TALLINN UNIVERSITY OF TECHNOLOGY
School of Information Technologies

Aleksei Fjodorov 182569IVEM

5G TESTBED IMPLEMENTATION AND MEASUREMENT CAMPAIGN FOR GROUND AND AERIAL COVERAGE AT 3.5 GHZ BAND

Master's Thesis

Supervisor: Muhammad Mahtab Alam
PhD

Sven Pärand
PhD

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Aleksei Fjodorov 182569IVEM

5G TESTPLATVORMI RAKENDAMINE NING MÕÕTMISKAMPAANIA 3.5 GHZ SAGEDUSALAS MAAPINNAL JA ÕHUS

Magistritöö

Juhendaja: Muhammad Mahtab Alam
Doktorikraad

Sven Pärand
Doktorikraad

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Author’s declaration of originality

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

Author: Aleksei Fjodorov

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Abstract

The thesis describes the implementation of a working testbed for the fifth generation of the cellular technology (5G) operating at 3.5 GHz frequency band and suitable for drones' applications, and its practical use for ground and aerial coverage and performance measurements of a 5G network deployed at Tallinn University of Technology (TUT). The main sections include a theoretical introduction to the 5G, its features, fields of use, deployment methods and future perspectives. Additionally, several 5G test campaigns performed worldwide, their results, and various drone technology-based potential and currently existent 5G applications are described.

The core part of the thesis expands upon the hardware and software used in the implemented testbed, their main features and relevant operational parameters with the necessary details. An elaborated description with all the key aspects, activity diagrams, available outputs, including source files and code, is provided for the specially implemented testbed program. Methodology behind the performed measurements, their description and obtained results are described separately, and include the coverage and signal quality measurement of the 5G network, its obtained latency and both uplink and downlink throughput capabilities on the ground level and at different altitudes, as well as evaluation of the influence that the drone itself had on the obtained aerial measurements.

In the latter sections of the thesis, the main problems and restrictions encountered during the testbed implementation and practical testing activities are introduced. These include several issues related to the tested positioning solutions, as well as drone flights restrictions at the TUT campus area. A summary provides conclusions about the performed work on the testbed implementation, its testing and obtained measurement results, as well as options for further possible testbed development, upgrading and use.

This thesis is written in English and is 101 page long, including 6 chapters, 48 figures and 1 table.

Annotatsioon

5G testplatvormi rakendamine ning mõõtmiskampaania 3.5 GHz sagedusalas maapinnal ja õhus

Käesolev magistritöö kirjeldab 3.5 GHz sagedusalas töötava ja droonidega kasutamiseks sobiva viienda põlvkonna mobiilsidetehnoloogia (5G) testplatvormi rakendamist ning selle praktilist kasutamist Tallinna Tehnikaülikoolis (TTÜ) paigaldatud 5G võrgu katvuse ning läbilaskevõime mõõtmiseks maapinnal ja õhus. Töö peamised osad keskenduvad 5G ning selle omaduste, kasutusvaldkondade, paigaldamismeetodite, ja tuleviku perspektiivide käsitlemisele. Lisaks on kirjeldatud mitmeid 5G testimiskampaaniaid kogu maailmast, nende tulemusi, samuti erinevad potentsiaalseid rakendusi ning praegu käimasolevaid droonide kasutamisel põhinevaid 5G projekte.

Töö keskne osa keskendub testplatvormil kasutatavale riist- ja tarkvarale, nende peamisele omadustele ja asjakohastele toimimisparameetritele. Üksikasjalikult on kirjeldatud testplatvormi jaoks spetsiaalselt rakendatud programmi, mis hõlmab selle põhiaspekte, tegevusdiagramme, saadaolevaid väljundeid, sealhulgas lähtefailide ja koodiga. Tehtud mõõtmised, kasutatud metoodika, ja saadud tulemused on kirjeldatud eraldi. Need hõlmavad 5G võrgu üldist katvuse ja signaali kvaliteedi mõõtmist, saadaolevat latentsust, nii üles- kui ka allalüli läbilaskevõimet maapinnal ja erinevatel kõrgustel ning drooni enda mõju hindamist õhus tehtud mõõtmistele.

Magistritöö viimastes osades tutvustatakse testplatvormi rakendamise ja praktilise kasutamise käigus ilmnenud peamisi probleeme ja piiranguid. Nende hulka kuuluvad mitmed erinevate testitud positsioneerimisseadmetega seotud probleemid, ning samuti drooni lennupiirangud TTÜ linnaku piirkonnas. Töö kokkuvõttes on esitatud järeldused testplatvormi rakendamise ja saadud mõõtmistulemuste kohta, samuti käsitletakse võimalusi selle edasiseks arendamiseks, ajakohastamiseks ja kasutamiseks.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 101 leheküljel, 6 peatükki, 48 joonist, 1 tabel.

List of abbreviations and terms

2G / 3G / 4G / 5G	2nd / 3rd / 4th / 5th generation of cellular networks
3D	Three-Dimensional
3GPP	3rd Generation Partnership Project
ABS	Acrylonitrile Butadiene Styrene
AT-command	Attention command
CAA	Civil Aviation Authority
CLI	Command-Line Interface
CUPS	Control/User Plane Separation
D2D	Device to Device
DOP	Dilution of Precision
DL	Downlink
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EB	Exabyte
eMBB	Enhanced Mobile Broadband
EN-DC	E-UTRAN New Radio – Dual Connectivity
eNB	Evolved Node B
EPC	Evolved Packet Core
EVB	Evaluation Board
FDD	Frequency-Division Duplex
GLONASS	Global Navigation Satellite System
gNB	Next Generation Node Base station
GNSS	Global Navigation Satellite System
GPIO	General Purpose Input/Output
GPS	Global Positioning System
HAP	High-Altitude Platform
HDMI	High-Definition Multimedia Interface
HSPA	High Speed Packet Access
I/O	Input/Output

I^2C	Inter-Integrated Circuit
IoT	Internet of Things
ITU-R	International Telecommunication Union (Radiocommunication sector)
LoS	Line of Sight
LTE	Long Term Evolution
MAV	Manned Aerial Vehicles
MBIM	Mobile Broadband Interface Model
MIMO	Multiple-Input Multiple-Output
mMTC	Massive Machine-Type Communications
mmWaves	Millimetre waves
NCSR “Demokritos”	National Centre of Scientific Research “Demokritos”
NCTA	National Cable & Telecommunications Association (currently The Internet & Television Association)
NGFF	Next Generation Form Factor
NMEA	National Marine Electronics Association
NR	New Radio
NSA	Non-Standalone
PC	Personal Computer
PCB	Printed Circuit Board
PCIe	Peripheral Component Interconnect express
PCM	Pulse Code Modulation
QAM	Quadrature Amplitude Modulation
QZSS	Quasi-Zenith Satellite System
RF	Radio Frequency
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Reference Signal Strength Indicator
RSSNR	Reference Signal SNR
Rx	Reception
SA	Standalone
SCTE•ISBE	Society of Cable Telecommunications Engineers • International Society of Broadband Experts
SDR	Software Defined Radio

SIM	Subscriber Identity Module
SINR	Signal to Interference plus Noise Ratio
SMA	Sub-Miniature version A
SNR	Signal to Noise Ratio
SS	Synchronization Signal
TDD	Time-Division Duplex
TUT	Tallinn University of Technology
Tx	Transmission
UAV	Unmanned Aerial Vehicles
UDN	Ultra-Dense Network
UE	User Equipment
UL	Uplink
URLLC	Ultra-Reliable Low Latency Communications
USB	Universal Serial Bus
USD	United States Dollar
USRP	Universal Software Radio Peripheral
Wi-Fi	Wireless Fidelity

Table of contents

List of figures

List of tables

1 Introduction

Nowadays, cellular technologies are rapidly developing in both performance and fields of use. While the second generation of cellular technology (2G) was focused on the mobile communications providing text and voice communications, third generation of the cellular technology (3G) expanded the list of use cases with video transmission supportive data rates and mobile internet, fourth generation of the cellular technology (4G) expanded and significantly improved the performance of cellular connection, the currently integrating fifth generation (5G) is intended to multiply the applications area of the cellular technologies with wide fields of Internet of Things (IoT), real time applications, various use cases in smart technologies, world automation, and of course increase the performance efficiency and wide availability of the currently existing cellular applications with lower latency and higher data rates.

In parallel, the popularity of various civil Unmanned Aerial Vehicles (UAV) and drones for various tasks is growing worldwide. Among others, these tasks include various cellular technology-based applications as portable relays for cellular base stations for various events or full-fledged and portable base stations for a cellular network delivery, as well as various applications where UAV platform represents a cellular end user and intended to use the connectivity for data exchange in various IoT, real-time, industrial or agriculture applications. Currently integrating 5G technology was designed with consideration of these applications and therefore, has a huge potential in drones projects as well.

1.1 Problem description

The problem to be solved with this work is an implementation of the portable and operational testbed prototype for mid-band 5G connectivity testing at the operating frequency band of 3.5 GHz, suitable for both ground and aerial applications. Thus, the testbed to be implemented should be relatively portable and lightweight to be attached to the commercial drone, capable to perform general connectivity testing procedures automatically, including coverage, signal quality and network throughput measurements. Eventually, the implemented testbed must be tested on the Non-Standalone (NSA) 5G connectivity deployed in Tallinn University of Technology campus area at possibly different environmental and weather conditions, as well as at both ground and above ground levels.

Tests should include the coverage, signal quality and both downlink and uplink throughput capability measurements at different distances from the base station considering the presence of typical obstacles for the urban area. Required testbed should is intended to be suitable for drones' applications, thus, understanding the connectivity patterns at various altitude is an additional dimension to be explored in this thesis. For that purpose, drone will be used to perform tests at the different altitudes.

1.2 Summary of the thesis contents

The main goal of this thesis was to implement and test a portable testbed setup for the 5G signal quality and throughput capabilities testing, suitable for drone applications. The implemented setup should have been possibly portable and lightweight to be attached to the commercial UAV, as well as possibly autonomous to perform proper and continuous measurements while it is attached to the drone. The testbed was intended to be based on one of two provided sub-6 GHz 5G modules from Quectel and SIMCom and focused on the 5G n78 band of 3.5 GHz.

Due to the specific driver's requirement of the used 5G modules, the processing device of the implemented testbed was required to use a proper operating system to support the necessary drivers, while remain portable for the further use on a drone.

As a powerful and portable solution, it was used a mini-PC (Personal Computer) with installed Windows 10 operating system, which is capable to support all the necessary drivers, run multiple complicated programs, as well as provide a widest field for the testbed improvements. Focusing on these hardware elements as the anchor points, the rest of the testbed was implemented. A proper solution for positioning was also an important part of the testbed to allow a further 5G coverage measurement. For this purpose, it was used a standalone GNSS (Global Navigation Satellite System) USB (Universal Serial Bus) dongle, capable of an autonomous positioning tracking with declared accuracy of two meters. In order to make the testbed setup maximally portable, it is powered up with a proper power bank, while the input and output peripherals were replaced with portable tablet. The implemented testbed was placed inside the plastic covering box for a more convenient use and attachment to the drone.

As a processing device, the mini-PC is intended to be a central unit of the testbed and operate with the rest of the connected hardware, available software, perform calculations and results logging procedures. For these purposes it was written a program using C# programming language and .NET framework. Program performs a detection and communication with the connected 5G module by using specific AT-commands (Attention commands), which allow to request a signal quality measurement, perform a basic control and setup for the connected module. Implemented program also performs the detection of the connected GNSS module, as well as the positioning information reception and decoding from it. In parallel, the program runs an Ookla Speedtest CLI (Command Line Interface) application on a background and receives the latency and throughput measurement results.

Once all the available data is received, the program performs a data logging procedure and repeats the process. The connected 5G module Evaluation Board (EVB) is recognized and used by Windows operating system as a proper network interface to gather an internet connection over 5G connectivity, which in its turn allows to test the established connectivity throughput capabilities or perform an actual data exchange.

The implemented testbed was first tested on the ground level, which includes the measurement of the overall 5G coverage within TUT campus area as well as outside of it. In order to evaluate the 5G signal coverage there were continuously measured and logged the main parameters of the 5G signal quality provided by used 5G module.

These parameters include Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ) and Signal to Interference plus Noise Ratio (SINR) of the 5G signal, while the signal quality and coverage evaluation were based on the measured RSRP results, as more informative results among available. Within the TUT campus area the peak latency and throughput measurements by using Ookla Speedtest CLI application were also performed. Measurements were performed using a local provider server with the highest observed results, and in static positions.

The same procedures were performed at different defined altitudes by using a provided commercial drone to carry an implemented testbed. In case of this work, measurements were also performed is static positions at altitudes of 10, 20, and 30 meters above the ground. Additionally, a separate set of ground measurements with reduced number of spots and increased number of throughput measurements at different conditions was performed. These conditions include different provider server selection modes of the Ookla Speedtest application to define the optimal provider server for the main measurements. Separate test was performed to evaluate the possible influence of the working drone on the obtained results and consists of the measurements performed on the same position and altitude, with and without a presence of the working drone near the testbed.

All the obtained measurement results were logged in a single format and saved in a separate log file. Logged measurement results were afterwards transferred to the Excel environment, at which it was represented as heatmaps by using the available 3DMaps (Three-Dimensional Maps) extension of Excel environment. Generated heatmaps were used to evaluate the overall 5G coverage and signal quality, as well as latency and throughput capabilities of the deployed 5G connectivity in Tallinn University of Technology at different altitudes.

2 Theoretical background

2.1 5G Overview

5G or 5th Generation is the next generation of broadband cellular networking, which is intended to replace or complement the currently existing and running 4G LTE (Long Term Evolution) connection. 5G technology is designed to expand current capabilities of the cellular networking, providing the uplink and downlink speed increase, the possible communication latency decrease, as well as spectrum expansion in order to provide a wider field for the IoT applications integration.

In accordance with the "5G Infrastructure Market by Communication Infrastructure Report" published in October 2019 [1], the 5G technology is expected to have nearly exponential market growth in next 7 years. Due to its huge potential in wide variety of different applications, 5G technology currently is and expected to be an object of interest and serious investments for many different industries. In particular, the global market size of 5G in 2019 was valued at USD (United States dollars) 0.784 billion, while by the year of 2027 it is estimated to grow nearly 61 times up to USD 47.775 billion. The yearly worldwide market cost estimation is shown on a Figure 1, where every year estimation is proportionally divided by regions. Expectedly, United States and especially Europe are going to hold and grow most of the market value. This worldwide demand growth of the 5G technology is expected to be caused by significantly wider applications opportunities provided with 5G, while the industrial applications are expected to become the largest user of the 5G technology.

The enormous potential of a wide spread of 5G technology in today's infrastructure will also cause a massive growth of data traffic demands. Thus, while the global mobile data traffic has reached 33EB (Exabytes) per month by the end of year 2019, the expected mobile data traffic may grow nearly 5 times and reach the value of 164EB per month, according to the estimations made by Ericsson company [2]. The graph of evaluated and estimated global mobile data traffic in exabytes in the range of years 2015-2025 is shown on a Figure 2.

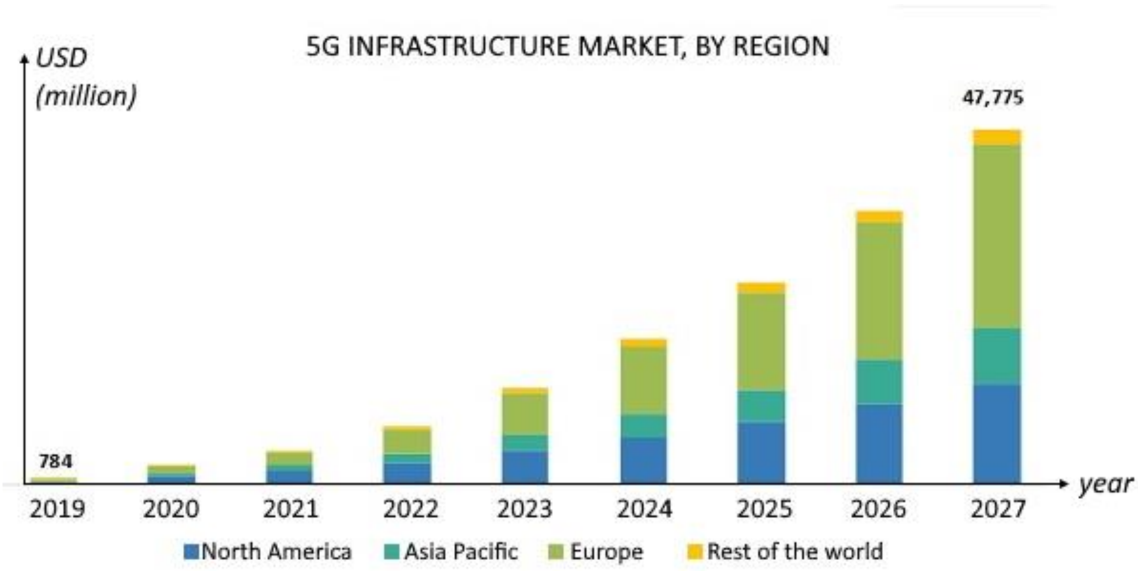


Figure 1. Visualized estimation of 5G infrastructure market size growth worldwide [1].

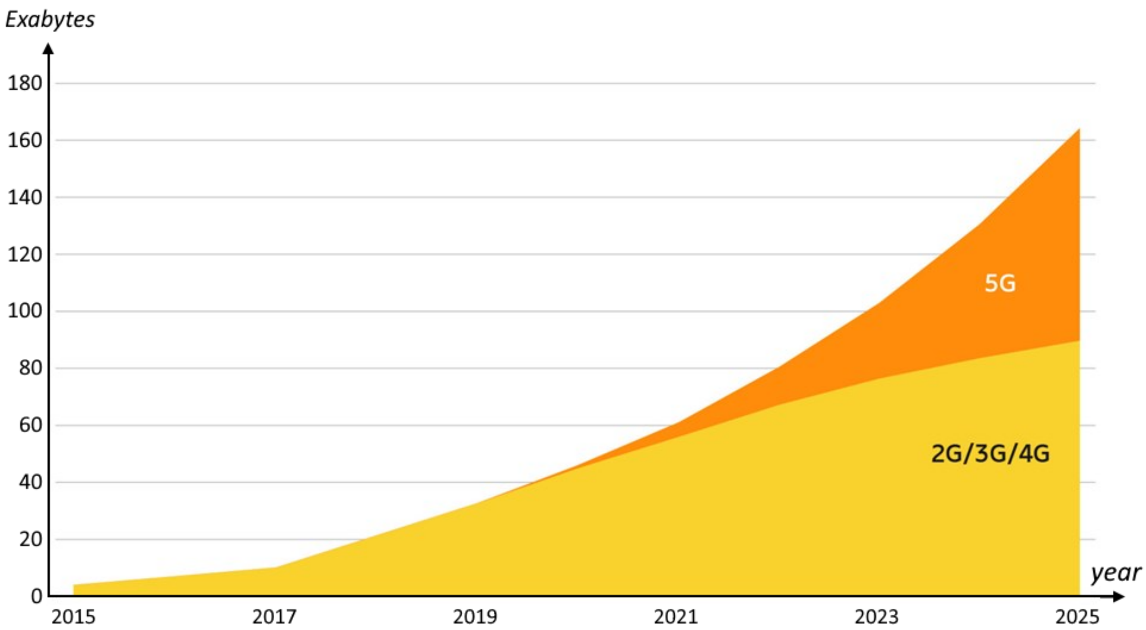


Figure 2. Illustrated growth of global mobile data traffic in EB evaluated and estimated in the range of years 2015-2025 [2].

While the currently used 4G LTE technology is based on the low and mid-band spectrum, which corresponds to sub-1 GHz band (includes frequency range of 400–900 MHz) and sub-6 GHz bands (1.5–6 GHz) accordingly, the 5G provides the use of both low and mid-bands, as well as supports mmWaves (Millimetre Waves band) – the high-band spectrum of 24 GHz–39 GHz and potentially up to 60 GHz [3]. The frequency increase leads to the higher achievable data rate, although it also brings the cover distance decrease and higher sensitivity to the possible obstacles. Thus, by using the low-band frequencies the 5G connection is able to cover miles of the outdoor area while providing the peak data rate of 100 Mbps. At the frequencies of mid-band, the data transmission speed increases up to 1 Gbps with moderate decrease of the coverage area and wall penetration ability. Since the main operating spectrum area in sub-6 GHz spectrum for 5G has moved to the higher frequencies (around 3.5 GHz) compared to the common spectrum area used in 4G LTE (around 2.6 GHz), the difference in the coverage distance, data rate and obstacle penetration is more perceptible as well. In order to minimize this difference and improve the mentioned parameters for 5G, there are being used massive MIMO (Multiple-Input Multiple-Output), beamforming and full duplex technologies. These technologies are based on grouping a larger number of antennas at the single base station to provide multiple the simultaneous beams to different users (massive MIMO), identifying the optimal transmission path and forming more focused and consistent beams to every single user (beamforming), and performing the transmission and reception procedures using the same channel for higher spectral efficiency (full duplex). By using the newly supported high-band frequencies, 5G may provide data transmission rates up to 10 Gbps. However, the covered area and the wall penetration ability of the signal also significantly reduces, which leaves the mmWave band effective to use only within the area of several buildings [4].

