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Using a 5G UE Rotator in an Anechoic Chamber

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ABSTRACT

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The aim of this Bachelor's thesis was to describe an OTA RF chamber as a testing environment, what a 5G UE Rotator is and how it is used to achieve better-quality test results in an OTA RF chamber environment. Measurements were taken to show the improvement in the test results. This thesis work was commissioned by Nokia Solutions and Networks Oy.

The thesis work consists of introduction of the work and the company, description of OTA RF chamber and UE Rotator, UE Rotator usage and measurements and finally results and conclusions. The testing method was created for the purpose of this thesis work.

Results of the measurements were visualized, and they showed how UE placement affects the test results in the anechoic chamber environment. This thesis work and its results showed the significance of precise UE placement and the value of UE Rotator as a tool for testing.

Keywords: 5G, Anechoic chamber, Radio frequency, Rotator, UE

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VOCABULARY

4G	Fourth Generation
5G	Fifth Generation
ADB	Android Device Bridge
AT	Attention
BLER	Block-error rate
BTS	Base Transceiver Station
CPRI	Common Public Radio Interface
DAC	Digital-to-Analog Converter
DC	Direct Current
DUT	Device Under Test
ELT	Extract, Load and Transfer
GND	Ground
GPIO	General Purpose Input/Output
IP	Internet Protocol
LMI	Local Management Interface
LTE	Long-Term Evolution
MCS	Modulation and Coding Scheme
MIMO	Multiple-In Multiple-Out
MTP	Mobile Testing Platform
NR	New Radio
NSA	Non-Standalone
OTA	Over the Air
OTAVA	Over the Air Validation Area
PWM	Pulse Width Modulation

QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
Rx	Receive
SA	Standalone
SSH	Secure Shell
TCP	Transmission Control Protocol
Tx	Transfer
UDP	User Datagram Protocol
UE	User Equipment
UI	User Interface

1 INTRODUCTION

Nokia was founded in 1865 and has been through many transitions since, from a paper mill operation to a producer of different products such as tires, televisions, and mobile phones to the present-day global technology leader in the communications industry [1]. This thesis work was completed in Nokia's Otava 5G testing laboratory in Oulu, Finland. Otava has about 8,500m² of space which includes different 5G test lines, multiple antenna walls and RF chambers [2].

Anechoic test chambers are the most common environment for testing in Otava. Anechoic chambers are explained generally in this thesis and Nokia's own version, OTA RF chambers, in more detail. The main benefits of using an anechoic chamber are the interference-free test environment and being able to have multiple test lines in a relatively small area.

A UE Rotator is a device that was internally developed in Nokia to improve test results by offering a way to change the UE's horizontal and vertical angle remotely in an OTA RF chamber environment. The UE's position has an effect on different testing parameters depending on how the UE's antennas are aligned relative to the radio unit's antennas. Prior to the development of the UE Rotator there was no way to change the UE's position without physically accessing the test chamber. A static position of the UE is rarely optimal and that is why using a UE Rotator is beneficial.

The aims of this thesis work are to describe an anechoic chamber, the UE Rotator as a device and how it is used to achieve better test results. Measurements will be taken to compare the results between a static UE position and a position founded and set with a UE Rotator.

2 ANECHOIC CHAMBER AS TEST ENVIRONMENT

This chapter contains general information about anechoic chambers and the OTA RF chamber as a test environment used at Nokia. An OTA RF chamber will be used as a measurement environment in this thesis. The main aim of the measurements is to show how the UE Rotator is used to improve test results.

2.1 General information on anechoic chambers

An anechoic chamber is a room that has radio-wave absorbing material on its inner walls to prevent radio waves from bouncing inside. Absorbers are usually pyramidal in shape, which reflects radio waves toward the bottom between the absorbers and attenuates them. Metal walls prevent any radio waves entering the chamber from outside. [3]

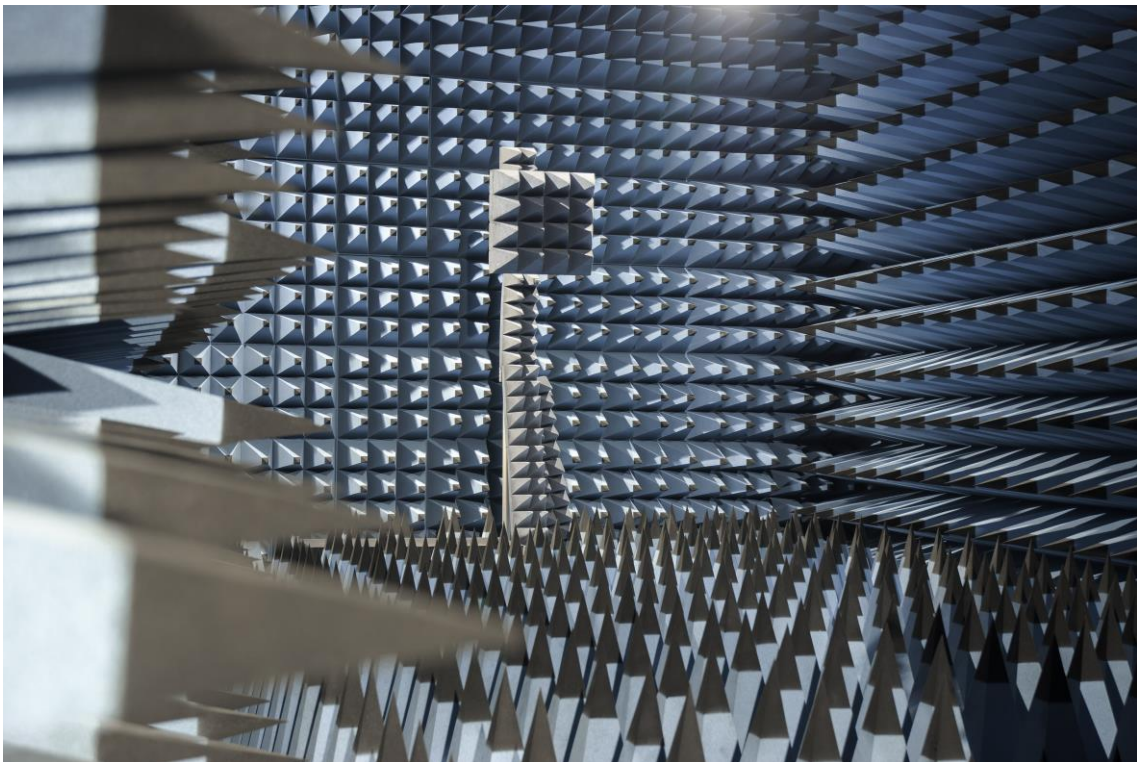


FIGURE 1. Example of an anechoic chamber [3]

