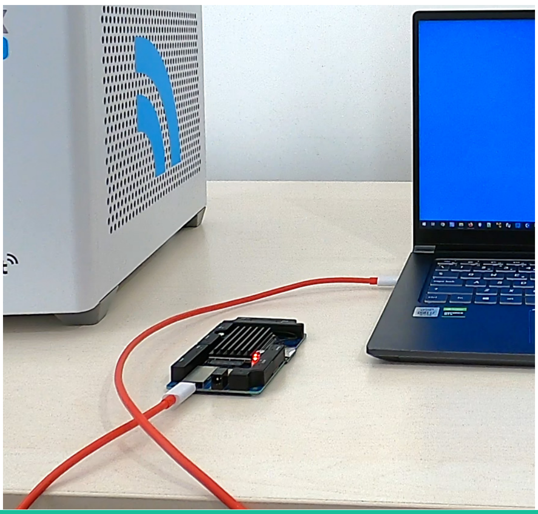
1. Use your computer/laptop to access the OAIBOX™ Dashboard "Downloads" section at: http://my.oaibox.com



2. Download the Quectel drivers for your system (Windows/Linux).
3. Install the Quectel drivers by following the steps on **section 1.2.4**
4. Connect the Quectel to your computer / laptop using the provided USB cable.

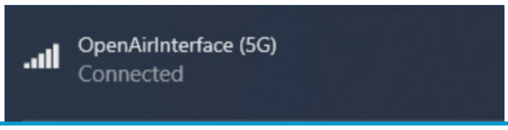
⚠ The recommended distance between the OAIBOX™ and the UE is **> 1m** and **< 3m**

⚠ The Quectel red led will turn ON first. The Quectel blue led will turn ON after.



Step 11. Connect your computer/laptop to the OpenAirInterface (5G) network

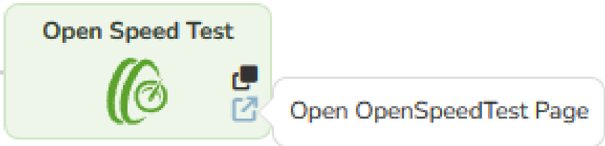
Once the Quectel is connected, your computer/laptop will automatically attempt to establish a connection to the OAIBOX™ "**OpenAirInterface (5G)**" network.



⚠ It could take approx. 1 minute for the computer to establish a successful 5G connection.

Step 12. Perform a 5G speed test using the OAIBOX™ "OpenAirInterface (5G)" network

1. **IMPORTANT!** On your computer/laptop, disable any other Internet connections (e.g., ethernet cable or Wi-Fi) you may have. **Make sure the 5G connection through the Quectel is the only active Internet connection**.
2. On your computer/laptop, at the OAIBOX™ Dashboard, click on the "**Open OpenSpeedTest Page**" module, and perform a 5G speed test.



> Note that your computer/laptop is now connected to the Internet via the "**OpenAirInterface (5G)**" network. You can browse the Internet using this connection or, alternatively, you can perform other online speed tests, such as the one provided by Ookla (www.speedtest.net), but the results will depend on your Internet connection speed and firewall security policies.

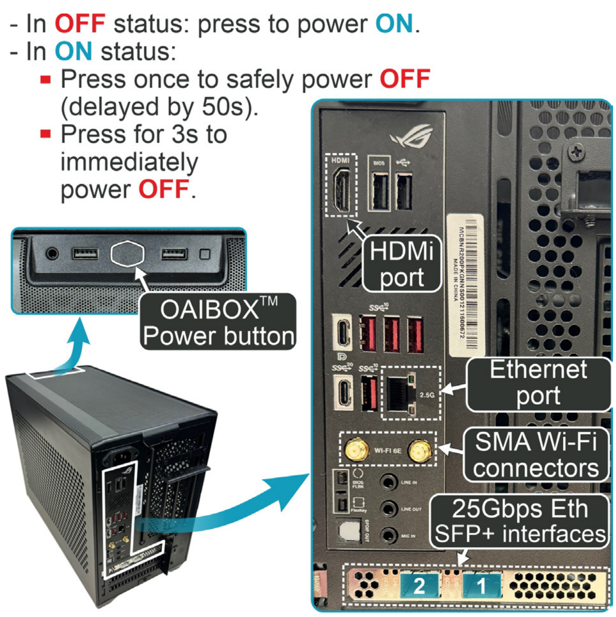
Figure 1-4 illustrates a typical OAIBOX™ 40 test setup that utilizes over-the-air transmission. You can also use an over-the-cable connection (see section 1.2.6).

Figure 1-4: OAIBOX™ 40 test setup

> The OAIBOX™ 40 only supports SISO. The OAIBOX™ MAX supports MIMO up to 4x4.

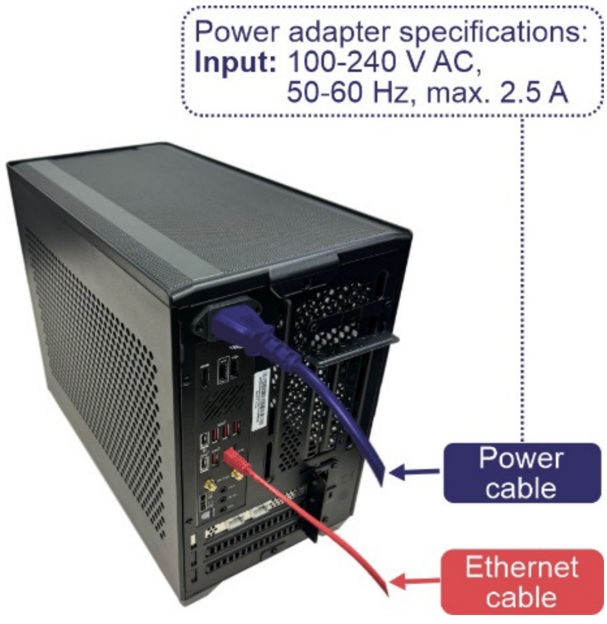
1.2.2 OAIBOX™ MAX quick setup guide

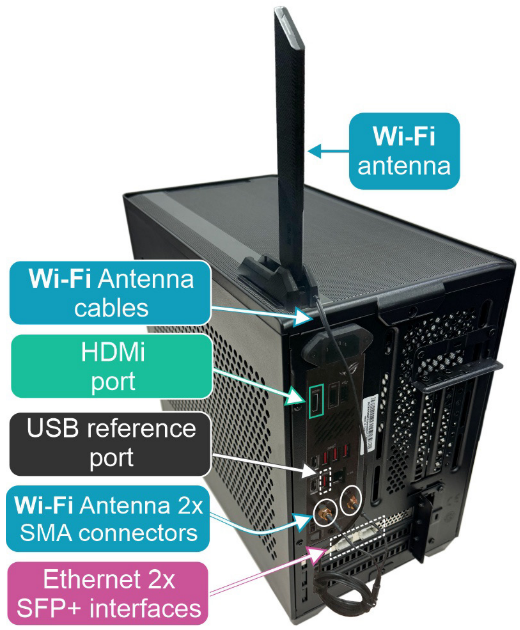
Step 1. Take the OAIBOX™ from the packaging box and place it on a flat surface



Step 2. Take note of the following OAIBOX™ ports and connectors

Step 3. Connect the **power** and **network** cables (the OAIBOX™ requires Internet access)





Step 4. *Optional* Assemble the Wi-Fi antenna

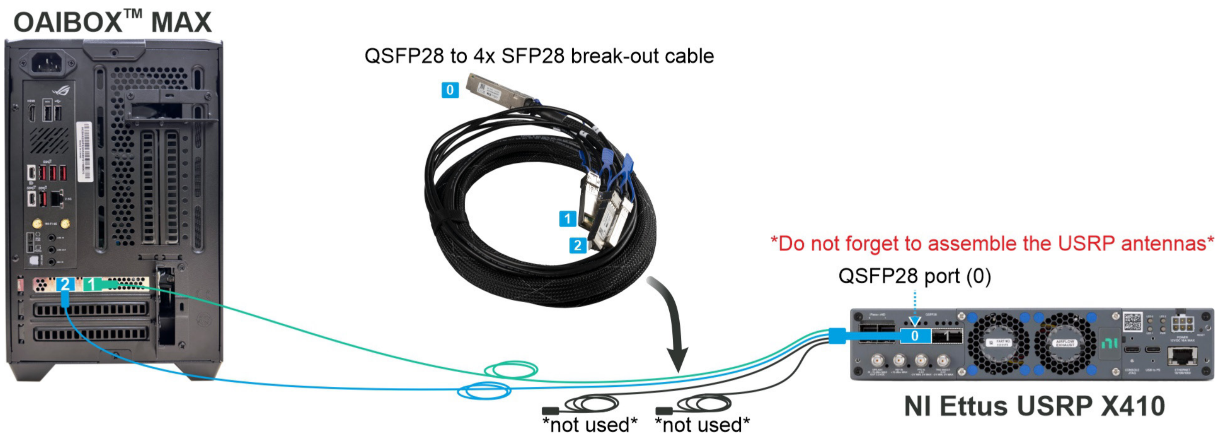
Step 5. *Optional* Configure the Wi-Fi connection to the Internet

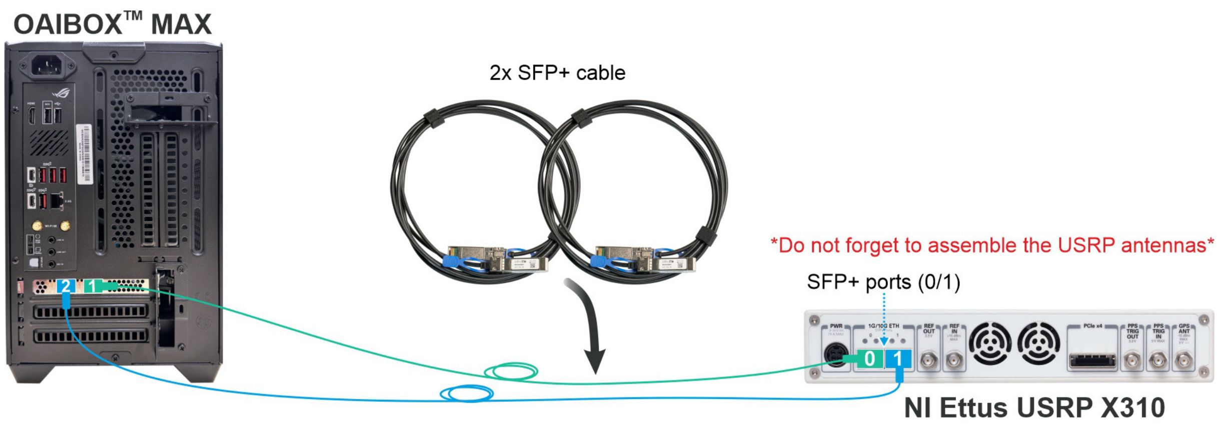
To connect the OAIBOX^{TM} to the Internet via a Wi-Fi connection, you will need to **temporarily** plug in a monitor, a mouse, and a keyboard.

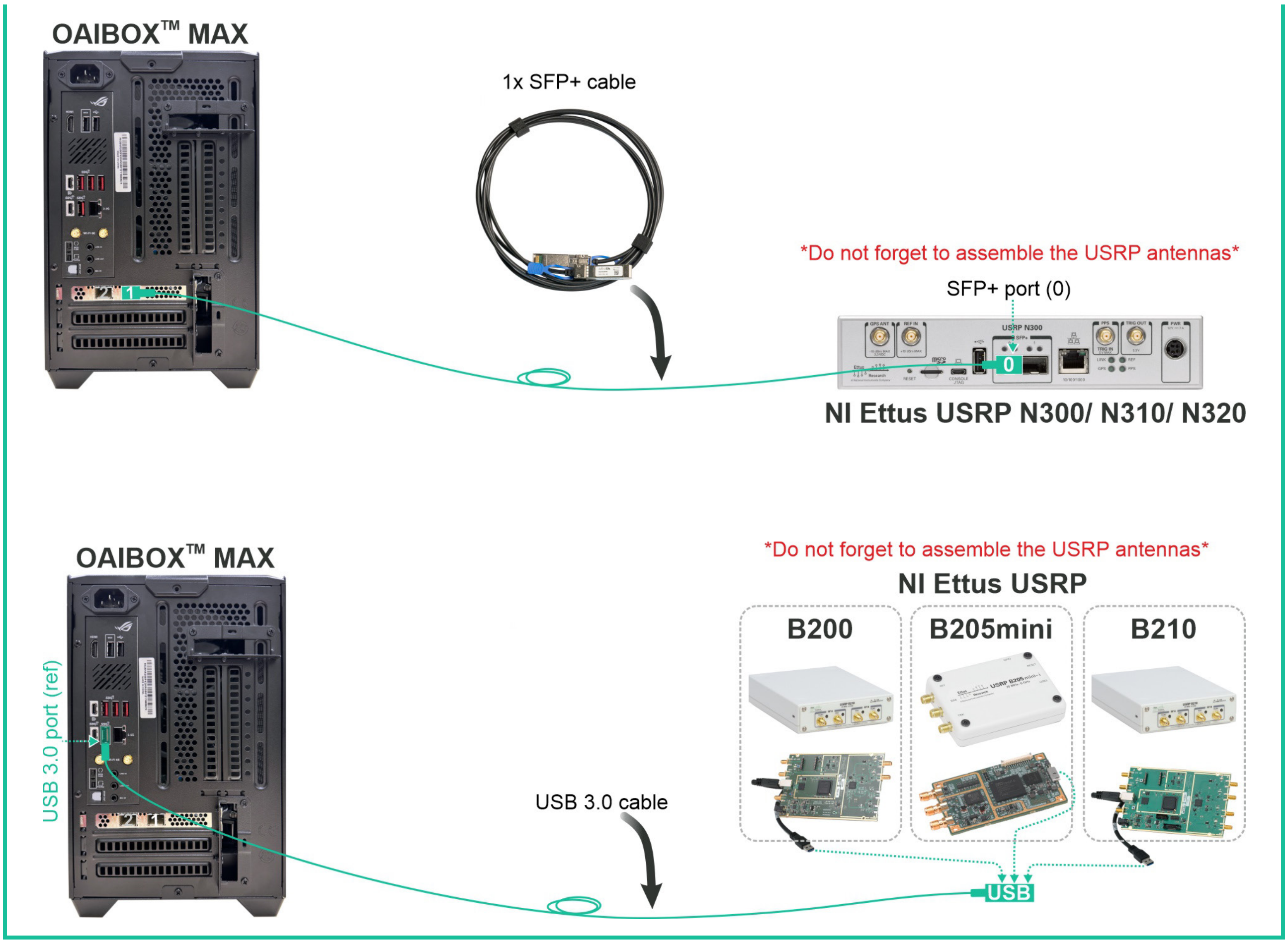
1. Connect the monitor to the HDMi port.
2. Connect the mouse to a USB port.
3. Connect the keyboard to a USB port.
4. Turn **ON** the OAIBOX^{TM} (see step **3.1**).
5. Use the Ubuntu GUI to configure your Wi-Fi connection.
6. Test the Internet connection.
7. You may unplug 1 2 and 3.

Step 6. Connect the OAIBOX^{TM} MAX to your USRP

The OAIBOX^{TM} MAX can be connected to different NI Ettus USRPs models, e.g., B200 / B205mini / B210 / N300 / N310 / N320 / X310 (UBX160) / X410. The connection differs depending on the USRP model. The examples provided below explains how to connect the OAIBOX^{TM} MAX to the different NI Ettus USRPs.







Step 7. Assemble the 5G antennas in your USRP

To use a 5G over-the-air connection, you will need to mount the 5G antennas in the SMA connectors located on the front panel of the NI USRP. Figure 1-5 depicts the scenario for the NI Ettus USRP N310.

Figure 1-5: Example of an OAIBOX™ MAX set up with an USRP N310

Next, follow **Step 7** to **Step 12** from Section 1.2.1 (OAIBOX™ 40 quick setup guide) to conclude/confirm the OAIBOX™ MAX setup.

Figure 1-6 depicts a typical OAIBOX™ MAX test setup, using over-the-air transmission. If you prefer to use an over-the-cable RF connection, please see section 1.2.6.

Figure 1-6: OAIBOX^{TM} MAX test setup (e.g., with USRP N300)

1.2.3 UE host PC

The host PC, where the Quectel is to be connected, is not included in the OAIBOX^{TM} solution.

Suggested minimum requirements for a laptop to host the UE:

- Operating System: Microsoft Windows 10 x64
- CPU: 4 cores x86_64
- RAM: 8 GB
- Driver: the Windows driver for the Quectel RM500Q-GL must be equal or higher than version 2.4.6. The Quectel Drivers can be directly downloaded from your OAIBOX^{TM} Dashboard interface, under the Downloads section.

1.2.4 Quectel 5G UE and SIM card

The OAIBOX^{TM} solution is delivered with a Quectel RM500Q-GL which contains a SIM card already programmed (Figure 1-7). This Quectel RM500Q-GL module already has antennas integrated with the 5G modem and, therefore, there is no need to connect external antennas to the UE. No additional configurations are required for authenticating devices using the provided SIM card.

Figure 1-7: The Quectel includes a 5G SIM card already programmed.

The SIM card specifications are as follows:

- IMSI: 001010000000001
- Key: fec86ba6eb707ed08905757b1bb44b8f
- OP: 1006020f0a478bf6b699f15c062e42b3
- OPC: C42449363BBAD02B66D16BC975D77CC1

- It is configured for 3GPP: GSM, WCDMA, LTE, NR with milenage algorithm to perform 3GPP standard subscriber identification.
- The card offers 2FF, 3FF and 4FF detachable formats.
- The card supports 5V, 3V and 1.8V.
- The card is also open for later personalization by our customers.

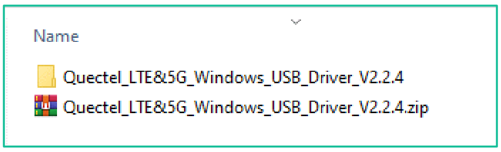
> Please do not remove the 5G SIM card from the Quectel, unless strictly necessary. If the Quectel is turned on without a SIM card, it will override its APN configuration and will need reconfiguration (see the reconfiguration steps at the end of section **1.2.4.3**)

1.2.4.1 Connecting the Quectel using Windows

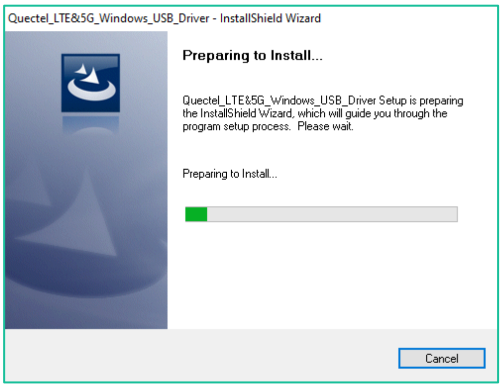
Before using the Quectel RM500Q-GL UE on a Windows computer you need to install the dedicated drivers. This is a simple and straight forward process:

Step 1. Download the Quectel driver from the "**Downloads**" section at: https://dashboard.oaibox.com

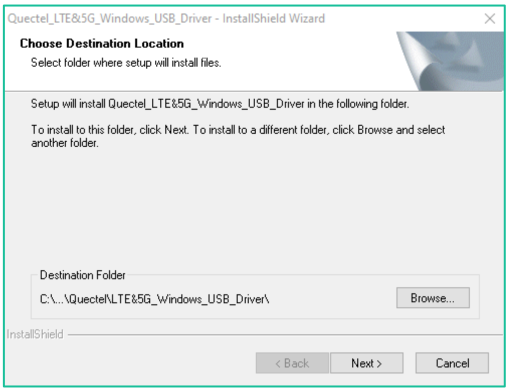
Step 2. Unpack the downloaded file to an empty folder.



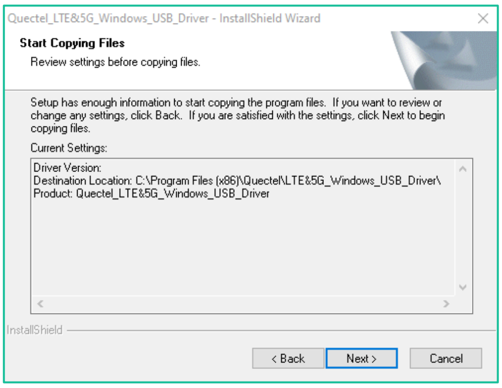
Step 3. Open the unpacked folder and execute the setup.exe file.

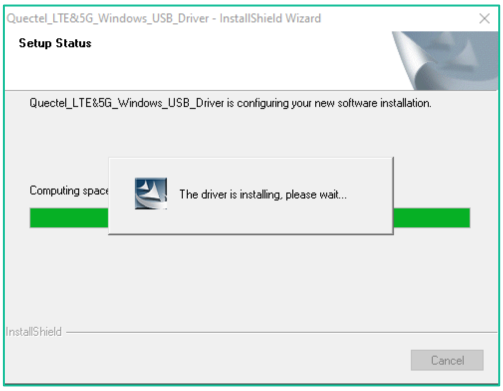


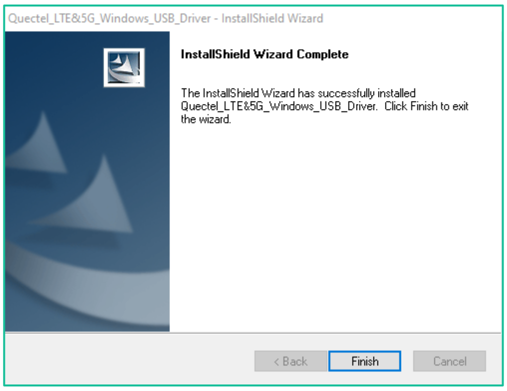
Step 4. Once the "Choose Destination Location" page appears, select your chosen installation folder, or just accept the default location provided. Then click Next.



Step 5. A review page appears. If everything is OK, click Next. Otherwise click Back and change the installation folder.







Step 6. Connect the Quectel to your computer using the provided USB cable. Upon connection the red led will turn on, and after successful modem initialization, a blue led will also turn on, as depicted in Figure 1-8.

Please wait a few seconds (< 1minute) for the Quectel modem to automatically discover and connect to the OpenAirInterface (5G) network, as also depicted in Figure 1-8 (right side).

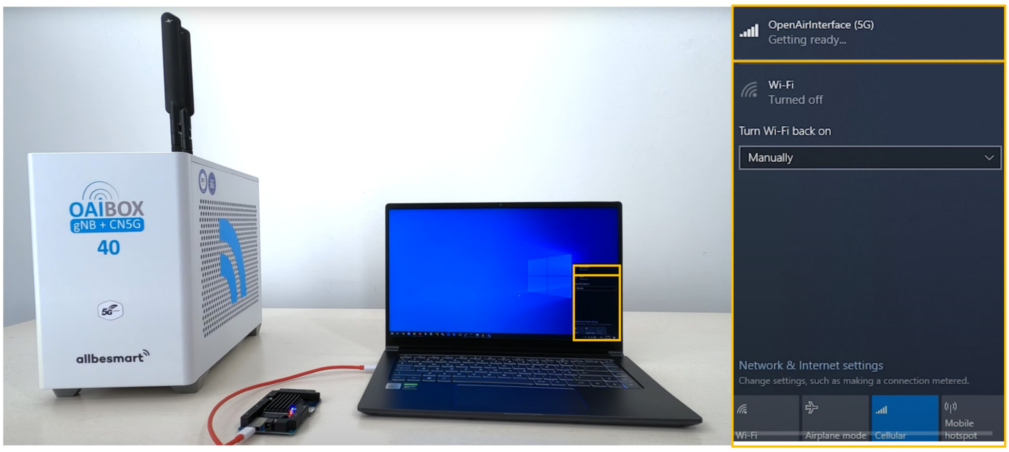


Figure 1-8: The Quectel UE connecting to the cellular OpenAirInterface (5G) network

1.2.4.2 Connecting the Quectel using Linux (as an alternative to Windows)

To use the Quectel UE on an Ubuntu Linux host, you need to install the dedicated drivers for that operating system. This is a simple and straight forward process:

Step 1. Install dependencies:

```
sudo apt install -y wget putty cmake build-essential iperf net-tools
```

Step 2. Download the Quectel Linux software from https://dashboard.oaibox.com
Alternatively use the following command which will download the software to the home folder:

```
wget -o ~/Quectel_QConnectManager_Linux_V1.6.4.zip
https://api.oaibox.com/quectel/Quectel_QConnectManager_Linux_V1.6.4.zip
```

Step 3. Unzip the downloaded file on the home folder of the Linux Host

```
unzip ~/Quectel_QConnectManager_Linux_V1.6.4.zip -d
~/Quectel_QConnectManager_Linux_V1.6.4
cd ~/Quectel_QConnectManager_Linux_V1.6.4
```

Step 4. Build the Quectel *QConnectManager* from sources:

```
make
```

Step 5. Start the Quectel Connection Manager

```
sudo ./quectel-CM -s oai
```

After *Step 5* is complete, the Quectel device may take up to 45 seconds to complete the registration process and enable a network interface named "**wwan0**". At this point, the host machine is connected and has Internet access via the OAI network.

1.2.4.3 Establishing a terminal connection with the Quectel modem

Step 1. Download MobaXterm Portable version from:
https://download.mobatek.net/2302023012231703/MobaXterm_Portable_v23.0.zip

Step 2. Extract and run MobaXterm.

Step 3. Start a new session, selecting 115200 bps for baud rate, and the "**Quectel USB AT Port**", the COM Port number may vary. See Figure 1-9.