Additionally, the 5G technology is designed to improve the latency and reliability in cellular networks. Thus, the commonly observed latency of 20–30 ms in 4G LTE communications is being reduced to 4–5 ms and in case of 5G-URLLC (Ultra Reliable Low Latency Communications) systems – up to 1 ms [5].

The new generation of cellular networking technology – 5G opens a wide variety of possible use cases and opportunities. Yet the Radiocommunication sector of International Telecommunication Union – ITU-R has defined three the most significant categories of 5G use cases [6]. According to ITU, defined use case categories are: eMBB – Enhanced Mobile Broadband, which includes virtual and augmented reality (virtual interfaces on a real background), and enhanced indoor/outdoor broadband; Massive Machine-Type Communications - mMTC, representing the IoT, smart home/city/agriculture, and various types of monitoring; URLLC – Ultra-reliable and low-latency communications, including autonomous vehicles, health, industrial and other types of real time monitoring. Visual representation of categorized 5G use cases provided by ITU-R is shown on a Figure 3. Currently, the eMBB category is expected to be a primary use case of 5G.

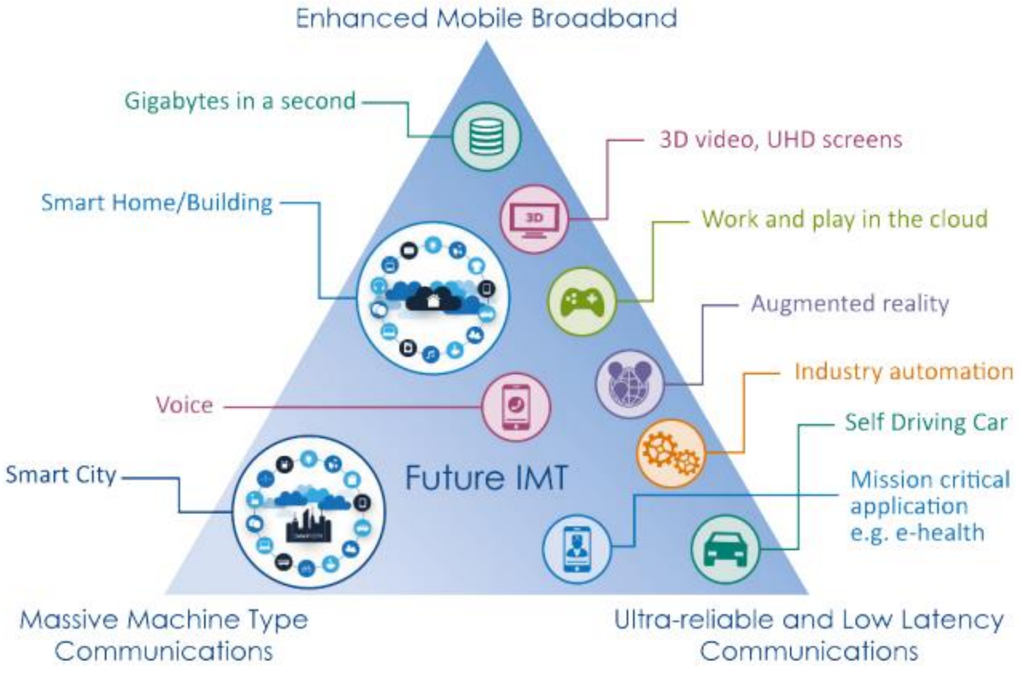


Figure 3. Visualization of main three 5G use case categories provided by ITU-R [6].

One of the crucial technologies used in 5G is NFV – Network Functions Virtualization. Used together with SDN – Software Defined Networking, it provides the increased flexibility of the 5G core network through replacing the part of specialized and traditionally used hardware with flexible software in virtual machines, which may be installed on a much more common hardware [7]. It leads to the higher flexibility and efficiency potential of the whole network. Particularly, it allows to utilize the network slicing technology, which is intended to increase the efficiency of the network by effective network resource allocation and use in various cases.

One of the essential concepts for the 5G network, which makes the overall network deployment and scaling more flexible, is known as CUPS – Control/User Plane Separation concept [8]. This concept provides the complete separation of user and control planes, which allows to perform all the necessary connection management, user authentication, quality of service procedures and other control processes independently from the much more loaded user data traffic forwarding. This plane separation concept leads to a very useful ability of scaling the user plane functions and capabilities without affecting the control plane, in the meantime allowing the simultaneous use of different user plane solutions. For instance, in case of the inevitable increase of the data traffic in a certain area, caused by deeper and massive integration of the 5G technology and consecutively increasing number of connected user devices, the CUPS concept allows the installations of the additional user plane nodes without any affecting or restructuring the control plane.

2.2 Massive MIMO and beamforming

MIMO stands for Multiple-input multiple-output and represents the technology which allows the simultaneous transmission and reception of several different signals over the same channel. It provides the increase of the transmission capacity without respective growth of the used spectrum. This effect is achieved by using several (up to four) antennas, and currently is widely used in 3G and 4G LTE standards [9].

Massive MIMO in its turn, significantly increases the number of used antennas up to hundreds, which allows to form a more focused beams for each antenna. It leads to the higher number of possible signal paths and higher power of each antenna beam, which provides a larger coverage area and higher overall transmission reliability. This technology compensates the initial coverage decrease in 5G compared the 4G LTE, which is caused by the higher used frequencies in the mid-band spectrum. Additionally, the beamforming technology is used - the coordinated work of multiple antennas allows to identify the most efficient signal propagation route to each user and provides the ability to combine multiple identical radiated signals into single directed high-power beam. Beam directing with perfect signal synchronization can be achieved by varying the initial phase of the involved antennas [10]. Use of large number of antennas with focused narrow beams allows to use the same frequency for simultaneous transmissions to different users in different directions, as well as use the different propagation paths to deliver different data parts to a single user. This approach significantly increases the spectrum efficiency. However, it also leads to the challenge of avoidance of simultaneous signals interference.

While the 2x2 or 4x4 MIMO typically used in 4G LTE requires accordingly 2 or 4 transmitting (Tx) and receiving (Rx) antennas, the Massive MIMO used in 5G requires already dozens or hundreds of smaller antennas. As it is shown on a Figure 4, these antennas are dual-polarized, which allows to add a second simultaneous transmission "layer" to a single channel, as differently polarized signal (with 90^o polarization difference) do not interfere each other. Antennas are grouped into large arrays, which represent the massive MIMO antennas for 5G [11].

Single antennas within the array can be differently grouped depending on the current task to be performed. Particularly, they may work completely separately in order to cover the higher number of user devices, or on the contrary, group and synchronize to increase the power of a single transmission, which is illustrated on a Figure 5. Combined use of the available features makes the 5G antenna array very flexible and useful in different environmental scenarios.

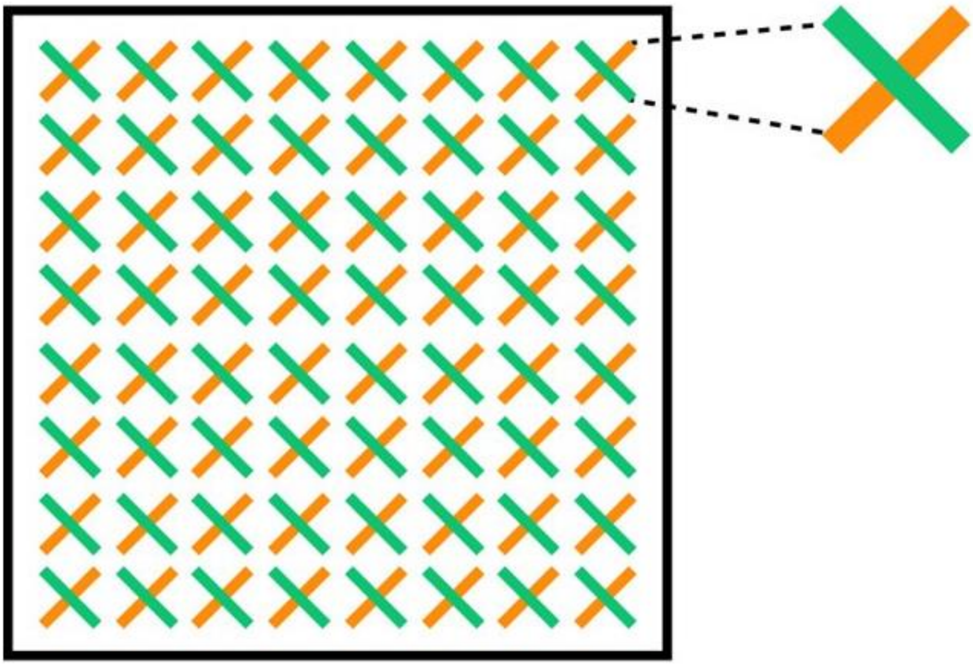


Figure 4. Visualization of single antenna and antenna array of 5G base station [11].

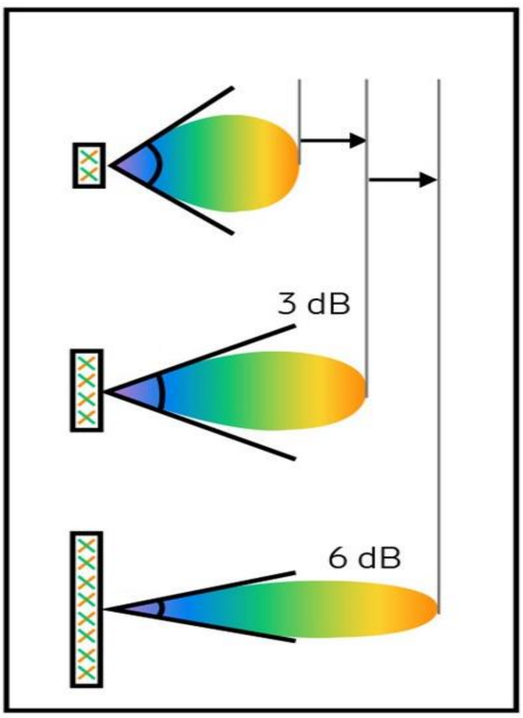


Figure 5. Visualization of the gain and width of the beam generated by different number of cooperative antennas in the array [11].

2.3 3GPP Deployment options

With the introduction of high-band spectrum – the mmWaves, the 5G is now able to utilize the technology of the small cells at its full potential. In combination with other advanced technologies used in 5G, such as massive MIMO, beamforming, or support of D2D (Device to Device) communications, small cells may significantly help to avoid numerous obstacles around the urban area. Small cells represent the smaller versions of base stations – access points or relays. If evenly spread around the area of the main base station, these access points may cover most of the areas, unreachable for the main base station caused by the high density of obstacles. At the same time the closer deployment of access points to end user equipment provides stable and fast wireless connection. This principle is visualised on a Figure 6. In case of 5G, small cells are the perfect way to realize the potential of high throughput, low latency, and short coverage of mmWaves band. This technological concept is known as UDN – Ultra-Dense Network.

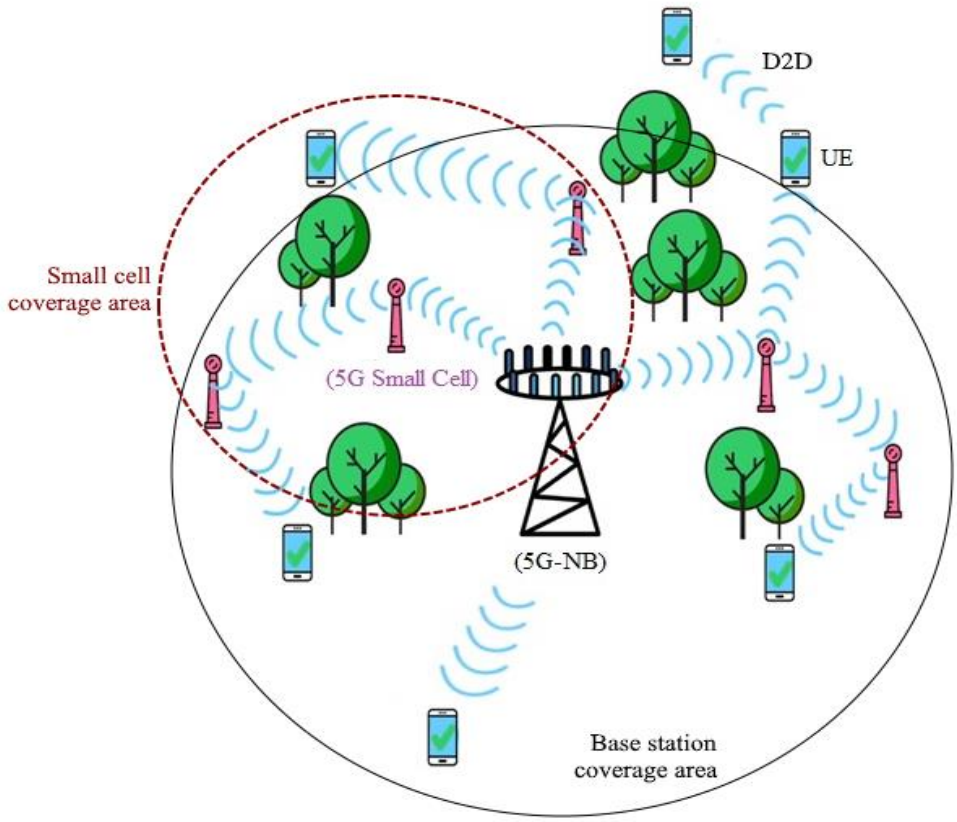


Figure 6. Visualized use principle of the 5G small cells and general network topology [12].

Despite the 5G provides its own advanced network core and cell designs, the new generation network deployment, especially at the early stages, is going to intersect the currently deployed 4G LTE network. Therefore, the 5G deployment scenarios defined by 3rd Generation Partnership Project (3GPP) include both SA (standalone) and NSA (non-standalone) options.

Standalone deployment scenarios represent a complete use of a single network core and single node technology. These deployment options are numbered with 1, 2 and 5, and represent a full LTE based deployment with LTE core and LTE node in case of option 1, fully deployed 5G with 5G core and node in case of option 2, and a hybrid type of deployment with 5G core and LTE node in case of option 5.

Non-standalone options are numbered with 3, 4 and 7, include several variations of each, and represent a use of both LTE and 5G nodes in combination with either LTE or 5G core. Option 3 is usually based on the existing LTE network and nodes, while options 4 and 7 are both based on the 5G core and differ by the node used for a control plane. NSA deployment options represent a smooth integration of the 5G to the existing LTE deployments at different levels – from slight addition to the LTE deployment (option 3), to its nearly full replacement (option 4) [13].

As any other technological upgrade or new technology version, the 5G cannot be fully deployed instantly, with simultaneous disabling of the used technology of 4G LTE. Expectedly, it must be gradually integrated into the currently used cellular network, and therefore, the 5G technology integration has started with non-standalone deployment scenarios from a slight integration to the existing LTE networks according to the option 3. There are three different variants of non-standalone deployment option 3 named option 3, 3A and 3X. All of them represent the integration of the 5G gNB (Next Generation Node Base station) into the existing 4G LTE setup [14]. These three NSA deployment configurations are shown on a Figure 7.

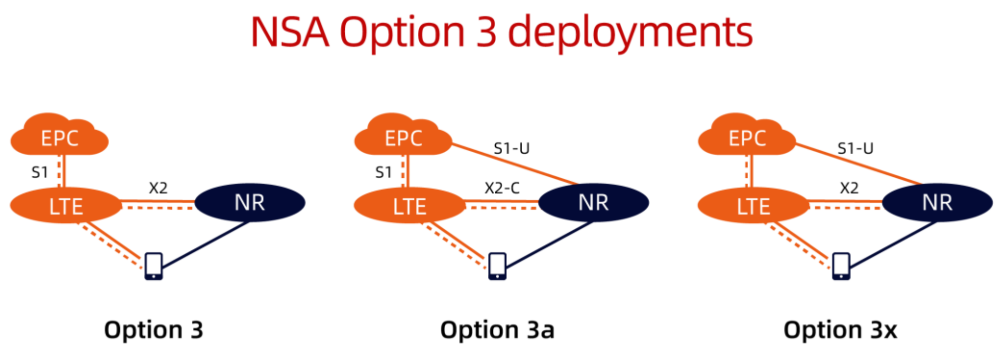


Figure 7. 5G non-standalone option 3 deployment variants [15].

Option 3 represents the integration of the 5G gNB to the existed 4G setup, where 5G base station has no direct connection with the 4G core EPC (Evolved Packet Core) network and communicates exclusively through 4G LTE base station (gNB). In this case the 4G LTE utilizes 5G gNB as an auxiliary base station and may forward part of a data to it.

Option 3a deployment configuration represents the deeper integration of 5G gNB to the 4G LTE setup, where 5G base station has direct connection to the 4G core network as well as the 4G base station. Although, the full connection between 4G and 5G base stations is missing, which leaves both base stations to work on separate tasks: for a single UE, the internet traffic may be covered by 5G while voice traffic is covered by 4G.

Option 3x configuration is the most used NSA deployment configuration and it represents the full integration of the 5G gNB part to the 4G LTE setup. In this configuration the 5G gNB has a direct connection to the 4G core network and operates with the user data flow directly. Also, 5G and 4G base stations have a full connection, and some of the user data traffic, especially with the slow data rate as the voice traffic may be forwarded to the 4G part with its own requisites. Since 4G base station also has a direct connection with the core network, it can operate the slower data traffic independently from the 5G base station.

3 State of the art

3.1 5G live performance tests

3.1.1 Tests by Nokia, Munich, Germany

According to Nokia research test results of 5G coverage at the sub-6 GHz frequencies shown on a Figure 8 [16], the uplink coverage at the typical for 5G mid-band frequency of 3.5 GHz shows a significant drop (slightly more than two times) compared to the closest tested 4G LTE sub-6 GHz frequency of 2.6 GHz, while the downlink loses nearly a quarter of coverage. In both cases it was used standard 2x2 MIMO. 5G at 3.5 GHz with the additional use of massive MIMO technology, on the other hand, significantly improves the coverage compared to 2x2 MIMO at the same frequency and shows slightly better results compared to 4G LTE at 2.6 GHz with 2x2 MIMO for both uplink and downlink. Therefore, the use of 5G massive MIMO technology at the mid-band frequencies is capable to fully compensate the coverage loss caused by the medium operating frequency increase (~ 1 GHz), while keeping the throughput advantages provided by the higher frequency. “Massive MIMO can improve spectral efficiency by a factor of two to four” [16].

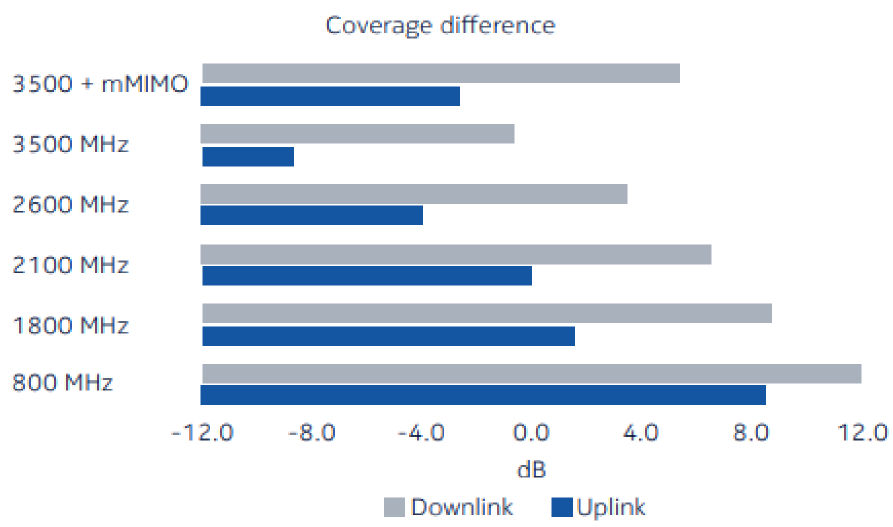


Figure 8. 5G coverage test results at the sub-6 GHz frequencies in comparison with 4G LTE performance (by Nokia) [16].