2.2 Nokia's OTA RF chamber

The OTA (=Over The Air) RF chamber is a 7.2 meter-long modified sea container designed and manufactured by Orbis Systems. The chambers are used for testing different 4G and 5G radio units. The DUT (=Device under test) is a radio unit, and it can be tilted and rotated using a DUT positioner. The chamber contains radio and UE partitions separated by a partition wall. The partition wall is used for better control of the transmitted RF signals by enabling the use of separate antennas and attenuators. The wall has a square hole in it that can be blocked by a metal plate. The metal plate has RF connectors which are used for connecting separate antennas when they are needed in testing (Figure 3). Attenuators can be used with separate antennas to reduce the amount of received power for the UEs. The level of attenuation is set so that the UE receives approximately the same amount of power as in a real use scenario. [4]

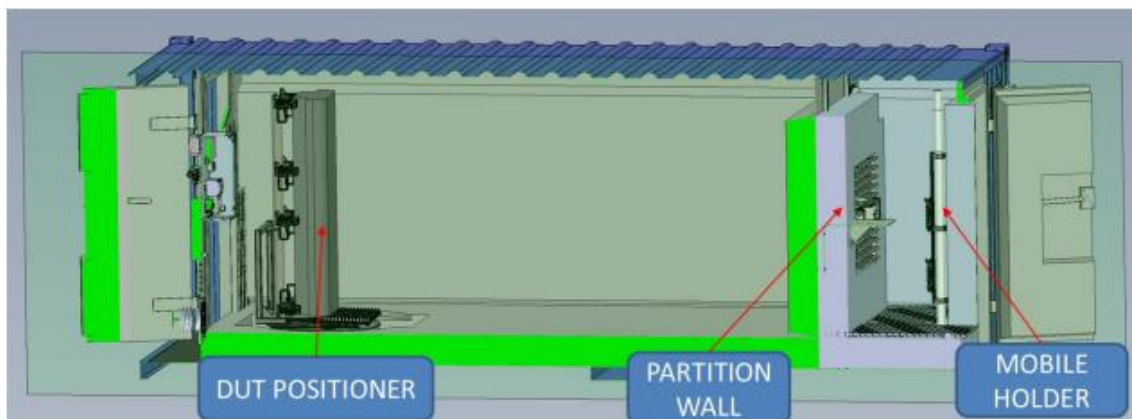


FIGURE 2. OTA RF Chamber [4, p.1]



FIGURE 3. Vivaldi antenna as a separate antenna

The mobile holder is a plate which can be height-adjusted (Figure 4). Even though we can use a DUT positioner, being able to also move the UE provides more control over the signal quality. The UE used to be commonly attached to the mobile holder by simply using zip ties, double-sided tape, or other similar means, but this is no longer the case when using the UE Rotator. The Rotator has 3D-printed parts that are attached to a mobile holder plate with plastic bolts (Figure 4).

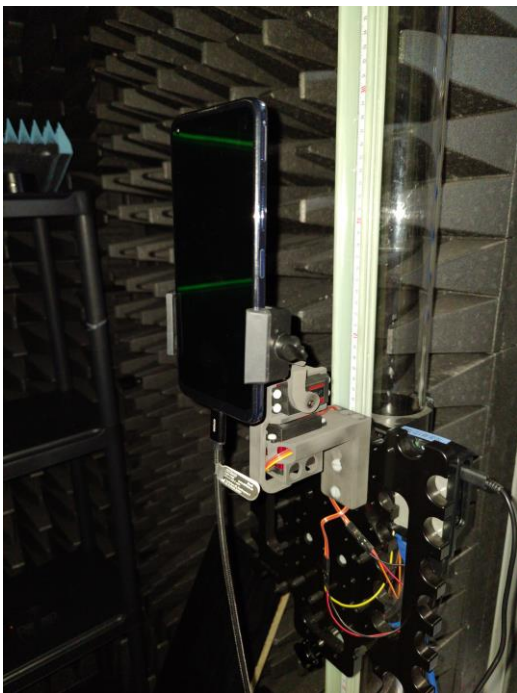


FIGURE 4. UE Rotator attached to mobile holder

3 UE ROTATOR

This chapter introduces the UE Rotator and its mechanical parts, hardware, and software.

3.1 Description of UE Rotator

The UE Rotator consists of 3D-printed mechanical parts, a Raspberry Pi 3B or newer, a USB camera, two servos, and power supplies. The Raspberry Pi is used to provide a control signal for the servos and hosting the website which includes the user interface. The Rotator can tilt the UE with movement ranges of 90° vertical and 180° horizontal.

3.2 Hardware

3.2.1 Raspberry Pi

The Raspberry Pi is a single-board computer series by the Raspberry Pi Foundation. Generally, there is an A model, which is more affordable, and a B model which has additional ports available. [5]

B Models include Ethernet and USB ports which are mandatory for this use case. The third and fourth-generation B models are proved to have enough performance for the purpose of the device. The Raspberry Pi provides control signals for the servo motors and hosts the user interface via a web page which is configured to be accessed from Nokia's internal test network. The USB camera is used to provide a camera feed from the OTA RF chamber. (Figure 5)