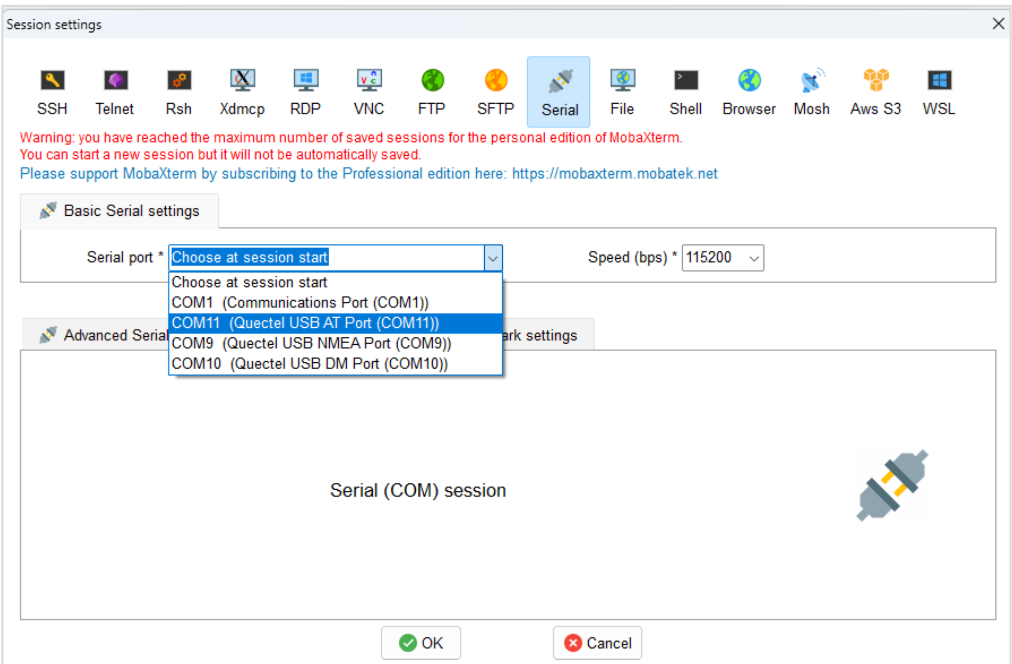


Figure 1-9: Details for the MobaXterm session with the Quectel

Step 4. Verify the *output* is similar to what is depicted in Figure 1-10.

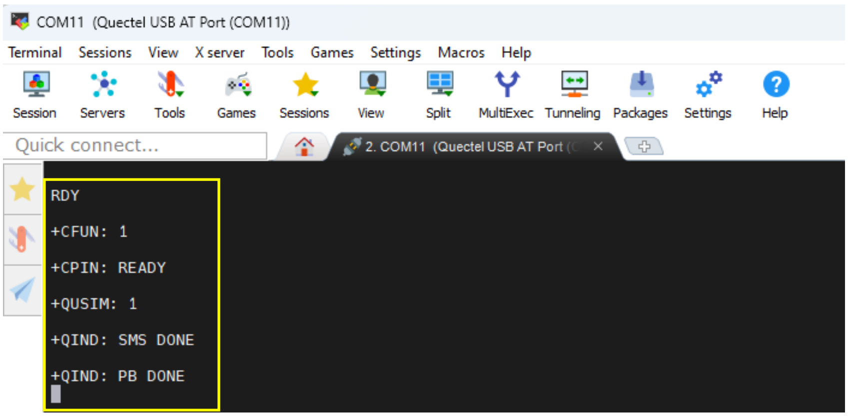


Figure 1-10: A successful MobaXterm session with Quectel

Step 5. Execute "**AT**" command and press enter, the output should be "**OK**", as depicted in Figure 1-11.

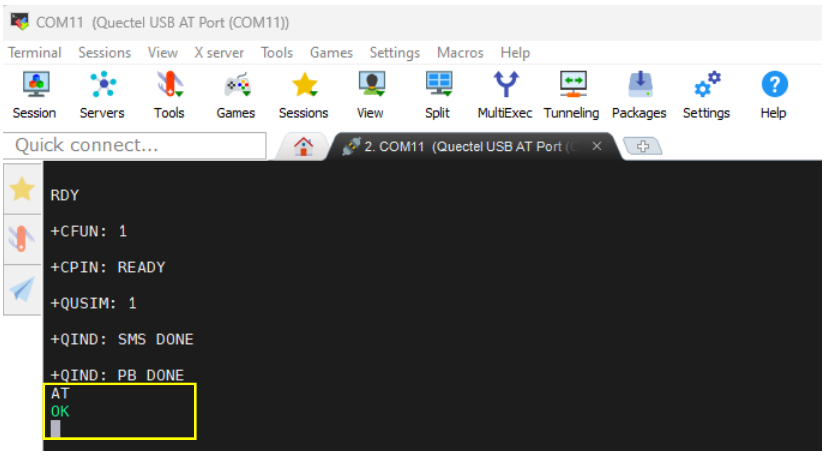


Figure 1-11: Testing the "AT" command

NOTE:

When typing the "AT" (or "at") command it is possible the characters will not appear on the console. This means the modem is not echoing the characters back to the user.

To see the typed characters, you must first execute the "AT E1" command, only after executing this command the echo command will be enabled. To disable, type "AT E0".

Step 6. Execute "**ATI**" command to obtain information on the connected Quectel module, as depicted by Figure 1-12.

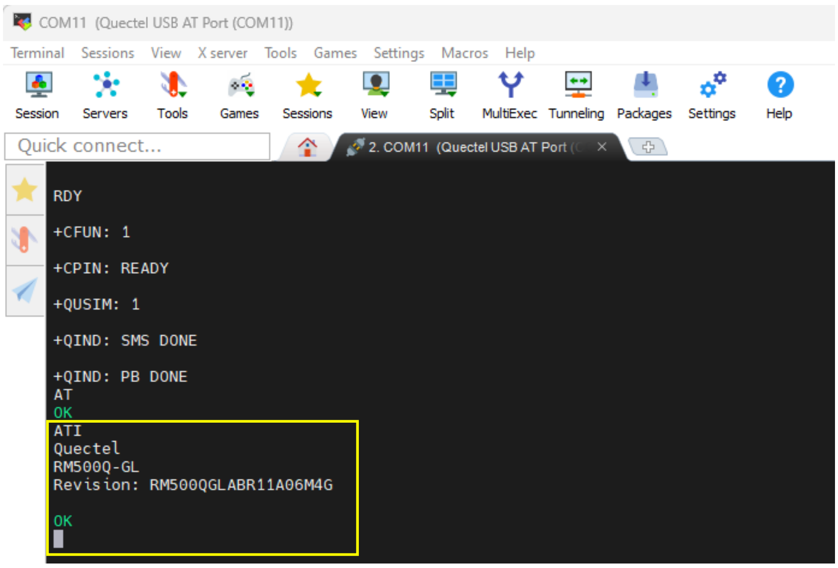


Figure 1-12: Obtaining information on the connected Quectel module through the "ATI" command

1.2.4.4 Reconfiguring the Quectel module with the correct APN configuration

In case the Quectel loses the correct *Access Point Name* (APN) configuration, e.g., due operation without the provided SIM card, the following AT commands must be executed in a terminal window (see previous section):

AT+CGDCONT?	*(*optional* command, returns the current configurations for each defined PDP contex)*
AT+CGDCONT=1,"IP","oai"	*(configures/write context 1 with the correct alues)*
AT+CGDCONT=2	*(configures/write an empty configuration for context 2)*
AT+CGDCONT=3	*(configures/write an empty configuration for context 3)*

1.2.5 OAIBOX™ and iPerf – network performance measurement tool

iPerf is a widely used network testing tool that allows users to measure network KPIs (e.g., throughput, delay and packet loss) between two devices on a network (iPerf works by generating traffic from a client to a server). You can check https://iperf.fr/ for more information and official documentation about iPerf.

Currently, OAIBOX™ comes with iPerf pre-installed for convenient network performance testing right out of the box. You can check how to enable and use iPerf with OAIBOX™ by reading ❽ **in** section 1.3.2.

1.2.6 RF cable Kit: over-the cable RF connection

1.2.6.1 OAIBOX™ 40

Before running any test in conducted mode, the first thing to do is to connect the OAIBOX™ 40 correctly to the UE as described in Figure 1-13. The RF cable kit is optional in the OAIBOX™ offer – in case you haven't order one, you can order it separately.

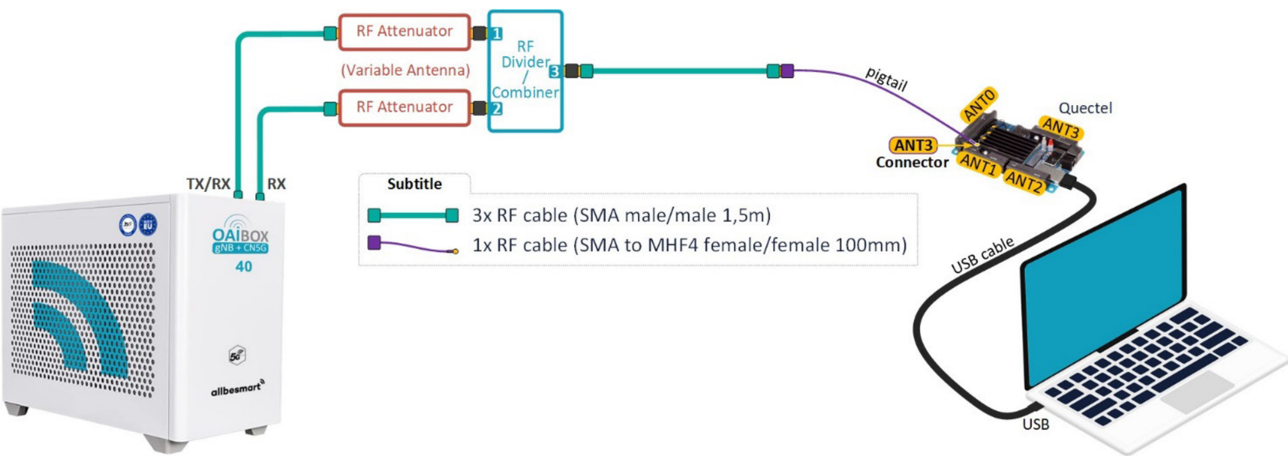


Figure 1-13: Over-the-cable setup

Figure 1-14, provides additional details on the cable kit and its assembly.

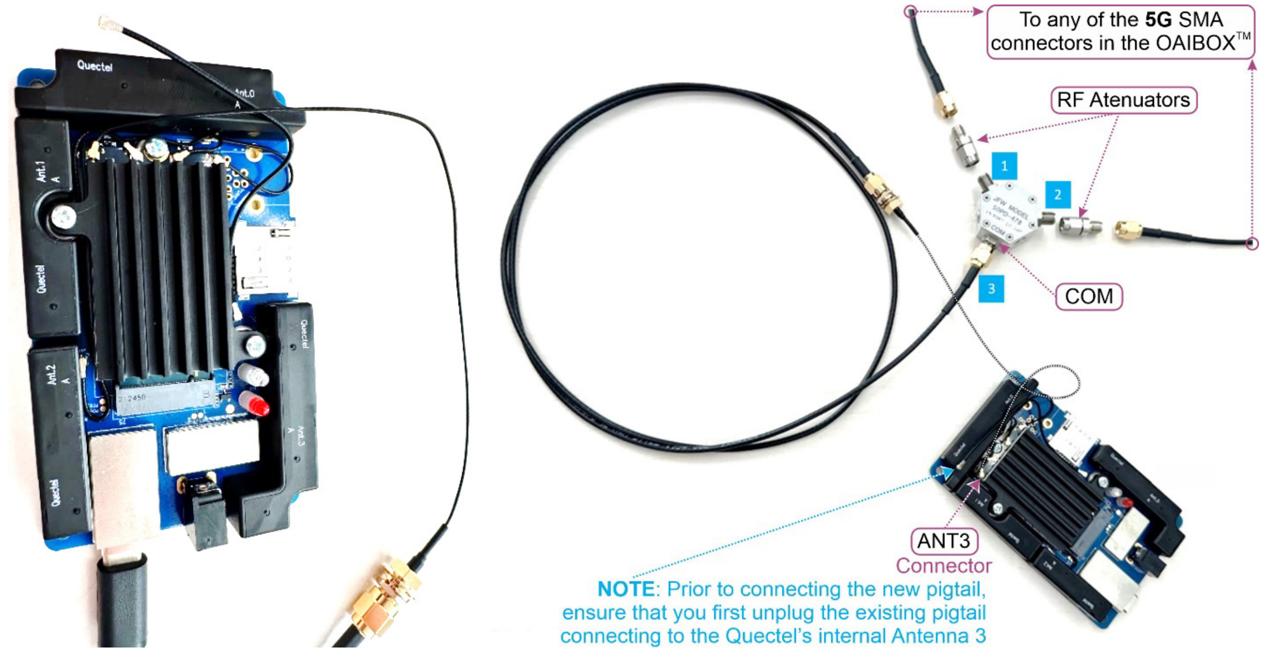


Figure 1-14: RF cable kit setup for SISO, with RF attenuators and RF divider/combiner connected to the Quectel antenna 3 connector (ANT3) -please also refer to Figure 1-13 for number mapping

1.2.6.2 OAIBOX™ MAX

Each antenna pin on the Quectel has a different function and it also depends on the band in use. Below, in Table 3, is the pin mapping for the different bands.

Table 3: RM500Q-GL Cellular Antenna Mapping (SISO)

Band	Antenna
n41	ANT1
n77/n78/n79	ANT3

Table 4: RM500Q-GL Cellular Antenna Mapping (MIMO 2x2)

Band	Antenna 0	Antenna 1
n41	ANT1	ANT0
n77/n78/n79	ANT3	ANT0

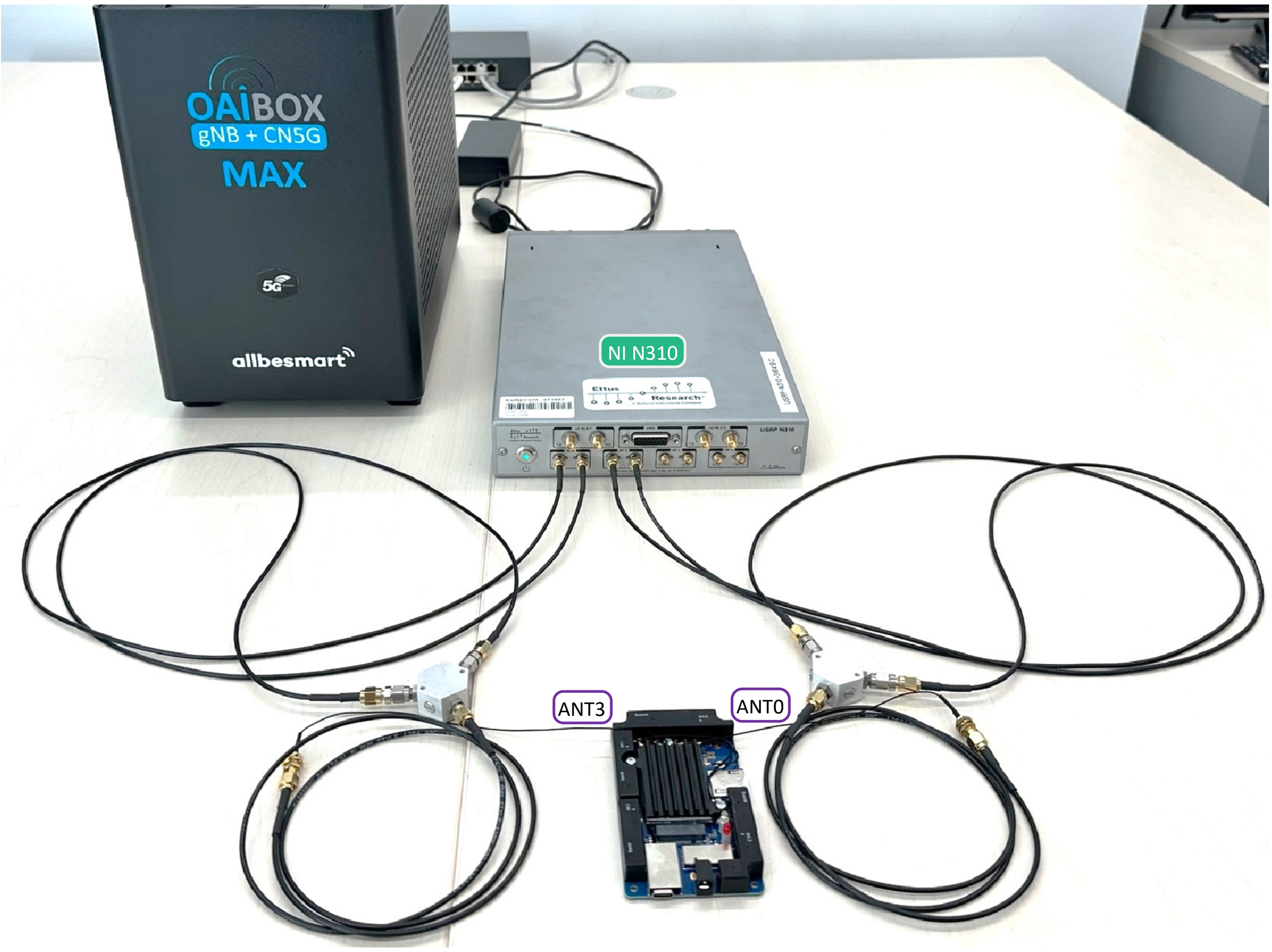


Figure 1-15: RF cable kit setup for bands n77/n78/n79 in MIMO 2x2 with OAIBOX™ MAX and USRP N310

1.2.7 Connecting to an outdoor antenna (optional)

To increase 5G coverage range the OAIBOX™ can be connected to an outdoor directive antenna.

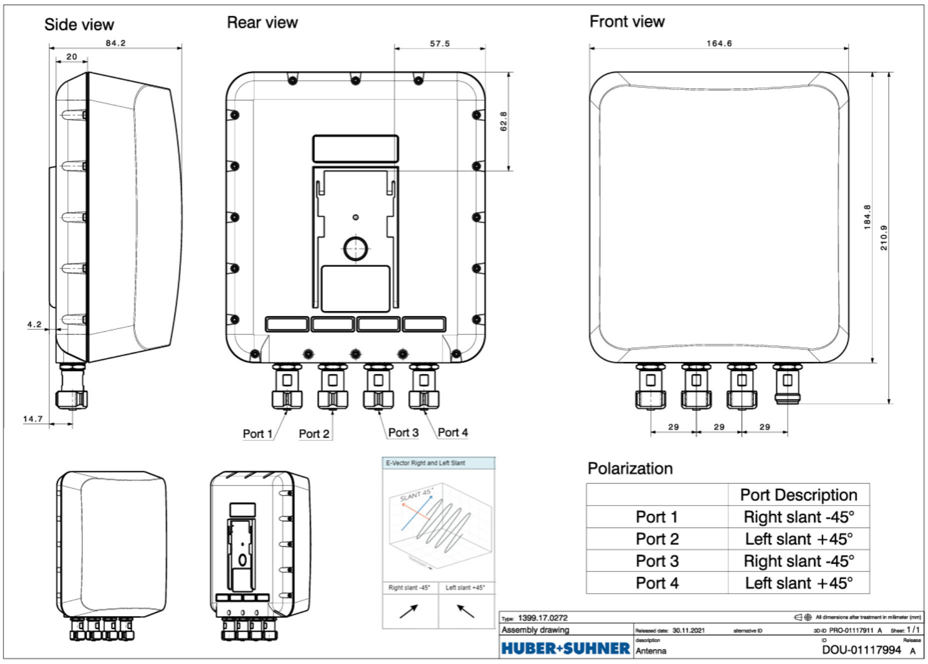


Figure 1-16: SENCITY® URBAN 200 drawing. [Source: HUBER+SUHNER]

As an option, we provide the antenna SENCITY® Urban 200 MIMO 4×4 with 11 dBi Gain, and 70° horizontal half power beamwidth in the 5G C Band frequency range (3400-3800 MHz) [17]. Details for this antenna are provided in Figure 1-16.

1.3 The OAIBOX™ Dashboard

The *OAIBOX™ Dashboard* is a web-based platform that can be used to both visualize and configure your 5G testbed based on *OpenAirInterface™*. It provides a set of features to facilitate the real-time monitoring of the OAI CN and RAN metrics, and includes pre-defined and easy-to-use 5G configuration scripts, accessible through intuitive menus to facilitate hands-on experimentation of 5G use cases.

1.3.1 OAIBOX™ Dashboard login page

You can access to the OAIBOX™ Dashboard through any web browser with the link: https://my.oaibox.com.

When the signup process is done with an institutional email domain, the registered users are enrolled automatically with any OAIBOX™ acquired by the institution, that is, different emails accounts can also have access to the OAIBOX™ via manual assignment. Registered users will be able to login after email verification.

Figure 1-17: The OAIBOX™ Dashboard sign in page

1.3.2 OAIBOX™ Dashboard tour

The OAIBOX™ Dashboard facilitates the analysis of end-to-end test results, that can be measured against real-time *Key Performance Indicators* (KPIs) plots being shown. All collected data can be stored and exported to common formats for further analysis and later discussion. The OAIBOX™ main panel is depicted in Figure 1-18. The figure reflects what you should see when accessing your OAIBOX™ Dashboard account for the first time (CN5G and gNB are both stopped).

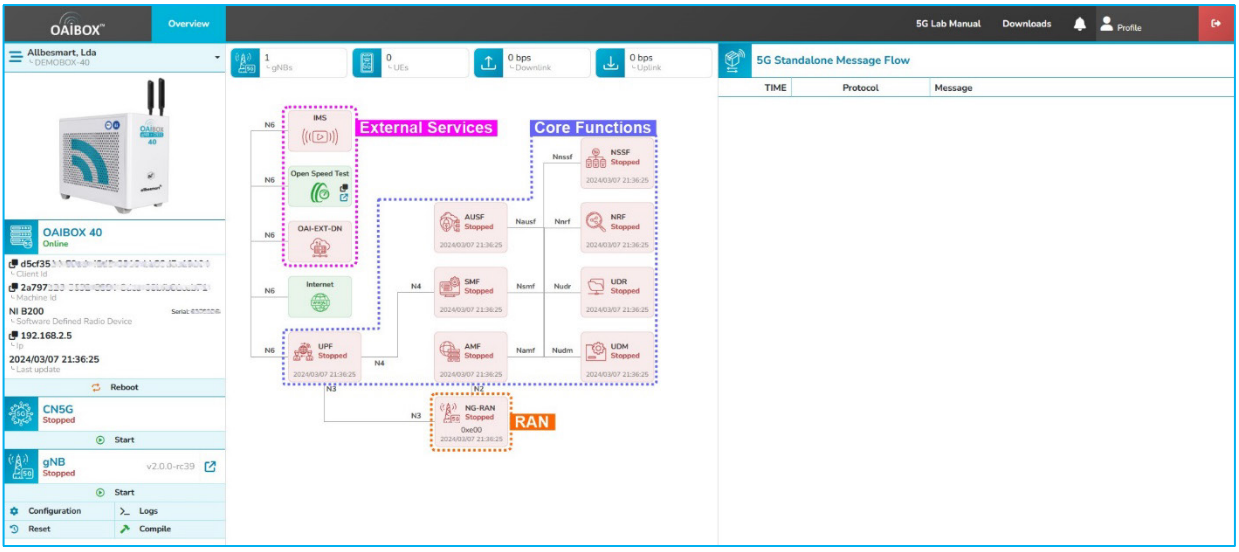


Figure 1-18: The OAIBOX™ Dashboard overview page (5GCN and gNB modules stopped).

On the left side we can see the following visual elements, as depicted by Figure 1-19.

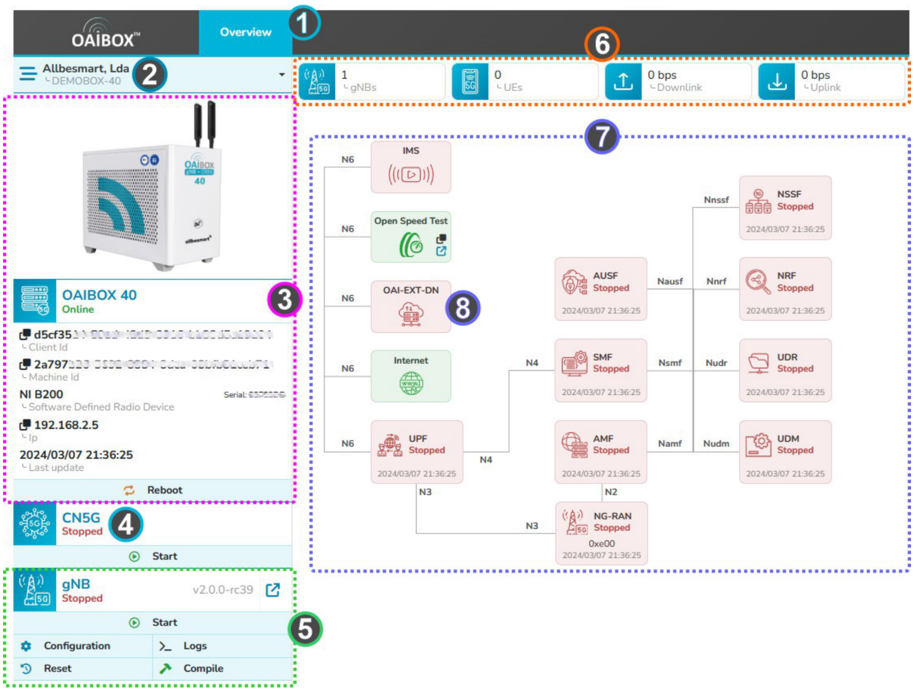


Figure 1-19: The OAIBOXTM Dashboard – details on the left part of the dashboard

Each identified number/area is explained below:

❶ Breadcrumb navigation, providing the user's current location on the OAIBOXTM Dashboard. It also enables the user to quickly jump to a specific navigation point or to trace the path back to its original landing point.

❷ OAIBOXTM selector, enabling the user to select which OAIBOXTM to monitor/control (in case many exist).

❸ A section identifying your OAIBOXTM, including the product's image, type (OAIBOXTM 40 or OAIBOXTM MAX), status (Red: *Offline*; Green: *Online*), the unique *Client Id* and *Machine Id*, the SDR being used, the locally assigned IP address, the latest timestamp indicating successful communication between the OAIBOXTM and the central OAIBOXTM API, and an action button to reboot the OAIBOXTM.

❹ The CN5G section provides information about the status of the 5G Core Network (Red: *Stopped*; Orange: *Starting*; Green: *Running*; Blue: *Upgrading*). There is a "Start" action button to start the CN5G, which is replaced by a "Restart" action button and a "Stop" action button once the core network is running.