3.1.2 Tests in Calgary, Canada

The other 5G performance test is described in a "Real-World Performance of 5G" research paper prepared for SCTE•ISBE (Society of Cable Telecommunications Engineers • International Society of Broadband Experts) and NCTA (The Internet & Television Association (formerly the National Cable & Telecommunications Association)) [17]. It includes the coverage and data throughput tests of 5G at its main frequencies of mid and high-bands (3.5 GHz and 28 GHz respectively) in the real urban environment in the city of Calgary, Alberta – province of Canada. Aside from 5G, the performance tests were also implemented for the 4G LTE connectivity at the frequency of 2.5 GHz in order to compare with the 3.5 GHz mid-band of 5G. As this thesis is focused on the mid-band frequency of 5G (3.5 GHz), the further references to 5G, related to the mentioned research paper are going to be within the context of 5G at 3.5 GHz.

According to the referenced research work, with the increasing distance between base station and user equipment in the range of 160–900 m, 5G has shown the non-linear data throughput decrease from 320 Mbps to 125 Mbps. The RSRP (Reference Signal Received Power) tests were performed for both 5G and 4G LTE connections, and have shown ambiguous results within, however, the expected range. The measurement results have shown quite close average RSRP decrease with the growing distance in both 4G LTE and 5G cases, with roughly 5 dBm higher results of 4G LTE.

3.1.3 Tests by Ericsson, Stockholm, Sweden

Testbed for the 5G performance at the sub-6 GHz band, deployed in Sweden by the Ericsson company, also has shown quite promising results [18]. Testbed has used the carrier frequency of 3.5 GHz along with use of massive MIMO and beamforming technologies. Downlink performance tests were implemented in dense urban area, including the performance in the line of sight (LoS) of the base station and out of it in both indoor and outdoor conditions, as well as at the longer range of open area.

According to the referenced research paper, long range test results have shown a throughput of 700 Mbps at the distance of 700 m in the line of sight of the base station. Moving out of the LoS of the base station causes a partial drop of the performance, however, the testbed was still able to achieve a throughput of 100 Mbps at nearly 1km distance. This performance was achieved without using small cells assuming the user equipment was located outside the urban area.

Tests in the dense urban area were performed by using the available small cell unit. Within the range of 380 m from the small cell, the performance results showed the downlink throughput between 700 Mbps and 1.2 Gbps in the line of sight of the small cell, while out of direct sight the throughput results were above 200 Mbps. As it is referenced in this research paper, the real dense urban deployment scenario will have up to several microcells within the range of approximately 200 m working together, which may almost exclude the significant performance drops of 5G. The testing results for the indoor conditions have shown the 21–22 dB drop of the signal gain.

This research paper also evaluates the signal gain drops within the buildings and, while referring to the other research paper, compares to the results of a similar test for 4G LTE at its carrier frequency of 2.1 GHz. According to the comparison results, the 5G without using the beamforming technology has shown the higher signal gain decrease of 5.1 dB outside and 7.1 dB indoor, caused by the higher carrier frequency of 3.5 GHz (compared with performance at 2.1 GHz). Although, enabling the beamforming technology fully compensates the gain loss caused by the higher frequency with an additional extra gain increase. It makes 5G at sub-6 GHz band a solid potential replacement for the existing 4G LTE.

3.2 Drones based 5G projects

The variety of existing 5G testbeds also include several examples based on the use of UAVs - Unmanned Aerial Vehicles, commonly named as drones. One of the drone-based testbeds was implemented by Ericsson company and slightly described in the article “Interference management in 5G with drones “ [19].

This testbed was set up in order to provide the convenient measurement possibility for the wireless transmission emission within the areas, where this parameter must be controlled and regulated. It is crucial in case of the multiple separate transmitters located within the relatively small area, which may cause the interference. Measurement equipment was fixed on the regular drone carrier. This carrying platform for the measurement equipment provides several significant advantages over the traditionally used methods – regular calculations based on the known transmission parameters which are limited to predictions of the actual results, or the walk/drive measurement tests. Using drone for the areal signal measurements is being much less time consuming and is not limited with most of the unreachable areas compared to the walk/drive methods, additionally allowing to fully include the altitude factor to the measurements, which is commonly unavailable during the measurement tests.

In the meantime, the Estonian company Hepta Airborne Group in cooperation with National Centre of Scientific Research (NCSR) "Demokritos", Cosmoste, Nokia and other companies related to the 5G!Drones project, and with the support from EIT InnoEnergy is working on the drone based solution for the common demand of massive mobile communications capacity during different crowded events [20]. Hepta Airborne Group company is specialized on the aerial inspection and surveying of the power and pipelines, substations and overhead lines of the energy sector and utility networks by using Manned (MAV) and Unmanned (UAV) Aerial Vehicles. The developed solution represents the installation of the portable cellular base station, small cell, or simple relay on the UAV carrier platform, which provides a huge flexibility and manoeuvrability for the cellular nodes compared to the currently used solutions.

Currently, in case of highly crowded events there are used the additional portable base stations installed within the planned area of upcoming event, which often takes up to 90 days for a full installation and necessary operability tests, while the expected time of full deployment of a portable base station on the UAV platform is rated as 90 minutes. Additionally, unlike the stationary solution, UAV provides and option to move the deployed node in order to adjust its performance, deploy additional stations, replace damaged or remove extra stations if they are not needed.

3.2.1 5G!Drones project

The mentioned 5G!Drones project is a cooperative European project of 20 different companies and research groups from 8 different countries including Nokia an University of Oulu (Finland), Hepta Groupe Airborne (Estonia), Unmanned Systems Limited (United Kingdom), National Centre of Scientific Research "Demokritos" (Greece), Eurecom (France) and many others [21]. This project is aimed to test, evaluate, and validate the use of unmanned aerial vehicles in wide area of three main use cases of 5G – eMBB, URLLC and mMTC. Main goal of this project is to demonstrate the ability of 5G networks to support its use cases in different challenging scenarios it is going to be facing in future including low-latency and reliability requirements in parallel with high bandwidth requirements and massive number of connections, as well as the reliability of UAV as a mobile platform in the same use cases. 5G!Drones project is aimed to focus on independent run of three types of UAVs to support three main services of 5G simultaneously, which is going to be achieved by using the network slicing.

Currently 5G!Drones project counts four different use case scenarios to work on [22]. First of them is the "UAV Traffic Management", which is aimed to properly integrate UAVs into the air traffic and demonstrate the overall functionality of their applications. It is required due to the massively increasing number of private and commercial drones in the low altitude airspace. It will lead to different regulations and drone control applications and traffic management systems to provide safety of low-altitude traffic, which, in its turn, will require a very low latency communication.

"Public safety/saving lives" use case considers the use of 5G based drones with different high-quality monitoring equipment in various disaster scenarios and conditions, very dangerous for human to be in. Scenarios may vary from natural disasters including earthquakes, wildfires, storms, as well as events with dangerous chemical, nuclear or biological pollution, or even scenarios related to acts of terrorism, explosions or unstable damaged unstable buildings. In these cases, a properly equipped drone with extra high resolution, night vision and thermal cameras, various sensors and separate high throughput transmission channel may provide highly detailed picture of the disaster area with all the possible information about current conditions, possible pollution and another potential threats without any mobile traffic problems, related to the expectedly high use of the mobile network by disaster witnesses.

Another use case of 5G!drones project – “Situation awareness” covers the drone use within the area of IoT in daily life, Smart City and Smart Agriculture. It includes extremely wide variety of possible options from environmental or weather monitoring, mobile 5G nodes, smart mail or package delivery, various services, remote and/or autonomous inspections or different agriculture applications.

Within this project, this use case is roughly separated into three main scenarios. First is the infrastructure monitoring and inspection focused scenario, which requires a sufficient throughput capability for a massive data transmission. Second scenario focuses on the data collection and relying from the stationary sources (sensors) and faces the challenge of handling the large number of connected terminal devices, while the third scenario is focused on the location services in areas, where global navigation cannot be used.

“Connectivity during crowded events” use case represents the previously described use of UAV mounted cellular network nodes and relays during heavily crowded events, which always bring the high communication capacity demand for the mobile networks and leads to overall poor connectivity and network performance. In this use case drones are intended to replace the temporarily installed base stations and regular vehicle-based stations, which are currently used by telecommunication companies.

3.2.2 Drone delivered 5G node, Jordanstown, Newtownabbey, United Kingdom

The performance testing and evaluation project of 5G connectivity delivered by drone was performed in the year 2017 in Ulster University, Jordanstown, UK [23]. The goal of this project was to evaluate the potential of low-altitude drones (UAVs) to be used as a delivery platform of the 5G connectivity for the relatively small areas, such as temporary and crowded events, disaster sites and other possible scenarios, which may require the short time presence or boost of the cellular connectivity. This project covers the signal power performance of 5G connectivity at the primary sub-6 GHz frequency band of 3.4–3.8 GHz, while the transmitting unit was installed on the commercial drone and the reception unit was attached to the smartphone. Project includes several testing cases for different areas and different altitudes of the transmitting unit.

The testing methodology is conceptually illustrated on a Figure 9a and represents drone with the installed transmitting antenna on board, linearly moving the distance of 20 m with the fixed velocity of 0.5 m/s at the different altitude above the ground – 5 m, 10 m and 15 m. Reception unit, attached to the smartphone and naturally held by a person, was located on the ground in the middle point of the drone movement line i.e. at the distance of 10 m from both starting and final points of drone movement line. Tests were performed for each of three altitude values, for both calling and texting types of communication, and within three different areas – open area, area enclosed with buildings and the tree-lined area – open area, next to the line of trees parallel to the UAV's movement direction. Illustrated areas of testing are shown of Figure 9b. Both Rx and Tx antennas used in this project were declared as identical with the average antenna return loss -15 dB and boresight gain of 2 dBi.

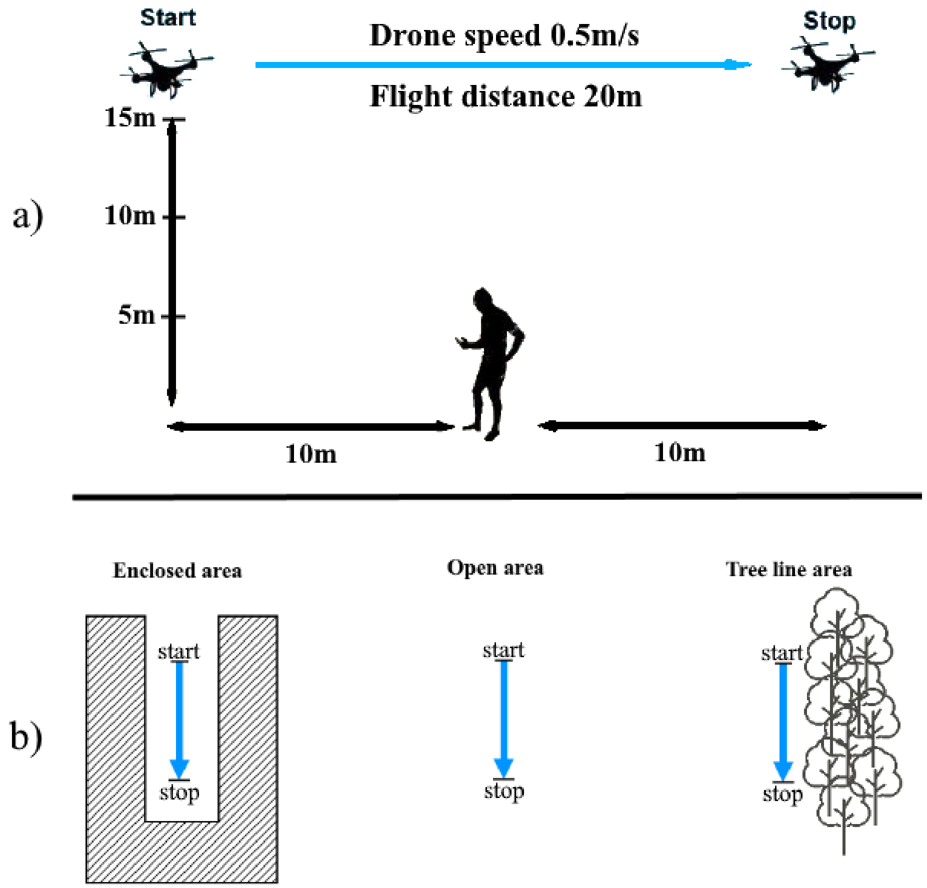


Figure 9. (a) Illustrated methodology for the drone delivered 5G connectivity tests and (b)illustrated areas of testing [23].

According to the provided test results, the received wideband power decreases with the increasing altitude of the transmitting unit relatively linearly in both calling and texting transmission cases. In all measurement cases, regardless of the area and transmission case the received power was decreasing within the range from -80 dBm to -110 dBm with the increasing transmitter height from 5 m to 15 m. Most likely it is caused by quite short transmission distance as for sub-6 GHz carrier frequency. Measurements for both open and close-to-trees areas have shown very similar results with the minor difference of the received power with slightly lower results for close-to-trees area, which may be explained by the signal scattering effect caused by trees. Since both mentioned areas are relatively open, while receiving and transmitting units are quite close to each other – it makes results expectable to be quite similar. Although, in case of the enclosed area, the received power was higher for all the related measurements, which is caused by the returned signal reflections from the surrounding walls of enclosed area.

Additionally, project covers the latency of the received signal for all the measurement cases. As for the received power measurement tests, the signal delay measurements have shown very similar results for both open and close-to-trees areas within the range of 13-14 ns, and with slightly higher latency in case of the close-to-trees area. In case of the enclosed area, the measured signal delay was nearly two times higher (in the range of 26.5–27.7 ns). Presumably, it is caused by high interference of the multiple signal reflections arriving to the receiving unit with different time shifts, which is quite expectable within the enclosed area.

Since the referred project evaluates the UAV as a delivery platform for 5G transmitting station, it also includes the test of the drone influence on transmitted signal. Received power measurement results from the drone with enabled and disabled rotors have shown very minor changes, which are not considered as relevant.

3.2.3 Stratosphere 5G nodes, Cambridge, United Kingdom

Development and technology consultancy firm from UK - Cambridge Consultants and Stratospheric Platforms Limited are working in cooperation on one of the latest and most ambitious UAV based 5G projects [24].

Project is aiming to provide the 5G network connection straight from stratosphere, where the wireless transmitter will be delivered using HAP or High-Altitude Platform – big and environmentally friendly UAV with the wingspan of 60 meters.

Using the hydrogen fuel, HAP will be able to fly at the altitude of 20 km for up to nine days carrying the required 5G networking equipment and only producing water as a waste. In the meantime, a large onboard antenna will be covering the round area of almost 440 km^2 (140 km in diameter) with the stabile 5G connection, which will potentially replace hundreds of ground base stations. In combination with flexibility of massive MIMO and beamforming technologies, the 5G connectivity may be focused on the areas with high connectivity demand including roads, railroads, farms, lone buildings or other structures, in the meantime avoiding the country borders. An organized fleet of high-altitude UAVs may be able to cover the whole country with the 5G network connection regardless of the different environmental obstacles.

4 Testbed implementation

4.1 5G deployment at Tallinn University of Technology

5G NR (New Radio) was deployed within the Tallinn University of Technology by using the widely utilized non-standalone Option 3x deployment configuration. With this configuration the 5G node – gNB is fully integrated to the already existed 4G LTE base station setup. Both gNB and LTE node – eNB (Evolved Node B) are directly connected to the 4G core network, and operate independently, which provides the E-UTRAN (Evolved UMTS Terrestrial Radio Access Network) and New Radio – Dual Connectivity type (EN-DC) for 5G supportive user equipment.

The 5G NR node antenna, shown on a Figure 10, represents an adaptive 64x64 massive MIMO antenna array with the beamforming technology. Set up for private research purposes of Tallinn University of Technology, antennas are significantly tilted down to cover only the TUT campus area. By default, the 5G NR connectivity is using n78 band of 3.5 GHz central frequency, carrier bandwidth of 60 MHz and the 4:1 TDD (Time-Division Duplex) configuration.

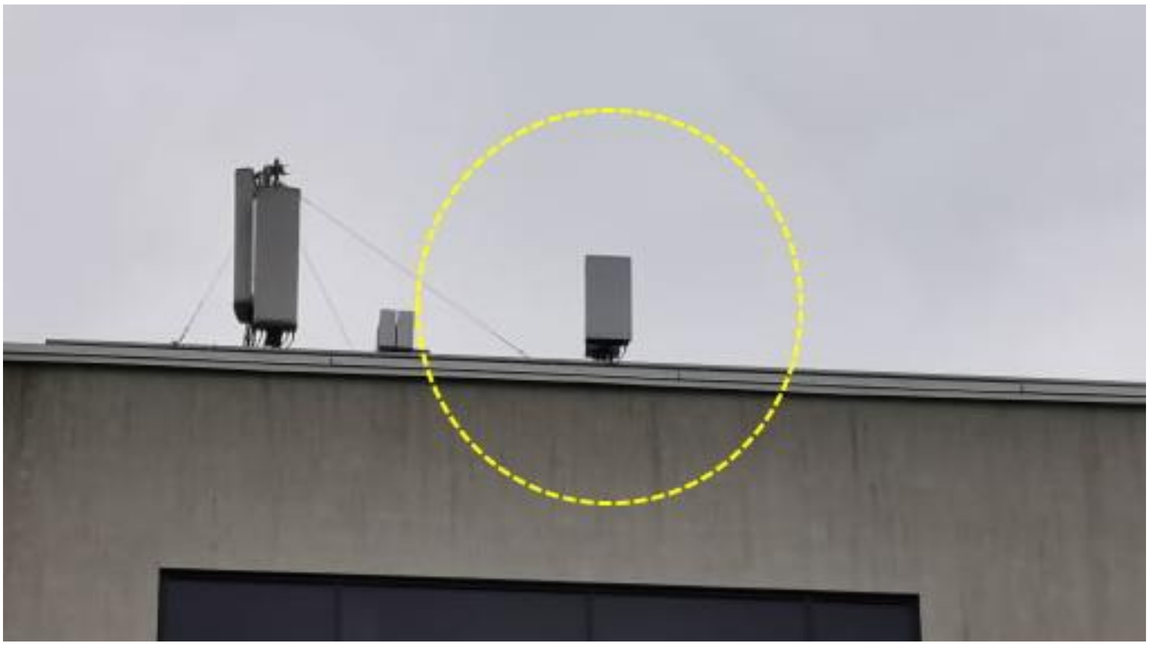


Figure 10. NR5G antenna deployed on a top of one of the TUT buildings.

Currently there are three active 5G antennas, deployed around the TUT campus area at the top of building with approximate height of ~25 m. Their locations and images are shown on a Figure 11.

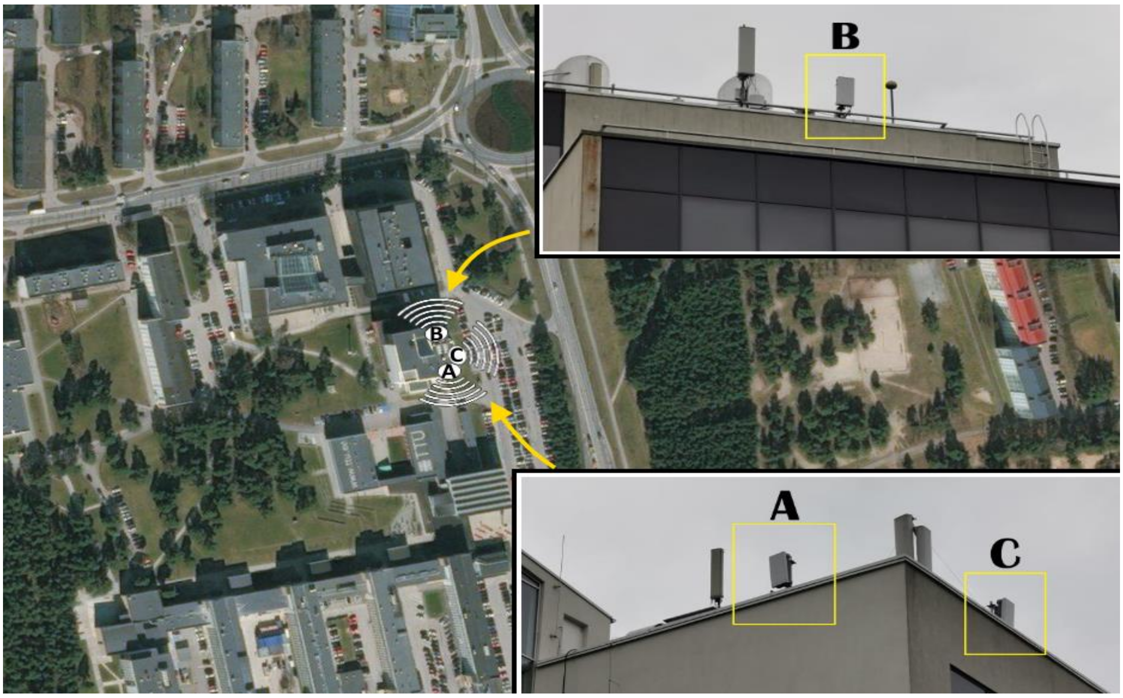


Figure 11. Locations and approximate directions of TUT NR5G antennas.