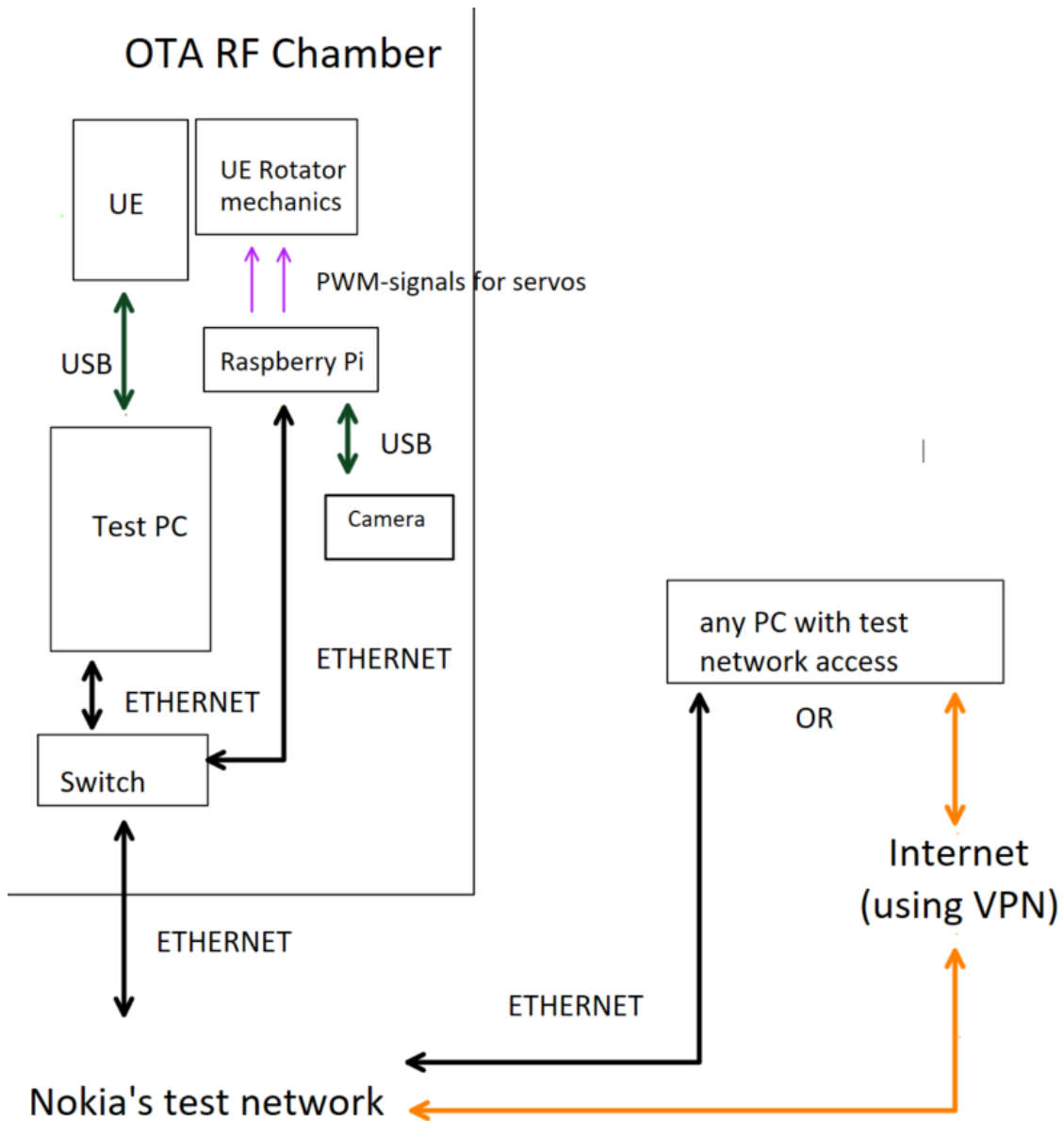


FIGURE 5. Topology for the UE Rotator remote control

3.2.2 Servo motors

A servo motor is an electrical device that rotates parts of the machine using either an analog or digital signal. Servo motors can be classified with different terms, but the most important consideration is the type of voltage it uses. DC- (=direct current) servos are the obvious choice because the Raspberry Pi can provide a control signal from a GPIO (=General purpose input/output)-pin without any additional hardware. The control signal type is PWM (=pulse width modulation) and it is calculated by a script dedicated to the UE Rotator. Two separate servos are used for horizontal and vertical movement and there are separate control signals for each servo. [6]

The servo model used in the UE Rotator is LF-20MG-270° by Power HD which has a 270° operating range and 20kg (at 6.6V) of maximum torque [7]. The horizontal utilized operating range is 180° and the vertical utilized range is 90°, which covers most of the available space for the UE. The 20kg of torque has been tested to be enough to hold even heavier UEs.

3.3 Mechanical parts

Four mechanical parts are needed for the assembly. 3D models of the mechanical parts are designed at Nokia. The mechanical parts are 3D-printed using the selective laser sintering method which uses polymer powder as a material. In the sintering method, a print is formed by heating polymer powder with laser layer by layer until the print is ready. Multiple parts are needed to achieve horizontal and vertical movement of a UE and have mechanics attached to the mobile holder plate. A general UE clamp is used to attach the UE to the rest of the mechanics (Figure 7). [8]



FIGURE 6. 3D-printed mechanical parts



FIGURE 7. General UE clamp

3.4 Software

3.4.1 Raspberry Pi OS: Raspbian GNU (Linux)

The operating system used in the Raspberry Pi is Linux 10-based Raspbian optimized for Raspberry Pi hardware [9]. The Rotator's UI is hosted to the test network as a web page in the operating system (Figure 8). The UI provides controls for changing the horizontal and vertical angles of the UE and camera feed from the chamber. The angles can be set with a given degree value or in 3-degree steps. The given angles are used in a Python script that converts angle values into a corresponding PWM signal for the servo motors.

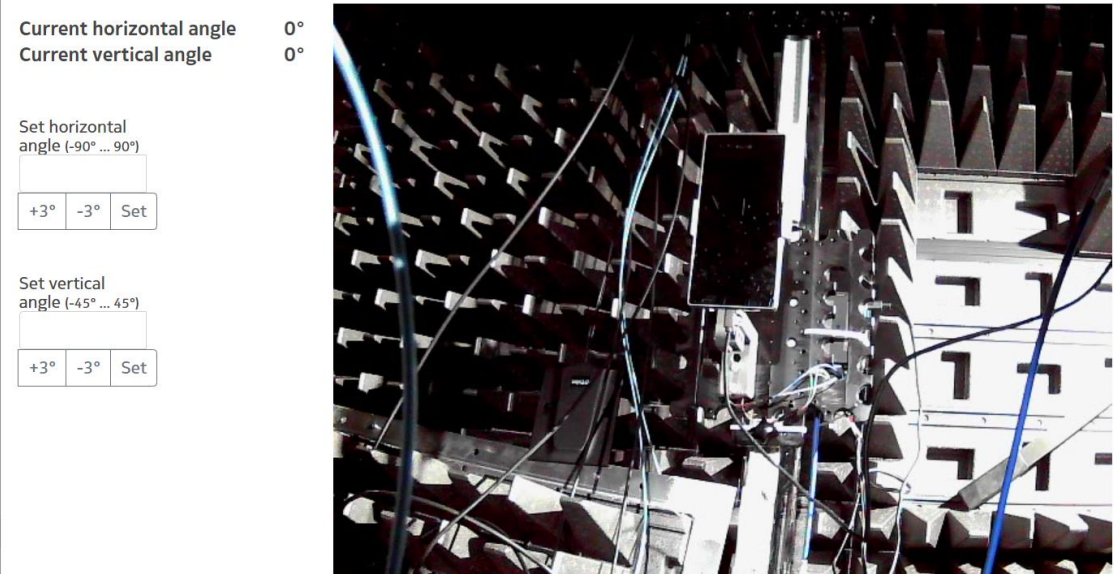


FIGURE 8. UE Rotator UI web page

3.5 Electronics

A general power supply set to 6V is used to power the servo motors. The Raspberry Pi's GND- (=ground) pin is connected to the power supply's ground to avoid interference to the servos' control signals (Figure 9). The control signals are delivered from GPIO pins using regular male-female jumper cables.