❺ The gNB section displays the status off the gNB (Red: *Stopped*; Orange: *Starting*; Green: *Running*; Blue: *Compiling, Upgrading*) depending on the current action being performed. The current OAIBOXTM gNB code release is also displayed. There are several action buttons available which allow:

- Changing the startup configuration of the gNB;
- See the Logs whenever the gNB is running, compiling, or upgrading;
- Reset the configuration to the default configuration for the selected gNB release;
- Compile when the code is changed by the user;
- A "Start" button to start the gNB. While the gNB is running, the start action button is replaced by a "Stop" action button and a "Restart" action button. Furthermore, the button opens the dedicated gNB page.

❻ Overview of the OAIBOXTM status. It includes information on the number of gNBs connected to CN5G, the number of UEs attached, the real-time aggregated downlink (DL) and uplink (UL) throughputs.

❼ The network status of each core function (AUSF, NRF, UDM, UDR, AMF, SMF and UPF – see Table 1-11 for additional information), and the status of the NG-RAN. Information about the Internet connection and IMS is also displayed. Each block is colour coded to Red: *Offline*; Orange: *Starting*; Green: *Online*.

> The NG-RAN area is clickable, it redirects to a dedicated gNB page, see Figure 1-22

❽ The OAIBOX™ is equipped with an integrated and preconfigured iPerf tool, that can be managed via OAIBOX™ Dashboard. To access its functionality, users can click on this button, which will open a modal window (see Figure 1-20) displaying iPerf configurations and test state management.

- To perform an **Uplink test** (UE sending data), users can initiate the test by clicking on the "**Start**" button and then use the following command in a terminal window in the UE.

  ```
  iperf -u -t 30 -b 200M -fm -i 1 -c 172.31.0.135
  ```

  In this scenario, the OAIBOX™ will function as an iPerf server (receiver), while the UE will operate as an iPerf client (sender). It's worth noting that in iPerf nomenclature, the 'client' is responsible for generating network traffic.
- To perform a **Downlink test** (UE receiving data), OAIBOX™ users can initiate the test by clicking on "**Start**". The desired transfer speed in Mbps ('Bandwidth') and destination IP address can be customized. Once the service has started, the IPerf modal window will update to provide the user with the pairing command line to be used in the UE. In this configuration the OAIBOX™ will act as an iPerf client (sender), while the UE will function as an iPerf server (receiver).

Figure 1-20 The OAIBOX™ Dashboard iPerf management modal window

On the right side of Figure 1-19, we can see the following visual elements, as depicted by Figure 1-21. Each identified number/area is explained below:

❾ A direct link to download the latest version of the OAIBOX™ 5G Lab Manual.

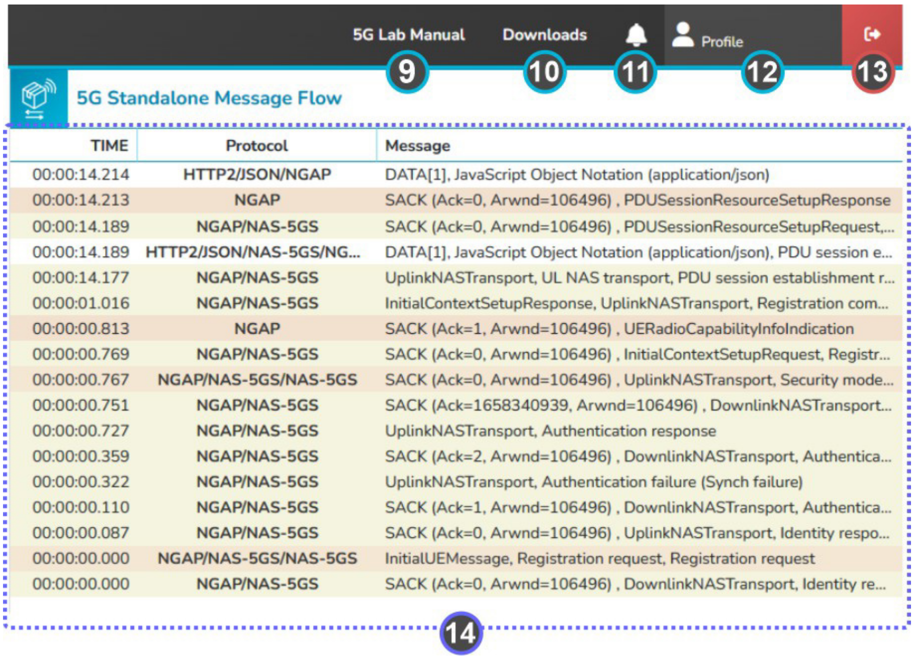
❿ A direct link for the OAIBOX™ download repository. It includes resources such as the Quectel driver software, amongst others.

⓫ The system alerts/notifications area, providing system feedback to the user.

⓬ The identification of the user account currently logged in the OAIBOX™ Dashboard. You can customize your profile, such as, change the e-mail address, the first and last name of the user associated with this account and activate the two-factor authentication.

⓭ The OAIBOX™ Dashboard logout button.

⓮ The *5G Standalone Message Flow Section*. The OAIBOX™ Dashboard uses Wireshark to perform quick packet inspection on the 5G Network. For efficiency, it only displays the timestamp, the protocol, and a short summary of the message contents. Deeper packet inspection can be separately done with Wireshark, as it is already included and configured in the OAIBOX™, for 5G Standalone.



TIME	Protocol	Message
00:00:14.214	HTTP2/JSON/NGAP	DATA[1], JavaScript Object Notation (application/json)
00:00:14.213	NGAP	SACK (Ack=0, Arwnd=106496) , PDUSessionResourceSetupResponse
00:00:14.189	NGAP/NAS-5GS	SACK (Ack=0, Arwnd=106496) , PDUSessionResourceSetupRequest,...
00:00:14.189	HTTP2/JSON/NAS-5GS/NG...	DATA[1], JavaScript Object Notation (application/json), PDU session e...
00:00:14.177	NGAP/NAS-5GS	UplinkNASTransport, UL NAS transport, PDU session establishment r...
00:00:01.016	NGAP/NAS-5GS	InitialContextSetupResponse, UplinkNASTransport, Registration com...
00:00:00.813	NGAP	SACK (Ack=1, Arwnd=106496) , UERadioCapabilityInfoIndication
00:00:00.769	NGAP/NAS-5GS	SACK (Ack=0, Arwnd=106496) , InitialContextSetupRequest, Registr...
00:00:00.767	NGAP/NAS-5GS/NAS-5GS	SACK (Ack=0, Arwnd=106496) , UplinkNASTransport, Security mode...
00:00:00.751	NGAP/NAS-5GS	SACK (Ack=1658340939, Arwnd=106496) , DownlinkNASTransport...
00:00:00.727	NGAP/NAS-5GS	UplinkNASTransport, Authentication response
00:00:00.359	NGAP/NAS-5GS	SACK (Ack=2, Arwnd=106496) , DownlinkNASTransport, Authentica...
00:00:00.322	NGAP/NAS-5GS	UplinkNASTransport, Authentication failure (Synch failure)
00:00:00.110	NGAP/NAS-5GS	SACK (Ack=1, Arwnd=106496) , DownlinkNASTransport, Authentica...
00:00:00.087	NGAP/NAS-5GS	SACK (Ack=0, Arwnd=106496) , UplinkNASTransport, Identity respo...
00:00:00.000	NGAP/NAS-5GS/NAS-5GS	InitialUEMessage, Registration request, Registration request
00:00:00.000	NGAP/NAS-5GS	SACK (Ack=0, Arwnd=106496) , DownlinkNASTransport, Identity re...

Figure 1-21: The OAIBOX^{TM} Dashboard – details on the right part of the dashboard

Additional information on the gNB can be accessed by clicking on the "NG-RAN" block (see Figure 1-19). The information provided there is depicted in Figure 1-22.

Figure 1-22: The gNB dedicated page

Each new identified area is explained below:

❶ Breadcrumb navigation, indicating the user is currently viewing gNB related data.

❷ The online status of the gNB (Red: *Offline*; Orange: *Starting*; Green: *Online*), summary information on the throughput speed (UL and DL) and number of attached UEs. The OAIBOX^{TM} needs to have Internet access to achieve the gNB Online status.

❸ Button that allows the download of telemetry data from the 5G gNB for additional analysis. Telemetry data includes gNB KPIs. These data could be used to gain additional insights into the gNB's performance, troubleshoot issues, optimize network efficiency, amongst others. The telemetry data is provided in *JavaScript Object Notation* (JSON) format.

❹ The current configuration parameters for the gNB. These currently are the 3GPP Frequency Band, the channel bandwidth, the *Time-Division Duplex* (TDD) slot configuration, MIMO configuration (logical and physical antennas), and modulation order (DL and UL).

> To change these parameters, the gNB needs first to be stopped!

> The configuration parameters can also be directly accessed through the gNB dedicated section on the overview page (⑤ in Figure 1-19).

❺ Button that opens the running logs from the OpenAirInterface gNB, exported from the OAIBOX™. The logs can be viewed and analysed directly from the OAIBOX™ Dashboard (see Figure 1-23). The gNB logs provide additional information about the status of the USRP, gNB, attached UEs, and are most relevant when troubleshooting connection issues.

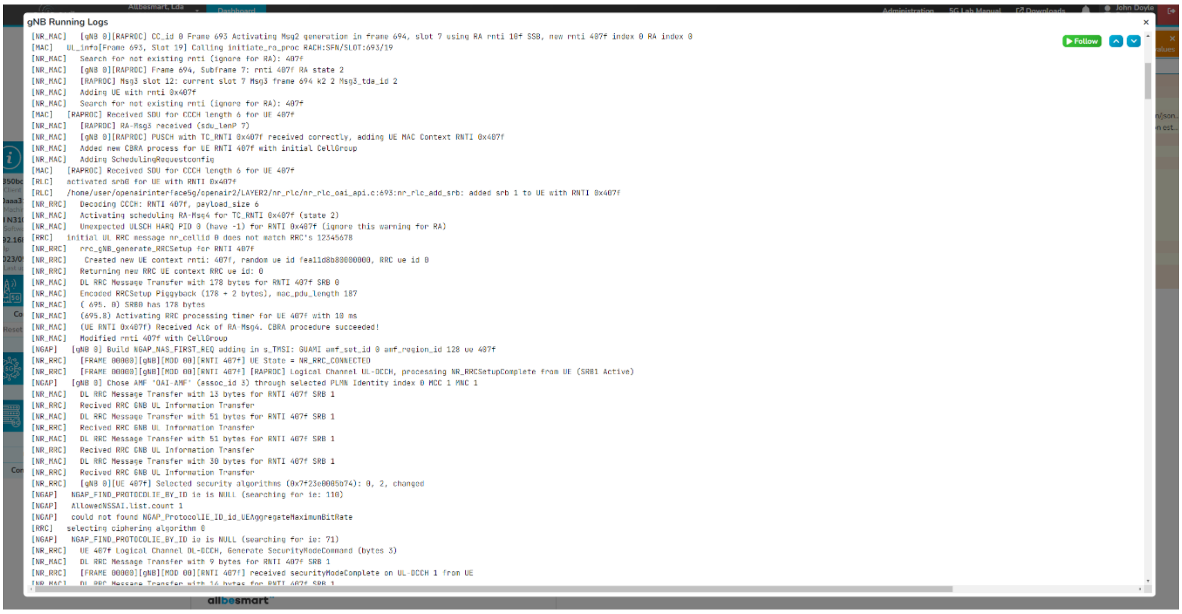


Figure 1-23: Example of OAI gNB logs

❻ Additional details on the current gNB configuration (non-editable).

❼ A real-time plot showing the historic evolution (last 10 minutes) of the gNB aggregated downlink and uplink throughputs.

❽ Summary information regarding the UEs currently connected to the gNB. A dedicated box appears for each attached UE.

> The Attached UEs area is clickable, it redirects to a dedicated UEs page, see Figure 1-24.

The additional information on each attached UE can be obtained by clicking on ❽ (Figure 1-22). The new information provided is depicted in Figure 1-24. Each identified area is explained further below:

❶ Navigation information regarding the page that is being displayed.

❷ Summary information regarding all monitored KPIs for this UE. Each KPI is explained in the next section (1.3.3).

❸ The real-time plots for all KPIs being monitored. The real-time plots adapt according to the rules set on the filters.

❹ An historic evolution of this UE's aggregated downlink and uplink throughputs – this plot is updated in real-time.

❺ The combined view of the *Physical Layer* (PHY) KPIs (for DL and UL). Each individual KPI can be turned ON or OFF. This feature facilitates the correlation analysis between KPIs.

Figure 1-24: The UE dedicated page

1.3.3 The UEs metrics and KPIs explained

A *Key Performance Indicator* (KPI) is a measurable value that demonstrates how effectively a network is serving the user. For instance, the KPIs are used for requirements for system definition, verification of proper functioning of installed networks and comparison of performance provided by specific vendors or technologies. In this subsection, we present the KPIs displayed by OAIBOX™ Dashboard.

1.3.3.1 RSSI

The *Received Signal Strength Indicator* (RSSI) measures the linear average of the total received power (in Watt) observed only per configured OFDM symbol and in the measurement bandwidth, over N_{RB} *resource blocks* (RB). It includes the power from co-channel serving and non-serving cells, adjacent channel interference, thermal noise, etc. [1]. The RSSI is given by:

$$RSSI = \frac{1}{N_{symb}} \sum_{l=1}^{N_{symb}} \sum_{r=1}^{N_{RB}} \sum_{k=1}^{N_{sc}^{RB}} \left|s_{l,r,k}\right|^2, \tag{1.1}$$

, where N_{symb} is the number of OFDM symbols used in the measurement, $N_{sc}^{RB} = 12$ is the number of subcarriers per resource block, and $s_{l,r,k}$ is the received signal power in lth OFDM symbol, rth resource block and kth subcarrier.

$$RSSI_{dBm} = 10 log_{10}\left(\frac{RSSI\ [W]}{10^{-3}}\right), \tag{1.2}$$

1.3.3.2 RSRP

The *Reference Signal Received Power* (RSRP) measures the linear average power (in Watt) of the resource elements that carry cell-specific reference signals within the considered measurement frequency bandwidth [1]. This value is usually presented in dBm, and is given by:

$$RSRP_{dBm} = RSSI_{dBm} - 10\, log_{10}(N_{sc}^{RB} N_{RB}). \tag{1.3}$$

SS-RSRP represents the RSRP based on the Secondary Synchronisation Signal, while CSI-RSSI corresponds to measurements based on OFDM symbols containing configured CSI-RS occasions. $N_{sc}^{RB} = 12$ is the number of subcarriers per resource block. A UE can provide SS-RSRP or CSI-RSRP measurements at Layer 1, for instance, when sending *Channel State Information* (CSI), and SS-RSRP measurements at Layer 3 when sending an RRC Measurement Report to gNB. The mapping between the measured RSRP, and the reported value for the gNB is shown in Table 1-5.

Table 1-5: RSRP measurement report mapping [3].

Reported value	Measured quantity value by Layer 3 (dBm)	Measured quantity value by Layer 1 (dBm)
0	RSRP < -156	Not valid
1	-156 ≤ RSRP < -155	Not valid
2	-155 ≤ RSRP < -154	Not valid
3	-154 ≤ RSRP < -153	Not valid
…	…	…
14	-143 ≤ RSRP < -142	Not valid
15	-142 ≤ RSRP < -141	Not valid
16	-141 ≤ RSRP < -140	RSRP < -140
17	-140 ≤ RSRP < -139	-140 ≤ RSRP < -139
18	-139 ≤ RSRP < -138	-139 ≤ RSRP < -138
…	…	…
111	-46 ≤ RSRP < -45	-46 ≤ RSRP < -45
112	-45 ≤ RSRP < -44	-45 ≤ RSRP < -44
113	-44 ≤ RSRP < -43	-44 ≤ RSRP
114	-43 ≤ RSRP < -42	Not valid

Reported value	Measured quantity value by Layer 3 (dBm)	Measured quantity value by Layer 1 (dBm)
115	-42 ≤ RSRP < -41	Not valid
125	-32 ≤ RSRP < -31	Not valid
126	-31 ≤ RSRP	Not valid
127	Infinity	Infinity

RSRP	Signal strength	Description
>= -80 dBm	Excellent	Strong signal with maximum data speeds
-80 dBm to -90 dBm	Good	Strong signal with good data speeds
-90 dBm to -100 dBm	Fair to poor	Reliable data speeds may be attained, but marginal data with drop-outs is possible. When this value gets close to -100, performance will drop drastically
<= -100 dBm	No signal	Disnonnection

1.3.3.3 RSRQ

RSRQ is used in 5G NR networks to determine the quality of the radio channel based on *Synchronization Signals* (SSs). RSRQ, unlike RSRP (wanted signal strength), also includes interference level due to the inclusion of RSSI in calculation. This parameter is also used for cell selection and handover, if the RSRP is not sufficient. This happens mainly near cell edge of a serving cell.

RSRQ	Signal quality	Description
>= -10 dB	Excellent	Strong signal with maximum data speeds
-10 dB to -15 dB	Good	Strong signal with good data speeds
-15 dB to -20 dB	Fair to poor	Reliable data speeds may be attained, but marginal data with drop-outs is possible. When this value gets close to -20, performance will drop drastically
<= -20 dB	No signal	Disconnection

1.3.3.4 PHR

In 5G networks, *Power Headroom Report* (PHR) reporting refers to a mechanism that allows the gNB to assess the available power margin of a UE. Power Headroom reporting is important for efficient power management and resource allocation in the network. Power Headroom is the difference between the maximum transmit power capability of the UE and the actual power required for the UE to maintain its connection with the base station while meeting the quality of service (QoS) requirements. It represents the power reserve that the UE has available to transmit higher power signals if needed. PHR control element is used to report the power headroom (PH) available at the UE. There are 3 types of PH [4]:

- Type 1: Difference between the nominal UE maximum transmit power and the estimated power for ULSCH transmission per activated Serving Cell;
- Type 2: Difference between the nominal UE maximum transmit power and the estimated power for ULSCH and PUCCH transmission on SpCell of the other MAC entity (i.e. E-UTRA MAC entity in EN-DC, NE-DC, and NGEN-DC cases);
- Type 3: Difference between the nominal UE maximum transmit power and the estimated power for SRS transmission per activated Serving Cell.

For instance, the PH calculation for type 1 based upon reference PUSCH transmission, when the UE transmits the PUSCH in transmission occasion i, on active UL-BWP b, carrier f, serving cell c, path loss measured by the UE using the reference signal with index q_d, parameter set configuration with index j and power control adjustment state with index l, is given by [5]:

$$PH_{type1,b,f,c}(i,j,q_d,l) = \tilde{P}_{CMAX,f,c}(i) - \{P_{O_{PUSCH},b,f,c}(j) + \alpha_{b,f,c}(j) \times PL_{b,f,c}(q_c) + f_{b,f,c}(i,l)\}, \quad (1.4)$$

where $\tilde{P}_{CMAX,f,c}(i)$ is the maximum UE transmit power, $P_{O_{PUSCH},b,f,c}(j)$ is the nominal UE transmit power, $\alpha_{b,f,c}(j)$ is the fractional power control multiplier, $PL_{b,f,c}(q_c)$ is the path loss measurement, and $f_{b,f,c}(i,l)$ is the closed loop power control component. The PH value is mapped into 6 bits and reported as in the Table 1-6 [3]:

Table 1-6: PHR mapping.

Reported value	PH value (dB)
0	PH < -32
1	-32 ≤ PH < -31
2	-31 ≤ PH < -30
…	…
52	19 ≤ PH < 20
53	20 ≤ PH < 21
54	21 ≤ PH < 22
55	22 ≤ PH < 24
56	24 ≤ PH < 26
57	26 ≤ PH < 28
…	…
61	34 ≤ PH < 36
62	36 ≤ PH < 38
63	38 ≤ PH

1.3.3.5 SINR

Signal to Interference plus Noise Ratio (SINR) is a quality measurement which represents the ratio of the wanted signal power to the interference plus noise power, i.e.,

$$SINR = \frac{S}{N+I}, \tag{1.5}$$

, where I is the interference power of other measured signals. For SS-SINR, the wanted signal power and the interference plus noise power are measured from resource elements used by the *Secondary Synchronization Signal* (SSS) [1]. SINR is reported using the values in Table 1-7.

1.3.3.6 SNR

Signal-to-noise ratio (SNR) is a measure that compares the level of a wanted signal to the level of power noise. It is defined as the ratio of wanted power to the noise power, i.e.,

$$SNR = \frac{S}{N}, \tag{1.6}$$

, where S is the power of measured wanted signals, and N is the power noise. Considering the UE antenna connectors as reference point, the SNR can also be defined as [6]:

$$SNR = \frac{\sum_{j=1}^{Nrx} E_s^{(j)}}{\sum_{j=1}^{Nrx} N_{oc}^{(j)}}, \tag{1.7}$$

, where N_{rx} is the number of receiver antenna connectors, $E_s^{(j)}$ is the level of transmitted wanted signal, and $N_{oc}^{(j)}$ is the power spectral density of a white noise source with average power per resource element normalized to the subcarrier spacing. For this definition, it is assumed that the resource elements are not precoded, or do not have any gain which can be associated to the precoding operation.

Table 1-7: Mapping between measured and reported SS-SINR [3].

Reported value	Measured SS-SINR (dB)
0	SS-SINR < -23
1	-23 ≤ SS-SINR < -22.5
2	-22.5 ≤ SS-SINR < -22
…	…
125	39 ≤ SS-SINR < 39.5
126	39.5 ≤ SS-SINR < 40
127	-40 ≤ SS-SINR

1.3.3.7 CQI

The *Channel Quality Indicator* (CQI) values allow a UE to quantify and report (using either the PUCCH or the PUSCH) its downlink radio channel conditions within a specific Bandwidth Part. CQI value should allow the UE to measure and achieve the desired SINR value. CQI values are signaled using a range from 0 to 15, where high CQI values indicate that the UE is able to receive high order modulation with a high coding rate. In [7] is specified three CQI tables which correspond to three PDSCH MCS tables, i.e., a 64QAM table, a 256QAM table and a Low Spectral Efficiency table. The CQI Table 2 (256QAM Table) for a *Transport Block* (TB) error probability equal to 0.1 is presented in **Table 1-8**.

Table 1-8: CQI Table 2 (256QAM Table) for a transport block error probability equal to 0.1 [7].

CQI Index	Modulation	Coding Rate	Spectral Efficiency
0		*Out-of-Range*	
1	QPSK	0.076	0.1523
2	QPSK	0.188	0.3770
3	QPSK	0.438	0.8770
4	16QAM	0.369	1.4766
5	16QAM	0.479	1.9141
6	16QAM	0.602	2.4063
7	64QAM	0.455	2.7305
8	64QAM	0.554	3.3223
9	64QAM	0.650	3.9023
10	64QAM	0.754	4.5234
11	64QAM	0.853	5.1152
12	256QAM	0.694	5.5547
13	256QAM	0.778	6.2266
14	256QAM	0.864	6.9141
15	256QAM	0.926	7.4063

1.3.3.8 MCS

The *Modulation and Coding Scheme* (MCS) corresponds to a row within the relevant MCS look-up table, and it is allocated by an algorithm belonging to the gNB. The MCS is signaled to the UE on the PDCCH (DCI Format 1_0 or 1_1). In general, higher MCS index corresponds to larger transport block sizes and consequently more information bits over the air-interface.

Three MCS tables are specified in [7] for the PDSCH: a 64QAM table, a 256QAM table, and a low spectral efficiency table. The MCS index Table 2 (256QAM Table) for PDSCH is presented in Table 1-9.

Table 1-9: MCS index Table 2 (256QAM Table) for PDSCH [7].

MCS index	Modulation order	Target code rate	Spectral efficiency
0	QPSK	0.117	0.2344
1	QPSK	0.188	0.3770
2	QPSK	0.301	0.6016
3	QPSK	0.438	0.8770
4	QPSK	0.588	1.1758
5	16QAM	0.369	1.4766
6	16QAM	0.424	1.6953
7	16QAM	0.479	1.9141
8	16QAM	0.540	2.1602
9	16QAM	0.602	2.4063
10	16QAM	0.643	2.5703
11	64QAM	0.455	2.7305
12	64QAM	0.505	3.0293
13	64QAM	0.554	3.3223
14	64QAM	0.602	3.6094
15	64QAM	0.650	3.9023
16	64QAM	0.702	4.2129
17	64QAM	0.754	4.5234
18	64QAM	0.803	4.8164
19	64QAM	0.853	5.1152
20	256QAM	0.667	5.3320
21	256QAM	0.694	5.5547
22	256QAM	0.736	5.8906
23	256QAM	0.778	6.2266
24	256QAM	0.821	6.5703
25	256QAM	0.864	6.9141
26	256QAM	0.895	7.1602
27	256QAM	0.926	7.4063
28	QPSK	*Reserved*	
29	16QAM	*Reserved*	
30	64QAM	*Reserved*	
31	256QAM	*Reserved*	

The **target code rate** is the number of information bits ratio between the top and bottom of the physical layer, i.e., a measure of the redundancy added by the physical layer.

The **spectral efficiency** (per layer) is given by the modulation order (QPSK: 2, 16QAM: 4, 64QAM: 6, 256QAM: 8) multiplied by the target code rate.

1.3.3.9 BLER

The *Block Error Rate* (BLER) is defined as the number of erroneous received code blocks, $N_{TB,err}$, dividing by the number of total blocks, N_{TB}, i.e.,

$$BLER = \frac{N_{TB,err}}{N_{TB}}. \qquad (1.8)$$

The code block is considered erroneous if its attached CRC code does not match the one calculated by the receiver. When performing receiver measurement, for every block of data payload received, the UE will send an acknowledgment (ACK) for blocks successfully decoded and send a negative acknowledgment (NACK) for blocks failing CRC. Throughput, is a metric to measure the actual data bits successfully received in a certain duration, which can be described mathematically as:

$$Troughput = (1 - BLER)\ bitrate \tag{1.9}$$

Thus, as BLER decreases, the throughput increases.

> Cyclic Redundancy Check (CRC) bits are bits which were added to each transport block at the transmitter to allow error detection at the receiver side.

> The typical **5G BLER threshold is ≤ 10%**. To maintain the BLER under this threshold, the gNBs use a link-adaptation algorithm based on the UE's feedback, to signal a lower MCS.