In case of the TUT deployed cellular base station, the 4G LTE part represents a fully operational public base station, currently used on a regular basis. Deployed 5G NR node in its turn, is currently available only for private research tasks within TUT and is not used for the local public communications. Currently, while in idle mode the EN-DC connectivity around the TUT campus is set up to keep 5G part disabled until the data transmission begins and disable shortly after it is finished.

Both nodes share the same 4G LTE core network, and thus all the public LTE users connected to TUT base station are reducing the maximal throughput available over the private 5G connectivity. The throughput reduction caused by public LTE users directly depends on the number of simultaneously connected users and their network activity. Additionally, the core network of TUT base station is artificially limited with 1 Gbps data throughput for downlink and with 110 Mbps for uplink. Therefore, the real values of throughput are expected to be lower. During the numerous throughput speed tests, the peak values observed were 781 Mbps for downlink, and 108 Mbps for uplink.

4.2 Hardware of the implemented testbed

The practical part of this work represents the implementation of a drone integrative 5G testbed setup and its testing by measuring the coverage and performance of the 5G network available within the Tallinn University of Technology campus area in different conditions. Since the testbed setup is intended to be attached to the drone, the main requirement for the implemented testbed is to be possibly portable and autonomous, for continuous measurements while it is attached to the drone.

The overall concept of a testbed was focused around two available 5G modules. Both modules represent cellular modem slave devices and are meant to be controlled by a master processing device. The processing device in its turn is intended to perform all the data gathering and control functions of the testbed setup, while the GNSS module represents a completely standalone position tracking unit. The whole testbed setup requires a power supply, and thus it was used a power bank with the proper output voltage of 19 V required for the mini-PC. Mini-PC as a processing device, in its turn, is capable to supply all the other peripherals connected to it. In order to make the testbed mobile and convenient to use outside, all the common I/O (Input/Output) peripherals including keyboard and mouse for input, and full-scale monitor for output were replaced with a single temporarily attachable touchscreen tablet. The use of Windows based mini-PC allows to connect a huge variety of sensors, cameras or other additional peripheral devices for extended data collecting and further processing, uploading to the server or live streaming over the established 5G connection. The number and type of additional devices is only limited with the physically available connectors of the used mini-PC. Attached to the independently controlled drone, the testbed is capable to operate autonomously performing all the necessary measurements, cellular transmissions, and logging. Structural scheme of the implemented testbed at its work during aerial measurements is shown on a Figure 12.

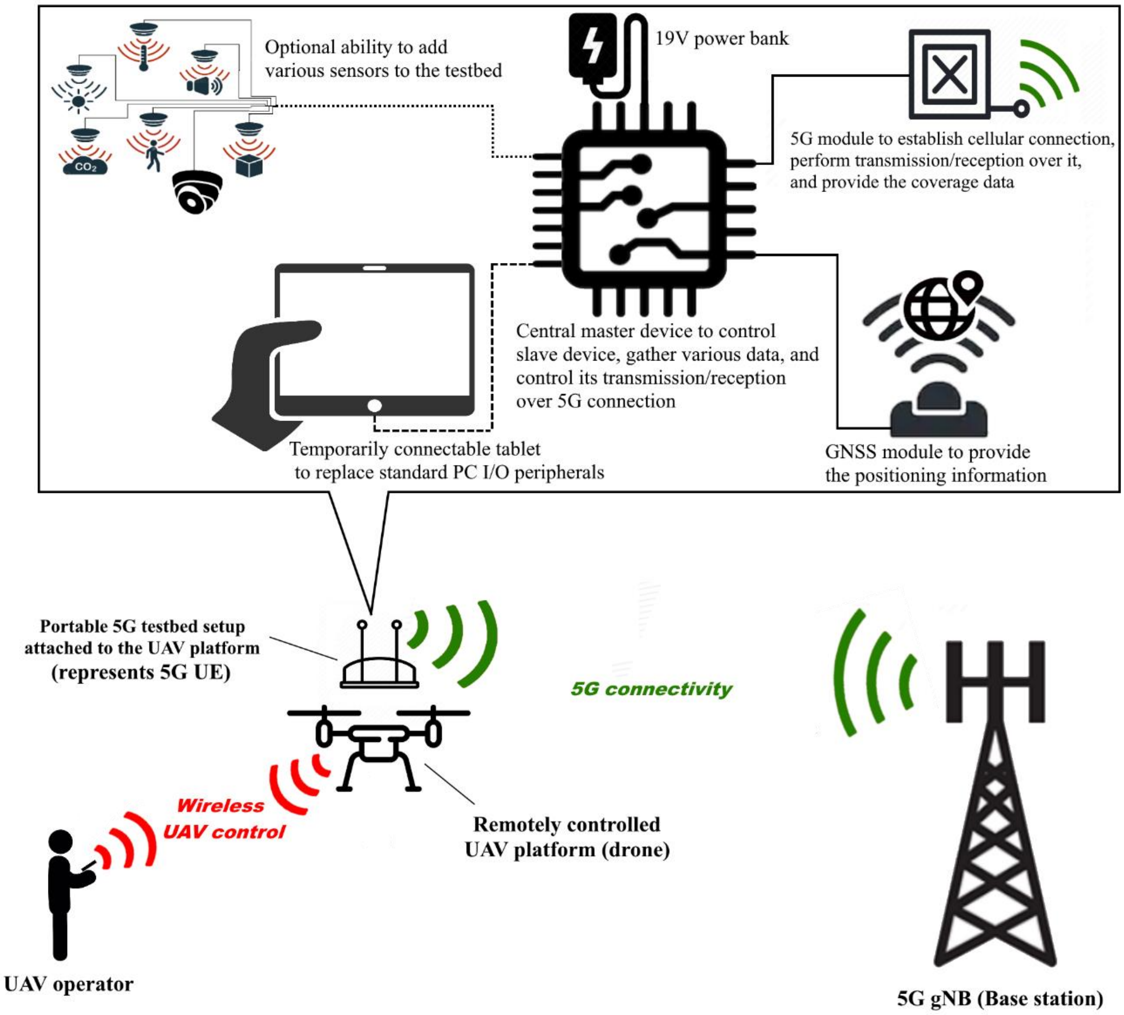


Figure 12. Full structural scheme of the implemented testbed, used for the aerial measurements.

Figure 13 shows the physically assembled testbed. For a practical use, the described testbed setup is fixed inside the ABS (Acrylonitrile Butadiene Styrene) plastic box with fixed metal rings for its further attachment to the drone using metal chains and carabines. Opened box with the testbed setup inside is shown on a Figure 14. Figure 15 shows the closed box with the testbed inside. The box cover has a 35 cm long attached metal arm, intended to hold the GNSS receiver module away from the possible RF noise radiated by the testbed, drone electronics, to prevent the cross interference with the GNSS receiver of the drone, as well as to keep it under the open sky for a better position fixing. Figure 16 shows a testbed setup attached to the DJI MATRICE 600 Pro drone and ready for the aerial measurements.

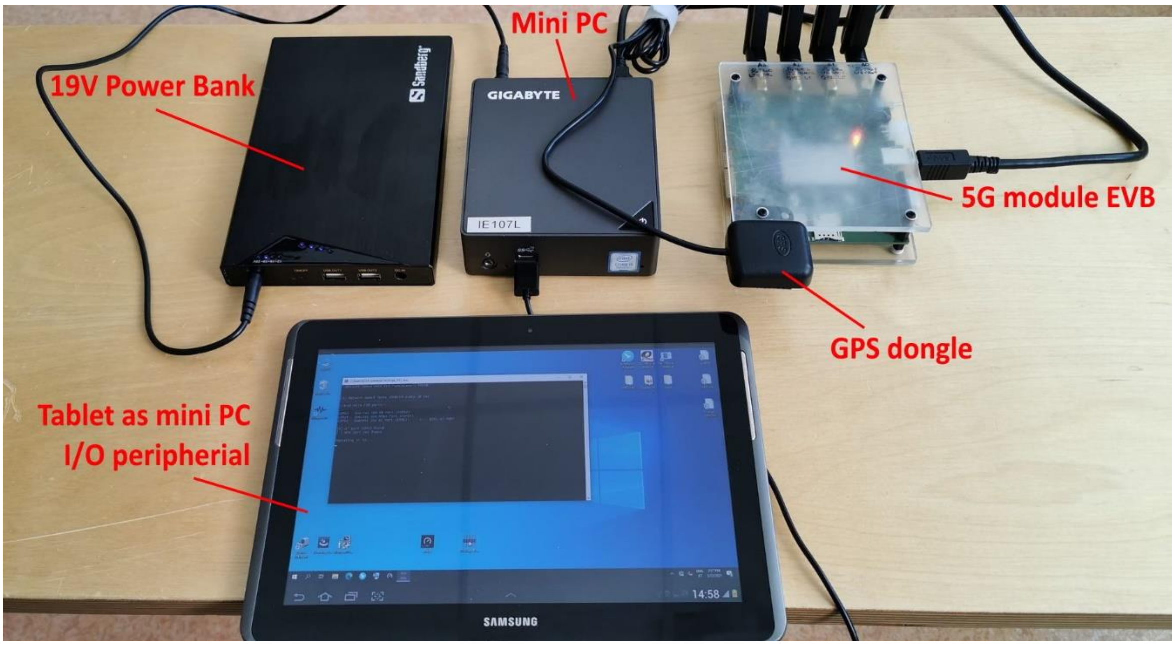


Figure 13. Hardware used in the implemented testbed setup.

Figure 14. Implemented testbed setup inside the ABS plastic box.

Figure 15. Testbed setup packed in a plastic box and prepared to be attached to the drone.

Figure 16. Used DJI MATRICE 600 Pro drone with the attached testbed setup.

4.2.1 5G modules

Since this work is focused on implementation of the 5G testbed setup for a drone, it is required to be possibly portable. The key equipment for the 5G testbed is modern 5G supportive cellular module. It was decided to test two available 5G supportive modules, provided by Telia company: RM500Q-GL module manufactured by Quectel, and SIM8202G-M2 by SIMCom. Modules are relatively similar and based on the same core chipset Snapdragon X55 5G Modem-RF System by Qualcomm, supporting 3GPP Release 15, including all the main cellular technologies up to standalone 5GNR, 256QAM (Quadrature Amplitude Modulation) for both downlink and uplink, 4x4 MIMO layers for downlink and 2x2MIMO for uplink. The main characteristics of each module are listed in a Table 1. Both modules were used with their evaluation kits: 8XG000-SIM8200-M2-EVB2_v1.01 evaluation board for SIM8202G module, and QL-RM500Q PCIECARDEVB-KIT for RM500Q-GL module.

Used modules with their corresponding development boards represent fully slave cellular devices, which are controlled using specific AT-Commands sent over corresponding AT Serial port. Both RM500Q-GL and SIM8202G 5G modules with their development boards are shown on Figure 17 and Figure 18, respectively. Both 5G modules use multiple virtual COM ports provided over a single physical USB connection, which requires special drivers at the processing master device side for the proper use, as well as require specific drivers for the USB MBIM (Mobile Broadband Interface Model) mode to support a high-speed transmission over USB 3.0 connection. Typical current consumption of each module is ~150 mA in the idle mode with the established cellular connection, and ~300 mA while the cellular connection is actively used for data transmission/reception.

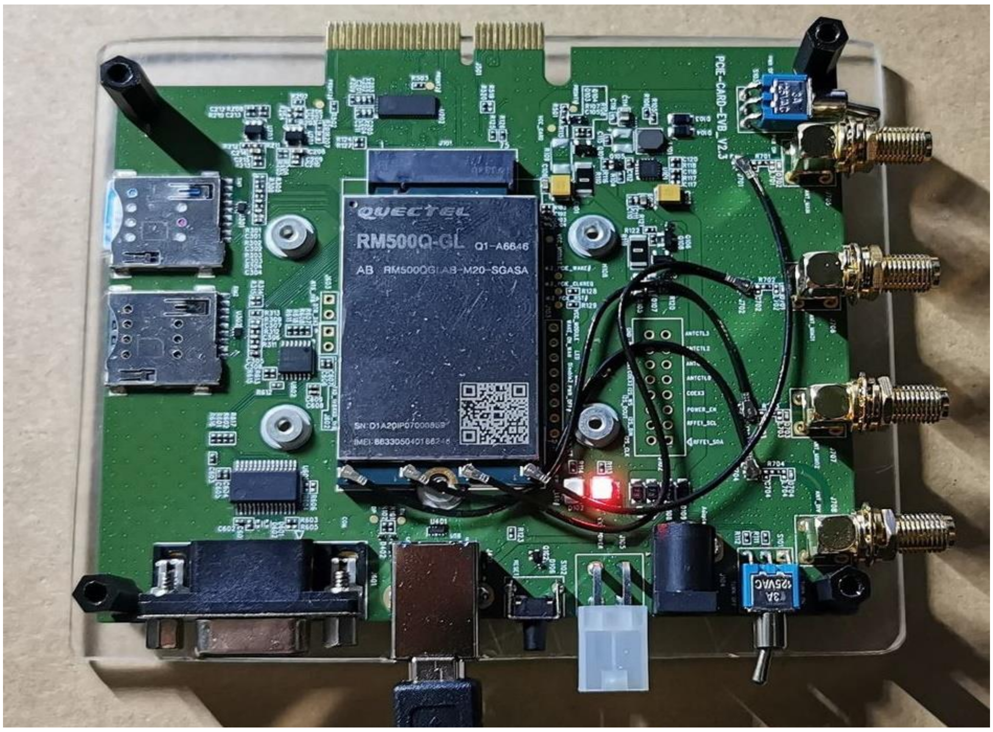


Figure 17. Quectel RM500Q-GL 5G module with PCIECARDEVB-KIT development board.

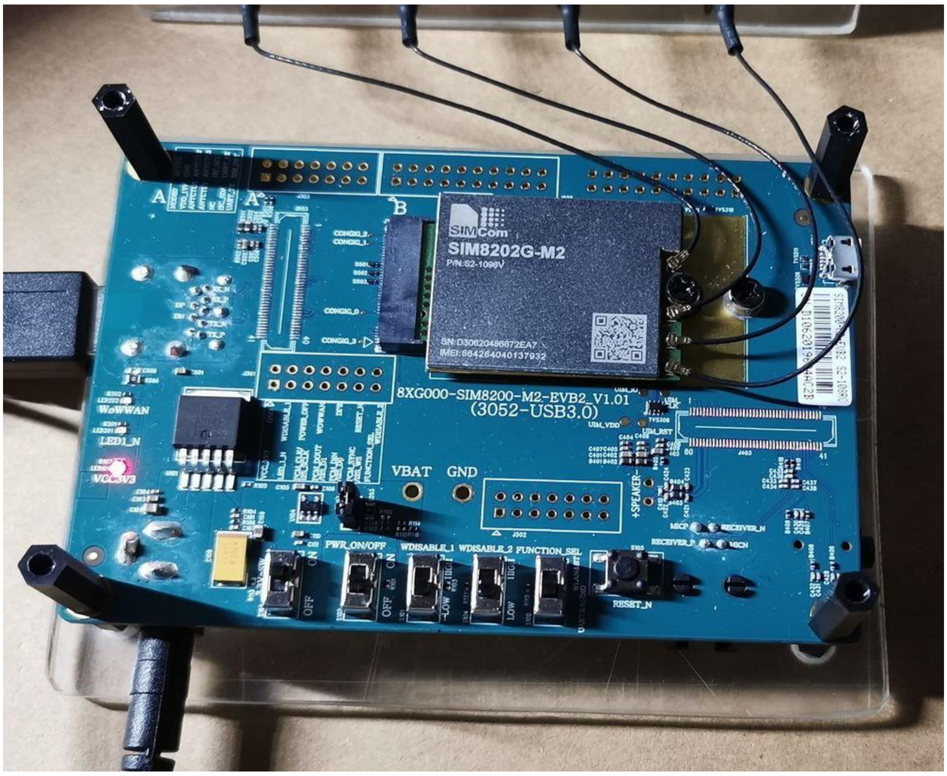


Figure 18. SIMCom SIM8202G 5G module with 8XG000-SIM8200-M2-EVB2 development board.

Table 1. Key features of available SIM8202G-M2 and RM500Q-GL 5G modules.

(5G related parameters)	SIM8202G-M2 [25]	RM500Q-GL [26]
Form factor	M.2 (formerly NGFF)	M.2 (formerly NGFF)
Technology	5G NR	5G NR SA/NSA
Modulation	256QAM	256QAM
Spectrum	Sub-6 GHz DL 4X4 MIMO UL 2X2 MIMO	Sub-6 GHz: DL 4X4 MIMO UL 2X2 MIMO
Transfer rate	NR Sub-6 GHz: 2.4 Gbps(DL) 500 Mbps(UL)	Sub-6 GHz (SA): 3.3 Gbps (DL) 250 Mbps (UL) Sub-6 GHz (NA): 3.4 Gbps (DL) 200 Mbps (UL)
Supply voltage	3.1–4.4 V 3.7 V avg	3.1–4.4 V 3.7 V avg
Transmit power	23–26 dBm	23–26 dBm
Idle mode	Sleep mode available (<5mA at supply voltage)	Idle mode available (Rated as very low)
Interfaces	Mini PCIe SIM (Dual SIM support) USB 3.1 PCM I^2C Diversity Receiver	Mini PCIe SIM (Dual SIM support) USB 3.1 PCM GPIO I^2C
Other supported modes (DL/UL)	LTE (1 Gb/200 Mb) HSPA+ (42 Mb/5.7 Mb) GNSS	LTE FDD (2 Gb/150 Mb) UMTS (42 Mb/5.7 Mb) GNSS
Operating temperature	Normal: -30°C to +70°C Extended: -40°C to +85°C	Normal: -20°C to +60°C Extended: -40°C to +85°C
Antennas	Four antennas for 3G/4G/5G and GNSS	Four antenna interfaces (supporting 3G/4G/5G and GNSS)

In terms of the hardware design, the Quectel development board is more optimized for multiple different setups, including the direct connection to the server motherboard option using available PCIe (Peripheral Component Interconnect express) interface, as well as the convenient mobile setup provided with PCB (Printed Circuit Board) mounted SMA (Sub-Miniature version A) antenna connectors and a single USB 3.1 cable support for both data exchange and power supply. SIMCom development board, in its turn, is slightly smaller in terms of physical size, while is missing all the advantages listed above: SMA antenna adapters have direct wired connection with the module and require additional reliable fixing to the development board for mobile setups. The other disadvantage is the hardware separation of main data exchange USB connection and the power supply into two wires. A prompt communication with the Quectel technical support in matter of software and firmware updates, various documentation, and technical issues solving made the Quectel RM500Q-GL a priority 5G module for the testbed setup implementation and further use in measurements.

4.2.2 Processing device

Processing device in its turn is intended to perform all the data collecting routine from various sources, ability to properly use the 5G module as a modem, as well as provide a sufficient memory space with its suitable read/write speed for close to 1Gbps data throughput, provided by 5G network at TUT. It also includes an ability to support specific USB drivers of the used 5G module to guarantee an efficient use of the UAB 3.0 connection. For this work it was decided to use a mini-PC GB-BRI5-8250 with installed Windows 10 operating system.