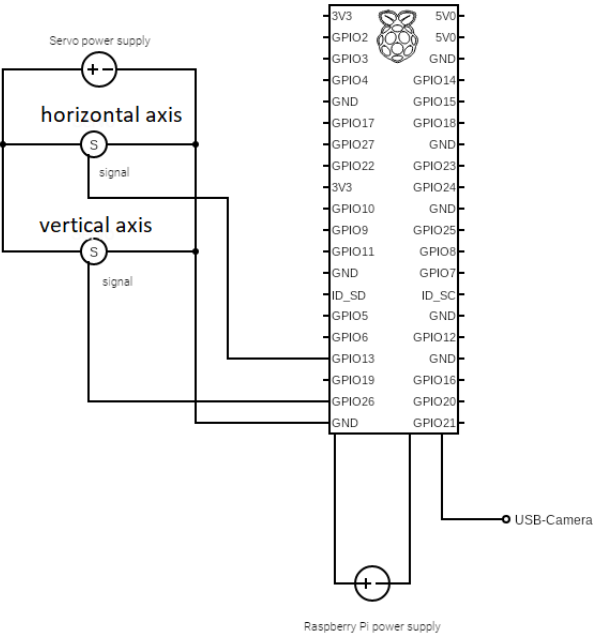


FIGURE 9. Wiring diagram of the UE Rotator

4 UE ROTATOR USAGE AND MEASUREMENTS

This chapter describes the test setup for measurements, preparations, UE Rotator usage and taking logs from the UE.

4.1 Test setup

The BTS (=base transceiver station) consists of a radio unit and baseband units which communicate using CPRI (=Common public radio interface). CPRI is a specification that defines the interface of transport, connectivity, and control communications. [10] Baseband units are located outside the OTA RF chamber and connected to the radio unit with an optical fiber. Configuration of the BTS is done from a dedicated PC which is connected to the baseband units using an LMI (=Local Management Interface) connection. LMI is a signaling standard used between routers and frame relay switches developed by Cisco. [11] A Linux-based data server is used for making data transfers in testing. A mmWave radio unit was used in the measurements for this thesis. (Figure 10)

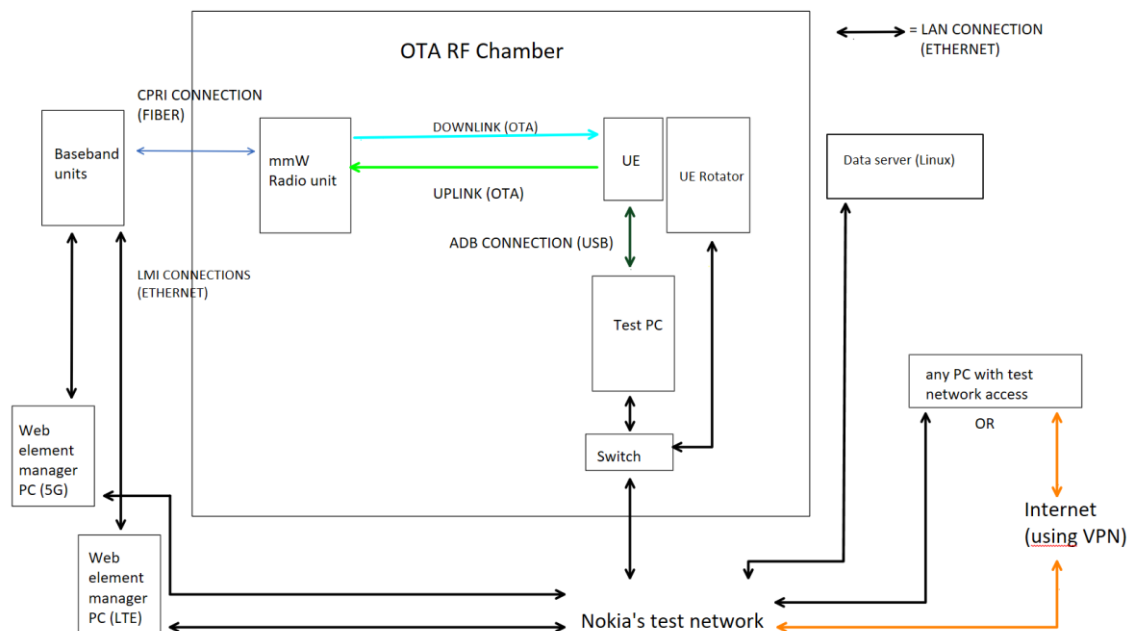


FIGURE 10. Connection topology of the OTA RF Chamber used in this thesis

4.1.1 MmWave radio unit

MmWave radios use extremely high-frequency waves (from 1-10mm wavelength), allowing the use of smaller antennas and beamwidth which makes beamforming more precise. Beamforming is a technique essential for 5G that uses multiple radiating elements to transmit the same signal at the same wavelength but in a different phase, which creates a more targeted stream than omni-directional antennas used with LTE (=Long-Term Evolution), for example. [12] MmWaves are significantly more prone to attenuating over the air than the more commonly used cmWaves and therefore they are only used over a short distance. The short range of mmWaves also means that the same frequencies can be used more often. [13]

4.1.2 Beam set

The beam set is a BTS parameter that includes the number of used beams and their patterns. The beam patterns are created by beamforming, which can be digital or analog. In analog beamforming, variations of amplitude and phase are applied to the analog signal at the transmitting end. In digital beamforming, variations of amplitude and phase are applied to the digital signal before the DAC (=Digital to Analog) conversion. The mmWave radio unit used in these measurements was configured with an analog beam set of 12 beams with patterns shown in Figure 11. The UE is initially placed approximately facing the center of the radio unit, and using the UE Rotator, the UE's antennas can be aligned with the beams for better signal quality and therefore better test results. In these measurements beam 63 is reachable for the UE. [14]