1.3.3.10 Bitrate

The *bitrate* is the total number of bits transferred per second. The total number of bits is the sum of the number of bits of each transport block, b_i, $i \in \{1, \dots, N_{TB}\}$, transferred in a given period ΔT, i.e.,

$$bitrate = \frac{\sum_{i=1}^{N_{TB}} b_i}{\Delta T}. \tag{1.10}$$

1.3.3.11 Rank Indicator

In 5G MIMO communication systems, the *Rank Indicator* (RI) is a feedback parameter that is sent by the UE to the gNB to indicate the number of independent spatial streams that can be supported by the radio channel. The rank of the MIMO channel matrix is an important parameter that determines the number of spatial streams that can be transmitted over the channel.

In 5G, the RI is used in conjunction with other feedback parameters, such as the Channel Quality Indicator (CQI) and Precoding Matrix Indicator (PMI), to enable the transmitter to perform precoding, which is a signal processing technique that allows the transmitter to optimize the transmission of data over the MIMO channel. Precoding helps to mitigate interference and improve the overall system performance. The RI value is determined based on the Singular Value Decomposition (SVD) of the MIMO channel matrix. Maximum RI is the number of antennae on each side if the number of Tx antenna and Rx antenna is the same. If the number of Tx and Rx are different, the one with less antenna is the same as maximum achievable RI.

For example, in the case of MIMO 2x2, illustrated in Figure 1-25, the RI value can be 1 or 2. When the value is 2 means that there is practically no correlation between the antennas and best performance is achieved. If the value is 1, it implies that the signal from the two Tx antenna is perceived by UE to be like a single signal coming from a single antenna, which means the worst performance.

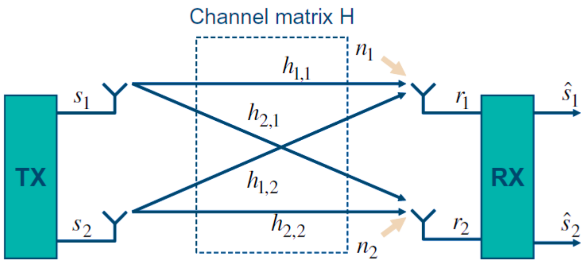


Figure 1-25: MIMO 2x2 antenna configuration with additive noise.

Based on Figure 1-25, the received signal can be expressed as:

$$\overline{r} = \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} = \begin{pmatrix} h_{1,1} & h_{1,2} \\ h_{2,1} & h_{2,2} \end{pmatrix} \cdot \begin{pmatrix} s_1 \\ s_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2 \end{pmatrix} = H \cdot \overline{s} + \overline{n}, \quad (1.11)$$

, where *H* is the 2x2 MIMO channel matrix.

1.4 OpenAirInterface background

The *OpenAirInterface™* (OAI) is an Open5G *Software Defined Radio* (SDR) platform gathering a community of developers from around the world, who work together to build wireless cellular *Radio Access Network* (RAN) and *Core Network* (CN) technologies.

Initially developed by EURECOM as platform for SDR research on cellular technologies OAI evolved to a major community-based software alliance led by EURECOM to enable open research and development of 5G wireless technologies (openairinterface.org). OAI comprises two main components: the 5G RAN and the 5G CN.

1.4.1 OAI 5G RAN

The scope of the OAI 5G RAN project is to develop and deliver a 5G software stack under the OAI Public Licence v1.1. The OAI 5G *New Radio* (NR) software architecture is depicted on Figure 1-26, both for the gNB and NR-UE case.

The *NG Application Protocol* (NGAP) function connects to the *5G CN* (5GC) *Access and Mobility Management Function* (AMF), whereas the N3 function connects to the 5GC *User Plane Function* (UPF). The *Service Data Adaptation Protocol* (SDAP) layer is an addition to the *5G System* (5GS) stack compared to the *Long Term Evolution* (LTE) stack. The SDAP handles the *Quality of Service* (QoS) mapping and adaptation to radio resources and radio bearers.

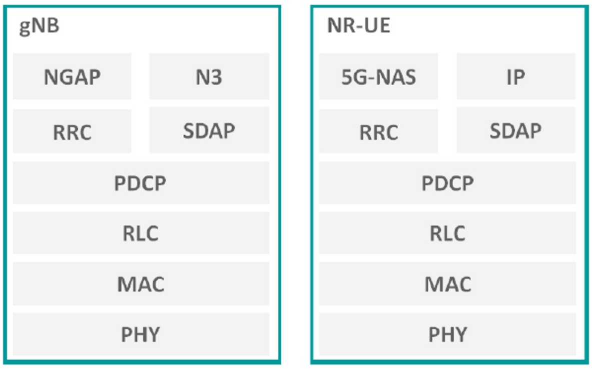


Figure 1-26: OAI RAN software architecture

1.4.2 OAI 5G CORE

The OAI 5G Core architecture is depicted on Figure 1-27. It shows the evolution of OAI 4G *Evolved Packet Core* (EPC) towards 5GCN, where old EPC functions are in white. OAI is actively working to develop a fully functional 5GCN. Table 1-10 describes the 5G NG RAN Functions, whilst Table 1-11 describes the 5G Core Functions.

Table 1-10: The 5G NG RAN Functions

Function	Description
UE	*User Equipment*, representing a 5G equipment capable of connecting to the 5G RAN.
RAN	*Radio Access Network*, provides radio access to between a public/private network and UEs via radio links.
UPF	*User Plane Functions*, support similar functionalities as L-GW and P-GW entities in LTE, enhanced to support network virtualization via Control and User Plane Separation (CUPS). It provides Packet routing & forwarding functions as well as IP address/prefix allocations, as well as the critical User Plane part of policy rule enforcement, e.g., Gating, Redirection or Traffic steering.
DN	*Data Network*, IP or non-IP based network, outside of the scope of 3GPP, which can either correspond to the Internet or a private data network.

Table 1-11: The 5G Core Functions

Function	Description
AMF	*Access and Mobility Management Function*, first entity connected to UE and RAN (gNB), which role is to provide various management tasks (registration, connection, reachability, mobility, access authentication and authorization). AMF is connected to the RAN and UE via the N2 and N1 reference point respectively.
SMF	*Session Management Function*, provides session management (establishment, release, modification of sessions, tunnelling between a UE and UPF), IP address allocation, DHCP or ARP functions. The SMF is connected to the UPF via the N4 reference point.
PCF	*Policy Control Function*, provides policy rules to Control Plane function(s) to enforce them
NEF	*Network Exposure Function* are critical to 5GS, as it enables to expose network functions to external entities without giving them access to the 5GS. Typical network functions exposed are network capabilities, secured provisioning of data from external networks, or translation between internal-external information
NRF	*Network Repository Function* maintains an up-to-date repository of network functions available in the 5G core. Network functions are key innovations of 5G and includes the previously described functions as well as MEC or D2D functions for instance
UDM	*Unified Data Management* handles several functions as generating AAA security credentials, access authorization, lawful interceptions etc
AUSF	*Authentication Server Function* deals with authentication mechanisms for 3GPP and untrusted non 3GPP entities
AF	*Application Function* interacts with other 5G core functions to support 3GPP services such as application influence over routing, time synchronization services. ProSe or V2X Application servers or TSN are typical illustration of AF
NSSF	*Network Slide Selection Function*, as its name indicates, deals with managing and selecting the appropriate network slice serving a UE and selecting the most appropriate AMF dealing with that slice.

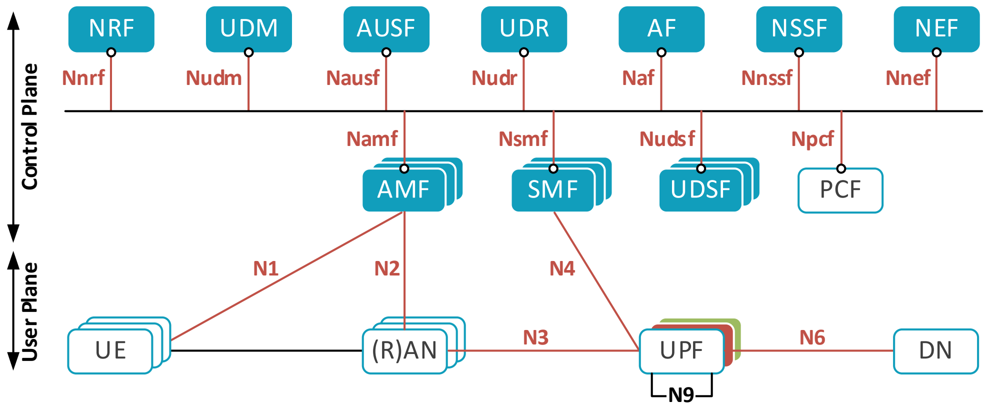


Figure 1-27: The 5G CN implementation (the blue blocks are implemented in OAI)

1.4.3 OpenAirInterface 5G SA software suite

The 5GCN uses a cloud-aligned *Service-Based Architecture* (SBA) that supports control-plane function interaction, re-usability, flexible connections and service discovery across all 5G core functions. The main 5GCN functions are AMF, SMF, NRF and UPF (SPGW-U-tiny), all of which have been implemented in OAI and can easily be deployed using docker-compose.

In the 5G system architecture the gNB needs to implement the complete *Radio Resource Control* (RRC) layer from 3GPP *Technical Specification* (TS) 38.331 and handling of all the associated messages as well as the NGAP from 3GPP TS 38.413 to interface with AMF (N2 interface) and UPF (N3 interface). Moreover, the gNB needs to support multiple bandwidth parts as the initial access happens only on the initial bandwidth part, which has a smaller bandwidth than the full cell bandwidth. Further support for contention-based random access is needed, as well as support for common and dedicated control channels. Only after the initial connection and authentication with the AMF, the full bandwidth part is configured and used for user-plane traffic.

Additional references:

- OAI 5G RAN project: https://openairinterface.org/oai-5g-ran-project/
- OAI 5G CN project: https://openairinterface.org/oai-5g-core-network-project/

LAB-1

Changing the 5G NR bandwidth

2 LAB-1: Changing the 5G NR bandwidth

2.1 Pre LAB-1: 3GPP Background

2.1.1 Overview of 5G NR frame structure and resource grid

In the 5G NR, the protocol architecture can be separated into two categories: user plane protocol stack and control plane protocol stack. The user plane protocol stack architecture is responsible for delivering user data and the control plane architecture is responsible for setting up the connection, maintaining mobility and providing end-to-end security.

The user plane protocol stack for 5G NR is shown in Figure 2-1. We see that at the physical layer interface (Air Interface) between the gNB and UE, the transmission occurs in the form of radio frames.

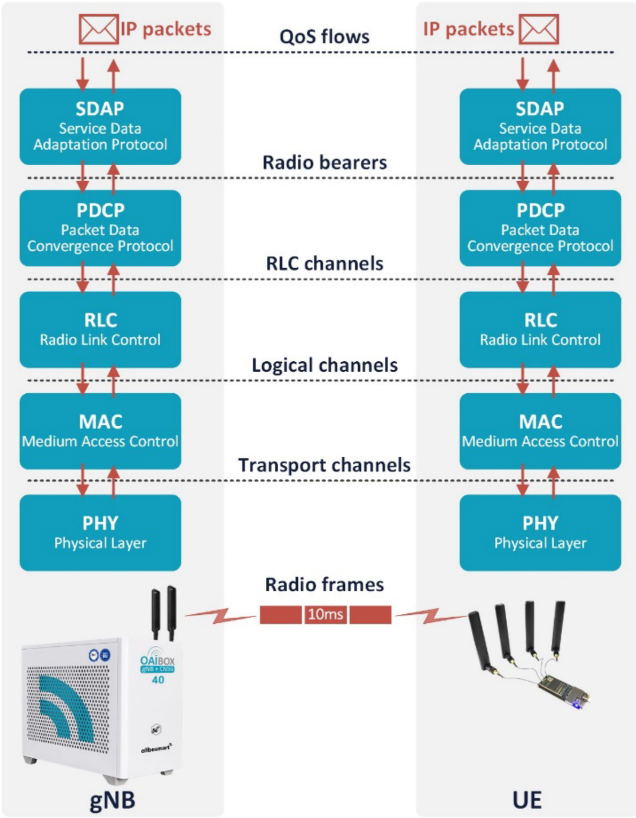


Figure 2-1: *5G NR user plane protocol stack architecture (example for OAIBOX™ 40)*

Looking at the 5G NR frame structure from the time domain perspective, the radio transmissions are categorized into radio frames, subframes, slots and mini-slots (Figure 2-2). A radio frame has a duration of 10 ms and is equally divided in 10 subframes of 1 ms duration each one. Each subframe may, within each slot, have a fixed number of 14 OFDM (Orthogonal Frequency Division Multiplexing) symbols for normal *Cyclic Prefix* (CP) values. The possibility of transmission over a fraction of a slot is referred to as mini-slot transmission and consists of a different approach to achieve low latency communications by enabling the immediate transmission of mini-slots containing a reduced number of OFDM symbols, minimizing the decoding delay.

Figure 2-2 shows the radio frame structure for the supported transmission numerologies (μ = 0, 1, 2, 3, 4) as per Figure 2-3.

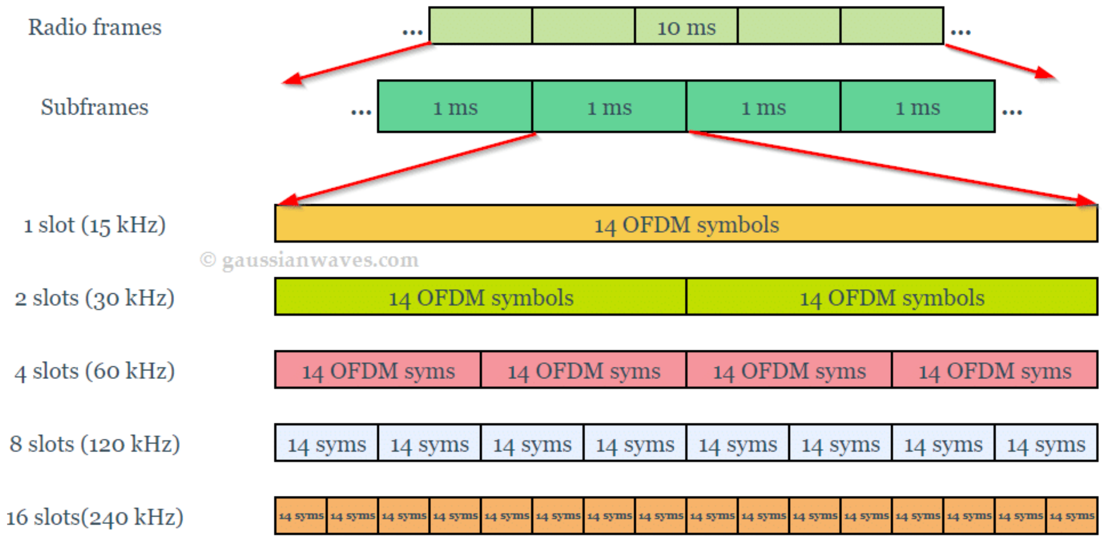


Figure 2-2: *5G NR frame structure [source: gaussianwaves]*

The content to be transmitted in downlink or uplink is placed in channels and mapped in resources, i.e., pairs (frequency, time). The resources are organized in resource elements, which are the smallest unit of the resource grid made up of one subcarrier in frequency domain and one OFDM symbol in time domain. A *resource block* (RB) is composed by 12 consecutive subcarriers with the same subcarrier spacing, $\Delta f = 2^{\mu} \times 15\text{kHz}$, where the value μ defines the numerology ($\mu = 0{,}1{,}2{,}3{,}4$) [8]. The RBs in the NR are organized in different *Bandwidth Parts* (BWP), which can be composed up to 275 RBs. A resource grid is represented in Figure 2-3.

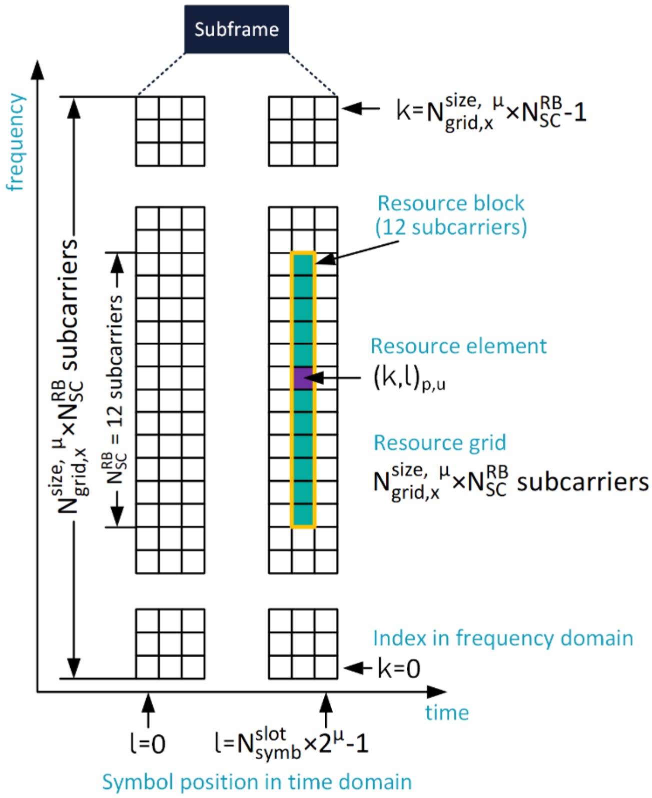


Figure 2-3: Resource element, Resource block and Resource grid in 5G NR.

Because the duration of an OFDM signal is inversely proportional to its subcarrier spacing, the time duration of a slot scales with the selected numerology, as we can see in Table 2-1.

Table 2-1: Supported values for each numerology [8].

μ	$\Delta f\,[kHz]$	Resource block bandwidth $12\Delta f$	Frame duration	Slots per frame	Slot duration	OFDM Symbols per slot	Symbol duration	Cyclic prefix
0	15	180 KHz	10 ms	10	1 ms	14	71.43 µ	Normal
1	30	360 KHz	10 ms	20	500 µs	14	35.71 µ	Normal
2	60	720 KHz	10 ms	40	250 µs	14	17.86 µ	Normal, Extended
3	120	1.44 MHz	10 ms	80	125 µs	14	8.93 µ	Normal
4	240	2.88 MHz	10 ms	160	62.5 µs	14	4.46 µ	Normal

Within the channel bandwidth, we have the guard band and the maximum bandwidth which can be configured for transmission, as shown in Figure 2-4. This means that we cannot use all available bandwidth for transmission. The number of Resource Blocks we can allocate, for each channel bandwidth, for example for $\mu = 1$, i.e., $\Delta f = 30\ kHz$, is shown in Table 2-2.

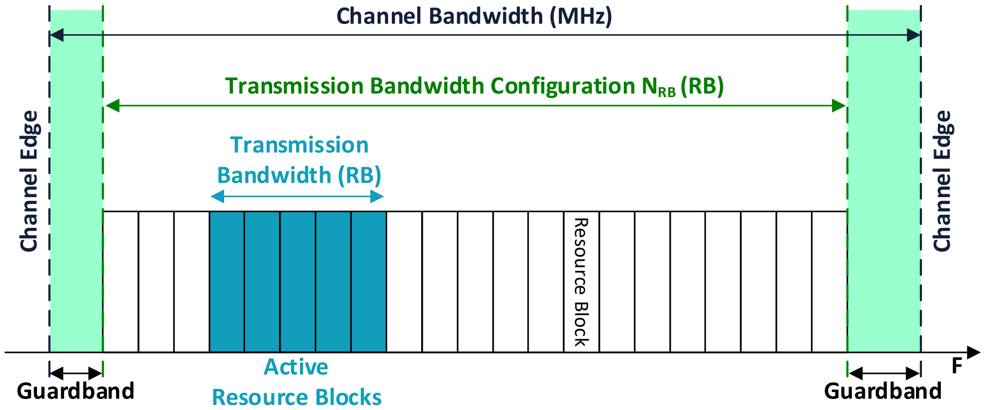


Figure 2-4: Channel bandwidth and the maximum transmission bandwidth configuration [9].

Table 2-2: Maximum number of resource blocks configured for transmission [9].

Bandwidth [MHz]	5	10	15	20	25	30	40	50	60	70	80	90	100
N_{RB}	11	24	38	51	65	78	106	133	162	189	217	245	273

The values in Table 2-2 mean that, for instance for bandwidths:

- 20MHz, the maximum transmission bandwidth is $51 \times 12 \times (30 \times 10^3) = 18.36\ \text{MHz}$;
- 30MHz, the maximum transmission bandwidth is $78 \times 12 \times (30 \times 10^3) = 28.08\ \text{MHz}$;
- 40MHz, the maximum transmission bandwidth is $106 \times 12 \times (30 \times 10^3) = 38.16\ \text{MHz}$.

2.1.1.1 5G NR bit rate computation

The simplest way to estimate the maximum 5G throughput for a specific air interface configuration is to calculate the maximum data rate carried by a single *Resource Block* (RB) into one-time slot. In 5G NR the Number of Subcarriers per Resource Block is 12 and the Number of Symbols per resource Block is 14. As shown in Figure 2-5 there are 2 symbols reserved for *Demodulation Reference Signals* (DMRSs) and 1 symbol reserved to *Physical Downlink Control Channel* (PDCCH). There are 11 *Physical Data Shared Channel* (PDSCH) symbols for user data.

Total Data Resource Elements = 12 x 11 = 132

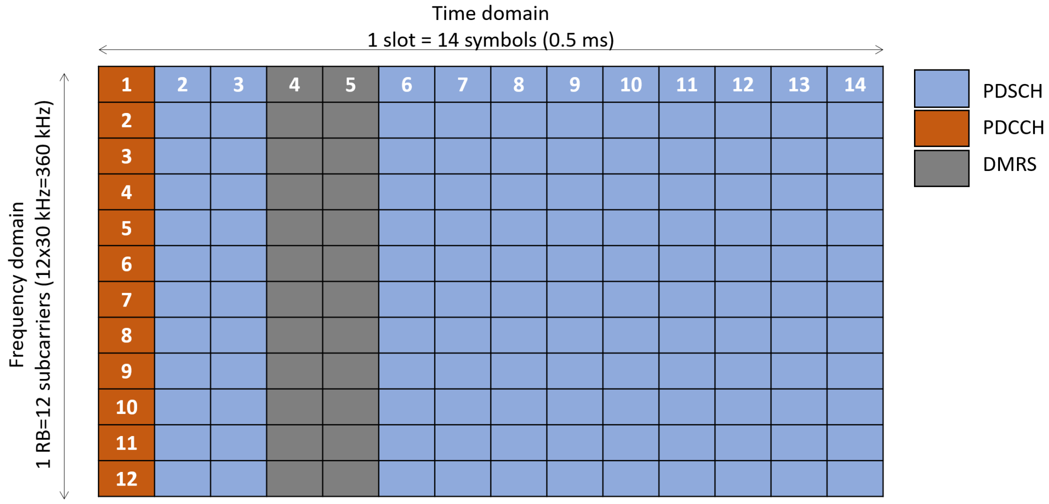


Figure 2-5: 5G Resource Block structure considering SCS of 30 KHz.

Considering a 256QAM (Modulation order 8) and code rate 0.925, results in:

Spectral efficiency = 8 x 0.925 = 7.4063

, which corresponds to MCS Index 27 in 3GPP 38.214 Table 5.1.3.1-2 (see Table 1-9).

Data carried in one Resource Block over one slot = 132 x 7.4063 = 978 bits in 0.5ms

Considering the example where the 5G Bandwidth is 40 MHz which is the maximum bandwidth supported by the OAIBOX™ 40:

Number of Resource Blocks in 40MHz = 40,000 KHz / 360 KHz = 111
(106 are used, 4 RBs are used as guard (Figure 2-4).

Total Number of Slots available in one second = 1,000 ms / 0.5 ms = 2,000 slots

Considering a TDD frame with DL/UL Ratio of 4:1

Downlink Slots = 1,600 and Uplink Slots = 400

Considering the number of MIMO layers = 1

Max DL bit rate = (978 bits x 106 RBs x 1600 slots x 1 layers)/10^6 = 166 Mbps

Max UL bit rate = (978 bits x 106 RBs x 400 slots x 1 layers)/ 10^6 = 41 Mbps

Note: the division by 10^6 is used to convert bps to Mbps.

A Guard Period overhead is introduced in special slots to shift from Tx to Rx and vice versa. There are also some symbols for uplink control channels, like *Sounding Reference Signals* (SRSs), therefore the maximum throughput will be slightly lower than the computed. For more information on 5G NR data rate calculation check 3GPP TS 38.306 [11].

2.2 Change the 5G NR bandwidth in the OAIBOX™

In this Lab you will learn how to change the 5G NR bandwidth in the OAIBOX™, using two different methods:

- Method 1: via the OAIBOX™ Dashboard;
- Method 2: via the OAI configuration files (advanced topic).

> Note: this Labs uses the OAIBOX™ 40 but it can be replicated with the OAIBOX™ MAX connected to an USRP that supports 40 MHz bandwidth.

2.2.1 Lab Equipment

Besides the OAIBOX™ 40 and the Quectel (UE), you will require a host computer/laptop to connect to the Quectel. The suggested minimum requirements for the computer/laptop are:

- Operating System: Microsoft Windows (10 or above) or Ubuntu Linux
- CPU: 4 cores x86_64
- RAM: 8 GB

2.2.2 Lab steps

Step 1. This lab will use the setup illustrated by Figure 2-6. For this initial over-the-air test the distance between the gNB and the UE should be between 1 m and 3 m in *Line-of-Sight* (LoS).

Figure 2-6: LAB-1 setup (example for the OAIBOX™ 40)

> Alternatively, you can connect the Quectel using an over-the-cable connection. Please check **section 1.2.6** for additional information on using an RF cable-kit.

Step 2. Make sure, both the OAIBOX™ and the UE are working as expected, by completing the quick setup guide provided in section 1.2.1 (for OAIBOX™ 40), or section 0 (for OAIBOX™ MAX).

Step 3. Use the UE (the term "UE" identifies the laptop connected to the Quectel) to access your OAIBOX™ Dashboard, by navigating to: https://my.oaibox.com,
Login with your credentials.

Step 4. On the overview page, access the gNB dedicated page by clicking the "**NG-RAN**" block (see Figure 1-19).

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Step 5. Observe the default OAIBOX^{TM} 40 configuration and confirm the current bandwidth value (see Figure 2-7).