Powered with suitable and compact power bank, the mini-PC represents a powerful and highly portable processing master device, providing a wide variety of capabilities, including dozens of Gb’s of memory space for any data collection, different Windows provided services, ability to support different drivers, programs, applications, and scripts, capable PC to fulfil all the main functions of the testbed. Hardware configuration provides two USB 3.0 and one USB 3.1 type A, one USB 3.1 type C ports, HDMI (High-Definition Multimedia Interface) 2.0, and mini-DisplayPort for displaying, 3.5 mm audio jack, Ethernet, and 19 V power supply connectors. Mini-PC requires 19 V power supply to work and is capable to supply all the currently used peripheral modules over USB connection with standard 5 V and maximum of 450 mA.

4.2.3 GNSS receiver module

In order to create proper heatmaps of the various collected data, a relatively accurate and continuous positioning tracking is required. Originally, it was planned to use a GNSS tracking service included in the used 5G modules. Although, due to different positioning issues encountered during the testbed implementation, several alternative solutions were tested. As the best tested GNSS receiver it was decided to use the GU-902MGG-USB portable GNSS dongle for the frequent location tracking. The chosen GNSS unit supports both GPS (Global Positioning System) and GLONASS (Global Navigation Satellite System) positioning at the L1 frequencies of 1575.42 MHz and 1602 MHz accordingly, QZSS (Quasi-Zenith Satellite System), provides declared positioning accuracy of ±2 m, and functions as a standalone module, periodically returning the current positioning data.

Connected to the mini-PC, it is powered up over USB connection, and consumes the average current of 60 mA at the voltage of 5 V, operates in standalone mode performing the current position tracking and returns full positioning information according to the National Marine Electronics Association (NMEA) 0183 standard over the USB connection. Magnetic and adhesive bottom of the dongle allows its tight attachment it to various places.

4.2.4 Rest of the used hardware

For the mini-PC power supply it was used the portable Sandberg 420-23 power bank, which provides the capacity of 20000 mAh/74 Wh with selectable output voltage at the main output port, and two USB power output ports with fixed voltage of 5 V. The voltage level at the main output can be manually selected out of 12 V, 16 V, 19 V and 20 V.

Since the mini-PC represents a miniature system block of a regular PC, it requires all the input and output peripherals to be used, although, the mobile nature of the testbed setup makes the regular I/O peripherals of the PC highly inefficient. Therefore, it was decided to use an old Samsung GT-P5100 tablet as a wired I/O peripheral for the mini-PC. With the specific TwomonUSB software, this solution allows to get a highly mobile and portable touchscreen monitor for the mini-PC.

As UAV platform for the above ground measurements, DJI MATRICE 600 Pro commercial drone was used, preliminarily provided by Tallinn University of Technology. According to the manufacturer's specification page for this drone [27], while fully deployed it has the dimensions of 166.8 cm × 151.8 cm × 72.7 cm, and total weight of 10 kg. It is powered up with six TB47S 4500 mAh batteries, which provide ~36 min of hovering time at full charge.

The maximal recommended payload for this drone is 6 kg, and it reduces the approximate hovering time to ~16 min. In case of using the implemented testbed as a payload, the average hovering time of the drone was ~20 min. Used drone has three white GPS antennas on top, which provide the positioning accuracy of ±0.5 m vertically, and ±1.5 m horizontally while the drone is hovering. The maximal declared wind resistance of the used drone equals to 8m/s, which must be considered during the flight.

4.3 Software of the implemented testbed

4.3.1 Third party software used

Using tablet or phone as a touchscreen monitor for PC requires a specific software. Numerous programs were developed to use the connected gadget as a monitor, although, the most popular of them (e.g., Windows Remote Desktop, Spacedesk or iDisplay) are using the local area connection (Windows Remote Desktop requires full internet connection) and Wi-Fi (Wireless Fidelity) to connect a gadget to PC. In case of this work, the testbed setup is intended to move freely outside and at different altitudes, which will cause multiple disconnects or even inability to connect to the PC due to weak or missing Wi-Fi signal. In order to make the testbed possibly flexible and mobile it was decided to use a wired USB connection to access and use the mini-PC between flights, when the drone and testbed are on the ground. TwomonUSB software was chosen to be used during this work, due to its ability to support both inputs from the touchscreen and visual outputs from the PC using wired connection. Additionally, since the used Samsung tablet is quite old, another requirement for the software was to be operational on the 4th version of Android, installed on the tablet. Software, installed on the PC side, is listed in the Windows start-up application, and can automatically detect the connected gadget with the corresponding application. All the necessary information and software is provided on the official website [28].

Since the connected 5G module operates as an USB modem, it also provides a mobile internet connection. Therefore, the actual throughput of the used 5G connectivity can be measured with a simple internet speed test. For this work one of the most popular speed tests from Ookla, and particularly – Ookla Speedtest CLI (Command Line Interface) application was used [29]. This application provides both downlink and uplink throughput measurements, the measurement of the latency between the testbed and the selected provider server, as well as the actual server selection.

By default, the application is measuring the latency value of all the available provider servers, and for the throughput measurements it uses a server with the lowest latency value. Although, different servers provide different throughput capabilities, and a server with the lowest latency should not be expected to provide the highest throughput capabilities. This mode is the best for the real-time applications with relatively low data traffic, where the lowest latency has the priority over a higher transmission speed. The preferred server for measurements can be selected as well.

In case of this work, it was chosen to focus on the highest achievable throughput rates, and it was used a local "CompicOU" server, which has shown the highest throughput values compared to other servers. The CLI version of this application was chosen as simplest and easiest application for the testbed program to run on the background and gather the measurements results from. Figure 19 shows the outputs of the Ookla Speedtest CLI application.

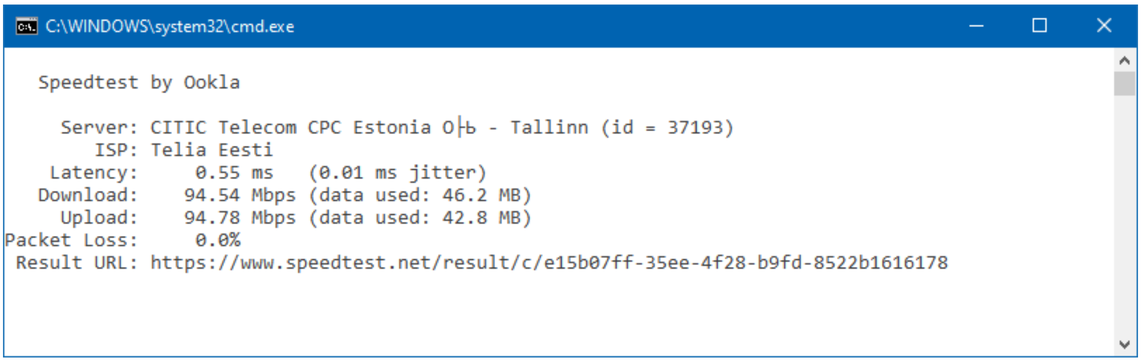


Figure 19. Sample outputs of Ookla Speedtest CLI application.

Various drivers can be also listed as used software. For instance, there were used specialized USB drivers for tested 5G modules. Since each module is designed to provide several different virtual COM ports over a single USB connection, the processing device requires specialized drivers to properly recognize, and use provided COM ports. These ports include a modem port for a main data traffic between PC and module, AT port used for AT commands exchange, NMEA port for continuous GNSS NMEA sentences transmission, diagnostics port, and several others.

Other drivers used were the USB MBIM drivers, which allows the proper use of USB 3.0 connection for high-speed data traffic between module and PC. These drivers are especially required for the 5G modems as they provide higher throughput, while by default the USB connection with the modem is usually recognized as Ethernet connection and operates at the corresponding speeds. In practice, a default mode of USB modem connection without proper drivers installed acts as a “bottleneck” for the data traffic between PC and modem, reducing the throughput potentially achieved with 5G connectivity.

4.3.2 Implemented software for the testbed

The program described further represents a Windows command-line interface software, created specifically for this work using C# programming language and .NET framework in Microsoft Visual Studio 2019 programming environment. Program was written, compiled, and used on Windows 10 operating system. Compiled program with all the source files is available online in MS OneDrive folder, and the corresponding link is provided in Appendix 2.

Figure 20 shows an activity diagram for the main function of the implemented testbed program. Program starts with definition of all default parameters to be used further, which includes COM port identification names of all used USB devices, including both 5G modules and GNSS module, definition of the Ookla Speedtest CLI executable file location and name, identification numbers of possible provider servers for Speedtest application, sets of AT commands and corresponding responses for both 5G modules, and other different default parameters.

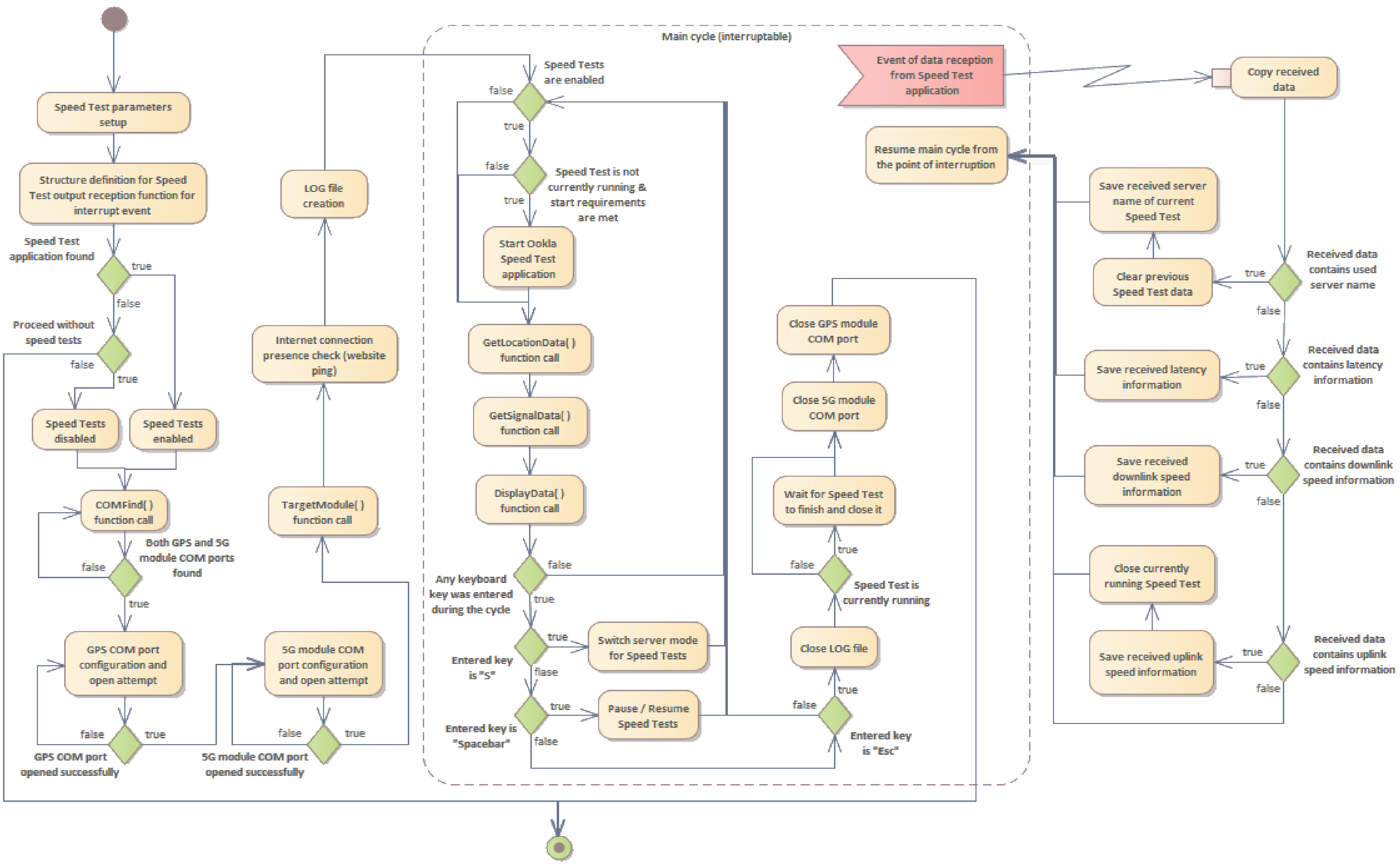


Figure 20. Activity diagram for the main function of the implemented program.

The first part of the program represents a preparation setup part at which all the necessary components are being checked, peripheral devices are being found, and serial communications are being established and validated. The setup part starts with definition and detection of the Ookla Speedtest CLI application, which is going to be repeatedly used for measurements. It also includes definition of the interruption subfunction – a short part of the code, which will be immediately executed every time the Speedtest application, which is going to be working independently in parallel with the implemented program, will send measured throughput results with an interruption.

Interruption subfunction is quite short and performs a line reading option from the buffer of received data from the active Ookla Speedtest application. The received line is being checked for the presence of the keywords, which include the corresponding information of the used server and measured latency, downlink and uplink speed results in a known order and format. The obtained data is being separately saved for the further logging. Other lines are being ignored. Afterwards it is performed the actual validity check of the Speedtest related parameters and its availability. In case if the application is missing, the program will give user an option to proceed without throughput measurements option, otherwise the execution of the program will be stopped.

As long as both GNSS and 5G modules are using simple serial connections for commands and measurements exchange, the program is using .NET framework features to access the list of serial connections of the current PC stored in registry. Usually, this type of connections is represented as numbered COM ports. In Windows device manager these COM ports are listed under the corresponding devices type as it is shown on a Figure 21. Both used 5G modules have several virtual COM ports provided over a single USB connection, which requires specialized drivers to be recognized. Additionally, the connection for the main networking data traffic between PC and 5G module is also provided over the same USB connection and requires additional MBIM drivers. This connection is recognized as a Networking device in the corresponding list in device manager. Device named Prolific USB-to-Serial Comm Port represents the connected GNSS module.

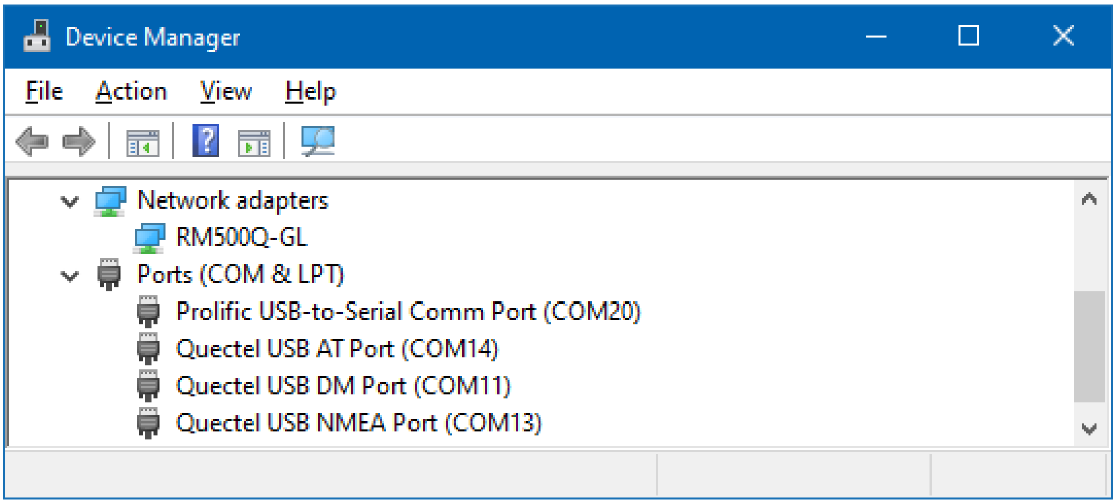


Figure 21. Windows device manager showing connected GNSS and 5G modules.

Once the Speedtest application is found and prepared to be used, the testbed program moves to the detection of connected hardware and its preparation. It is being performed in a called separate function named “COMFind”. This function is intended to find both 5G and GNSS modules and ensure if thein COM ports are ready for the use, and it is being repeatedly called with the delay of 5s until both modules are successfully connected and detected. The activity diagram for this function is shown on a Figure 22. Function starts with resetting both modules detection flags to “not found” state. Afterwards, the function accesses the list of available serial connections and compares provided names of each serial device with predefined expected names.

In case if the name of serial device matches the predefined name of known GNSS of 5G modules, its COM port number is being saved with detection flag change to the “found” state. It is required to detect one of two known 5G modules (from Quectel or SIMCom), and a GNSS module. Current modules detection status is being displayed in console. Once both GNSS and 5G modules are found, the program leaves the detection cycle.

Once both modules are connected and recognized, the implemented testbed software proceeds with their COM ports preparation and availability check. Generally, serial connection has different configuration parameters, which should be set up for the connection. Aside from defining the actual COM port number it also includes the defined baud rate – a measure of number of bits to be transmitted over one second, flow control type, byte size, parity control and number of stop bits.

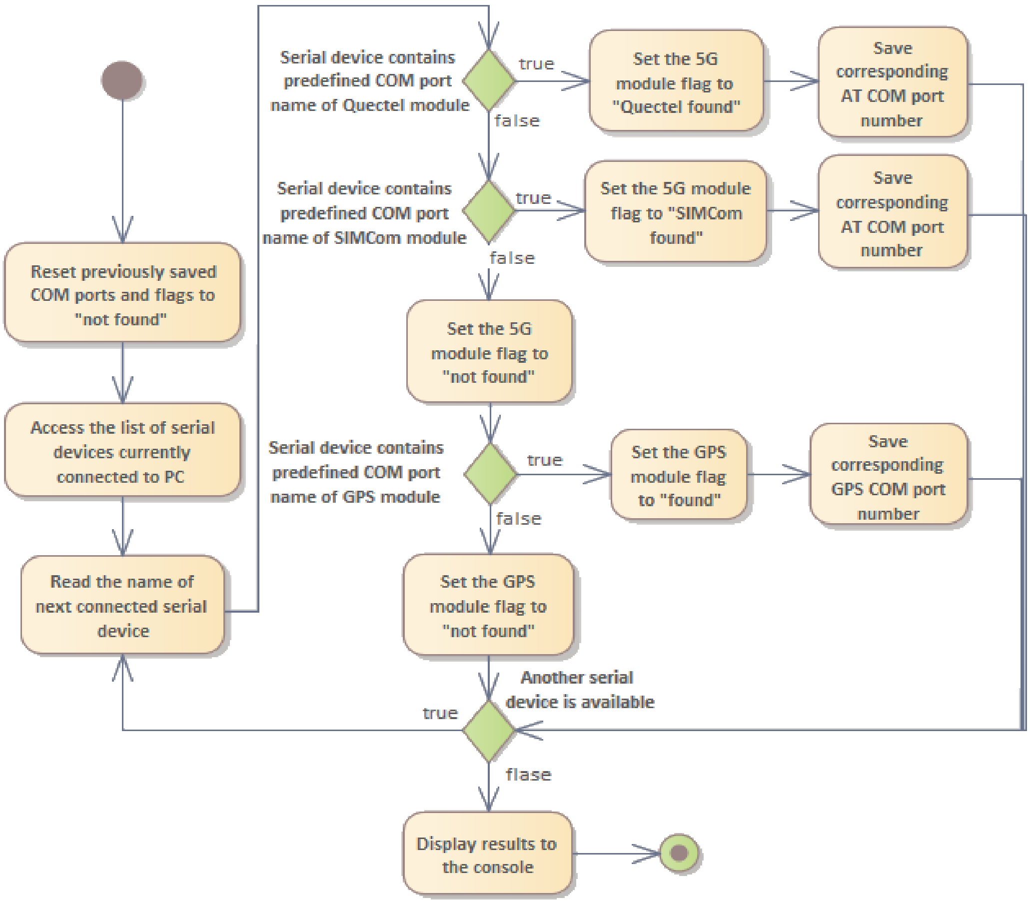


Figure 22. Activity diagram for the "COMFind" function.

Both 5G modules, as well as GNSS module use the same default settings: byte size of 8 bits, no flow or parity control and one stop bit. As for the baud rate, the GNSS module has a fixed baud rate of 9600 it is using for measured positioning information transmission. Both 5G modules are adaptive to the selected baud rate and support each of default baud rates from 4800 to 921600. By default, it is used the baud rate of 115200. Corresponding settings are used to set up the serial connection for both modules. Each set up serial connection is being established for the test purposes and if successful, the connection is marked as "ready to use" and closed. This procedure is being performed for both modules separately, and each of them is being repeated until both connections are ready for the further work.

The testbed program proceeds with the “TargetModule” function, which is intended to define the actual list of AT-command and expected responses depending on the connected 5G module. This short procedure is being performed in “TargetModule” function, which activity diagram is shown on a Figure 23. Since the module detection flag also indicates the actual module found, this function refers to this flag in order to determine the AT-commands list.