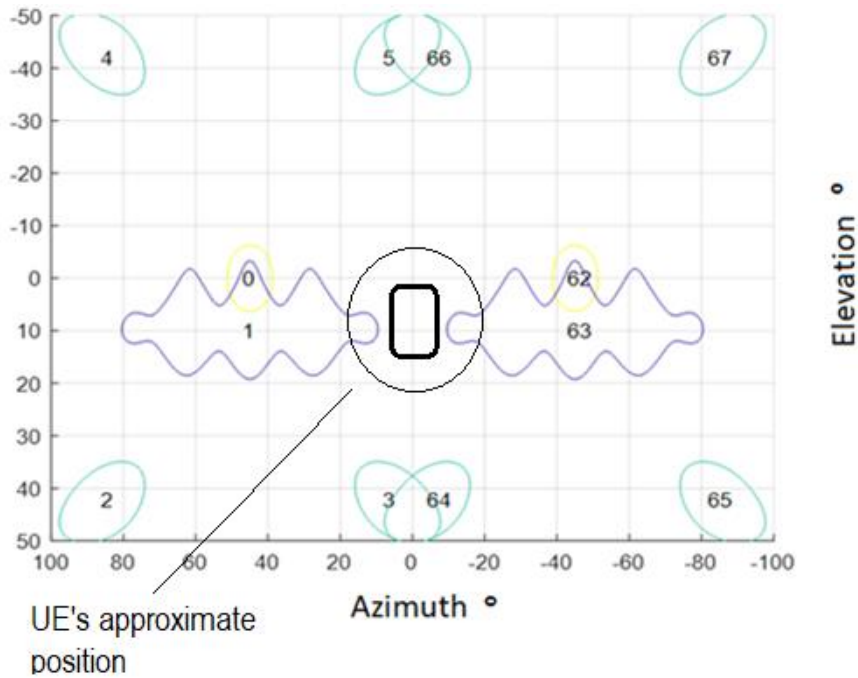


FIGURE 11. Beam pattern of the tested mmW radio [15, p.30]

4.1.3 5G architecture and bands

There are two different implementations of 5G architectures: SA (=Standalone) which is end-to-end 5G and NSA (=Non-standalone) which uses LTE infrastructure with 5G-based radio antennas [16]. NSA was used in this test setup with a band combination of b66+n261. b66 is used as an LTE anchor which is for initial connection establishment, and n261 is a mmWave frequency (28Ghz) used for 5G connection.

4.1.4 Test equipment

The test PC is a standard laptop with Nokia's Windows package installed for testing purposes. Because the test PC is in the chamber, it is always used remotely while the radio is on air. The UE used in these measurements was a MediaTek MTP (=Mobile testing platform) which supports the b66+n261 band combination used in these measurements. The software used in the measurements was ELT logging software used with MediaTek devices. ELT is used for monitoring and for taking logs including messages between the BTS and UE and different parameters from the UE's network interface. The UE and test PC communicate through a standard USB-C cable using an ADB (=Android Debug Bridge) connection. ADB is a command-line tool for PC that is used for communicating with an Android device. [17]

4.2 Testing method

4.2.1 Data transferring technique

The data transferring technique used was maximum artificial load in downlink and uplink with iPerf software using UDP(=User Datagram Protocol). UDP is preferred over TCP(=Transmission Control Protocol) as it has much higher speed and also causes less variance in results between different UEs. iPerf is a tool used for testing maximum bandwidth in an IP network [18]. Data transfer in the uplink is turned on with iPerf in the UE using the ADB shell with a command prompt and downlink transfer is turned on from an external Linux PC using an SSH(=Secure Shell)-connection. The bandwidth in downlink is set to 450MB and 50MB in uplink, which are enough to reach maximum throughputs. The IP address is static on the Linux PC, but the UE's IP changes every time it attaches to the LTE anchor. The IP address of the UE can be checked within the ADB shell using the "ifconfig" command (Figure 12).

4.2.2 Taking measurements

After the test setup was prepared and the UE Rotator was in the default position, the UE attach was tested by enabling and disabling airplane mode which connects UE to the 5G cell and turning data transfers on using iPerf commands in the UE (uplink) and data server (downlink). Airplane mode can be changed remotely using Vysor software or using AT(=Attention)-commands "at+cfun=4" which disables the receive and transmit circuits and "at+cfun=1" which restores full functionality from the ELT [19]. Vysor software is used to remotely control iOS or Android devices by Windows, Mac, or Linux [20]. Initial measurements showed that detach takes place quite fast if UE's position is not good, so the results were saved after about 10 seconds of successful connection with data transfers on. The results were saved by screen capturing the ELT's NR info view with the UE Rotator UI, which shows the UE's angles at the given moment. The UE angles were changed from -5° to 5° in 1° steps horizontally and vertically in both directions until there were multiple detaches, meaning that the UE was in a clearly bad position. This method was repeated to create a map of 121 UE positions in which the UE was able to stay connected in the 5G (Figure 13).

```
$ iperf -c 192.232.122.147 -u -i 1 -l 1360 -b 450M -t 99999
```

-c client (destination ip) -u (UDP) -i (interval (sec)) -l (length of buffers (KB)) -b (bandwidth (Bit)) -t (time (sec))

FIGURE 12. Example of an iPerf command for downlink transfer [21]