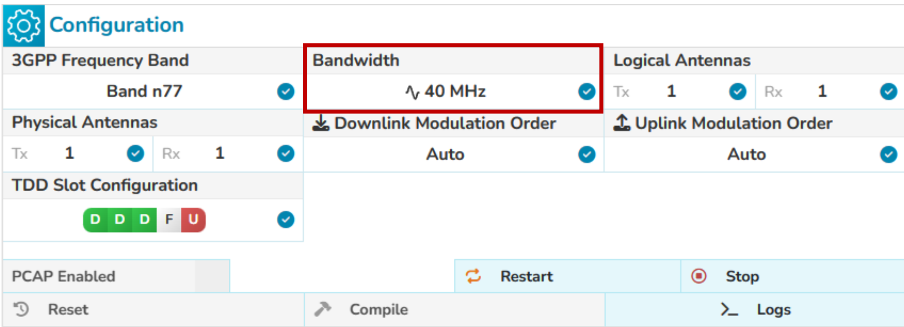


Figure 2-7 - OAIBOX^{TM} 40 default configuration

Step 6. On the gNB page, scroll down until you see the "**Attached UEs**" section. Click on the UE block (❽ in Figure 1-22) to access the UE dedicated page.

Step 7. Fill in Table 2-3, but only the row associated with **40 MHz**, with the values observed.

> You can obtain the exact values by hovering the mouse over the graphics

Step 8. Use the OAIBOX^{TM} Dashboard breadcrumbs (❶ in Figure 1-24) to navigate back to the *Overview* page.

Step 9. Click on the button at the "**Open Speed Test**" block to open the 5G speed test page.

This will open a new browser window.

Step 10. On the new browser window, start the speed test.

Step 11. On a different browser window go to the UE dedicated page (see Step 6) to visualize the real-time bit rate plot evolution during the Speedtest. Figure 2-8 depicts the expected results for this test.

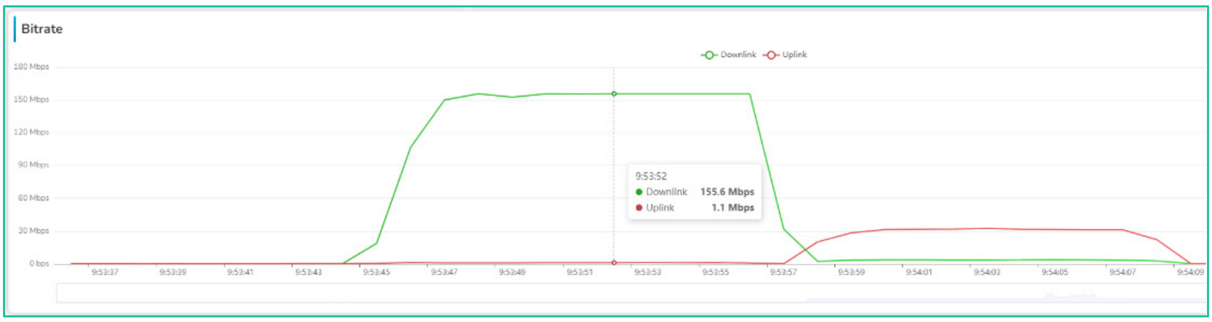


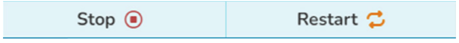
Figure 2-8: Typical results for a 5G speed test with the default OAIBOX^{TM} 40 configurations.

Step 12. Fill in Table 2-4 (only the row associated with 40MHz) with the average measured values.

Step 13. Perform the theoretical calculations (see section 2.1.1.1) for the expected UL and DL throughputs.

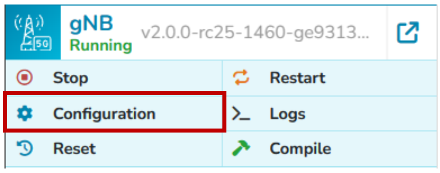
Step 14. Use the OAIBOX™ Dashboard breadcrumbs (❶ in Figure 1-24) to navigate back to the *Overview* page.

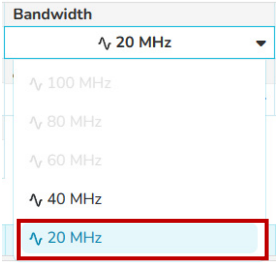
Step 15. Stop the gNB.



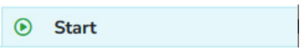
Step 16. Click 'Proceed' to confirm the operation and wait until the "NG-RAN" block turns red with status "Stopped".

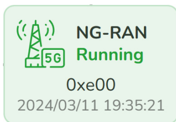
Step 17. At the gNB section (❺ in Figure 1-19), click on "Configuration" and then change the bandwidth configuration to 20 MHz.





Step 18. Start the gNB and wait until the "NG-RAN" block turns green with status "Running".





Step 19. Repeat **Step 4** to **Step 13**, now applicable to 20MHz.

2.3 LAB-1: Report

Table 2-3: Average values measured for the UE PHY layer parameters

Bandwidth	RSSI	RSRP	RSRQ	SINR	SNR	CQI	MCS	BLER
40 MHz								
20 MHz								

Table 2-4: Throughput measured and theoretical bit rate values

	DL		UL	
Bandwidth	**Measured bit rate**	**Theoretical bit rate**	**Measured bit rate**	**Theoretical bit rate**
40 MHz				
20 MHz				

LAB-1: Suggested topics for discussion:

- Analise the impact of the 5G signal bandwidth on the measured DL and UL bitrates.
- Based on the measured air interface parameters, classify the overall received 5G signal quality at UE.
- Compute the theoretical Shannon capacity of the 5G link and explain the difference from the measured bit rate.
- Compute the SNR considering the thermal noise floor for 20 MHz and 40 MHz bandwidth and compare it with the measured value.
- Elaborate on the impact of the measured BLER on the 5G link throughput.

2.4 Advanced topic - Change the 5G NR bandwidth in the OAI configuration files

In this section we explain how to change the 5G bandwidth configuration in the OAI code base, preparing students and researchers for advanced uses of OAI beyond the pre-defined configurations in the OAIBOX™ Dashboard.

Step 1. If you didn't complete the previous steps in this lab, please setup your testbed according to Figure 2-6. Consider a distance between 1 and 3 m between the gNB and the UE with clear LoS for optimum propagation conditions.

Step 2. To ensure the gNB is with the default parameters, use the dashboard *Overview* page to:

i. Take note of your OAIBOX™ IP address (❸ in Figure 1-19);
ii. "**Stop**" the gNB;
iii. Perform a "**Reset Configuration**".

Step 3. In the UE, open a command line and remotely access to your OAIBOX™ through SSH:

```
ssh user@your_oaibox_IP_address
```

Use "**user**" as password.

> Alternatively, in case you have a keyboard and a monitor directly attached to your OAIBOX, you can access the file through the GUI.

Step 4. Navigate to the folder where the OAIBOX™ configuration file resides and open it with *nano*:

```
cd ~/openairinterface5g/targets/PROJECTS/GENERIC-NR-5GC/CONF/
```

```
nano oaibox.conf
```

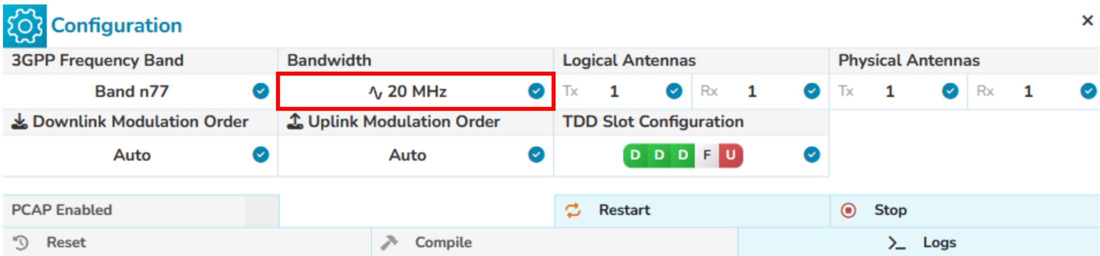
Step 5. Update the following values, (example below is for 20 MHz):

```
dl_carrierBandwidth = 51;
initialDLBWPlocationAndBandwidth = 13750;
…
ul_carrierBandwidth = 51;
…
initialULBWPlocationAndBandwidth = 13750;
```

Step 6. Save the file (**CTRL** + **O**) and exit (**CTRL** + **X**) the *nano* editor.

Step 7. Use the dashboard *Overview* page to "**Start**" the gNB.

Step 8. Click on the gNB "**Configuration**" button and observe the new values (image reflects a change in "**Bandwidth**" to 20 MHz, based on the example provided in Step 5):



Step 9. You can also confirm these new network parameters at the UE side, through AT commands (see section 1.2.4.3):

```
AT+QENG="servingcell"
+QENG: "servingcell","NOCONN","NR5G-SA","TDD",
001,01,E00,0,1,667296,77,3,-70,-11,25,1,-

OK
```

The description for the Quectel UE AT command is provided in Table 2-5, below.

Table 2-5: Description of the Quectel UE AT commands.

AT+QENG Query Primary Serving Cell and Neighbour Cell Information	
Test Command **AT+QENG=?**	Response **+QENG:** (list of supported <cell_types>) **OK**
Write Command Query the serving cell information **AT+QENG="servingcell"**	Response in SA mode: **+QENG: "servingcell", <state>, "NR5G-SA", <duplex_mode>, <MCC>, <MNC>, <cellID>, <PCID>, <TAC>, <ARFCN>, <band>, <NR_DL_bandwidth>, <RSRP>, <RSRQ>, <SINR>, <scs>, <srxlev>** **<NR_DL_bandwidth>** Integer type. DL bandwidth. (The value is only valid in RRC connected state.) 0: 5 MHz ; 1: 10 MHz ; 2: 15 MHz ; **3: 20 MHz** ; 4: 25 MHz ; 5 : 30 MHz; 6: 40 MHz ; 7: 50 MHz ; 8: 60 MHz ; 9 : 70 MHz ; 10 : 80 MHz ; 11 : 90 MHz ; 12 : 100 MHz ; 13 : 200 MHz ; 14 : 400 MHz

LAB-2

Changing the 5G NR central frequency carrier

3 LAB-2: Changing the 5G NR central frequency carrier

3.1 Pre LAB2: 3GPP Background

3.1.1 Overview of 5G NR operating bands

5G operates in different frequency bands depending on the specific operator and region. Frequency bands for 5G NR are separated into two different frequency ranges.

- *Frequency Range 1* (FR1) includes sub-6GHz frequency bands, some of which are bands traditionally used by previous standards but has been extended to cover potential new spectrum offerings from 410 MHz to 7125 MHz. Figure 3-1 presents a chart of 5G FR1.
- *Frequency Range 2* (FR2) includes frequency bands from 24.25 GHz to 52.6 GHz. Bands in this millimetre wave range have shorter range but higher available bandwidth than bands in FR1.

OAIBOX™ 40 and MAX models only supports FR1. The OAIBOX™ Dashboard comes with 3 bands pre-configured as listed in Table 3-1. Other 3GPP bands can be configured changing the open-source OAI code as explained in section 3.4.

Table 3-1: 3GPP bands pre-configured in the OAIBOX™ Dashboard.

3GPP Band	Duplex mode	*f* (MHz)	Band common name	5G ARFCN
n41	TDD	2496-2690	BRS (subset of Band n90)	518910
n77	TDD	3300-4200	C-Band	660672
n78	TDD	3300-3800	C-Band (subset of Band n77)	641280

An *Absolute Radio-Frequency Channel Number* (ARFCN) is a code that specifies a pair of reference frequencies used for transmission and reception in radio system. In a FDD system one ARFCN number is required for downlink and another for uplink, as downlink and uplink frequencies are different while for TDD systems only one ARFCN number is enough, as downlink and uplink frequency remains same (which is the case of the OAIBOX™). NR-ARFCNs for 5G new radio are defined in 3GPP TS 38.101-1 and 38.101-2.

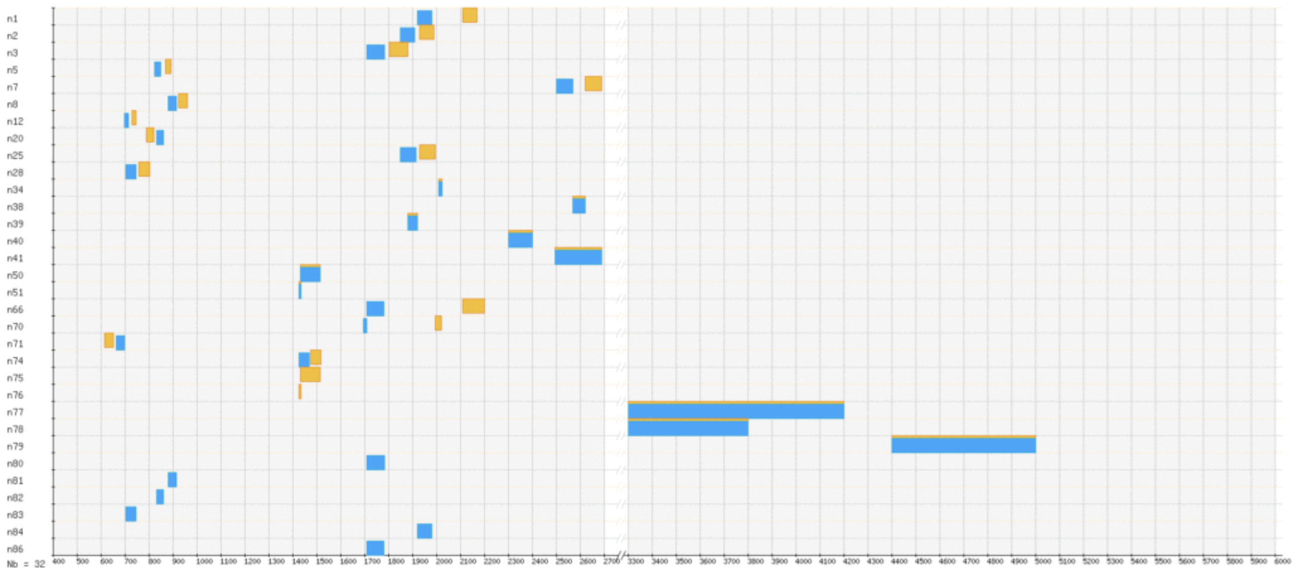


Figure 3-1: Chart of the 5G FR, Band number vs. Frequency Bands (UL and DL) [source: CableFree]

3.1.1.1 Introduction to the 5G path loss computation

The performance objectives of the 5G standard require large blocks of contiguous spectrum to operate channel widths up to 100 MHz. Given the invaluable nature of spectrum as a resource, *Mobile Network Operators* (MNOs) have had little choice but to implement 5G NR on higher cellular bands compared with previous generations. The n77 (3700 MHz), or commonly referred to as the C-band, is a popular tested and deployed 5G frequency. This band brings extra challenges for 5G cellular coverage compared with 2G/3G and 4G bands.

Link Budget is a calculation used to estimate the *received signal level* (R_xSL) from a transmitter. To ensure a good radio link performance the R_xSL should be higher that the *receiver sensitivity* (R_xS). Figure 3-2 illustrates an example of the different parameters used for the downlink budget calculation for the OAIBOX™ system.

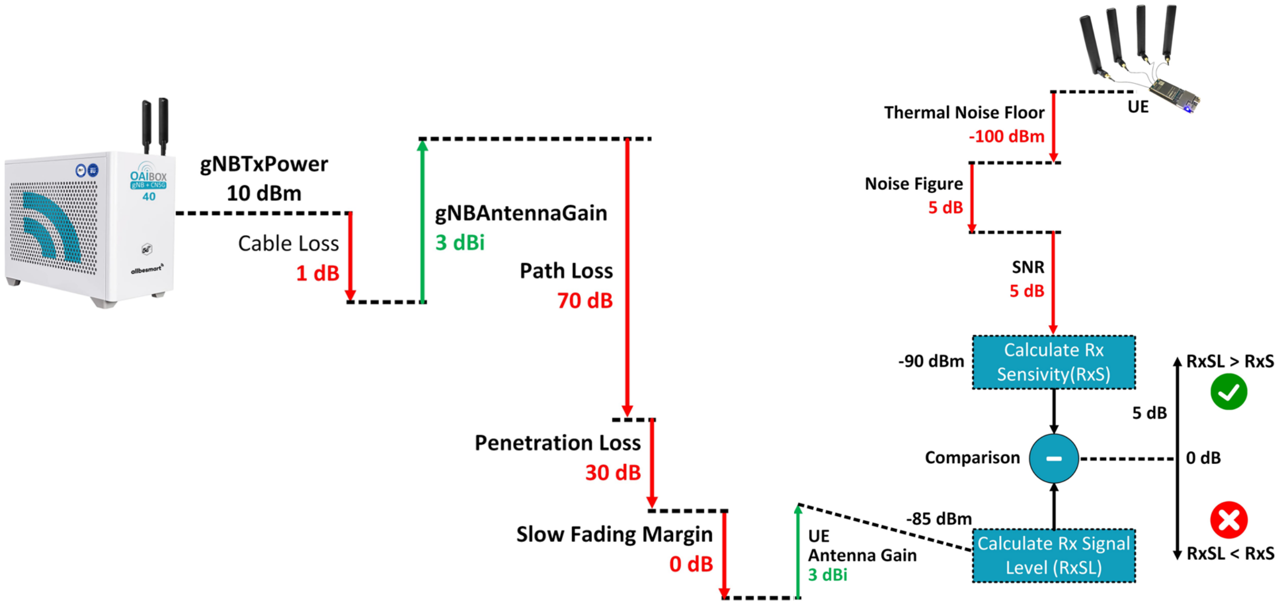


Figure 3-2: Example of 5G downlink budget calculation for the OAIBOX™.

The following formula is used to calculate the 5G received signal level (R_xSL):

$$\mathrm{R}_x\mathrm{SL[dBm]} = \mathrm{gNBT}_x\mathrm{Power[dBm]} - \mathrm{CableLoss[dB]} + \mathrm{gNB\_A\_Gain[dB]} - \mathrm{PathLoss[dB]} - \mathrm{PenetrationLoss[dB]} + \mathrm{UE\_A\_Gain(dB)} \quad (3.1)$$

In the example of Figure 3-2, the R_xSL is -85 dBm, i.e., 5 dB higher than the receiver sensitivity (R_xS), -90 dBm, therefore the downlink power budget is suitable for the target SNR. Usually, the limiting link is the uplink, and it is recommended to calculate downlink and uplink link budget separately and then consider the worst link.

To calculate the Path Loss, we need a suitable radio propagation model, 5G use 3D propagation models defined in 3GPP TS 36.873. *The urban macro-cellular* (UMa) model Path Loss formula, for the *Line of Sight* (LoS) case, is given as following (see Table 7.2-1 in 3GPP 36.873):

$$\text{Path Loss [dB]} = 28.0 + 22\log_{10}(d[\mathrm{m}]) + 20\log_{10}(f_c[\mathrm{GHz}]) \quad (3.2)$$

Where d is the distance in meters between the transmitter and receiver (cell radius) and fc is the central frequency in GHz. Figure 3-2 includes other propagation effects such as the penetration losses to model the extra signal fading due to obstruction (e.g., building walls). Receiver sensitivity depend on the *Thermal Power Noise Floor* (PN), the receiver *Noise Figure* (NF) of the UE and the target SNR:

$$\mathrm{R}_x\mathrm{S}\ [\mathrm{dBm}] = \mathrm{PN}\ [\mathrm{dBm}] + \mathrm{NF}[\mathrm{dB}] + \mathrm{SNR}\ [\mathrm{dB}] \tag{3.3}$$

PN is calculated using the following formula:

$$\mathrm{PN}\ [\mathrm{dBm}] = 10\log_{10}\left(\frac{k\ B\ T}{1\ mW}\right) \tag{3.4}$$

Where *T* is the temperature in Kelvin, *B* is the signal bandwidth (in Hz) and *k* is the Boltzmann´s constant ($1.381\times10^{-23}\ m^2kg\ s^{-2}K^{-1}$).

The NF and the target SNR are vendor specific values which depend mainly on hardware performance and MCS decoding performance. Note that the target SNR is directly linked with the throughput we want to achieve at the cell edge.

In case we want to estimate the cell radius that correspond to specific reception sensitivity, we can use the link budget formula (2.1) and replace the R_xSL with the required receiver *sensivity* (R_xS) to estimate the maximum Path Loss allowed between the gNB and the UE. By knowing *fc*, we can compute the cell radius (*d*) by using the Path Loss propagation model (e.g., equation (3.2) for LoS).

> Note that the accuracy of the cell radius estimation will depend on how well the propagation model fits the actual path loss of the specific radio environment.

3.2 Changing the central frequency in the OAIBOX™

In this Lab you will learn how to change the 5G NR central carrier in the OAIBOX™, using two different methods:

- Method 1: via the OAIBOX™ Dashboard;
- Method 2: via the OAI configuration files (advanced topic) – see section 3.4.

3.2.1 Lab Equipment

- Same as the previous Lab
- Spectrum analyser (optional)

3.2.2 Lab steps

Step 1. **Scenario 1: Line-of-Sight**
Setup your testbed according to Figure 2-6. Consider a distance of 2 m between the gNB and the UE with clear LoS for optimum propagation conditions.

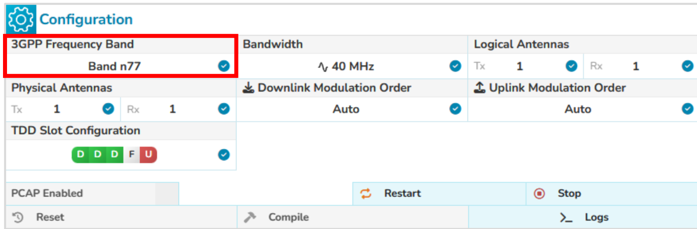
Step 2. Make sure, both the OAIBOX™ and the UE are working as expected, by completing the quick setup guide provided in section 1.2.1 (for OAIBOX™ 40), or section 0 (for OAIBOX™ MAX).

Step 3. To ensure the gNB is with the default parameters, use the dashboard *Overview* page to:

i. "**Stop**" the gNB;
ii. Perform a "**Reset Configuration**".
iii. "**Start**" the gNB;

Step 4. Access the gNB dedicated page by clicking in the "**NG-RAN**" block.

Step 5. Observe the default OAIBOX™ 40 configuration and confirm the current 3GPP Frequency Band being used.



Step 6. Fill in Table 3-2 (only the row associated with Band n77 and Scenario 1) with the values observed.

Step 7. Use the Host PC to connect to https://www.speedtest.net/ and perform a speed test.

Step 8. Visualize the bit rate plot evolution during the speed test using ❻ in Figure 1-22.

Step 9. Fill in Table 3-3 (only the associated row) with the average measured values.

Step 10. [Optional] Measure the 5G signal central frequency and bandwidth using a Spectrum Analyzer. Consider the frequency range in Table 3-1.

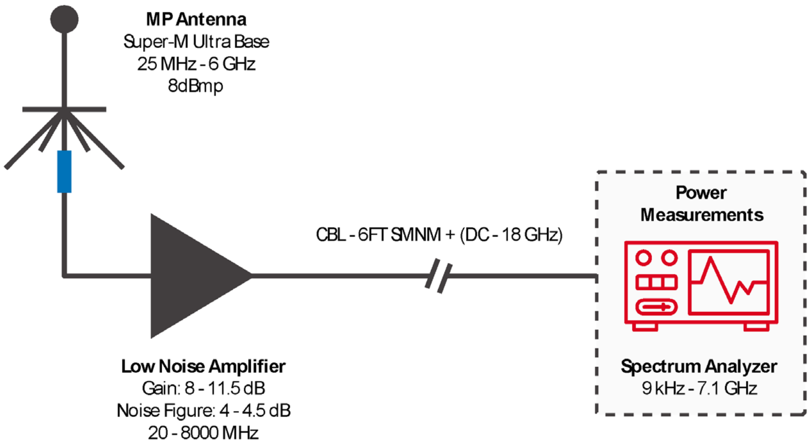
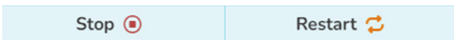


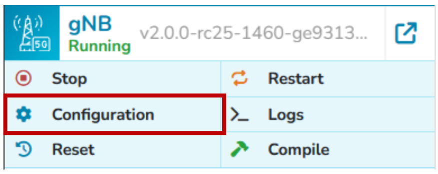
Figure 3-3: Example of a spectrum analyser setup for 5G FR1.

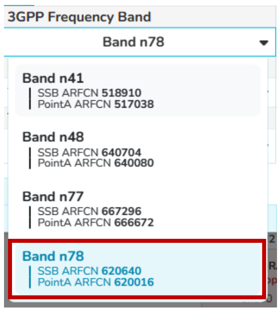
Step 11. "**Stop**" the gNB.



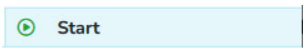
Step 12. Click '**Proceed**' to confirm the operation and wait until the "NG-RAN" block turns red with status "Stopped".

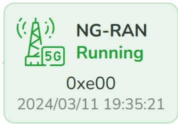
Step 13. At the gNB section (❺ in Figure 1-19), click on "**Configuration**" and then click on "**3GPP Frequency Band**" and select "**Band n78**".





Step 14. "**Start**" the gNB and wait until the "NG-RAN" block turns green with status "Running".





Step 15. Repeat **Step 5** to **Step 9**, now applicable to Band n78.

Scenario 2: Non-Line-of-Sight

Move the Quectel UE away from the gNB and break the LoS to create a strong Path Loss attenuation.

Step 16. Repeat **Step 5** to **Step 9**, now applicable to Scenario 2.

Step 17. Use the `AT+QENG="servingcell"` AT Command to confirm the 3GPP Band being used.

Step 18. Include your findings in the next section "LAB2 report".