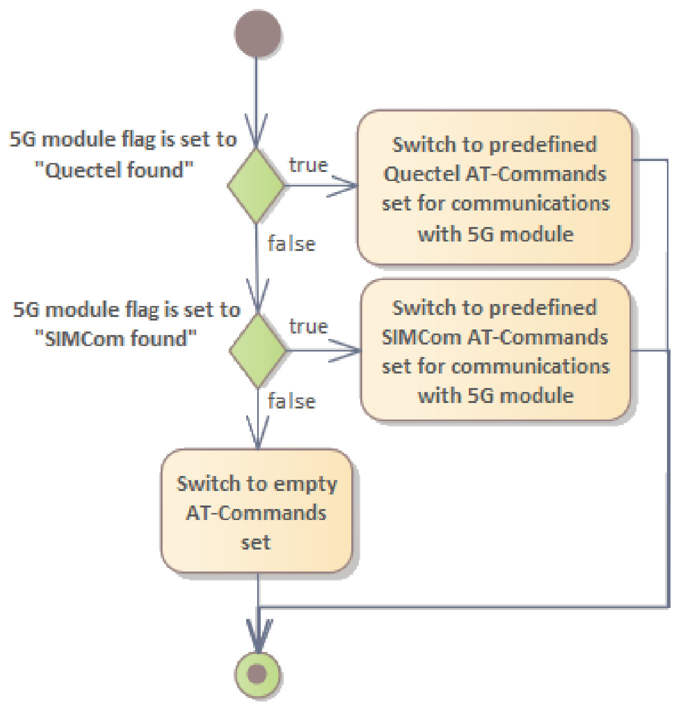


Figure 23. Activity diagram for the “TargetModule” function.

Currently, the defined list of AT-commands for the use includes “ATE0” command used for module response testing equally for both Quectel and SIMCom 5G modules. This command disables the AT-command echo for module responses. The default response for this command from both modules is “OK”. List also includes a software power off commands – “AT+QPOWD” for Quectel module and “AT+CPOF” for SIMCom module. The main commands for the signal quality requests of the current connectivity are “AT+QENG=”servingcell”” and “AT+CPSI?” for Quectel and SIMCom modules respectively. The Quectel module respond with several lines – one for each connectivity band.

In case of EN-DC connectivity, the response from Quectel RM500Q-GL module has the following structure:

+QENG: "servingcell",<state>
+QENG: "LTE",1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17
+QENG: "NR5G-NSA",1,2,3,4,5,6,7,8

Highlighted with yellow position 7 contains the used LTE band, positions 11, 12, 13 and 14 contain respectively RSRP, RSRQ, RSSI and SINR measurement results for used LTE band. Positions highlighted with green contain the 5G band related information in the following order: positions 4, 5, 6 and 8 contain RSRP, SINR, RSRQ and used NR5G band, respectively. This line appears only if the NR5G band is detected.

In case of EN-DC connectivity, the response from SIMCom SIM8202G module has the following structure:

+CPSI: LTE,1,2,3,4,5,6,7,8,9,10,11,12,13
+CPSI: NR5G_NSA,1,2,3,4,5,6

Highlighted with yellow position 7 contains the used LTE band, positions 10, 11, 12 and 13 contain respectively RSRQ, RSRP, RSSI and RSSNR (Reference Signal Signal to Noise Ratio) measurement results for used LTE band. Positions highlighted with green contain the 5G band related information in the following order: positions 2, 4, 5 and 6 contain used NR5G band, RSRP, RSRQ and SNR (Signal to Noise Ratio) information, respectively. This line appears only if the NR5G band is detected.

Once the list of AT-commands and responses are selected according to the used module, the program performs a short pinging session of a selected website in order to check the internet connection presence. Further the website pinging sessions will be used to keep the NR5G band in use and prevent its switching to the idle mode. Afterwards, the main program creates the log file with the defined columns pre-set, which will be used for all the measured data saving. When the log file is prepared, the preparation setup phase of the implemented program is finished, the program moves to the second part represented with the main operational loop. Key stages of the preparation phase are displayed with corresponding notifications in console as it is shown on a Figure 24.

```
::SpeedTest CLI "ookla.exe": FOUND::

[x] SpeedTests ENABLED every 15 sec
-------------------------------------------
::Available COM ports::

COM11 - Quectel USB DM Port (COM11)
COM1  - Communications Port (COM1)
COM13 - Quectel USB NMEA Port (COM13)
COM14 - Quectel USB AT Port (COM14)                <--- QTEL AT-PORT
COM15 - Prolific USB-to-Serial Comm Port (COM15)   <--- GPS

[x] AT port COM14 found
[x] GPS port COM15 found
-------------------------------------------
: Opening GPS COM15... done
: Opening AT COM14... done

Target Module: Quectel_RM500Q-GL
-------------------------------------------
```

Figure 24. Preparation stage related notifications displayed in console.

The main operating loop of the implemented software represents a repetitive part of the program, which includes all the measuring, data processing, displaying, and logging functions, and is intended to run infinitely until a stop command is received. The main loop part starts with an attempt to run the Speedtest application, which begins with the application availability check. In case if the Ookla Speedtest application was not previously found during the preparation part, the application initiating attempt will be skipped. Otherwise, the other Speedtest related checks will be performed to define if the application can be safely started.

These checks include the presence of internet connection, determined by short pinging session of a local website, check of the “pause” flag to ensure if throughput tests were not manually paused, currently running processes check to ensure that the Speedtest application is not currently running, and the current time check, which is intended to control the frequency of performed Speedtest. In case of this work, Speedtests were typically performed every 30 seconds for ground measurements and every 15 seconds for measurements from the drone. If all the requirements are met, the application is being initiated. Knowing the exact time of each possible measurement start allowed to track the potentially performed measurements with any other clock from the ground.

Ookla Speedtest application is running independently from the implemented program and returns the network throughput measurement results by using an interruption. By using it, the program may proceed with rest of the measurements without waiting for the Speedtest application to finish, and gradually save all the measurement results when they are received. Results, obtained from the Ookla application include the used provider server, latency, downlink transmission speed and uplink transmission speed for the used server.

Once the Speedtest application has started, the program proceeds with the reception of the positioning information. It is being performed in "GetLocationData" function, which activity diagram is shown on a Figure 25. To prevent an unexpected crash of the program, it performs a regular COM port availability check of the connected GNSS dongle. If the COM port is opened and operational, the positioning data will be received continuously, as the used GNSS module is standalone and transmits the measured positioning information independently with 1 second delay.

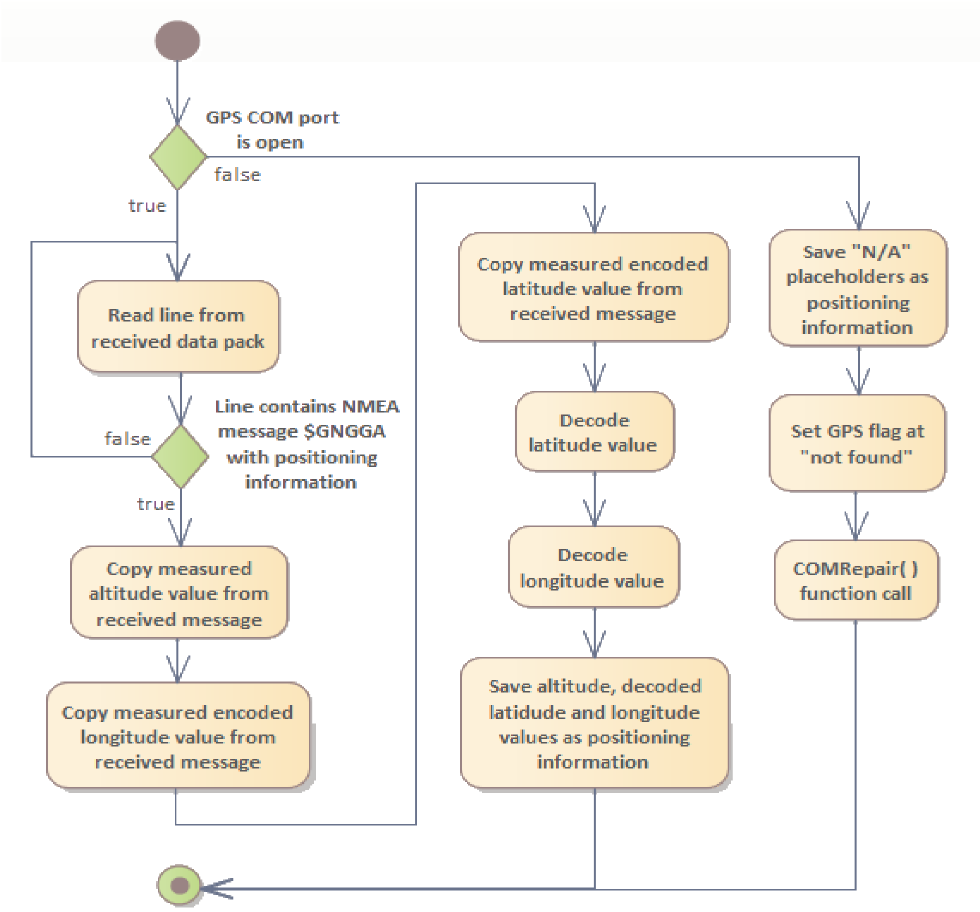


Figure 25. Activity diagram for the "GetLocationData" function.

One-time received data represents a full positioning data combined to sentences in accordance with NMEA 0183 standard. An example of the received sentences has the following structure:

```
$GNRMC,221411.00,A,5924.01933,N,02441.69869,E,0.030,,140421,,,D*66
$GNVTG,,T,,M,0.030,N,0.055,K,D*3B
$GNGGA,221411.00,5924.01933,N,02441.69869,E,2,03,1.61,127.7,M,18.6,M,,0000*44
$GNGSA,A,2,21,,,,,,,,,,,1.90,1.61,1.00*11
$GNGSA,A,2,78,76,,,,,,,,,,1.90,1.61,1.00*1C
$GPGSV,3,1,10,04,38,208,19,06,13,314,19,12,,,26,21,28,165,38*4A
$GPGSV,3,2,10,25,09,036,20,31,37,091,20,36,22,172,28,40,18,146,*79
$GPGSV,3,3,10,41,07,118,34,49,21,203,*7A
$GLGSV,3,1,10,67,03,066,,68,52,062,,69,70,258,,70,10,250,*6F
$GLGSV,3,2,10,76,07,347,25,77,28,034,,78,20,093,35,83,09,179,22*65
$GLGSV,3,3,10,84,56,223,,85,38,321,*6E
$GNGLL,5924.01933,N,02441.69869,E,221411.00,A,D*7E
```

Among others, the line starting with $GNGGA is used in the implanted software, as it contains the main positioning information of current latitude, longitude, and altitude, which are respectively highlighted with yellow, green, and blue. The implemented program examines the received sentence pack until the needed line is found and copies the positioning information for the further use. Received values of latitude and longitude are encoded according to the NMEA 0183 standard and should be decided, which is being performed immediately after the data was received.

In case if the COM port of the GNSS dongle is not opened, the positioning data will be replaced with “N/A” placeholders, GNSS port will be marked as “not found”, and the “COMRepair” function will be called in order to attempt to redefine and reopen the corresponding COM port.

Figure 26 shows an activity diagram for the “COMRepair” function, which represents an extended version of the previously described “COMFind” function, intended to define and redefine the connected 5G and GNSS modules, and open their COM ports for the actual use. This function is called as an automatic and emergency solution for the case of unwanted module disconnect to prevent the program crash and automatically restore the operational capabilities of the testbed. As in the “COMFind” function, using the list of available serial connections accessed in the registry of the PC, names of all detected serial devices are being compared to predefined names of known modules. In case of matching, the corresponding COM port is being opened to check its availability, and the successfully opened COM port is being saved and marked as operational.

In case of defined 5G module and successful open of its COM port, the program will additionally send a control AT-command to the module to ensure in its correct work. This procedure is being repeated until the correct response is received from the 5G module. Once the list of available serial devices is checked, the described "TargetModule" function is being called in order to redefine the AT-commands and responses list in case if the 5G module was changed to another.

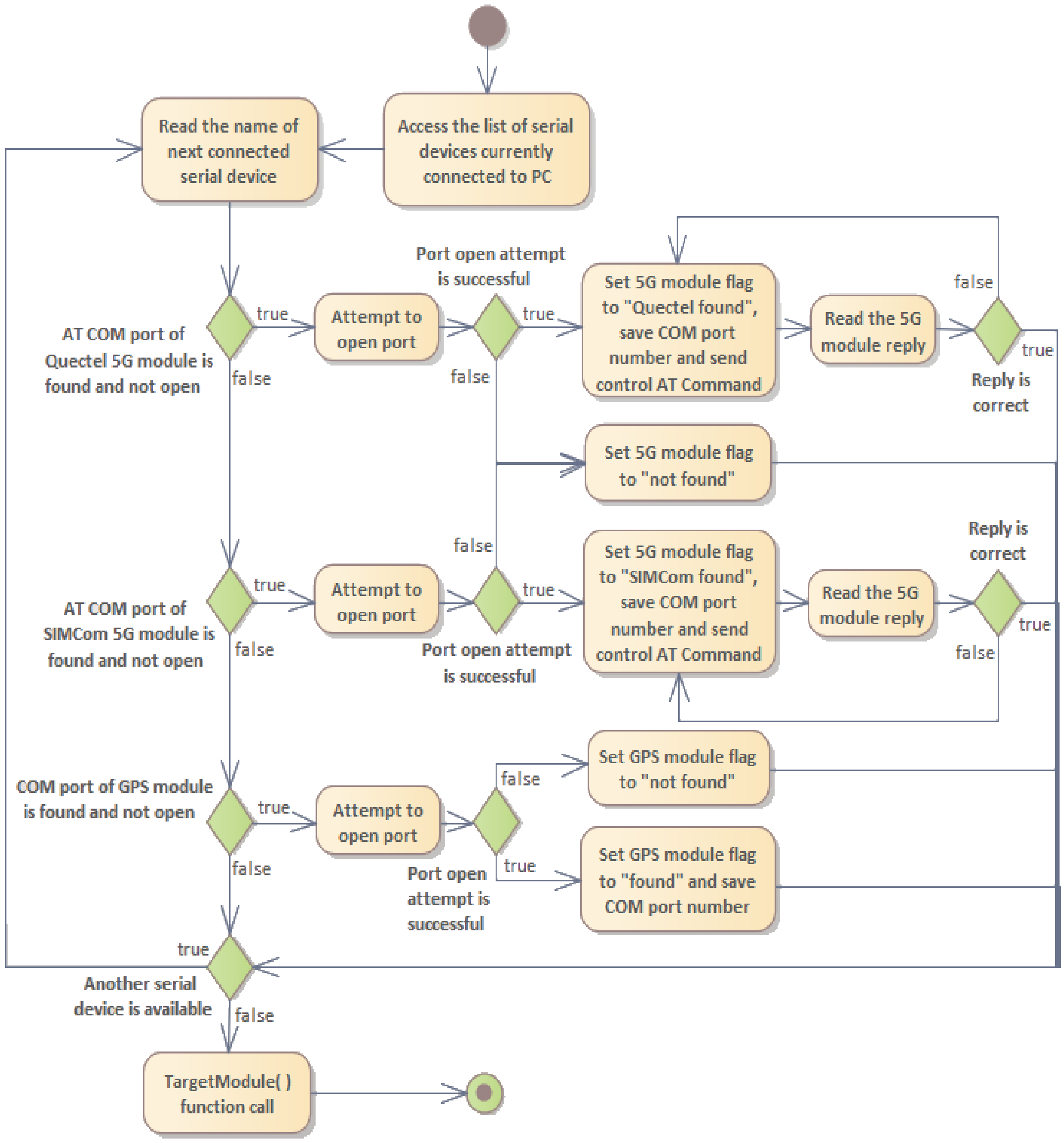


Figure 26. Activity diagram for the "COMRepair" function.

Regardless of the positioning information obtained in the previous “GetLocationData” function, the program proceeds with “GetSignalData” function in order to request and receive the signal quality information of the current connectivity. Activity diagram for “GetSignalData” function is shown on a Figure 27. Function starts with a single attempt of defined website pinging, using the default data packet of 32 bytes. Since the deployed 5G connectivity in Tallinn University of Technology by default is keeping the 5G band in idle mode until the actual data is transmitted, a short pinging session included to the program process is intended to imitate the data transmission to “wake up” the 5G band before measuring its signal quality. For this work it was decided to use Telia website www.telia.ee for pinging, although the pinged website is irrelevant. As with the GNSS module, the function proceeds with a regular 5G module AT COM port check it order to ensure if the serial connection is present and operational. In case if the COM port of 5G module is not opened or operational, all the signal related data is being replaced with “N/A” placeholders, the 5G module flag is set to “not found”, and the previously described “COMRepair” function is called.

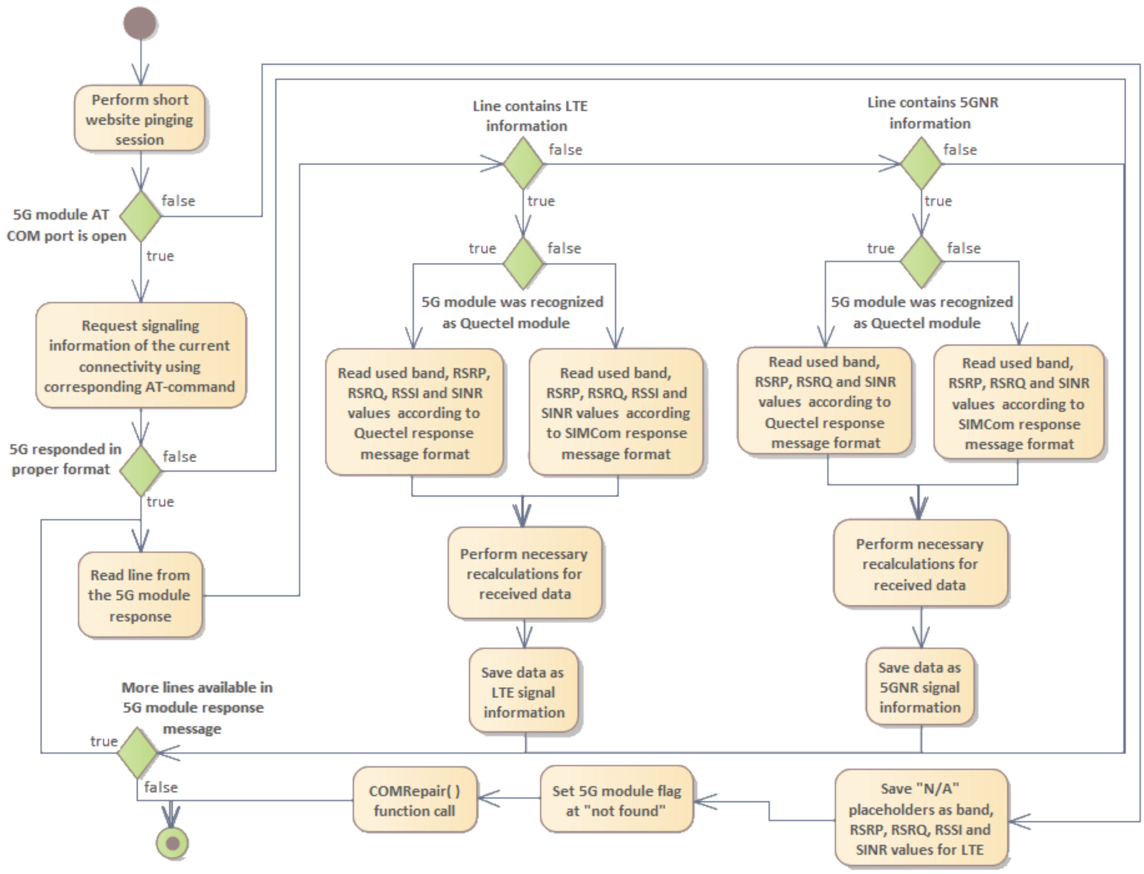


Figure 27. Activity diagram for the “GetSignalData” function.