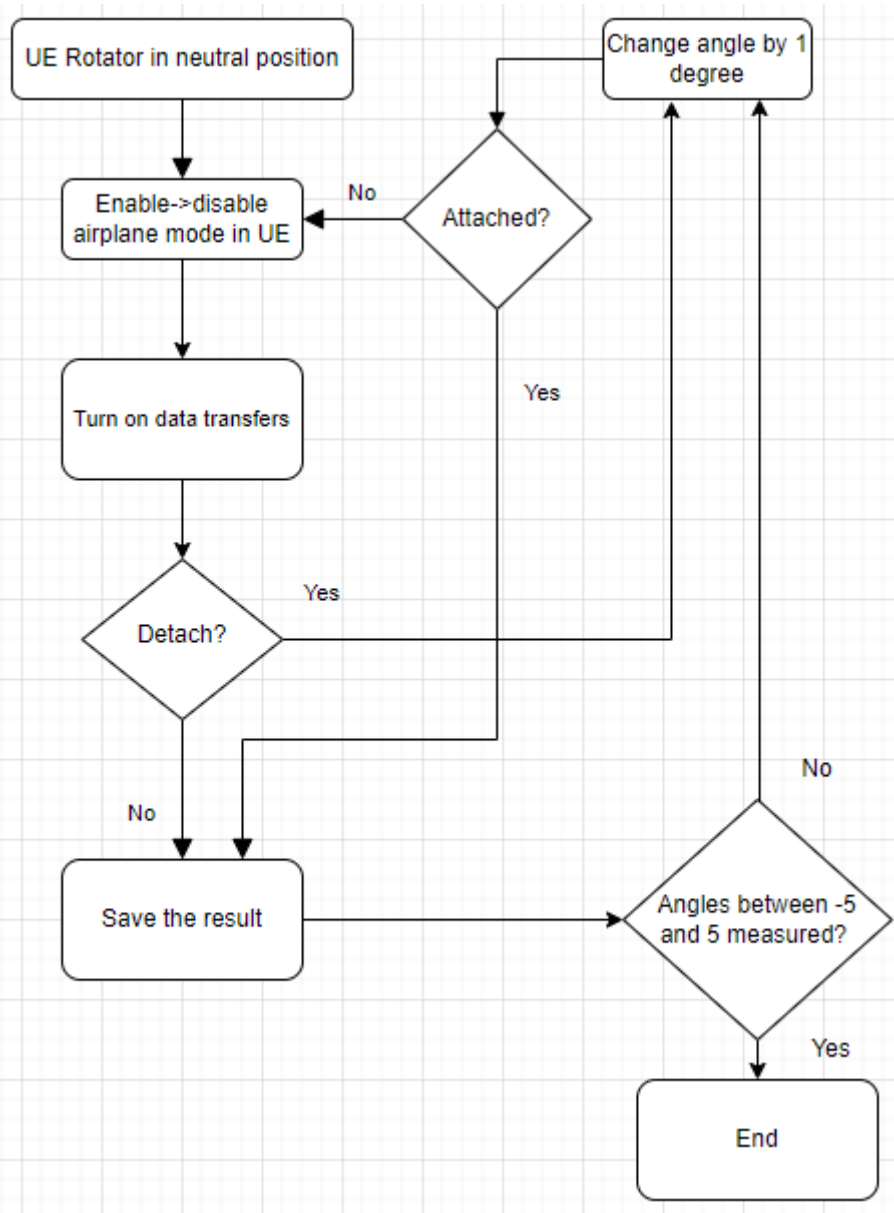


FIGURE 13. Measuring flow chart

5 RESULTS

In this chapter the most important parameters are explained, and the results are examined and conclusions reached.

5.1 Parameters

The most important parameters when thinking about the use case of the UE Rotator are the throughput in downlink and uplink, the BLER (=Block-Error Rate) and the MCS (=Modulation and Coding Scheme) and rank. The throughput measures how many bits are successfully decoded from the sent data on the receiving side in a given timeframe [22]. The timeframe is usually one second and is also true in the measurements. The BLER measures the percentage of erroneous data blocks out of the total number of transmitted data blocks [23]. The target BLER in uplink is configured at 10%, which is widely used as an acceptable rate for a radio link to work properly. A lower BLER target would mean a lower MCS and therefore a modulation technique with less capacity to send the actual data. The MCS defines the number of bits that can be sent in a symbol. Symbols are used in modulation techniques to transmit bits by modulating the carrier signal. The modulation techniques that 5G supports are QPSK, which changes only the phase of the signal, and QAM16, QAM64, and QAM256 which additionally change the amplitude of the signal. QPSK can transmit 2 bits and in QAM techniques the number of transmittable bits is presented in the name. [24] MIMO (=Multiple-input and multiple-out) is technology that uses multiple antennas to send and receive different data streams simultaneously [25]. The rank indicator shows how many antennas are receiving a signal without interfering with each other [26]. The maximum rank indicator is practically the same as the number of Tx(=Transfer)-Rx(=Receive) pairs. The rank was constantly 2 because the BTS was configured with 2x2 spatial multiplexing, which means that the maximum number of data streams was 2 [27].

5.2 Position maps

In this section, position maps visualized from the results are presented and examined. Position maps are samples of 121 different positions from -5° to 5° vertically and horizontally.

5.2.1 Active positions

This visualization shows the positions where the UE could maintain a 5G connection when data transfers were active. Regarding the shape of the visualization (Figure 13), it seems that the UE's initial position was on the edge of beam 63 (Figure 14).

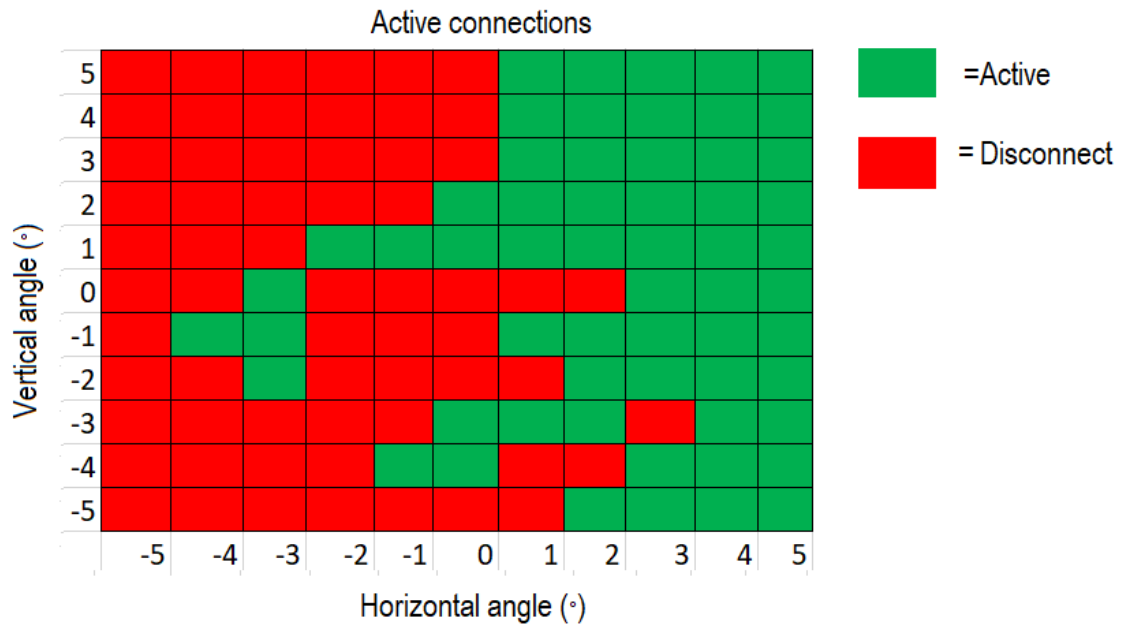


FIGURE 14. Positions by active/disconnected connection status

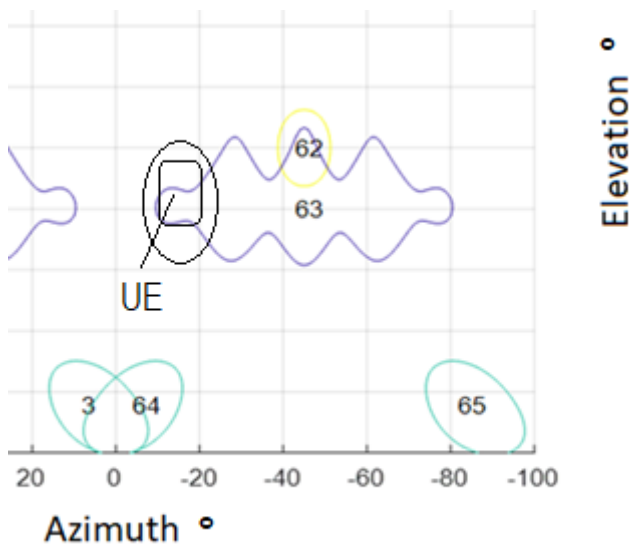


FIGURE 15. UE's initial position

5.2.2 UL BLER

The modulation used was mostly QAM16 with a few exceptions of dropping into QPSK-modulation. The UL BLER stayed in a range of 7-10%, but clearly the best position area with a constantly lower BLER was between the 3-5° horizontal and 3-5° vertical angles.