3.3 LAB2: Report

Table 3-2: Average values measured for the UE PHY layer parameters for Band n77 and n78

Scenario 1 - LoS								
3GPP Band	**RSSI**	**RSRP**	**RSRQ**	**SINR**	**SNR**	**CQI**	**MCS**	**BLER**
n77								
n78								

Scenario 2 - NLoS								
3GPP Band	**RSSI**	**RSRP**	**RSRQ**	**SINR**	**SNR**	**CQI**	**MCS**	**BLER**
n77								
n78								

Table 3-3: Throughput measured for Band n77 and n78

Scenario 1 - LoS		
3GPP Band	**Measured bit rate**	
	DL	**UL**
n77		
n78		

Scenario 2 - NLoS		
3GPP Band	**Measured bit rate**	
	DL	**UL**

LAB2: Suggested topics for discussion:

- Analyse the impact of the 3GPP Band on the 5G air interface KPIs.
- Analyse the impact of the propagation scenario (LoS vs. NLoS) on the 5G air interface KPIs.
- Based on the measured RSRP value at the UE which is indicated in the OAIBOX™ Dashboard, estimate the overall Path Loss in dB between the gNB and the UE (see Figure 3-2).
- Using the 3GPP 36.873 UMa propagation model for LoS (Section 3.1.1.1), estimate the OAIBOX™ cell radius for 3GPP n77 and n78 central frequencies. Consider 10 dB transmit power in the gNB, cable losses of 1 dB, gNB antenna gain of 3 dB, UE antenna gain of 1 dB, a bandwidth of 40 MHz (required to compute the Thermal Noise Floor – equation (3.4), UE NF of 5 dB and a target SNR of 10 dB.
- Optional: Using a spectrum analyser (see Figure 3-3) measure the central frequency and bandwidth of 5G radio signals in bands n77 and n78. Discuss the results.

3.4 Advanced topic - Change the central frequency carrier in the OAI configuration files

This section explains how to change the central frequency configuration in the OAI code base, preparing students and researchers for advanced uses of OAI, beyond the pre-defined configurations in the OAIBOX™ Dashboard. This is useful in case you want to adapt your OAIBOX™ setup for a specific trial band.

Step 1. If you didn't complete the previous steps in this lab, please setup your testbed according to Figure 2-6. Consider a distance between 1 and 3 m between the gNB and the UE with clear LoS for optimum propagation conditions.

Step 2. To ensure the gNB is with the default parameters, use the dashboard *Overview* page to:

iv. Take note of your OAIBOX™ IP address (❸ in Figure 1-19);
v. "**Stop**" the gNB;
vi. Perform a "**Reset Configuration**".

Step 3. In the UE, open a command line and remotely access to your OAIBOX™ through SSH:

```
ssh user@your_oaibox_IP_address
```

Use "**user**" as password.

> Alternatively, in case you have a keyboard and a monitor directly attached to your OAIBOX, you can access the file through the GUI.

Step 4. Navigate to the folder where the OAIBOX™ configuration file resides and open it with *nano*:

```
cd ~/openairinterface5g/targets/PROJECTS/GENERIC-NR-5GC/CONF/
```

```
nano oaibox.conf
```

Step 5. Update the following values with your configuration:

```
absoluteFrequencySSB = 620640;
dl_frequencyBand = 78;
dl_absoluteFrequencyPointA = 620016;
…
ul_frequencyBand = 78;
ul_absoluteFrequencyPointA = 620016;
…
```

```
bands = [78];
```

Step 6. Save the changes and start the gNB.

Step 7. Check the new values on the OAIBOX™ Dashboard:

Details

Band	SSB ARFCN	Duplex Mode
n78	620640	TDD
MNC	**Dl PointA ARFCN**	**SCS**
01	--	30 kHz
MCC	**Ul PointA ARFCN**	**DL Bandwidth**
001	--	40 MHz
	DL Central Frequency	**UL Bandwidth**
	4019.160 MHz	40 MHz
	UL Central Frequency	
	4019.160 MHz	

Step 8. Start the UE (it may take up to 60 seconds to find the new SSB).

Step 9. After the UE connects to the gNB, use the following AT command to check the new values are being used (refer to Table 2-5):

```
AT+QENG="servingcell"
+QENG: "servingcell","NOCONN","NR5G-SA","TDD",
001,01,E00,0,1, 620640,78,6,-69,-11,36,1,-

OK
```

LAB-3

Changing the 5G NR TDD slot configuration

4 LAB-3: Changing the 5G NR TDD slot configuration

4.1 Pre-LAB-3: 3GPP Background

There are 5G use cases that require much higher uplink capacity than downlink. For example, in 3GPP TS 22.261 [10] there are requirements for cloud rendering and virtual reality which range from 100 Mbps to 10 Gbps per user. The 3GPP NR specification provides flexible TDD frame structures. The TDD frame structure configurations are often described as, i.e., DDDFU or DDDFUUDDDD, where D/U indicates slots where downlink/uplink-only symbols are transmitted, and F is the flexible. The special slot, in turn, consists of 14 symbols, and is often described as, for example, 4:6:4, which indicates that the first 4 symbols are downlink, the following 6 are silent, and the last 4 symbols are uplink (Figure 4-1). A straightforward solution to improve UL performance in terms of throughput is to increase the number of UL slots. Also, the latency performance may be improved shortening the waiting time for UL access by more frequently alternating UL/DL slots in the TDD frame.

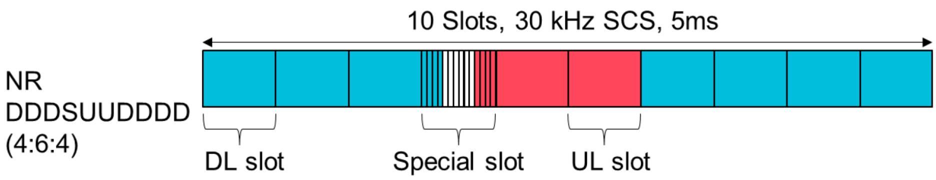


Figure 4-1: Example of TDD configuration for 5G NR.

4.2 Changing the TDD slot configuration in the OAIBOX™

In this Lab you will learn how to change the TDD slot frame configuration in the OAIBOX™ 40, using two different methods:

- Method 1: via the OAIBOX™ Dashboard;
- Method 2: via the OAI configuration files (advanced topic) – see section 4.4.

4.2.1 Lab Equipment

- Same as the previous Lab

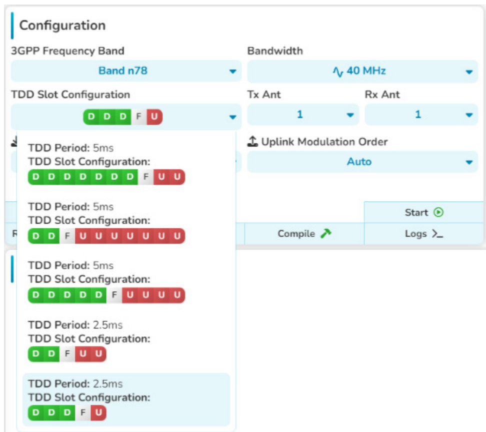
4.2.2 Lab steps

Step 1. Setup your testbed according to Figure 2-6. Consider a distance between 1 and 3 m between the gNB and the UE with clear LoS for optimum propagation conditions.

Step 2. To ensure the gNB is with the default parameters, use the dashboard main page to: - stop the gNB, perform a *Reset Configuration*, and start the gNB.

Step 3. Access your OAIBOX™ Dashboard and access the gNB dedicated page using the NG-RAN area.

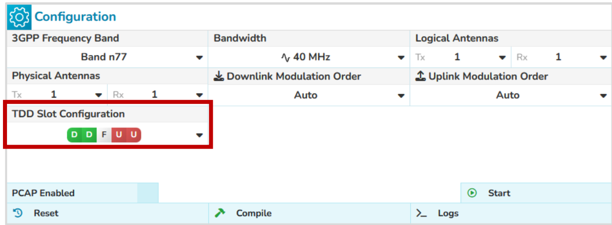
Step 4. Observe the default OAIBOX™ 40 configuration and confirm the TDD slot configuration being used:

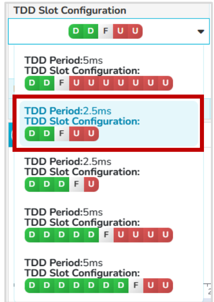


Step 5. Use the Host PC to connect to https://www.speedtest.net/ and perform a speed test.

Step 6. Stop the gNB and click 'Proceed' to confirm the operation.

Step 7. Change the TDD slot configuration to DDFUU.





Step 8. Start the gNB.

Step 9. Access the UE dedicated page using ❼ in Figure 1-22.

Step 10. Use the Host PC to connect to https://www.speedtest.net/ and perform a speed test.

Step 11. Fill in Table 4-1 with the DL and UL speed values observed.

Step 12. Compare these values with the ones observed in Table 2-4 (LAB1-1).

Step 13. Use the OAIBOX™ Dashboard breadcrumbs (❶ in Figure 1-24) to navigate back to the gNB dedicated page.

Step 14. Include your findings in the next section "LAB-3 report".

4.3 LAB-3: Report

Perform the theoretical calculations that give the expected UL and DL throughputs for each TDD slot configuration.

Check **Section 2.1.1.1** to assist you on this calculation.

Table 4-1: Average values measured for different TDD configurations

TDD configuration	DL throughput		UL throughput	
	Measured bit rate	Theoretical bit rate	Measured bit rate	Theoretical bit rate
3-1-1 (DDDFU) (DL oriented)				
2-1-2 (DDFUU) (balanced)				

LAB-3: Suggested topic for discussion:

- Analise the impact of the TDD configuration on the DL and UL throughput.

4.4 Advanced topic - Change the 5G NR TDD slot configuration in the OAI configuration files

This section explains how to change the 5G NR TDD slot configuration in the OAI code base, preparing students and researchers for advanced uses of OAI beyond the pre-defined configurations in the OAIBOX™ Dashboard. This is useful in case you want to adapt your OAIBOX™ setup for a specific trial band.

The next steps assume the current TDD slot configuration is DDFUU (from the previous steps).

Step 1. Setup your testbed according to Figure 2-6. Consider a distance between 1 and 3 m between the gNB and the UE with clear LoS for optimum propagation conditions.

Step 2. Use the dashboard main page to stop the gNB. Do not start the gNB.

Step 3. Open the OAIBOX™ 40 configuration file using SSH, or using the OAIBOX™ directly, in case you have a keyboard and a monitor directly attached to it:

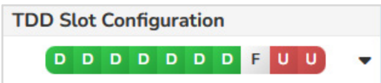
```
gedit ~/openairinterface5g/targets/PROJECTS/GENERIC-NR-5GC/CONF
/OAIBOX.conf
```

Step 4. Update the following values with your configuration, to understand why, please check section 6.3.2 in [16]:

```
Dl_UL_TransmissionPeriodicity = 6;
nrofDownlinkSlots = 7;
nrofDownlinkSymbols = 6;
nrofUplinkSlots = 2;
nrofUplinkSymbols = 4;
```

Step 5. Save the changes and start the gNB.

Step 6. Check the new values on the OAIBOX™ Dashboard:



Step 7. Start the UE.

Step 8. After the UE has connected to the gNB, use the the following AT command to confirm if the UE has accepted the new values:

```
AT+QENG="servingcell"
+QENG: "servingcell","NOCONN","NR5G-SA","TDD",
001,01,E00,0,1,620640,78,6,-69,-11,36,1,-

OK
```

There is no particular AT command to check the TDD slot configuration. If the Quectel UE reports "**servingcell**", the new TDD slot configuration was accepted.

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LAB-4

Changing the 5G NR Modulation and Coding Scheme

5 LAB-4: Changing the 5G NR Modulation and Coding Scheme

5.1 Pre-LAB-4: 3GPP Background

Modulation and Coding Scheme (MCS) defines the numbers of useful bits that are carried by one symbol. In wireless links, the MCS depends on radio signal quality - better quality the higher MCS and the more useful bits can be transmitted within a symbol.

Typically, there is a BLER threshold equal to 10%. To maintain BLER within this value, the gNB uses link adaptation algorithms to determine the MCS in varying radio conditions. The allocated MCS is signalled to the UE using DCI over the PDCCH channel, e.g., DCI 1_0, DCI 1_1. For more details on MCS go to section 1.3.3.10 and 3GPPP TS 38.214 [7].

5.2 Changing the MCS in the OAIBOX™

In this Lab you will learn how to change the Modulation and Code Scheme in the OAIBOX™, using two different methods:

- Method 1: via the OAIBOX™ Dashboard;
- Method 2: via the OAI configuration files (advanced topic) [section not yet available]

5.2.1 Lab Equipment

- Same as the previous Lab

5.2.2 Lab steps

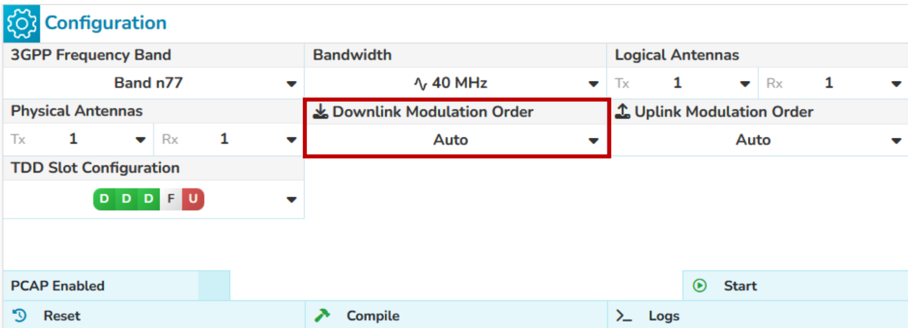
Step 1. Setup your testbed according to Figure 2-6. Consider a distance between 1 and 3 m between the gNB and the UE with clear LoS for optimum propagation conditions.

Step 2. To ensure the gNB is with the default parameters, use the dashboard main page to:
- "**Stop**" the gNB, perform a "**Reset**".

Scenario 1: Line-of-Sight

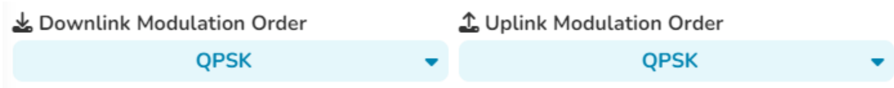
Access your OAIBOX™ Dashboard and the access the gNB dedicated page using the "**NG-RAN**" block.

Step 3. Observe the default OAIBOX™ configuration and confirm that the Modulation Order being used is "**Auto**", which means that MCS can change between 0 and 27 depending on the channel conditions.



Note that, when configuring the Modulation Order in the OAIBOX^{TM} Dashboard, the code rate is automatically adjusted within the MCS indexes defined for this specific Modulation Order, e.g., for 256QAM the MCS index varies from 20 to 27 (see Table 1-9). The code rate is selected based on the quality of the 5G radio link.

Step 4. Change both the "**Downlink Modulation Order**" and the "**Uplink Modulation Order**" to QPSK.



Step 5. "**Start**" the gNB.

Step 6. Access the UE dedicated page using ❼ in Figure 1-22.

Step 7. Use the Host PC to use the built in Speedtest tool in OAIBOX^{TM}, by accessing http://172.31.0.100, and perform a Speedtest. Alternatively, you can use the Ookla speedtest at: https://www.speedtest.net/

Step 8. Fill in Table 5-1 and Table 5-2 with the DL and UL speed values and spectrum efficiency observed.

Step 9. Compare these values with the ones observed in Table 2-4 (LAB1-1).

Step 10. Repeat **Step 4** to **Step 9**, now applicable to 16QAM, 64QAM and 256QAM (both for DL an UL).

Scenario 2: Non-Line-of-Sight
Move the Quectel UE away from the gNB and block the LoS to create strong Path Loss attenuation.

Step 11. Repeat **Step 4** to **Step 11**, now applicable to Scenario 2.

Step 12. Include your findings in the next section "LAB-3 report".

5.3 LAB-4: Report

Table 5-1: Measured DL and UL throughputs vs Modulation Order vs Scenario

Scenario 1 - LoS		
Modulation Order (DL , UL)	**Measured DL bit rate**	**Measured UL bit rate**
(QPSK , QPSK)		
(16QAM , 16QAM)		
(64QAM , 64 QAM)		
(256QAM , 256QAM)		

Scenario 2 - NLoS		
Modulation Order (DL , UL)	**Measured DL bit rate**	**Measured UL bit rate**
(QPSK , QPSK)		
(16QAM , 16QAM)		
(64QAM , 64QAM)		
(256QAM , 256QAM)		

Table 5-2: Measured DL and UL spectrum efficiency

Scenario 1 - LoS		
Modulation Order (DL , UL)	**DL spectrum efficiency (b/s/Hz)**	**UL spectrum efficiency (b/s/Hz)**
(QPSK , QPSK)		
(16QAM , 16QAM)		
(64QAM , 64QAM)		
(256QAM , 256QAM)		

Scenario 2 - NLoS		
Modulation Order (DL , UL)	**DL spectrum efficiency (b/s/Hz)**	**UL spectrum efficiency (b/s/Hz)**
(QPSK , QPSK)		
(16QAM , 16QAM)		
(64QAM , 64QAM)		
(256QAM , 256QAM)		

LAB-4: Suggested topics for discussion:

- Analise the impact of the Modulation Order on the spectrum efficiency and measured bit rate. Explain why in some scenarios, a 256-QAM modulation order may not be possible.
- Analise the impact of the propagation scenario (LoS vs. NLoS) on the measured bit rate considering the adaptative modulation and coding scheme.

LAB-5

Changing the 5G BWP configuration

6 LAB-5: Changing the 5G BWP configuration

6.1 Pre-LAB-5: 3GPP Background

Bandwidth Parts (BWPs) is a 5G NR feature introduced in 3GPP Release 15 for dynamically adapting the carrier bandwidth and numerology in which a UE operates. BWP enables UEs to operate in narrow bandwidth and when user demands more data (bursty traffic) it can inform gNB to enable wider bandwidth.

A wider bandwidth in 5G NR has direct impact on the peak and user experienced data rates, however users are not always demanding high data rate. The use of wide bandwidth may imply higher idling power consumption both from RF and baseband signal processing perspectives. Regarding this, a new concept of BWP has been introduced for 5G-NR provides a means of operating UEs with smaller BW than the configured carrier bandwidth, which makes NR an energy efficient solution despite the support of wideband operation.

Alternatively, one may consider scheduling a UE such that it only transmits or receives within a certain frequency range. Compared to this approach, the difference with BWP is that the UE is not required to transmit or receive outside of the configured frequency range of the active BWP, which attributes power saving from the following aspects:

- BWP reduces the signal processing requirement to transmit or receive narrow bandwidth.
- BWP enables RF-Baseband interface operation with a lower sampling rate.
- UE RF bandwidth adaptation can provide UE power savings at least if carrier bandwidth, before adaptation, is large.

Even though multiple BWPs (max 4) can be defined in DL and UL, only one BWP can be active at each specific moment. Some mechanism needs to exist to select a specific BWP as the active one. According to 3GPP 38.321-5.15, BWP selection (or BWP switching) can be done by several different way as listed below.

- By PDCCH (i.e., DCI): A specific BWP can be activated by Bandwidth part indicator in DCI Format 0_1 (a UL Grant) and DCI Format 1_1 (a DL Schedule)
- By the *bwp-InactivityTimer*: *ServingCellConfig.bwp-InactivityTimer*.
- By RRC signalling.
- By the MAC entity itself upon initiation of random access procedure.

When using the mechanisms listed above, a specific BWP becomes active depending on various situations in the call processing. The switching process can be summarized as illustrated in Figure 6-1.

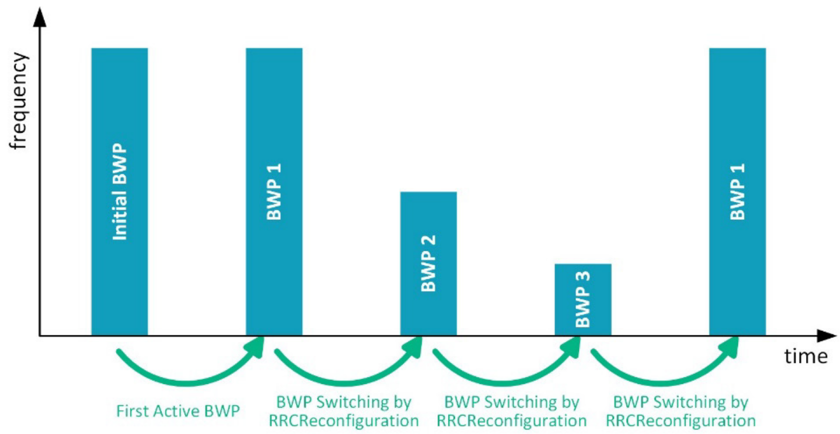


Figure 6-1 Examples of BWP switching

Additional references:
- Understanding 5G New Radio Bandwidth Parts – Keysight [12]
- 5G/NR - Carrier Bandwidth Part – ShareTechNote [13]
- 5G NR Bandwidth Part (BWP) – TechPlayOn [14]

6.2 Changing the BWP configuration in the OAIBOX^{TM}

In this Lab you will learn how to change the 5G NR Bandwidth Parts (BWP) in the OAIBOX^{TM} via the OAI configuration files. The goal is to implement in the OAI code base a BWP switching procedure that changes the BWP every 15 seconds and check the impact on the bit rate.

- Dedicated BWP 1: 40 MHz
- Dedicated BWP 2: 20 MHz
- Dedicated BWP 3: 10 MHz

6.2.1 Lab Equipment

- Same as the previous Lab

6.2.2 Lab steps

Step 1. Setup your testbed according to Figure 2-6. Consider a distance between 1 and 3 m between the gNB and the UE with clear LoS for optimum propagation conditions.

Step 2. To ensure the gNB is with the default parameters, use the dashboard *Overview* page to:

iv. Take note of your OAIBOX^{TM} IP address (❸in Figure 1-19);
v. "**Stop**" the gNB;
vi. Perform a "**Reset Configuration**".

Step 3. In the Host PC (UE), open a command line and remotely access to your OAIBOX^{TM} through SSH:

```
ssh user@your_oaibox_IP_address
```

Use "**user**" as password.

Alternatively, in case you have a keyboard and a monitor directly attached to your OAIBOX, you can access the file through the GUI.

Step 4. Navigate to the folder where the OAIBOX^{TM} configuration file resides and open it with *nano*:

```
cd ~/openairinterface5g/targets/PROJECTS/GENERIC-NR-5GC/CONF/
```

```
nano oaibox.conf
```

Step 5. Add the "*servingCellConfigDedicated*" section, below, on the configuration file after "*servingCellConfigCommon*" section, in the "gNBs" section:

```
# Dedicated Serving Cell Configuration
servingCellConfigDedicated = ({
  # BWP-Downlink
    # BWP 1 Configuration
      dl_bwp-Id_1 = 1;
      dl_bwp1_locationAndBandwidth = 28875; // RBstart=0, L=106 (40 MHz BW)
```

```
      # subcarrierSpacing
      # 0=kHz15, 1=kHz30, 2=kHz60, 3=kHz120
      dl_bwp1_subcarrierSpacing = 1;

    # BWP 2 Configuration
      dl_bwp-Id_2 = 2;
      dl_bwp2_locationAndBandwidth = 13750; // RBstart=0, L=51 (20 MHz BW)
      # subcarrierSpacing
      # 0=kHz15, 1=kHz30, 2=kHz60, 3=kHz120
      dl_bwp2_subcarrierSpacing = 1;

    # BWP 3 Configuration
      dl_bwp-Id_3 = 3;
      dl_bwp3_locationAndBandwidth = 6325; // RBstart=0, L=24 (10 MHz BW)
      # subcarrierSpacing
      # 0=kHz15, 1=kHz30, 2=kHz60, 3=kHz120
      dl_bwp3_subcarrierSpacing = 1;

    firstActiveDownlinkBWP-Id = 1;  #BWP-Id
    defaultDownlinkBWP-Id     = 1;  #BWP-Id

    # bwp-InactivityTimer        ENUMERATED {ms2, ms3, ms4, ms5, ms6, ms8, ms10, ms20, ms30,
    #                            ms40,ms50, ms60, ms80,ms100, ms200,ms300, ms500,
    #                            ms750, ms1280, ms1920, ms2560, spare10, spare9, spare8,
    #                            spare7, spare6, spare5, spare4, spare3, spare2, spare1 }

  # UplinkConfig
    # BWP-Uplink
      # BWP 1 Configuration
        ul_bwp-Id_1 = 1;
        ul_bwp1_locationAndBandwidth = 28875; // RBstart=0, L=106 (40 MHz BW)
        # subcarrierSpacing
        # 0=kHz15, 1=kHz30, 2=kHz60, 3=kHz120
        ul_bwp1_subcarrierSpacing = 1;

      # BWP 2 Configuration
        ul_bwp-Id_2 = 2;
        ul_bwp2_locationAndBandwidth = 13750; // RBstart=0, L=51 (20 MHz BW)
        # subcarrierSpacing
        # 0=kHz15, 1=kHz30, 2=kHz60, 3=kHz120
        ul_bwp2_subcarrierSpacing = 1;

      # BWP 3 Configuration
        ul_bwp-Id_3 = 3;
        ul_bwp3_locationAndBandwidth = 6325; // RBstart=0, L=24 (10 MHz BW)
        # subcarrierSpacing
        # 0=kHz15, 1=kHz30, 2=kHz60, 3=kHz120
        ul_bwp3_subcarrierSpacing = 1;

      firstActiveUplinkBWP-Id = 1;  #BWP-Id
});
```

Step 6. Save the file (**CTRL** + **O**) and exit (**CTRL** + **X**) the *nano* editor.