If the AT COM port is opened and operational, the program requests the signal quality data of the current connectivity using the corresponding AT-command, specific for 5G module manufacturer. In case of the actively used RM500Q-GL module from Quectel, the mentioned AT-command is “AT+QENG=”servingcell””. The module responds with the measured signal quality parameters for each used band. In case of the EN-DC connectivity, the response contains signal quality results for both LTE and 5GNR bands separately. Example of the module response has the following structure:

+QENG: "LTE","FDD",248,01,30E4B14,367,3050,7,5,5,2724,-81,-9,-51,13,15,-150,-
+QENG:"NR5G-NSA",248,01,163,-72,7,-12,635040,78,8

For the used LTE band, the provided information includes the actual band number, highlighted with blue, RSRP, RSRQ, RSSI and SINR measured values highlighted with yellow and positioned in the corresponding order. For the NR5G band the provided information includes measured RSRP, SINR and RSRQ values highlighted with green respectively, as well as the used band number highlighted with blue.

Once the signal quality data is requested the program remains waiting for the response. For the received response from 5G module, the implemented software performs a format validity check. Received data line with incorrect format is being ignored, while the data lines with correct formatting are being processed further. Processing starts with defining the technology the received information is related to – LTE or NR5G. In accordance with the used 5G module, the signal quality data is being copied from the received template and recalculated if it is necessary, as Quectel and SIMCom 5G modules provide the same information using different templates.

Once the whole positioning and signal quality information is collected, the program proceeds with its displaying and logging. It is being performed in a “DisplayData” function, which activity diagram is shown on a Figure 28. Visually, all the available information is displayed in console as table, which example is shown on a Figure 29. It includes the general information as the current time, information about the program as a its version, time spent on a single cycle of the main loop, pinged website, and ping value to visually indicate the presence of an internet connection. The available positioning information is being displayed as a separate row, and it includes an indicator for the availability of GNSS module, its COM port number, as well as the received latitude, longitude, and altitude results.

In case if Speedtests are enabled, the corresponding information is also being as a separate row, and includes an indicator of the corresponding application availability, its current status, number of performed Speedtests, used provider server, and the latest measured latency, downlink speed and uplink speed results. If throughput measurements are disabled or paused, all the listed parameters are skipped. Signal quality measurements of the current cellular connectivity are displayed in the separate rows also divided by the used band. In case of the EN-DC connectivity, information related to both used LTE and NR5G bands is separated into two corresponding rows. In parallel, all the collected information including current positioning, Speedtest results and signal quality measurements are being saved in the log file using a single defined template.

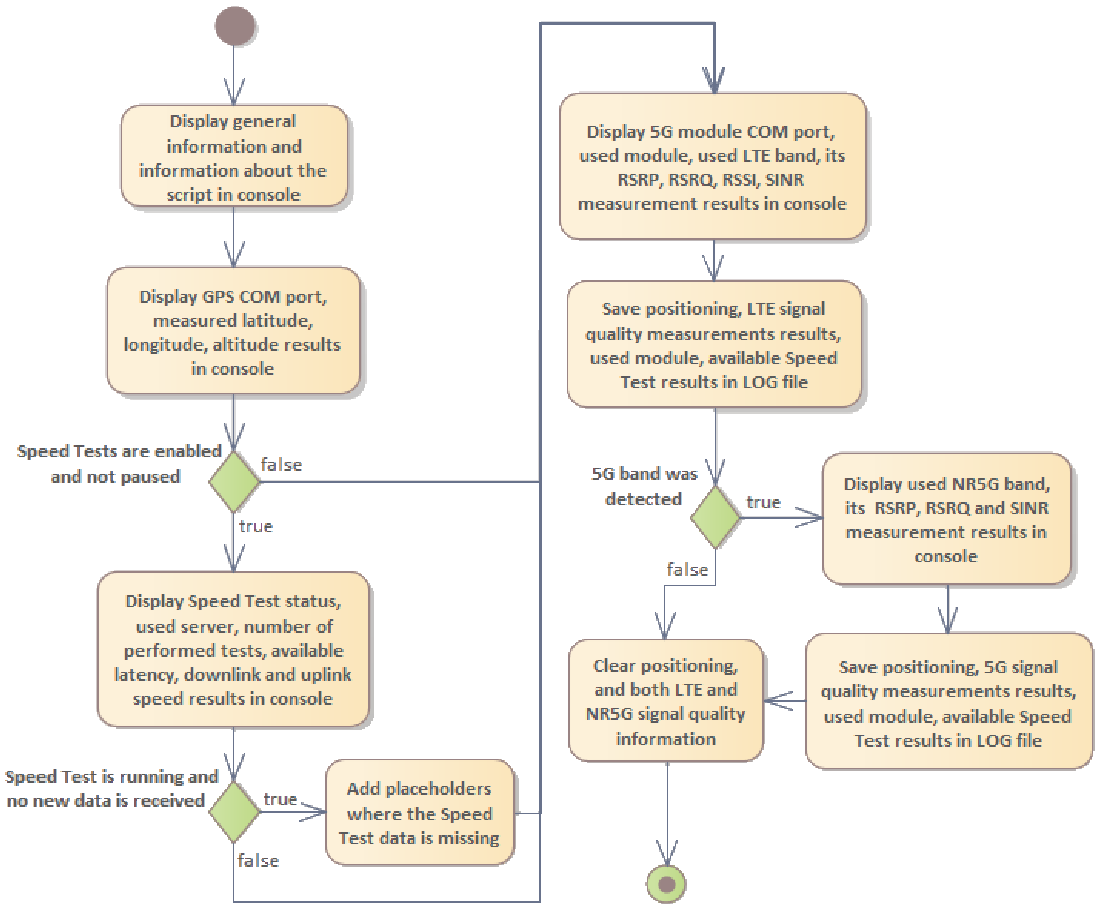


Figure 28. Activity diagram for the “DisplayData” function.

```
:Keys:
:    [S]     - Switch speed test server
:                   AUTO / Compic
:    [Space] - Pause speed tests
:    [ESC]   - Stop & Exit
-------------------------------------------
=||===================||==========||==================================================================||=
 ||                   || V.0.5.5  ||  www.telia.ee                                        Ping: 22 ms ||
=||===================||==========||==================================================================||=
 || [x] GPS    : COM24 ::----------:: Lat: 59,3966265        | Lon: 24,6713915        | Alt: 23,0    m ||
_||___________________|| 15:39:41 ||__________________________________________________________________||_
 || [x] SpTest : >>>>> ::----------:: Server:  Compic OU - Tallinn (id = 3207)                         ||
 ||                                                                                                    ||
 ||     Count  :  0 2  ||----------|| Latency 10,04 ms | Download 776,31 Mbps  | ..........          ||
_||___________________|| CompicOU ||__________________________________________________________________||_
 || [x] Module : COM13 ::----------:: ------------------| Quectel_RM500Q-GL |------------------------ ||
 ||                                                                                                    ||
 ||     Tech   : LTE   ||----------|| RSRP[dBm]: -75     | RSRQ[dB]: -8      |------------------------||
 ||     Band   : n7    ||  0.916s  || RSSI[dBm]: -45     | SINR[dB]: 22      |------------------------||
 ||                    ||          ||                                                                  ||
 ||     Tech   : NR5G  ||----------|| RSRP[dBm]: -66     | RSRQ[dB]: -11     |------------------------||
 ||     Band   : n78   ||----------|| RSSI[dBm]:         | SINR[dB]: 24      |------------------------||
=||===================||----------||==================================================================||=
```

Figure 29. All the collected information displayed in console as a table.

An example of the log file contents is shown on a Figure 30. All the results are saved in the defined order separated with ";" symbol, which can be used further in Excel environment to format the log file into the table for a convenient use. Once all the collected information is logged, it is being cleared from the internal program process memory.

```
Module;Latitude;Longitude;Altitude;Technology;Band;RSRP;RSRQ;RSSI;SINR;Parameter;Value;Unit;SpeedTest_Server;19:19:52_15.04.2021
Quectel_RM500Q-GL;59,3938835;24,672614;33,7;LTE;n7;-64;-7;-37;26;;;;
Quectel_RM500Q-GL;59,3938835;24,672614;33,7;NR5G;n78;-88;-11;;14;;;;
Quectel_RM500Q-GL;59,3938933333333;24,6726116666667;34,1;LTE;n7;-64;-7;-38;28;Latency;9,95;ms;CompicOU-Tallinn(id=3207);19:20:01
Quectel_RM500Q-GL;59,3938933333333;24,6726116666667;34,1;NR5G;n78;-89;-12;;14;Latency;9,95;ms;CompicOU-Tallinn(id=3207);19:20:01
Quectel_RM500Q-GL;59,3938896666667;24,6726115;34,1;LTE;n7;-65;-8;-38;28;*;*;*;CompicOU-Tallinn(id=3207);19:20:02
Quectel_RM500Q-GL;59,3938896666667;24,6726115;34,1;NR5G;n78;-88;-11;;12;*;*;*;CompicOU-Tallinn(id=3207);19:20:02
Quectel_RM500Q-GL;59,3938976666667;24,672613;34,7;LTE;n7;-65;-8;-38;28;*;*;*;CompicOU-Tallinn(id=3207);19:20:03
Quectel_RM500Q-GL;59,3938976666667;24,672613;34,7;NR5G;n78;-88;-12;;14;*;*;*;CompicOU-Tallinn(id=3207);19:20:03
Quectel_RM500Q-GL;59,3939041666667;24,6726121666667;35,4;LTE;n7;-65;-8;-38;28;*;*;*;CompicOU-Tallinn(id=3207);19:20:04
Quectel_RM500Q-GL;59,3939041666667;24,6726121666667;35,4;NR5G;n78;-87;-11;;14;*;*;*;CompicOU-Tallinn(id=3207);19:20:04
Quectel_RM500Q-GL;59,393912;24,6726121666667;35,7;LTE;n7;-64;-11;-34;30;*;*;*;CompicOU-Tallinn(id=3207);19:20:05
Quectel_RM500Q-GL;59,393912;24,6726121666667;35,7;NR5G;n78;-87;-11;;14;*;*;*;CompicOU-Tallinn(id=3207);19:20:05
Quectel_RM500Q-GL;59,3939245;24,6726173333333;36,7;LTE;n7;-64;-11;-34;30;*;*;*;CompicOU-Tallinn(id=3207);19:20:06
Quectel_RM500Q-GL;59,3939245;24,6726173333333;36,7;NR5G;n78;-87;-11;;14;*;*;*;CompicOU-Tallinn(id=3207);19:20:06
Quectel_RM500Q-GL;59,3939251666667;24,672616;37,3;LTE;n7;-64;-11;-34;30;*;*;*;CompicOU-Tallinn(id=3207);19:20:07
Quectel_RM500Q-GL;59,3939251666667;24,672616;37,3;NR5G;n78;-84;-11;;16;*;*;*;CompicOU-Tallinn(id=3207);19:20:07
Quectel_RM500Q-GL;59,3939261666667;24,6726146666667;37,7;LTE;n7;-65;-10;-39;30;*;*;*;CompicOU-Tallinn(id=3207);19:20:08
Quectel_RM500Q-GL;59,3939261666667;24,6726146666667;37,7;NR5G;n78;-84;-11;;16;*;*;*;CompicOU-Tallinn(id=3207);19:20:08
Quectel_RM500Q-GL;59,3939343333333;24,672617;37,6;LTE;n7;-65;-10;-39;30;*;*;*;CompicOU-Tallinn(id=3207);19:20:09
Quectel_RM500Q-GL;59,3939343333333;24,672617;37,6;NR5G;n78;-84;-11;;16;*;*;*;CompicOU-Tallinn(id=3207);19:20:09
Quectel_RM500Q-GL;59,393938;24,6726165;37,8;LTE;n7;-65;-10;-39;30;*;*;*;CompicOU-Tallinn(id=3207);19:20:10
Quectel_RM500Q-GL;59,393938;24,6726165;37,8;NR5G;n78;-87;-11;;16;*;*;*;CompicOU-Tallinn(id=3207);19:20:10
Quectel_RM500Q-GL;59,393938;24,6726176666667;38,1;LTE;n7;-65;-10;-35;28;*;*;*;CompicOU-Tallinn(id=3207);19:20:11
Quectel_RM500Q-GL;59,393938;24,6726176666667;38,1;NR5G;n78;-85;-11;;14;*;*;*;CompicOU-Tallinn(id=3207);19:20:11
Quectel_RM500Q-GL;59,3939353333333;24,6726143333333;37,9;LTE;n7;-65;-10;-35;28;Download;694,17;Mbps;CompicOU-Tallinn(id=3207);19:20:12
Quectel_RM500Q-GL;59,3939353333333;24,6726143333333;37,9;NR5G;n78;-89;-11;;14;Download;694,17;Mbps;CompicOU-Tallinn(id=3207);19:20:12
Quectel_RM500Q-GL;59,3939321666667;24,6726113333333;37,1;LTE;n7;-65;-10;-35;28;*;*;*;CompicOU-Tallinn(id=3207);19:20:13
Quectel_RM500Q-GL;59,3939321666667;24,6726113333333;37,1;NR5G;n78;-89;-12;;12;*;*;*;CompicOU-Tallinn(id=3207);19:20:13
Quectel_RM500Q-GL;59,393947;24,6726165;36,8;LTE;n7;-61;-7;-33;30;*;*;*;CompicOU-Tallinn(id=3207);19:20:14
Quectel_RM500Q-GL;59,393947;24,6726165;36,8;NR5G;n78;-89;-11;;14;*;*;*;CompicOU-Tallinn(id=3207);19:20:14
```

Figure 30. Example of the log file structure.

After the information displaying and logging function, a cycle of the main loop is almost complete, and includes the last check for any user input from the keyboard, which allows a manual control of actions performed in the main loop. Currently, control options include three available actions. “S” key entered from the keyboard will trigger a default server change for Ookla Speedtest application, which in its turn allows switching between automatic server picking mode and forced use of the “CompicOU” server mode. After the server mode switch, the main loop proceeds. Another option allows to pause or resume Speedtests with “Spacebar” keyboard input. The last option is triggered by the “Esc” keyboard input, and initiates the exit sequence of the program, which is intended to properly exit the main loop, save, and close the created log file, close the currently running Ookla Speedtest application, close both 5G module and GNSS module COM ports, perform a final log file formatting procedure, and close the program process.

5 Measurements and results

5.1 Methodology

To evaluate the coverage of the 5G connectivity within TUT area, there were continuously measured the main parameters of corresponding signal quality by using implemented testbed setup. The measured key parameters of 5G signal quality provided by 5G module are: SS-RSRP – Synchronization Signal - Reference Signal Received Power, which indicates the average level of received synchronization signals from the main serving cell, SS-RSRQ – Synchronization Signal - Reference Signal Received Quality, which indicates the quality of the radio channel, SS-SINR – Synchronization Signal - Signal to Interference plus Noise Ratio indicates the average ratio of the synchronization signal carrying resource element's power divided by the average interference and noise power over these resource elements. Used 5G modules are unable to provide the RSSI – Reference Signal Strength Indicator measurement for the 5G band, which originally was planned to use for the 5G signal coverage evaluation as it comprises the average of the total received power from the serving and neighbour cells, including noise and interference. Signal quality measurements were performed continuously every second, alongside with the current positioning of the measuring testbed, which was moving around the TUT campus area and beyond.

Additionally, to evaluate the throughput capabilities of the 5G network deployed in TUT there were performed downlink and uplink speed measurements, as well as measurements of the latency between the testbed setup and the used local provider server. To measure the latency and throughput capabilities of the EN-DC connectivity in TUT campus area, 5G module in the testbed setup was used as a modem to establish a proper internet connection over the available EN-DC connectivity. Afterwards, it was used an Ookla Speedtest CLI application, which is capable to measure the latency to the provider's server, as well as its downlink and uplink available throughput capabilities. Ookla Speedtest provides several throughput measurement modes based on the provider server selection: automatic switching to the server with the lowest measured latency, and a single, manually defined server.

For this work it was decided to focus on a single selected server with the highest throughput speeds achieved. During the numerous practical measurement tests, the highest throughput speeds were achieved while using the server named “CompicOU”, and therefore, it was used for the actual throughput measurements.

Throughput measurements were performed from static positions at the key spots around TUT campus area. To increase measurements precision, five throughput measurements for every key spot were continuously performed. The same approach was used for the throughput measurements at different altitudes – the implemented testbed, while attached to the drone platform performed five continuous measurements at 10, 20 and 30 meters above the ground level from possibly static position. Testbed was positioned at the correct altitude with the available accuracy of 0.5 m by using the positioning system of the carrier drone, which measured altitude was tracked on the screen of the remote controller. Drone was kept on each altitude for measurements for a minimal amount time of 3 minutes to guarantee the minimal number of five throughput measurements performed at each spot and altitude. Hovering time was additionally synchronized with a watch.

In order to minimize the possible drone influence on the measured signal, the drone with the attached testbed was facing the direction to the base station antenna at every measurement spot. To measure the influence of different weather conditions (e.g., rain, snow), as well as the different provider server selection modes of the used Speedtest there were used seven different spots. At each spot there were performed ten throughput measurements instead of five. To evaluate a possible interference of the working drone on the obtained measurement results it was performed an additional test, which consists of five performed throughput and latency measurements, as well as continuous signal quality measurements, performed on the same position and height of ~1 m above the ground. These measurements were performed with the testbed attached to the hovering drone at the mentioned height, as well as without a drone presence near the testbed.

Figure 31 represents the map with all the planned throughput measurement spots, moving route used for the signal quality measurements for the 5G coverage evaluation, as well as marked areas of key areas for measurements, and positions of all three 5G antennas. Antennas are marked with letters “A”, ”B” and “C”.

Key areas for measurements are highlighted with green – for completely opened area, yellow – for mostly wide opened areas with small number of nearby obstacles, red – for completely enclosed or tight areas, and orange – for partially enclosed areas with major obstacles, usually without the line of sight to the 5G antenna. Key areas for measurements are named in accordance with the antenna, in which sector they are located, while areas named with “X” are located outside of all three operational antennas sectors.

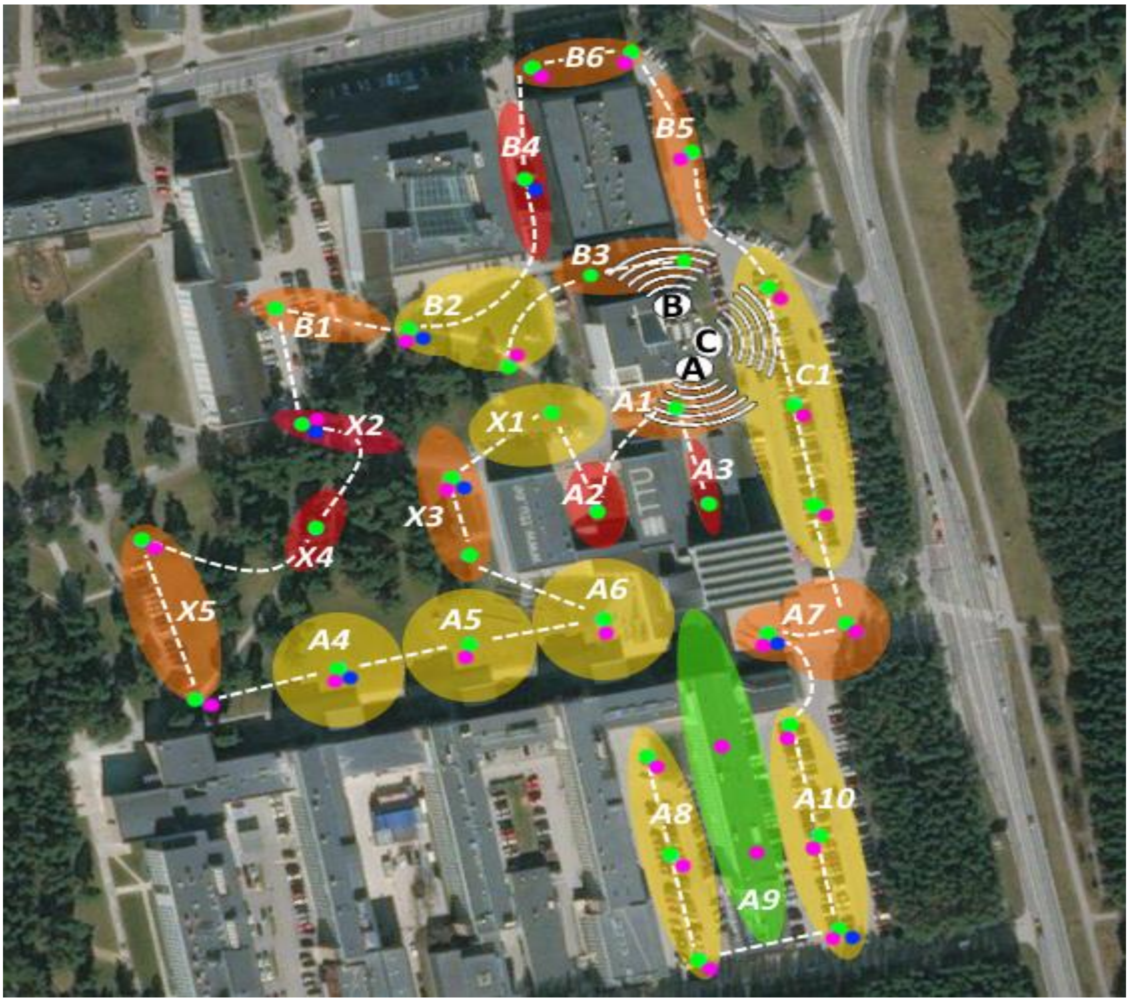


Figure 31. TUT campus area map with marked 5G antennas, key areas for measurements, exact measurement spots and routes of planned coverage and throughput measurements.