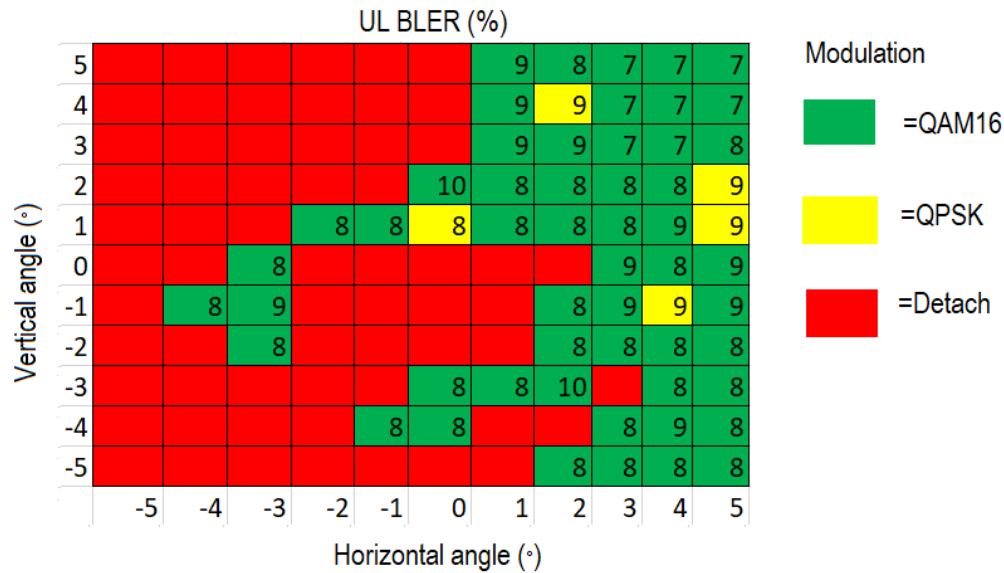


FIGURE 15. Positions by uplink BLER and modulation

5.2.3 MCS

The MCS had the expected relation with the UL BLER and the MCS can also be seen as a basis for the used modulation technique.

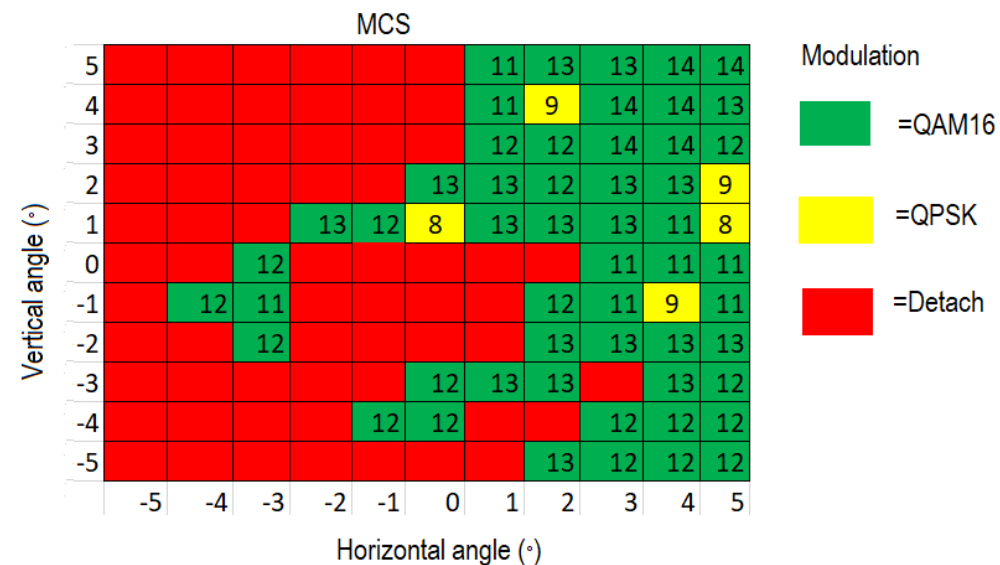


FIGURE 16. Positions by MCS and modulation

5.2.4 Uplink throughput

The maximum uplink throughput results followed the same phenomena as the previous results, but the effect was not as noticeable in the throughputs.

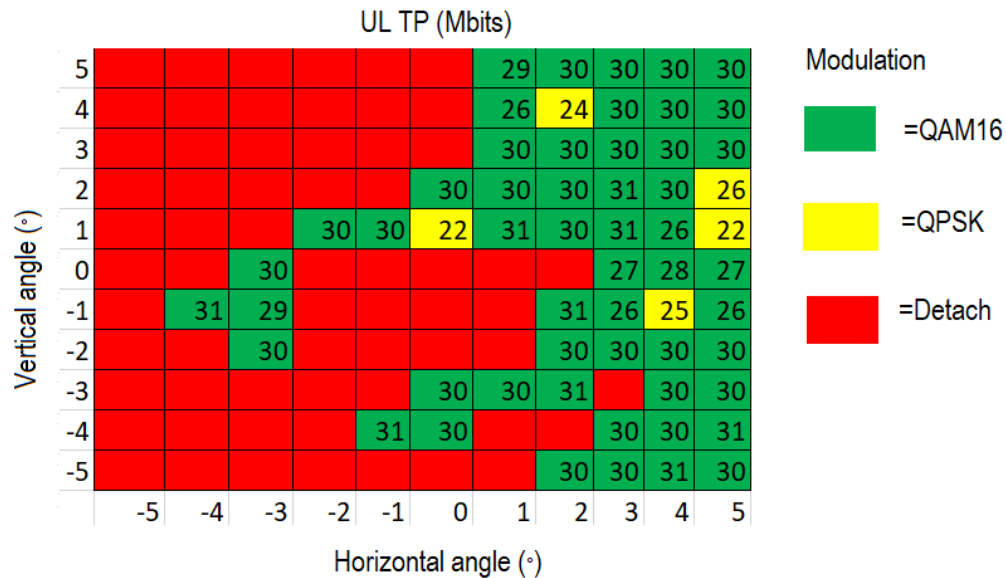


FIGURE 17. Positions by uplink throughput and modulation

5.3 Conclusions

The matter of precise UE positioning can be seen from the results, and therefore the value of the UE Rotator as a useful tool for testing. Precise adjustments that were made with the UE Rotator would not be possible by moving the UE in a chamber by hand. The UE Rotator is also a viable option when testing cmWave radios, but the effect of the UE angle is more drastic when using the smaller mmWave.