Step 7. Navigate to the folder where the "**gNB_scheduler_primitives.c**" file is, and open it with *nano*:

```
cd ~/openairinterface5g/openair2/LAYER2/NR_MAC_gNB/
```

```
nano gNB_scheduler_primitives.c
```

Step 8. Add the example source code below to schedule BWP switching every 30000 slots (15 seconds), at the end of the file:

```
// BWP switching algorithm

// Periodic switching algorithm - to be developed a better switching algorithm.
// Currently, and only for demo purposes, we are going through all the bands. The UE stays a
few seconds in each one.
int bwp_switch_timer = 0;
int bwp_switch_period = 30000;
```

```
void schedule_nr_bwp_switch(module_id_t module_id, frame_t frame, sub_frame_t slot)
{
  /* already mutex protected: held in gNB_dlsch_ulsch_scheduler() */
  NR_SCHED_ENSURE_LOCKED(&RC.nrmac[module_id]->sched_lock);

  NR_UEs_t *UE_info = &RC.nrmac[module_id]->UE_info;

  UE_iterator (UE_info->list, UE) {
    NR_UE_sched_ctrl_t *sched_ctrl = &UE->UE_sched_ctrl;

    if (UE->Msg4_ACKed != true || sched_ctrl->rrc_processing_timer > 0 || !UE->CellGroup ||
!UE->CellGroup->spCellConfig
        || !UE->CellGroup->spCellConfig->spCellConfigDedicated
        || !UE->CellGroup->spCellConfig->spCellConfigDedicated->downlinkBWP_ToAddModList
        || UE->CellGroup->spCellConfig->spCellConfigDedicated->downlinkBWP_ToAddModList-
>list.size <= 1
        || !UE->CellGroup->spCellConfig->spCellConfigDedicated->uplinkConfig
        || !UE->CellGroup->spCellConfig->spCellConfigDedicated->uplinkConfig-
>uplinkBWP_ToAddModList
        || UE->CellGroup->spCellConfig->spCellConfigDedicated->uplinkConfig-
>uplinkBWP_ToAddModList->list.count <= 1) {
      continue;
    }

    bwp_switch_timer++;
    if (bwp_switch_timer % 1000 == 0) {
      LOG_I(NR_MAC, "[UE %04x][bwp_id %ld] bwp_switch_timer: %d\n", UE->rnti, UE-
>current_DL_BWP.bwp_id, bwp_switch_timer);
    }

    if (sched_ctrl->rrc_processing_timer == 0 && bwp_switch_timer % bwp_switch_period == 0)
{
      int next_dl_bwp_id = UE->current_DL_BWP.bwp_id;
      if (UE->CellGroup->spCellConfig->spCellConfigDedicated->downlinkBWP_ToAddModList) {
        next_dl_bwp_id++;
        if (next_dl_bwp_id > UE->CellGroup->spCellConfig->spCellConfigDedicated-
>downlinkBWP_ToAddModList->list.count) {
          next_dl_bwp_id = 1;
        }
      }

      int next_ul_bwp_id = UE->current_UL_BWP.bwp_id;
      if (UE->CellGroup->spCellConfig->spCellConfigDedicated->uplinkConfig-
>uplinkBWP_ToAddModList) {
        next_ul_bwp_id++;
        if (next_ul_bwp_id > UE->CellGroup->spCellConfig->spCellConfigDedicated-
>uplinkConfig->uplinkBWP_ToAddModList->list.count) {
          next_ul_bwp_id = 1;
        }
      }

      LOG_W(NR_MAC,
            "%4d.%2d UE %04x Scheduling BWP switch from DL_BWP %ld to %d and from UL_BWP %ld
to %d\n",
            frame,
            slot,
            UE->rnti,
            UE->current_DL_BWP.bwp_id,
            next_dl_bwp_id,
            UE->current_UL_BWP.bwp_id,
            next_ul_bwp_id);

      *UE->CellGroup->spCellConfig->spCellConfigDedicated->firstActiveDownlinkBWP_Id =
next_dl_bwp_id;
      *UE->CellGroup->spCellConfig->spCellConfigDedicated->defaultDownlinkBWP_Id =
next_dl_bwp_id;
      *UE->CellGroup->spCellConfig->spCellConfigDedicated->uplinkConfig-
>firstActiveUplinkBWP_Id = next_ul_bwp_id;

      //  Trigger RRC Reconfiguration
      LOG_I(NR_MAC, "BWP switch for UE 0x%04x, triggering RRC Reconfiguration\n", UE->rnti);
      nr_mac_trigger_reconfiguration(RC.nrmac[0], UE);
      UE->reconfigCellGroup = UE->CellGroup;
      nr_mac_enable_ue_rrc_processing_timer(RC.nrmac[0], UE, true);
```

```
schedule_nr_bwp_switch()
      bwp_switch_timer = 0;
    }
  }
}
```

Step 9. Still in the "**gNB_scheduler_primitives.c**", in function "**nr_mac_apply_cellgroup()**", add the highlighted code (in bold) below:

```
static void nr_mac_apply_cellgroup(gNB_MAC_INST *mac, NR_UE_info_t *UE, frame_t frame,
sub_frame_t slot)
{
  LOG_D(NR_MAC, "%4d.%2d RNTI %04x: RRC processing timer expired\n", frame, slot, UE->rnti);

  /* check if there is a new CellGroupConfig to be applied */
  if (UE->apply_cellgroup && UE->reconfigCellGroup != NULL && UE->reconfigCellGroup == UE-
>CellGroup) {
    UE->reconfigCellGroup = NULL;
    UE->apply_cellgroup = false;
  } else if (UE->apply_cellgroup && UE->reconfigCellGroup != NULL) {
    LOG_D(NR_MAC, "%4d.%2d RNTI %04x: Apply CellGroupConfig after RRC processing timer
expiry\n", frame, slot, UE->rnti);
    ASN_STRUCT_FREE(asn_DEF_NR_CellGroupConfig, UE->CellGroup);
    UE->CellGroup = UE->reconfigCellGroup;
    UE->reconfigCellGroup = NULL;
    UE->apply_cellgroup = false;
```

Step 10. Save the file (**CTRL** + **O**) and exit (**CTRL** + **X**) the *nano* editor.

Step 11. Open file "**gNB_scheduler.c**"

```
nano gNB_scheduler.c
```

Step 12. Go to function "**gNB_dlsch_ulsch_scheduler()**" and, immediately after calling function "**nr_mac_update_timers()**", add the highlighted code (in bold) below:

```
nr_mac_update_timers(module_idP, frame, slot);

schedule_nr_bwp_switch(module_idP, frame, slot);

// This schedules MIB
schedule_nr_mib(module_idP, frame, slot, &sched_info->DL_req);
```

Step 13. Save the file (**CTRL** + **O**) and exit (**CTRL** + **X**) the *nano* editor.

Step 14. Open a *Terminal* and build the OAI gNB:

```
cd ~/openairinterface5g/cmake_targets
./build_oai -w USRP --ninja --gNB -c
```

Step 15. Start the gNB using the OAIBOX™ Dashboard.

Step 16. Connect the UE to the gNB.

Step 17. Start **iPerf** to test the maximum **downlink** bitrate. Observe the maximum bit rate changing every 15 seconds, corresponding to the maximum downlink bitrate supported by each BWP. Figure 6-2 illustrates the expected results.

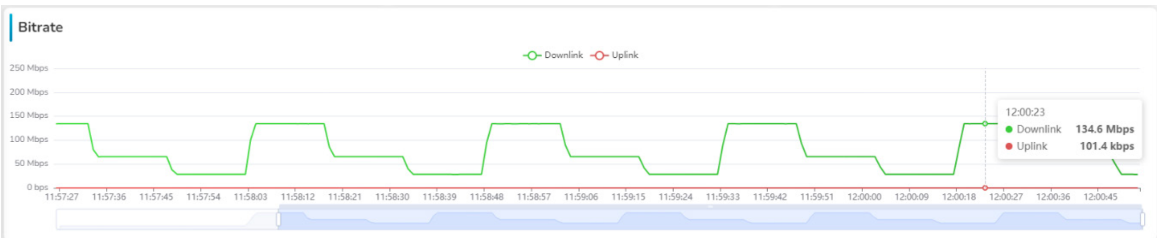


Figure 6-2: Impact of the BWP configuration on the maximum downlink bitrate.

Step 18. Fill in Table 6-1 with the DL speed values observed.

Step 19. Start **iPerf** to test the maximum **uplink** bitrate. Observe the maximum bit rate changing every 15 seconds, corresponding to the maximum uplink bitrate supported by each BWP.

Step 20. Complete Table 6-1 with the UL speed values observed.

6.3 LAB-5: Report

Table 6-1: Impact of the BWP selection on the maximum DL bit rate.

BWP	DL bit rate	UL bit rate
BWP 1 - 40 MHz		
BWP 2 - 20 MHz		
BWP 3 - 10 MHz		

LAB-5: Suggested advanced topic:

- Adapt the OAI code to change the BWP 2 from 20 MHz to 5 MHz, check UL and DL bit rate plots and analyse the results.

LAB-6

Testing the 5G NR RACH

7 LAB-6: Testing the 5G NR RACH

7.1 Pre LAB-6: 3GPP Background

The uplink comprises several physical channels. These channels are the PUSCH, PUCCH, SRS and PRACH. The PRACH is associated with the RACH transport channel [15], which is used in multiple procedures, such as:

- Initial access from RRC_IDLE;
- Transition from *RRC_Inactive* to *RRC_CONNECTED*;
- RRC connection reestablishment;
- Handover;
- Beam failure recovery;
- Synchronous reconfiguration;
- Timing alignment during secondary cell addition;
- DL out of sync – gNB triggers PDCCH order;
- UL out of sync;
- SR max transmission reached;
- UL data arrival – no PUCCH configured for SR;
- On demand System information.

The RACH (Random Access Channel) procedures are categorized into two types: 4-Step-RACH (introduced in 3GPP release 15) and 2-Step-RACH (introduced in 3GPP release 16). Each type can be subdivided into *Contention-based Random Access* (CBRA) and *Contention-free Random Access* (CFRA) procedures. In this manual, we focus on CBRA procedure based on 4-Step-RACH, for initial access from RRC_IDLE, which we can see in Figure 7-1.

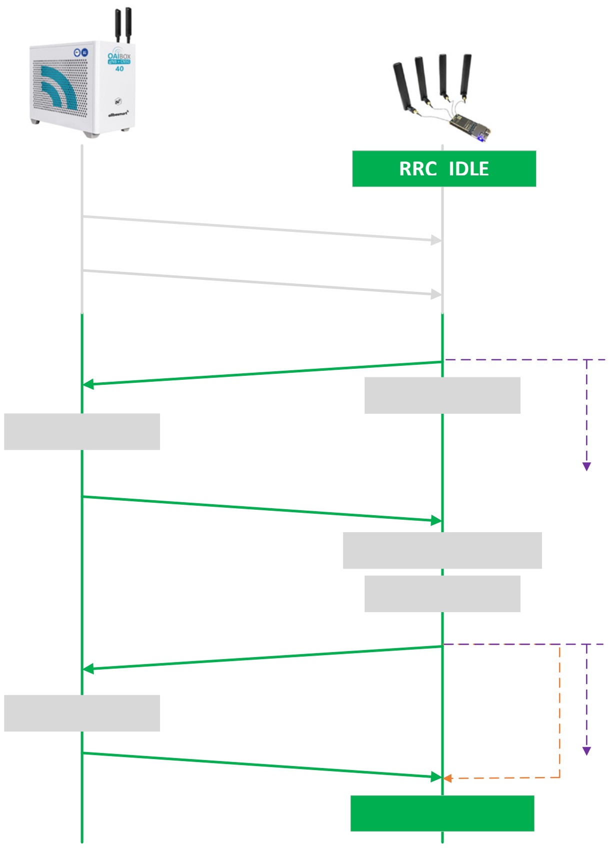


Figure 7-1: Initial access procedure for the Standalone 5G NR.

After the initial synchronization procedures, Random Access starts with the sending of a Preamble (**Msg1**) from the UE to the gNB. The preamble transmission is a Zadoff-Chu sequence, which is referenced with the *Random Access Preamble Id* (RAPID). Each preamble is associated with an RA-RNTI, given by:

$$RA - RNTI = 1 + s_{id} + 14t_{id} + 1120f_{id} + 8960c_{ul,id} \tag{7.1}$$

where s_{id} is the index of the first OFDM symbol of the PRACH, t_{id} is the index of the first slot of the PRACH, f_{id} is the index of the PRACH in the frequency domain, and finally $c_{ul,id}$ is the uplink carrier used for **Msg1** transmission.

In this way, depending on the detected Preamble, the gNB gets the RA-RNTI. Then, the DCI Format 1_0, with the CRC scrambled with RA-RNTI, is used to assign downlink resources of **Msg2**, and the **Msg2** is sent. The UE looks for **Msg2** during a configured window of length *ra-ResponseWindow*. The **Msg2** contains: (i) the *Temporary C-RNTI* which indicates the temporary identity that is used by the MAC entity during Random Access; (ii) the *Timing Advance Command* to time adjustment, and; (iii) the *Uplink Grant* field which indicates the frequency/time resources and the MCS to be used on the uplink for **Msg3**.

To transmit **Msg3**, the UE generates a random identity and gets the uplink allocation contained in the RAR. This message is transferred using SRB 0 on the *Common Control Channel* (CCCH), since SRB 1 has not been established yet. When UE starts sending **Msg3**, the UE starts *ra-ContentionResolutionTimer*. The **Msg3** for initial access procedure is the *RRCSetupRequest*, with the following content:

```
RRCSetupRequest ::=                    SEQUENCE {
    rrcSetupRequest                        RRCSetupRequest-IEs
}

RRCSetupRequest-IEs ::=                SEQUENCE {
    ue-Identity                            InitialUE-Identity,
    establishmentCause                     EstablishmentCause,
    spare                                  BIT STRING (SIZE (1))
}

InitialUE-Identity ::=                 CHOICE {
    ng-5G-S-TMSI-Part1                     BIT STRING (SIZE (39)),
    randomValue                            BIT STRING (SIZE (39))
}

EstablishmentCause ::=                 ENUMERATED {
                                           emergency, highPriorityAccess,
                                           mt-Access, mo-Signalling,
                                           mo-Data, mo-VoiceCall,
                                           mo-VideoCall, mo-SMS, mps-PriorityAccess,
                                           mcs-PriorityAccess,
                                           spare6, spare5, spare4,
                                           spare3, spare2, spare1}
```

Then, the gNB configures the SRB 1 to use the *Dedicated Control Channel* (DCCH) rather than the CCCH used by SRB 0. To send the **Msg4**, the DCI message, which indicates the frequency/time resources assigned for the *Transport Block*, is scrambled by C-RNTI. The **Msg4** carries the *radioBearerConfig* and *masterCellGroup* information, as we can see in the content of the following message:

```
RRCSetup ::=                           SEQUENCE {
    rrc-TransactionIdentifier              RRC-TransactionIdentifier,
    criticalExtensions                     CHOICE {
        rrcSetup                               RRCSetup-IEs,
        criticalExtensionsFuture               SEQUENCE {}
    }
}

RRCSetup-IEs ::=                       SEQUENCE {
    radioBearerConfig                      RadioBearerConfig,
    masterCellGroup                        OCTET STRING (CONTAINING CellGroupConfig),
```

```
    lateNonCriticalExtension              OCTET STRING   OPTIONAL,
    nonCriticalExtension                  SEQUENCE{}     OPTIONAL
}

RadioBearerConfig ::=                     SEQUENCE {
    srb-ToAddModList                        SRB-ToAddModList      OPTIONAL,   -- Cond HO-Conn
    srb3-ToRelease                          ENUMERATED{true}      OPTIONAL,   -- Need N
    drb-ToAddModList                        DRB-ToAddModList      OPTIONAL,   -- Cond HO-toNR
    drb-ToReleaseList                       DRB-ToReleaseList     OPTIONAL,   -- Need N
    securityConfig                          SecurityConfig        OPTIONAL,   -- Need M
    ...
}

...

CellGroupConfig ::=                           SEQUENCE {
    cellGroupId                                   CellGroupId,

    rlc-BearerToAddModList   SEQUENCE (SIZE(1..maxLC-ID)) OF RLC-BearerConfig
    rlc-BearerToReleaseList  SEQUENCE (SIZE(1..maxLC-ID)) OF LogicalChannelIdentity

    mac-CellGroupConfig      MAC-CellGroupConfig

    physicalCellGroupConfig  PhysicalCellGroupConfig

    spCellConfig             SpCellConfig
    sCellToAddModList        SEQUENCE (SIZE (1..maxNrofSCells)) OF SCellConfig
    sCellToReleaseList       SEQUENCE (SIZE (1..maxNrofSCells)) OF SCellIndex
    ...,
    [[
    reportUplinkTxDirectCurrent-v1530   ENUMERATED {true}
    ]]
}
...
```

The complete contents of **Msg4** can be found at [16]. After receiving the *RRCSetup* message, the UE stops the T300 timer and makes the transition to *RRC Connected* mode.

7.2 Testing the 5G NR RACH (Random Access Procedure) in OAI

When a UE triggers the RA procedure, it is possible to check on the gNB logs from the OAIBOX™ dashboard some messages about the RA. Figure 7-2 depicts the gNB logs with the typical messages of a RA procedure.

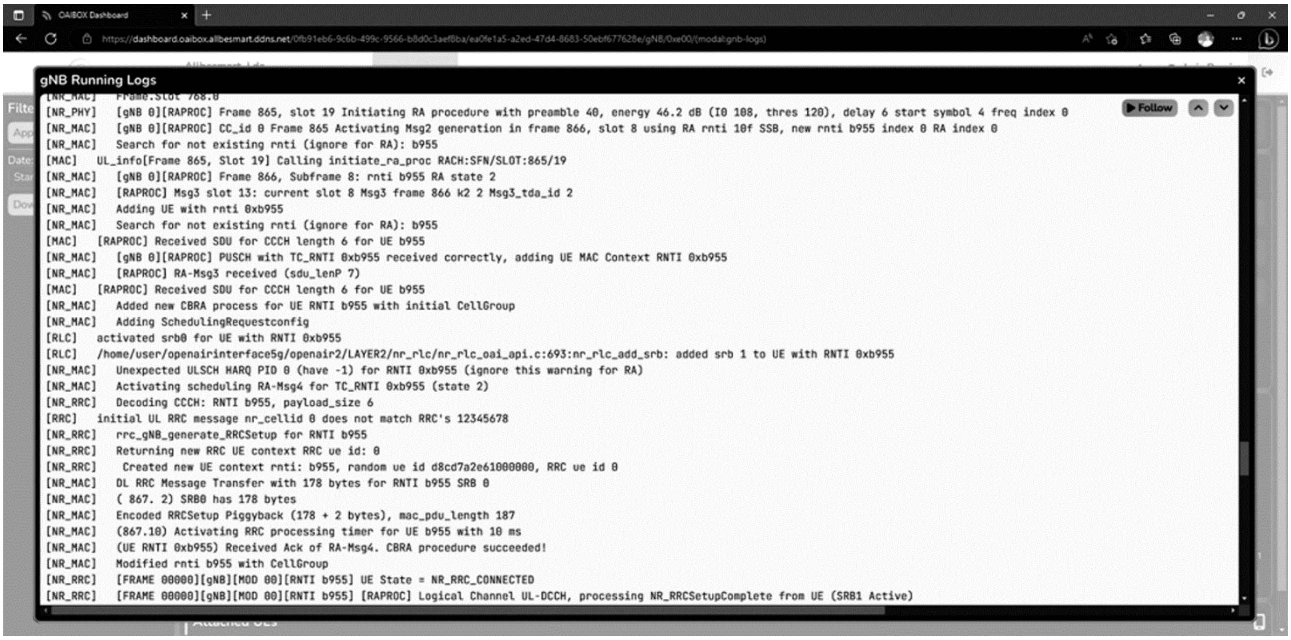


Figure 7-2: Example of gNB logs showing typical messages of a RA procedure

Preamble

When gNB detects a preamble, it outputs the following message:

```
[NR_PHY]   [gNB 0][RAPROC] Frame 865, slot 19 Initiating RA procedure with preamble 40,
energy 46.2 dB (I0 108, thres 120), delay 6 start symbol 4 freq index 0
```

Where we can see the time when it happens, in terms of frame and slot; the preamble ID with the strongest correlation detected; the energy of that preamble measured in dB; the noise level; the estimated delay in samples and the start symbol where the preamble was detected and other parameters.

Msg2 - Scheduling of Msg2 with the new RNTI assigned to that UE:

```
[NR_MAC]   [gNB 0][RAPROC] CC_id 0 Frame 865 Activating Msg2 generation in frame 866,
slot 8 using RA rnti 10f SSB, new rnti b955 index 0 RA index 0
```

Msg3 - Confirmation of the reception and successful decoding of Msg3:

```
[NR_MAC]   [RAPROC] RA-Msg3 received (sdu_lenP 7)
```

Msg4 – Scheduling of Msg4:

```
[NR_MAC]   Activating scheduling RA-Msg4 for TC_RNTI 0xb955 (state 2)
```

Ack of Msg4 - Reception of the Ack of Msg4 at Physical Layer

This is the last step in a successful CBRA procedure:

```
[NR_MAC]   (UE RNTI 0xb955) Received Ack of RA-Msg4. CBRA procedure succeeded!
```

7.2.1 Lab steps

Step 1. "**Start**" the gNB.

Step 2. Connect the UE.

Step 3. Check the gNB running "**Logs**" on the dashboard and search for the RA messages described above.

Step 4. Take note of the preamble energy.

7.2.2 Adjusting the Preamble Received Target Power

7.2.2.1 Lab steps

Step 5. "**Stop**" the GNB and disconnect the UE.

Step 6. Navigate to the folder where the "**OAIBOX.conf**" configuration file is, and open it with *nano*:

```
cd ~/openairinterface5g/targets/PROJECTS/GENERIC-NR-5GC/CONF/
```

```
nano OAIBOX.conf
```

Step 7. Search for the "preambleReceivedTargetPower" parameter and reduce it by 10 (for example, if it is -90, change to -100):

```
preambleReceivedTargetPower = -100;
```

Step 8. "**Start**" the gNB and reconnect the UE.

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Step 9. Check the gNB running "**Logs**" on the OAIBOX™ Dashboard and search for the RA messages. Take note of the preamble energy and compare with the previous value (from *Step 4*).

The new preamble energy is about 10 dB lower than initially, as shown in Figure 7-3.

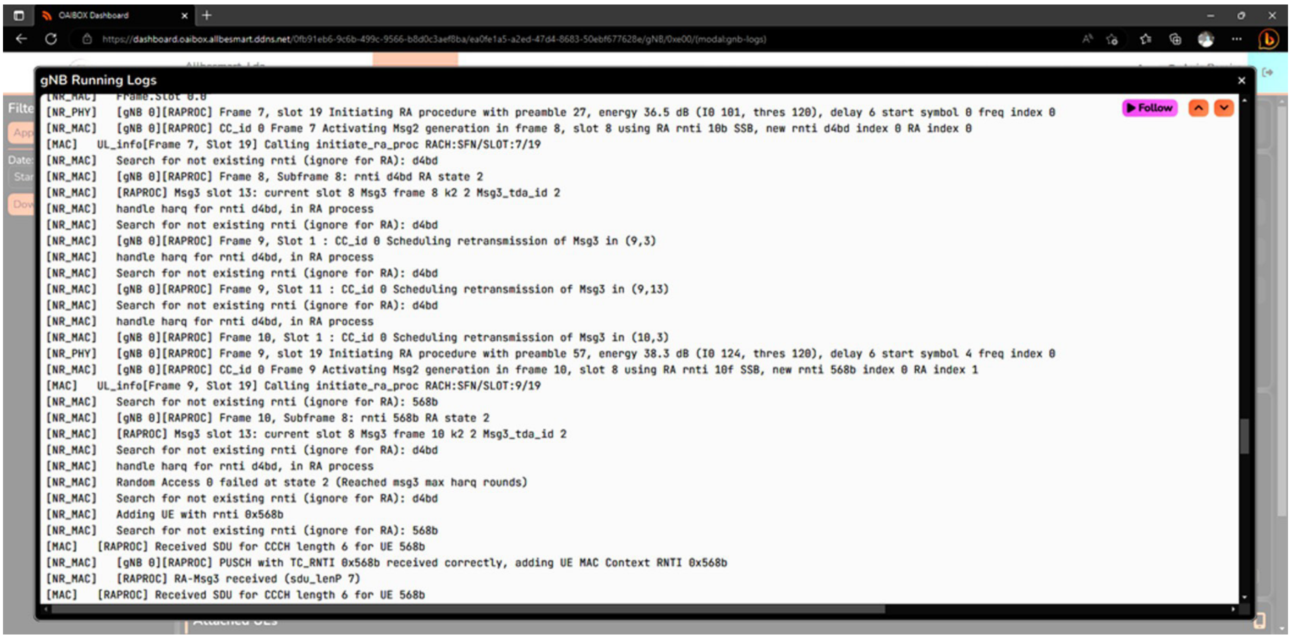

Figure 7-3: Example of gNB Logs after reducing 10 dB on the preambleReceivedTargetPower

7.2.3 Changing the PRACH Configuration Index

Step 10. Take note of the start symbol from the previous step. Stop the UE and stop the gNB.

Step 11. Navigate to the folder where the OAIBOX™ configuration file resides and open it with *nano*:

```
cd ~/openairinterface5g/targets/PROJECTS/GENERIC-NR-5GC/CONF/
```

```
nano oaibox.conf
```

Step 12. Search for the PRACH Configuration Index parameter and change it from 98 to 100:

```
prach_ConfigurationIndex  = 100;
```

Step 13. Start the gNB and the UE

Step 14. Check the "gNB Running Logs" on the OAIBOX™ dashboard and search for the RA messages. Take note of the start symbol and compare with the first one.

7.3 LAB-6: Report

Include your findings in the following tables.

Table 7-1: Impact of the preambleReceivedTargetPower

preambleReceivedTargetPower	-90	-100	-110	-120
Preamble energy				

Table 7-2: Impact of the prach_ConfigurationIndex

prach_ConfigurationIndex	Start symbol
98	
100	

LAB-6: Suggested topics for discussion:

- Keep reducing the *preambleReceivedTargetPower* until the signal energy remains with a constant value or the gNB does not detect the preamble anymore. Read the 3GPP standard about the other PRACH configuration parameters to understand the PRACH procedures. As a suggestion, start with *powerRampingStep* and *preambleTransMax*.
- Adapt the OAI code, as in Step 11, to change the prach_*ConfigurationIndex* so the PRACH will change from slot 19 to another slot. As a suggestion, you may need also to play with the TDD configuration. The PRACH Configuration Index and the preamble formats are specified in 3GPP TS 38.211 Section 6.3.3 Physical random-access channel. The table for unpaired spectrum is Table 6.3.3.2-3: Random access configurations for FR1 and unpaired spectrum.

LAB-7

Testing MIMO configurations

8 LAB-7: Testing MIMO configurations

8.1 Pre LAB-7: 3GPP Background

Multi-Input-Multiple Output (MIMO) is a complex topic of the 5G NR protocol, which includes techniques such as *Space Time Block Codes* (STBC), *Spatial Multiplexing* (SM), Beamforming, *Multi-User MIMO* (MU-MIMO) and Massive MIMO. The following is a high-level introduction to some MIMO techniques used in 5G.