6 SUMMARY

The objective of this thesis work was to describe the OTA RF chamber as a testing environment, the UE Rotator and how it is used to achieve better-quality test results.

The specific test setup and fundamental configurations for the measurements of this thesis are described in this document. The measurements were made in an OTA RF chamber using an mmWave radio unit because mmWaves are more sensitive to the UE position than cmWaves and therefore better-suited for the target of this thesis. The testing method was to create map of UE positions and measure how the positions affect different parameters.

The results of the measurements showed the value of being able to move the UE precisely in improvements in different parameters. If we compare the UE Rotator to the previous situation with a fixed UE position moved by hand, the improvement is significant, also considering the efficiency of remote control.

REFERENCES

1. Nokia. 2021. Our History. Date of retrieval 30.8.2022. <https://www.nokia.com/about-us/company/our-history/>.
2. Kilponen, Anna. 2019. Oulussa toimii Nokian harvinaislaatuinen Otava-testilaboratorio, jossa kehitetään 5G-verkkoteknologiaa – valloittaako Nokia taas maailman? Date of retrieval 25.8.2022. <https://www.kaleva.fi/oulussa-toimii-nokian-harvinaislaatuinen-otava-tes/1731888>.
3. Antenna test lab. 2021. What is an anechoic chamber? Date of retrieval 10.8.2022. <https://antennatestlab.com/antenna-education-tutorials/what-is-an-anechoic-chamber>.
4. OTA chamber tech spec 0.4.0 Internal reference. Date of retrieval 10.8.2022.
5. Opensource.com. 2012. What is a Raspberry Pi? Date of retrieval 6.10.2022. <https://opensource.com/resources/raspberry-pi>.
6. Gastreich, W. 2018. What is a Servo Motor and How it Works? Date of retrieval 6.10.2022. <https://realpars.com/servo-motor/>.
7. LF-20MG Datasheet. Date of retrieval 9.10.2022. <https://static.digitecgalaxus.ch/Files/1/2/6/7/9/8/3/4/LF-20MG.pdf>.
8. 3DSourced. 2019. Selective Laser Sintering: Everything You Need To Know About SLS 3D Printing. Date of retrieval 10.10.2022. <https://www.3dsourced.com/guides/selective-laser-sintering-sls/>.
9. FrontPage - Raspbian. 2012. Date of retrieval 10.10.2022. <https://www.raspbian.org/>.
10. Gillis, Alexander. 2019. What is CPRI (Common Public Radio Interface)? Date of retrieval 23.10.2022. <https://www.techtarget.com/searchnetworking/definition/CPRI-Common-Public-Radio-Interface>.
11. Shekhar, A. Fossbytes. 2016. What Is Local Management Interface (LMI) In Frame Relay? Date of retrieval 23.10.2022. <https://fossbytes.com/local-management-interface-lmi-frame-relay/>.
12. Holm, A., Gayle, A.T., Tramm, K., Pettitt, K.-K. and Jhaveri, N. 2022. Extremely high frequency. Date of retrieval 23.10.2022. https://golden.com/wiki/Extremely_high_frequency-MNNV86.
13. RCR Wireless News. 2018. 5G NR: Massive MIMO and Beamforming – What does it mean. Date of retrieval 10.10.2022. <https://www.rcrwireless.com/20180912/5g/5g-nr-massive-mimo-and-beamforming-what-does-it-mean-and-how-can-i-measure-it-in-the-field>.

14. RF Wireless World. 2012. Difference between Analog Beamforming vs Digital Beamforming. Date of retrieval 27.10.2022. <https://www.rfwireless-world.com/Terminology/Analog-Beamforming-vs-Digital-Beamforming.html>.
15. Beam set design. Internal reference. Date of retrieval 27.10.2022.
16. Sha, A. 2022. 5G SA vs NSA: Difference Between Standalone and Non-standalone 5G Architecture. Date of retrieval 30.10.2022. <https://beebom.com/sa-vs-nsa-5g/>.
17. Android Developers. 2022. Android Debug Bridge (adb). Date of retrieval 30.10.2022. <https://developer.android.com/studio/command-line/adb>.
18. Gueant, V. 2013. iPerf – The TCP, UDP and SCTP Network Bandwidth Measurement Tool. Date of retrieval 30.10.2022. <https://iperf.fr/>.
19. M2MSupport. 2022. AT+CFUN – Set phone functionality. M2MSupport.net. Date of retrieval 8.11.2022. <https://m2msupport.net/m2msupport/atcfun-set-phone-functionality/>.
20. Vysor.io. 2022. Vysor. Date of retrieval 8.11.2022. <https://www.vysor.io/>.
21. iperf.fr. 2022. iPerf – iPerf3 and iPerf2 User Documentation. Date of retrieval 30.10.2022. <https://iperf.fr/iperf-doc.php>.
22. Burke, J. 2015. Throughput. Date of retrieval 30.10.2022. <https://www.techtarget.com/searchnetworking/definition/throughput>.
23. Rowe, M. 2021. BLER: A Critical Parameter in Cellular Receiver Performance. 5G Technology World. Date of retrieval 9.11.2022. <https://www.5gtechnologyworld.com/bler-a-critical-parameter-in-cellular-receiver-performance/>.
24. Techplayon. 2020. 5G NR Modulation and Coding Scheme – Modulation and Code Rate. Date of retrieval 9.11.2022. <https://www.techplayon.com/5g-nr-modulation-and-coding-scheme-modulation-and-code-rate/>.
25. McGrath, D. 2020. What is 5G Massive MIMO? Keysight Blogs. Date of retrieval 9.11.2022. <https://blogs.keysight.com/blogs/inds.entry.html/2020/02/19/what-is-5g-massive-mimo>.
26. ShareTechnote. 2022. 4G. ShareTechnote. Date of retrieval 10.11.2022. https://www.sharetechnote.com/html/Handbook_LTE_RI.html.
27. Lin, Lekun. 2009. Choosing Between Open- and Closed-Loop MIMO in BTS Systems. Date of retrieval 10.11.2022. <https://embeddedcomputing.com/application/networking-5g/choosing-between-open-and-closed-loop-mimo-in-bts-systems>.