8.1.1 Space-Time Block Coding (STBC)

STBC is a technique used in 5G NR to transmit data over multiple antennas. STBC is a form of spatial diversity used to improve the transmission's reliability and quality by exploiting the radio channel's spatial dimension. Alamouti is a widely used STBC scheme that transmits two symbols over two antennas in two-time slots. Figure 8-1 depicts STBC 2T2R (2 Transmit, 2 Receive) configuration. Here at the time instant T1 data symbols (x1, x2) are transmitted from antenna-1 and antenna-2 while after some duration at time instant T2, modified copies of the data symbols $(\overline{-x2}, \overline{x1})$ are transmitted from antenna-1 and antenna-2 respectively. STBC algorithms at the receiver combine all the copies of the received signals to extract the information transmitted.

The goal of STBC is to create a signal that is robust to fading and other channel impairments. By encoding the data over multiple antennas and time slots, STBC creates space and time redundancy in the signal that helps to mitigate the effects of fading and other channel impairments. This results in a more reliable transmission and greater signal coverage.

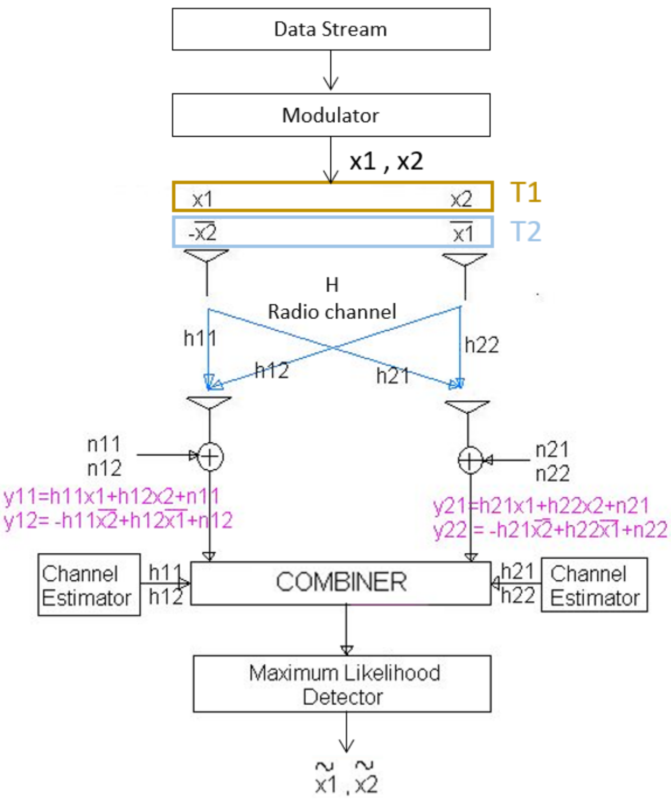

Figure 8-1: STBC MIMO with 2x2 antennas

8.1.2 Spatial Multiplexing (SM)

SM (Spatial Multiplexing) is a MIMO technique to transmit independent and separate data symbols. These encoded data symbols are called Streams from each of the transmit antennas. As illustrated in Figure 8-2 at instant T1 data symbols (x1, x2) are transmitted from antenna-1 and antenna-2, while after some duration at instant T2 different data symbols (x3, x4) are transmitted from antenna-1 and antenna-2, respectively. Hence data from multiple information sources are separately encoded and modulated before transmission from multiple antennas simultaneously. At the receiver, the number of antennas should be the same or more than the number of transmit antennas This increases the data rate of the system compared to STBC technique.

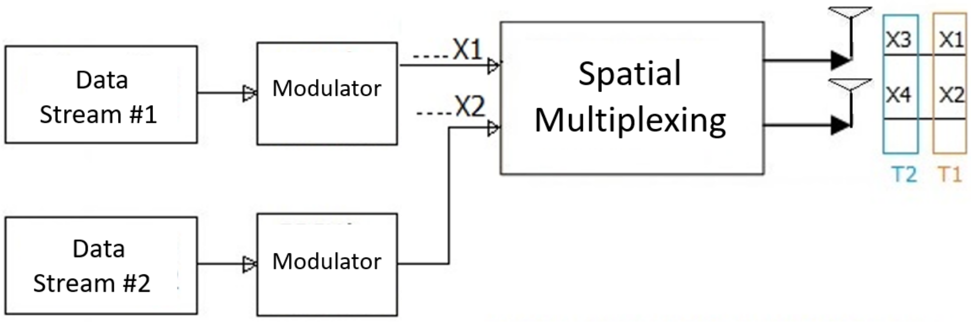

Figure 8-2: Spatial Multiplexing, transmitter side for MIMO 2x2.

8.1.3 Spatial Multiplexing with precoding

Linear precoding algorithms are used to optimize the transmission of data over multiple antennas in SM implementations (Figure 8-3). The algorithm uses a linear transformation matrix to optimize the transmission based on the channel conditions and other constraints. In the following is a summary of how MIMO SM with precoding works in 5G NR:

- Channel estimation: The first step in MIMO SM with precoding is to estimate the channel conditions between the transmitter and receiver. In TDD we can assume channel reciprocity, and the gNB can estimate the downlink channel quality from uplink signal (e.g., from SRS or PUSCH DMRS) and select the codebook matrix best fit for the downlink transmission.
- Precoding matrix calculation: Once the radio channel (H) is estimated, a precoding matrix (W) is calculated at the transmitter. The precoding matrix is a linear transformation matrix applied to the transmit signal to optimize the transmission. The detailed specification of PMI – Precoding Matrix Indicator is in 3GPP TS 38.214, Section 5.2.2.2.
- Transmit signal processing: The precoding matrix is applied to the transmit signal to optimize the transmission over multiple antennas. The precoded signal is then transmitted over multiple antennas simultaneously to the receiver.
- Receive signal processing: At the receiver, the signal received over multiple antennas is processed to decode the transmitted data. This involves estimating the channel conditions and applying decoding algorithms to separate the data transmitted over multiple antennas.

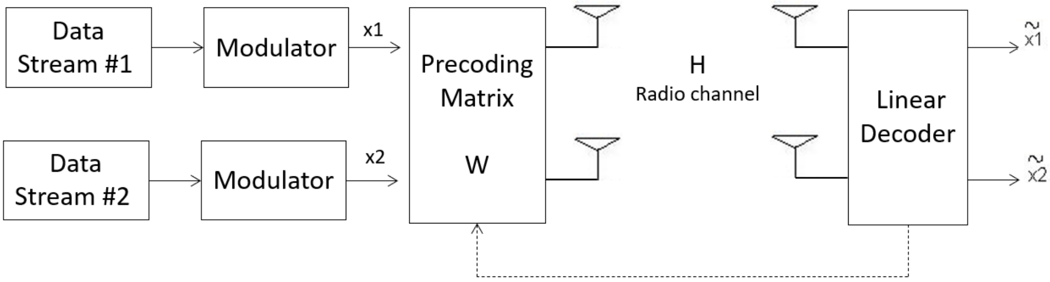

Figure 8-3: High-level view of SM with precoding for 2x2 MIMO.

8.1.4 OAI implementation of the Spatial Multiplexing with precoding

Figure 8-4 illustrates the MIMO Spatial Multiplexing scheme implemented for DL in OAI and available as open source code in the OAIBOX™ MAX.

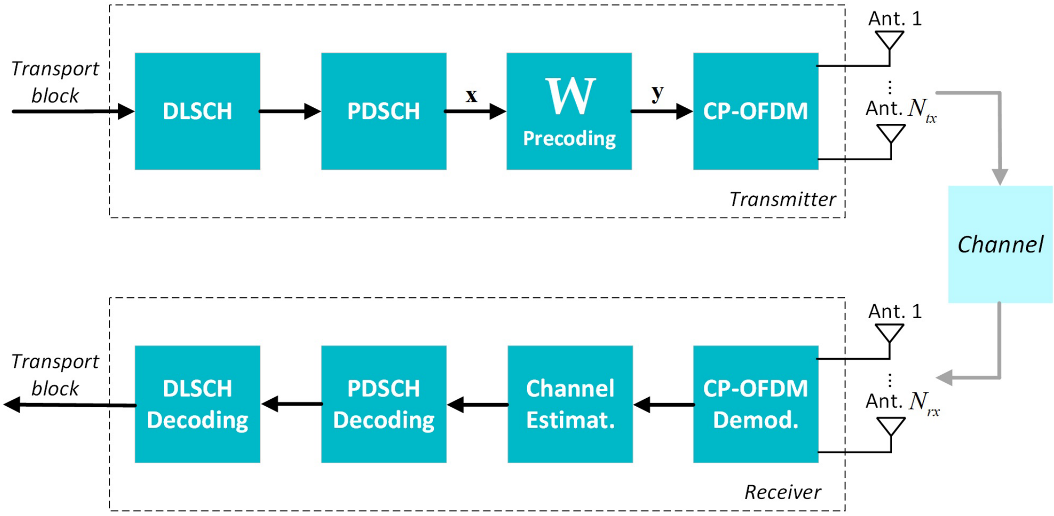

Figure 8-4: DL block diagram of physical-layer for MIMO SM.

The logical *Downlink Shared Channel* (DLSCH) is mapped onto the physical resources of the *Physical Downlink Shared Channel* (PDSCH). Let us assume that the output of PDSCH is defined by $\boldsymbol{x} \in \mathbb{C}^{P \times P}$, where P is the number of layers, i.e., the number of downlink parallel streams to be transmitted, which can be up to 8 layers [7]. Then, the precoder matrix $\boldsymbol{W} \in \mathbb{C}^{N_{tx} \times P}$ is applied such that

$$\mathbf{y} = \mathbf{W}\mathbf{x}, \tag{8.1}$$

where $\boldsymbol{y} \in \mathbb{C}^{N_{tx} \times P}$. Finally, the symbols are modulated using the *Cycle Prefix Orthogonal Frequency Division-multiplexing Modulation* (CP-OFDM) and the signal is transmitted over-the-air. At the UE, the CP-OFDM is demodulated, and then, the radio channel is estimated using the *Demodulation Reference Signal* (DMRS) to perform the channel compensation. Finally, the PDSCH and DLSCH are decoded to get the Transport block.

As for the precoding matrix, $\mathbf{W}$, OAI uses a Closed Loop scheme where the UE sends a *Precoding Matrix Indicator* (PMI) through the *Physical Uplink Control Channel* (PUCCH) format 2. PMI reporting is based on a set of 4 codebook categories [7]:

- Type 1 Single Panel: primary utilisation for single-user MIMO, maximum rank of 8;
- Type 1 Multi Panel: primary utilisation for single-user MIMO, maximum rank of 4;
- Type 2 Single Panel: primary utilisation for multi-user MIMO, maximum rank of 2;
- Type 2 Port Selection: primary utilisation for multi-user MIMO, maximum rank of 2.

Type 1 codebooks provide relatively coarse information, while Type 2 codebooks provide more detailed information, which results in increased signalling overhead. OAI uses Type 1 Single Panel. Codebooks for 1-layer and 2-layer are in Table 8-1 (3GPP TS 38.214).

Table 8-1: Codebooks for 1-layer and 2-layer CSI reporting [7]

Codebook index	Number of layers	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{\sqrt{2}}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	---
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	---

For the precoder matrix, $\mathbf{W}$, one of the matrices of Table 8-1 is selected, because the *Channel State Information Reference Signal* (CSI-RS) is sent to UE to estimate the DL channel, as well as the *Channel State Information Interference Measurement* (CSI-IM) to estimate the interference power. Using the estimated DL channel and the interference power, the UE tests each precoder matrix of Table 8-1 to maximise the SINR. The UE, then sends the corresponding codebook index of Table 8-1 to the gNB, through PUCCH format 2.

8.2 Changing the MIMO configuration

8.2.1 Lab Equipment

- OAIBOX™ MAX, USRP N300/N310/X310/X410, Quectel module

Figure 8-5: Setup for testing MIMO 2x2.

8.2.2 Lab steps

Step 1. Setup your testbed with the OAIBOX™ MAX connected to a USRP N310 (N300 and X310 are also supported). Consider a distance between 1 and 3 m between the gNB and the UE with clear LoS for optimum propagation conditions.

Step 2. To ensure the gNB is with the default parameters, use the dashboard *Overview* page to:

i. "**Stop**" the gNB;
ii. Perform a "**Reset Configuration**".

Step 3. In the OAIBOX™ Dashboard, go to the gNB configuration page and set the configuration matching the Figure 8-6.

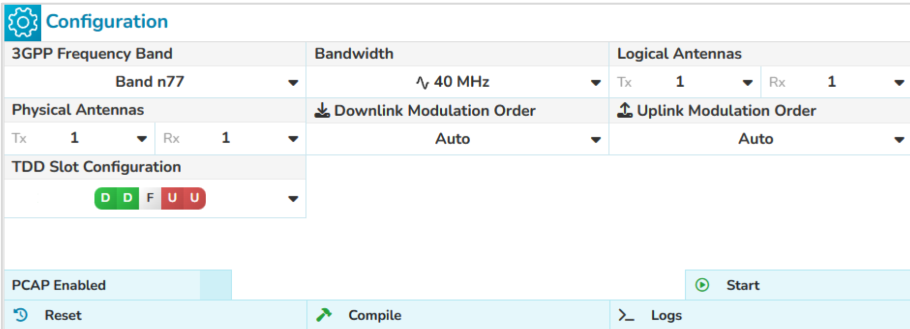

Figure 8-6: gNB configuration for SISO, n77 with 40MHz bandwidth

Step 4. "**Start**" the gNB.

Step 5. Connect the Quectel module to the Host UE, check if the Host system has a 5G interface.

Step 6. Start the iPerf downlink test in the OAIBOX™ Dashboard, as depicted in Figure 8-7.

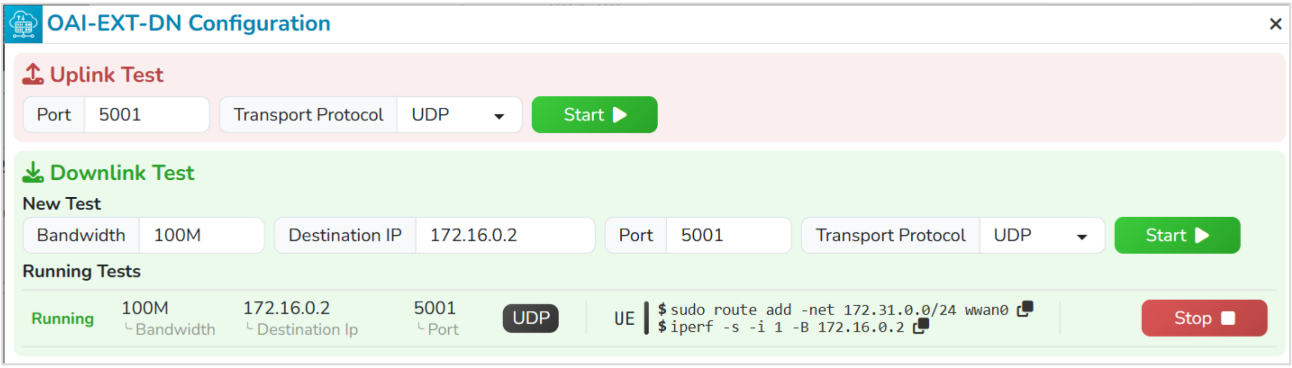

Figure 8-7: iPerf downlink test

Step 7. Wait for the Downlink test to complete, then write down the results for the SISO configuration in Table 8-2.

Step 8. Start the iPerf uplink test in the OAIBOX™ Dashboard, as depicted in Figure 8-8.

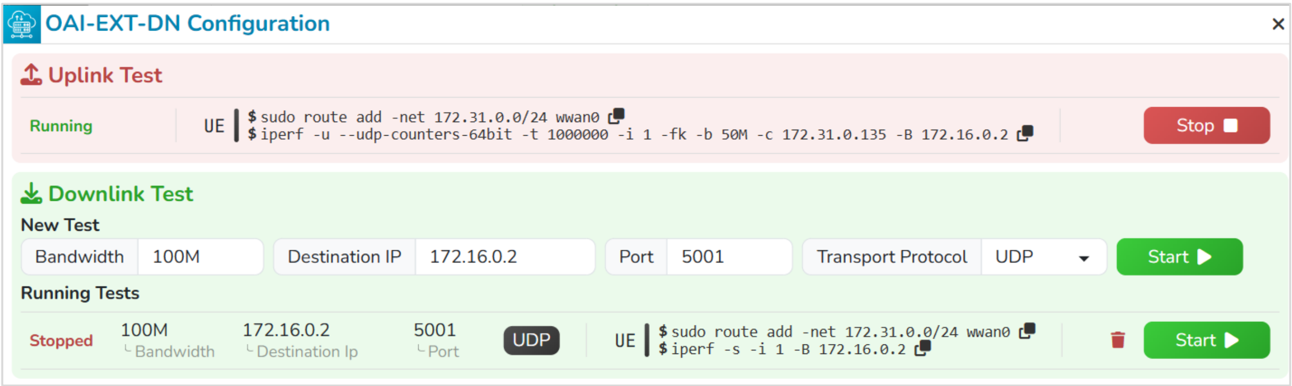

Figure 8-8: iPerf uplink test

Step 9. Start the iPerf uplink test in the host UE, with the commands that can be found in the iPerf modal window (Figure 8-8).

Step 10. Wait for the uplink test to complete, then write down the results for the SISO configuration in Table 8-2.

Step 11. "**Stop**" the gNB.

Step 12. Change the "**Logical Antennas**" "**Tx**" parameter in the gNB configuration to **2**, this will setup the gNB in a 2X1 MIMO configuration.

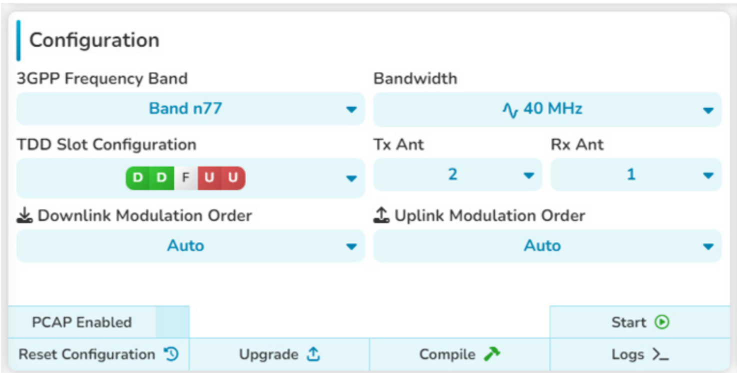

Figure 8-9: gNB configuration for SISO, n77 with 40MHz bandwidth

Step 13. "**Start**" the gNB.

Step 14. Repeat steps 6 to 9, and write down the results for the MIMO 2X1 configuration in Table 8-2

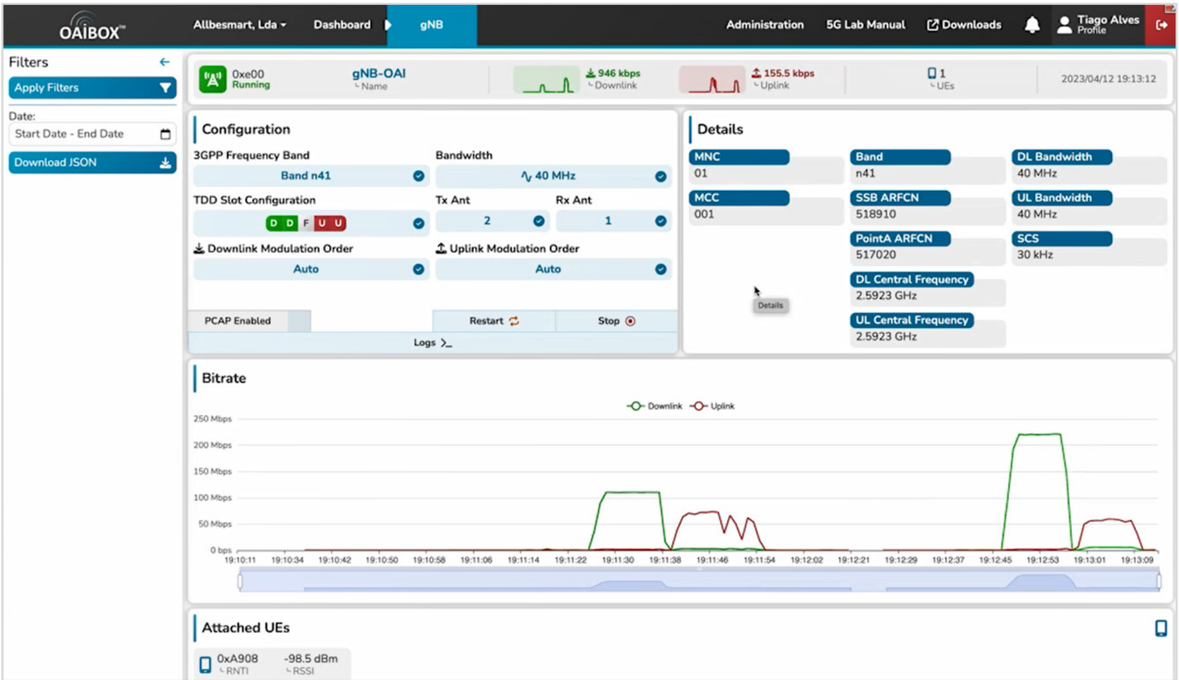

Figure 8-10 Example of changing the configuration from SISO to MIMO (2x1). The MIMO DL bitrate is almost double the SISO value.

Step 15. "**Stop**" the gNB.

Step 16. Change the "**Logical Antennas**" "**Rx**" parameter in the gNB configuration to **2**, this will setup the gNB in a 2X2 MIMO configuration.

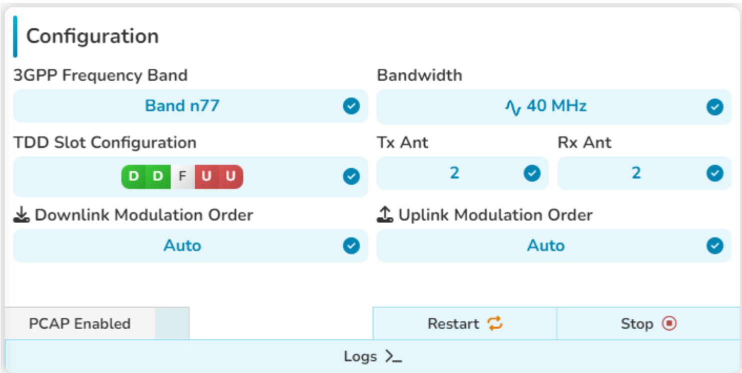

Figure 8-11: gNB configuration for SISO, n77 with 40MHz bandwidth

Step 17. "**Start**" the gNB.

Step 18. Repeat steps 6 to 9, and write down the results for the MIMO 2X1 configuration in Table 8-2

Scenario 2: Non-Line-of-Sight

Move the Quectel UE away from the gNB and block the LoS to create strong Path Loss attenuation.

Step 19. Repeat **Step 2** to **Step 19**, now applicable to Scenario 2.

Step 20. Include your findings in the next section "LAB-7 report".

8.3 LAB-7: Report

Table 8-2: Measured DL and UL throughputs for LoS scenario.

Scenario 1 - LoS		
	Measured DL bit rate	**Measured UL bit rate**
SISO (1x1)		
MIMO (2x1)		
MIMO (2x2)		

Table 8-3: Measured DL and UL throughputs for NLOS scenario.

Scenario 1 - NLoS		
	Measured DL bit rate	**Measured UL bit rate**
SISO (1x1)		
MIMO (2x1)		
MIMO (2x2)		

LAB-7: Suggested topics for discussion:

- Analise the impact of the MIMO configuration on the spectrum efficiency and measured bit rate.
- Analise the impact of the propagation scenario (LoS vs. NLoS) on the MIMO configuration.
- Observe the value of the Rank Indicator of the MIMO channel in the Dashboard and explain the measured value (see Section 1.3.3.11).

References

[1] USRP B200 SDR Kit - Single Channel Transceiver (70 MHz - 6GHz) - Ettus Research, [online]: https://www.ettus.com/all-products/ub200-kit/

[2] 3GPP, "TS 38.215: Physical layer measurements", Tech. Spec., Jul. 2020, v16.2.0.

[3] 3GPP, "TS 38.133: Requirements for support of radio resource management", Tech. Spec., Dec. 2020, v16.5.0.

[4] 3GPP, "TS 38.321: Medium Access Control (MAC) protocol specification", Tech. Spec., Sep. 2021, v16.5.0.

[5] 3GPP, "TS 38.213: Physical layer procedures for control", Tech. Spec., April 2021, v16.5.0.

[6] 3GPP, "TS 38.521-4: User Equipment (UE) conformance specification", Tech. Spec., Jan. 2021, v16.6.0.

[7] 3GPP, "TS 38.214: Physical layer procedures for data", Tech. Spec., Jul. 2020, v16.2.0.

[8] 3GPP, "TS 38.211: Physical channels and modulation", Tech. Spec., Jul. 2020, v16.2.0.

[9] 3GPP, "TS 38.101-1: User Equipment (UE) radio transmission and reception", Tech. Spec., Nov. 2020, v16.5.0.

[10] 3GPP, "TS 22.261 : "Service requirements for the 5G system"

[11] 3GPP, "TS 38.306: NR; User Equipment (UE) radio access capabilities", Tech. Spec., Sep. 2022, v17.2.0.

[12] Understanding 5G New Radio Bandwidth Parts – Keysight, [online]: https://blogs.keysight.com/blogs/inds.entry.html/2018/10/31/understanding_5gnew-iYIV.html

[13] 5G/NR - Carrier Bandwidth Part – ShareTechNote, [online]: http://www.sharetechnote.com/html/5G/5G_CarrrierBandwidthPart.html

[14] 5G NR Bandwidth Part (BWP) – TechPlayOn, [online]: https://www.techplayon.com/5g-nr-bandwidth-part-bwp/

[15] 3GPP, "TS 38.212: Multiplexing and channel coding", Tech. Spec., Jul. 2020, v16.2.0.

[16] 3GPP, "TS 38.331: Radio Resource Control (RRC)", Tech. Spec., Jul. 2020, v16.1.0.

[17] Antenna datasheet SENCITY® Urban 200 MIMO 4×4

https://www.hubersuhner.com/en/products-en/radio-frequency/antennas/das-ibc/sencity-urban-200