Routes for the signal quality measurements are represented with white dashed line. The exact key spots within highlighted areas are marked with three colours: green spots for ground throughput measurements, blue for signal quality and throughput measurements at different weather conditions and different provider server selection modes, and purple spots stand for the different altitude measurements spots.

In order to refer the all the measurement results to specific locations they were obtained, it was used a GNSS position tracking module. Thus, all the positions of performed measurements were also collected and used for the further data analysis and heatmaps creation. To remove minor position changes detected by the used GNSS module during static position measurements, for each spot there were calculated and used average values of coordinates. All the measured and logged data was copied directly to the MS Excel environment and used to generate corresponding heatmaps by using Excel 3DMaps tool.

5.2 Performed measurements and obtained results

5.2.1 5G coverage

To evaluate the coverage of TUT deployed 5G network, the 5G signal quality parameters were measured using the implemented testbed setup on the ground level. The main 5G signal level and quality measurements of SS-RSRP, SS-RSRQ and SS-SINR were performed continuously while moving within TUT campus area. Measured SS-RSRP results were used to create a heatmap of the overall 5G coverage within TUT campus area shown on a Figure 32. As it can be seen, the 5G band of 3.5 GHz signal is quite sensitive to various environmental obstacles on its way and is losing a significant amount of power while passing through the urban environment.

For instance, a single skybridge in a narrow space between two buildings on the northern side of Tallinn University of Technology campus is capable to fully block the signal from the nearby antenna. Within this squared area, at the part of the route coloured with red the 5G signal was completely missing, and only LTE signal was present. A completely missing 5G signal in a narrow space between buildings indicates that the signal is also losing a significant amount of power while reflecting from the building walls before it passes over the skybridge. USRP (Universal Software Radio Peripheral) B210 SDR (Software Defined Radio) hardware and HDSDR software environment were tuned to the used 5G band n78 and used to observe its spectrum measured under and behind the skybridge. Corresponding spectrogram measured for used 5G band is shown on a Figure 33 top and bottom accordingly.

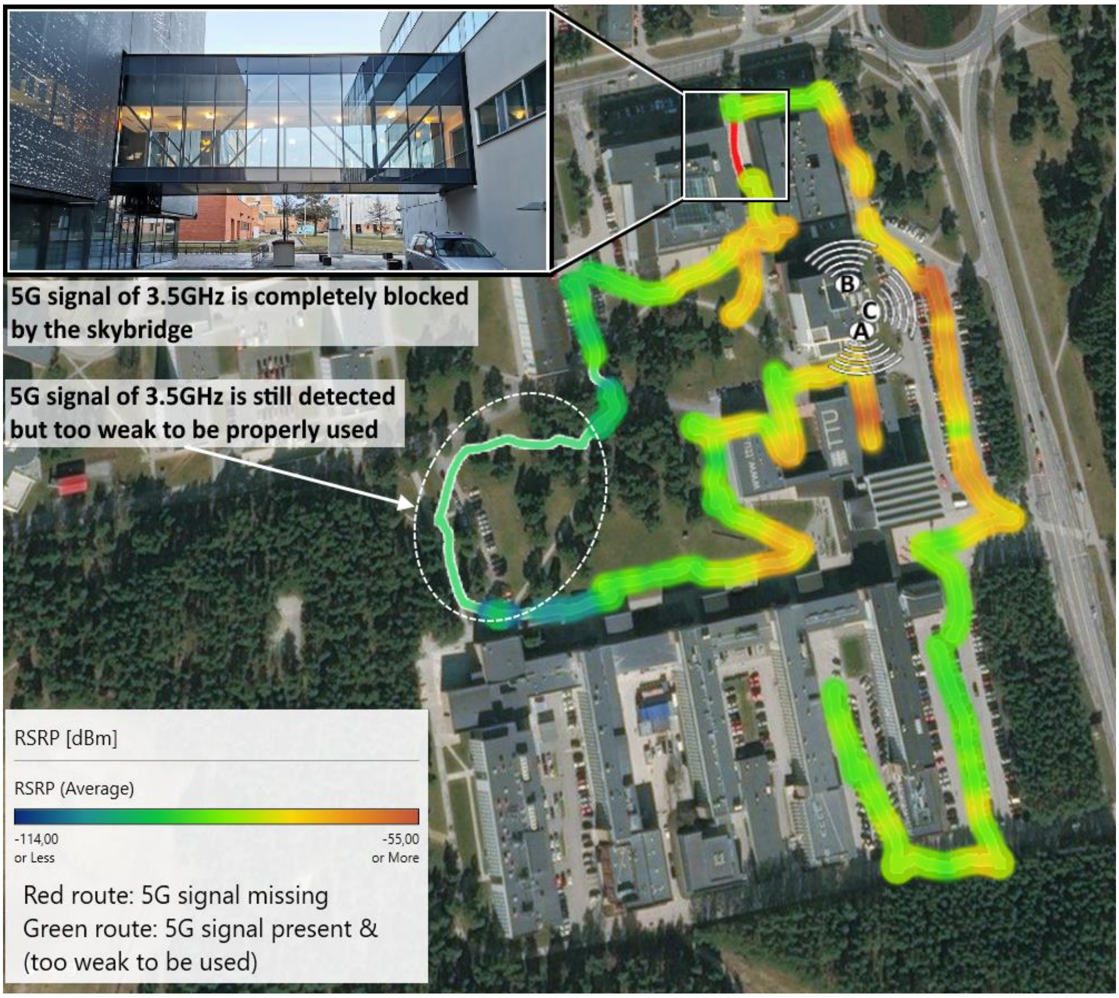


Figure 32. 5G signal coverage heatmap based on the measured SS-RSRP within TUT campus area.

Park trees on the western side of Tallinn University of Technology campus, located outside of the bounds of available antennas, are also influencing the signal spread by gradually reducing its power. At the circled part of the route coloured with green the presence of 5G signal was still recognisable by the testbed, although, its power level was low enough to make the signal unusable for the cellular communications. While the overall signal power at opened areas and within the line of sight of the antenna is high and smoothly reduces with distance, even minor obstacles at relatively short distance from the antenna, such as lone trees, are noticeably reducing the signal power received by user equipment (UE).

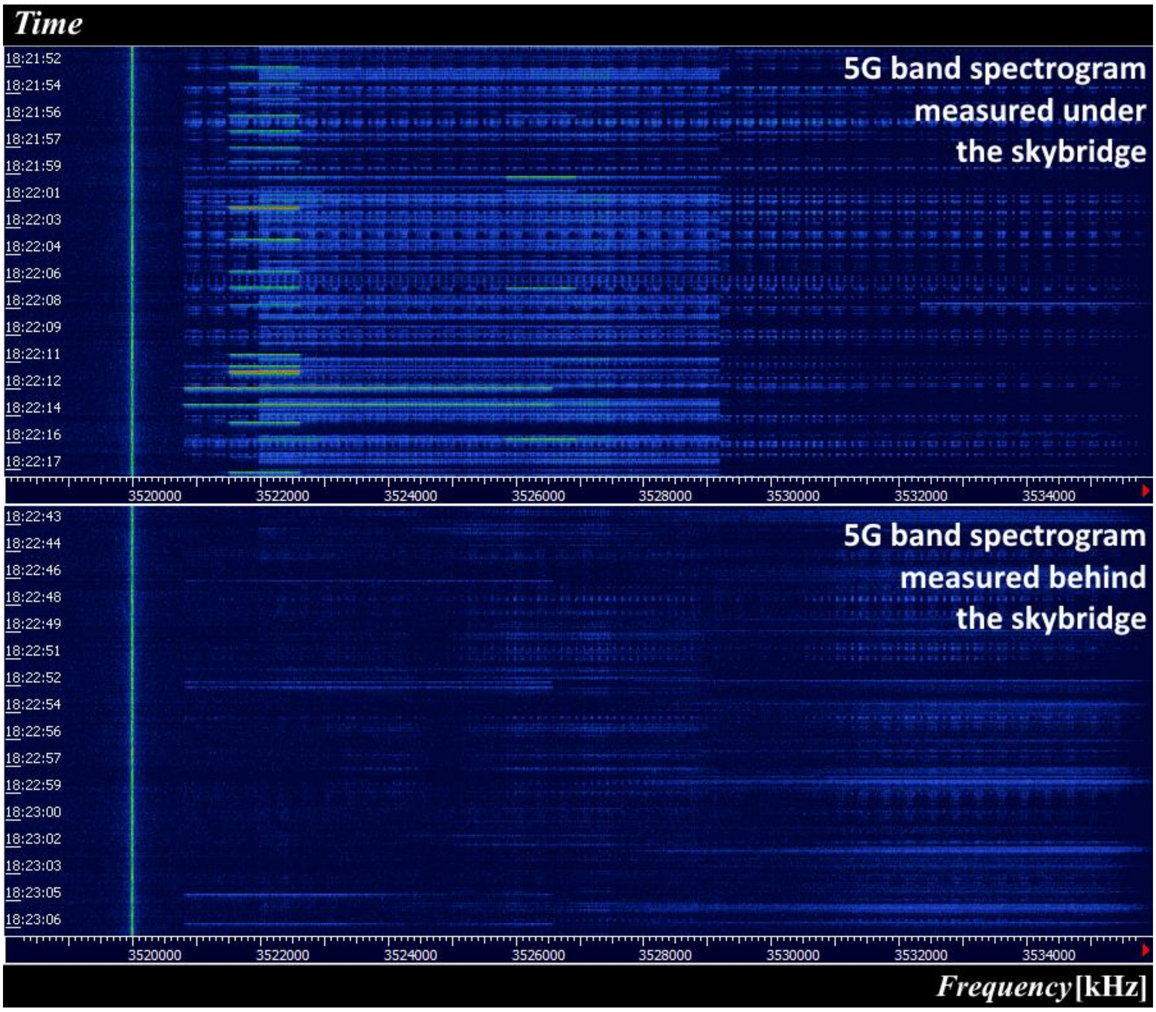


Figure 33. Spectrogram of the 5G band, measured under the skybridge (up), and behind the skybridge (bottom), displayed in HDSDR software.

Figure 34 shows the SS-RSRP based heatmap of the 5G coverage at the larger scale, and additionally includes the external area slightly outside TUT campus. At the larger scale, the 5G signal coverage shows the same behaviour as within TUT campus area shown on a Figure 32: clusters of trees located relatively close to the gNB antenna are noticeably reducing power of the 5G signal, and without other proper propagation paths for the signal, it becomes weak enough to be considered as unusable by the 5G module of the testbed. Locations with this behaviour of the signal are represented as green coloured path. Red coloured path parts represent locations with totally missing 5G signal, at which it was completely blocked by environmental obstacles.

The overall measured coverage results of the sub-6 GHz 5G signal meet the expectations and show a signal power and quality drop with the distance, as well as higher sensitivity to various urban environmental obstacles compared to usual LTE bands. It is especially noticeable in case of park areas, where even rare tree clusters may significantly affect the sub-6GHz 5G signal. Locations outside of the direct line of sight of the base station antenna show a significant decrease of 3.5 GHz signal strength as well.

These results practically demonstrate the actual necessity of additional 5G signal small cells relays briefly described in chapter 2.3, which could be additionally placed within enclosed urban and park areas to compensate the significant 5G signal power drops caused by various urban obstacles.

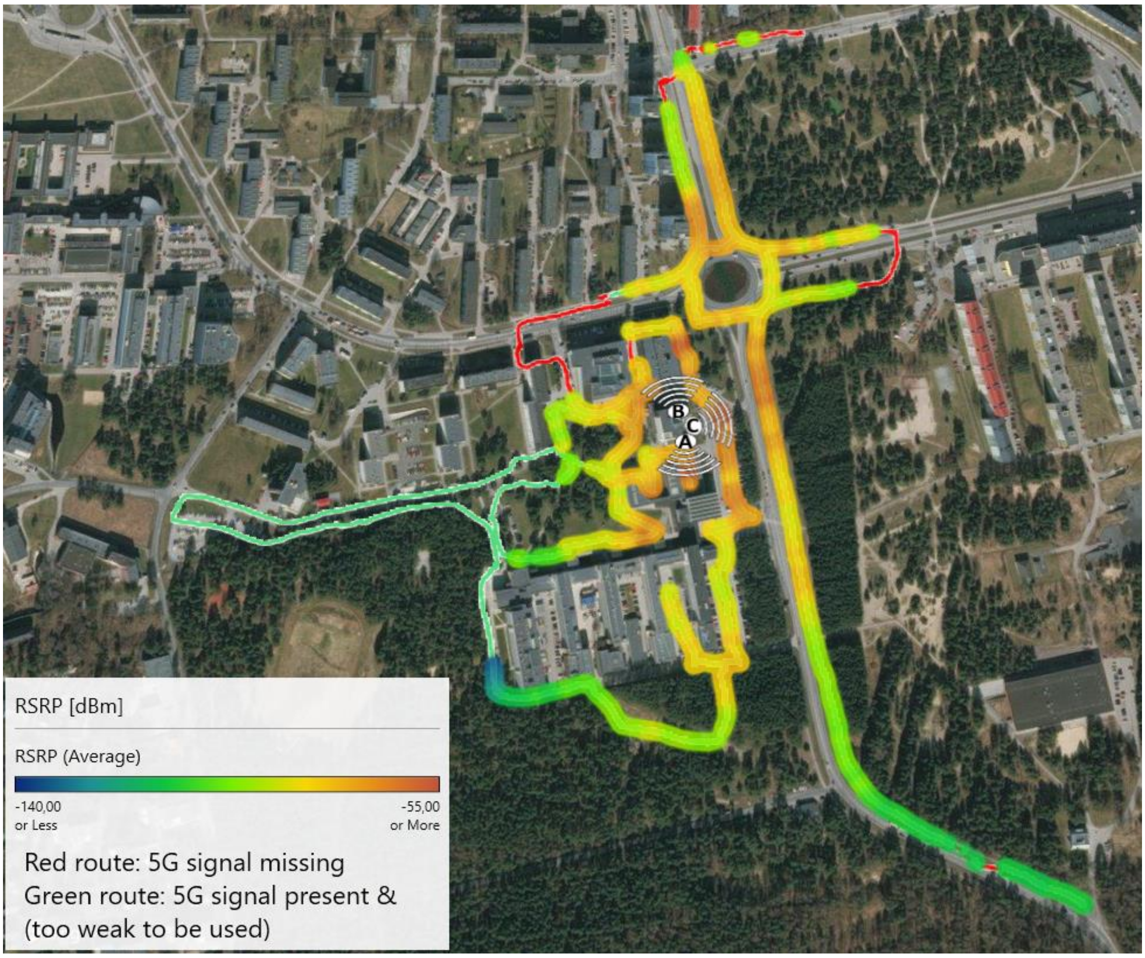
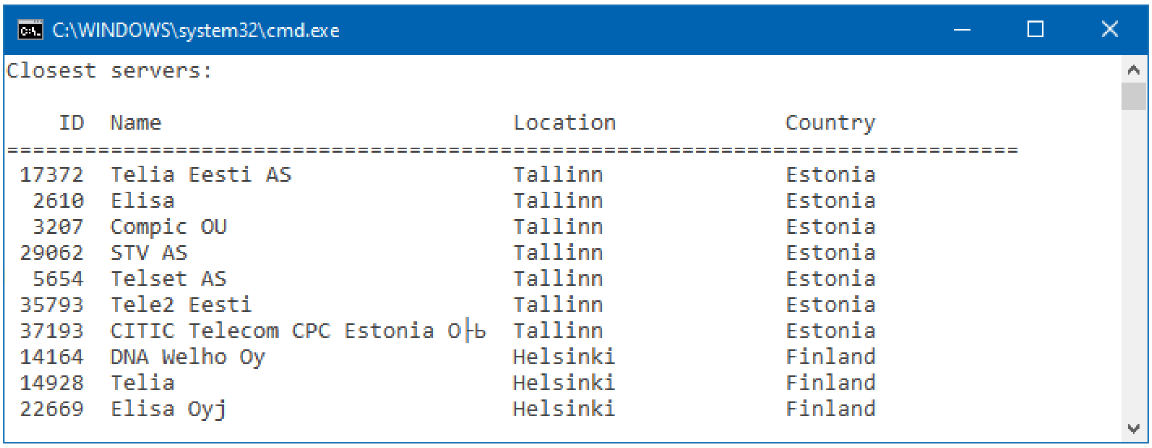


Figure 34. 5G signal coverage heatmap based on the measured SS-RSRP within and slightly outside TUT campus area.

5.2.2 Throughput at different provider server selection modes

Used Ookla throughput measurement application provides several measurements configurations regarding the used provider server. Provider server, which will be used for the connectivity throughput and latency measurements can be selected manually from the closest available servers, detected by the application. List of closest servers generated by Ookla application within TUT area is shown on a Figure 35.

Each server provides its own throughput capabilities for testing. The highest downlink speed results practically observed were measured for “CompicOU” server, which was used for the implemented testbed. By default, the Ookla application is using a server with the lowest latency measured at the test start. Thus, in this mode, for every upcoming speed test the application may switch to a new server, which, however, will provide its own throughput capabilities, and in this case the measured results may significantly differ at the same location. This mode is useful for real-time applications, focused on the lowest obtainable latency instead of the highest throughput results.



```
C:\WINDOWS\system32\cmd.exe
Closest servers:

    ID  Name                           Location             Country
==============================================================================
 17372  Telia Eesti AS                 Tallinn              Estonia
  2610  Elisa                          Tallinn              Estonia
  3207  Compic OU                      Tallinn              Estonia
 29062  STV AS                         Tallinn              Estonia
  5654  Telset AS                      Tallinn              Estonia
 35793  Tele2 Eesti                    Tallinn              Estonia
 37193  CITIC Telecom CPC Estonia O├ь   Tallinn              Estonia
 14164  DNA Welho Oy                   Helsinki             Finland
 14928  Telia                          Helsinki             Finland
 22669  Elisa Oyj                      Helsinki             Finland
```

Figure 35. List of closest provider servers generated by Ookla CLI application.

In order to demonstrate the difference between two described modes, there were performed measurement tests at different locations within TUT campus area. Measurements were performed in groups of 10 measurements for each spot and for each mode. Figure 36 shows two heatmaps for the average measured latency at different spots – heatmap for the manually selected “CompicOU” provider server (top) and heatmap for the automatic server pick by the currently best latency (bottom). Heatmap for the automatic server pick mode represents a heatmap of the best momentary latency levels among all available servers at the measurement locations. Measurement spots are marked with dots. Since the number of measurement spots is limited with 7, it was possible to include a scatter diagram with all measurement results, highlighted highest, lowest, and average results at each spot, and for each heatmap within this subchapter for more illustrative representation of the obtained results.

As it can be seen, the average latency measurement results for the manually selected server, with minor differences are nearly the same compared to the average results of the automatic server selection, and regardless of the UE position relative to the antenna coverage sector. According to the diagram representation of average latency measurement results attached to both heatmaps, the measured average latency difference between two tested modes at each spot is less than a half of millisecond, which can be considered as expected error, caused by various environmental, network, or other interfering factors. Nevertheless, in case of a single defined server, the overall measured latency results are more stable and precise, compared to the automatic server selection. Additionally, due to the weak 5G signal at the spot number 3, observed in the previous chapter, the testbed was unable to stably use 5G band and was using the available LTE band instead. For this reason, the number of successfully performed measurements at this spot is 3 out of 10 for “CompicOU” server, and 4 out of 10 for automatic server selection mode. This emergency switch to LTE band expectedly leads to the latency increase to the corresponding LTE values above 15–20 ms.

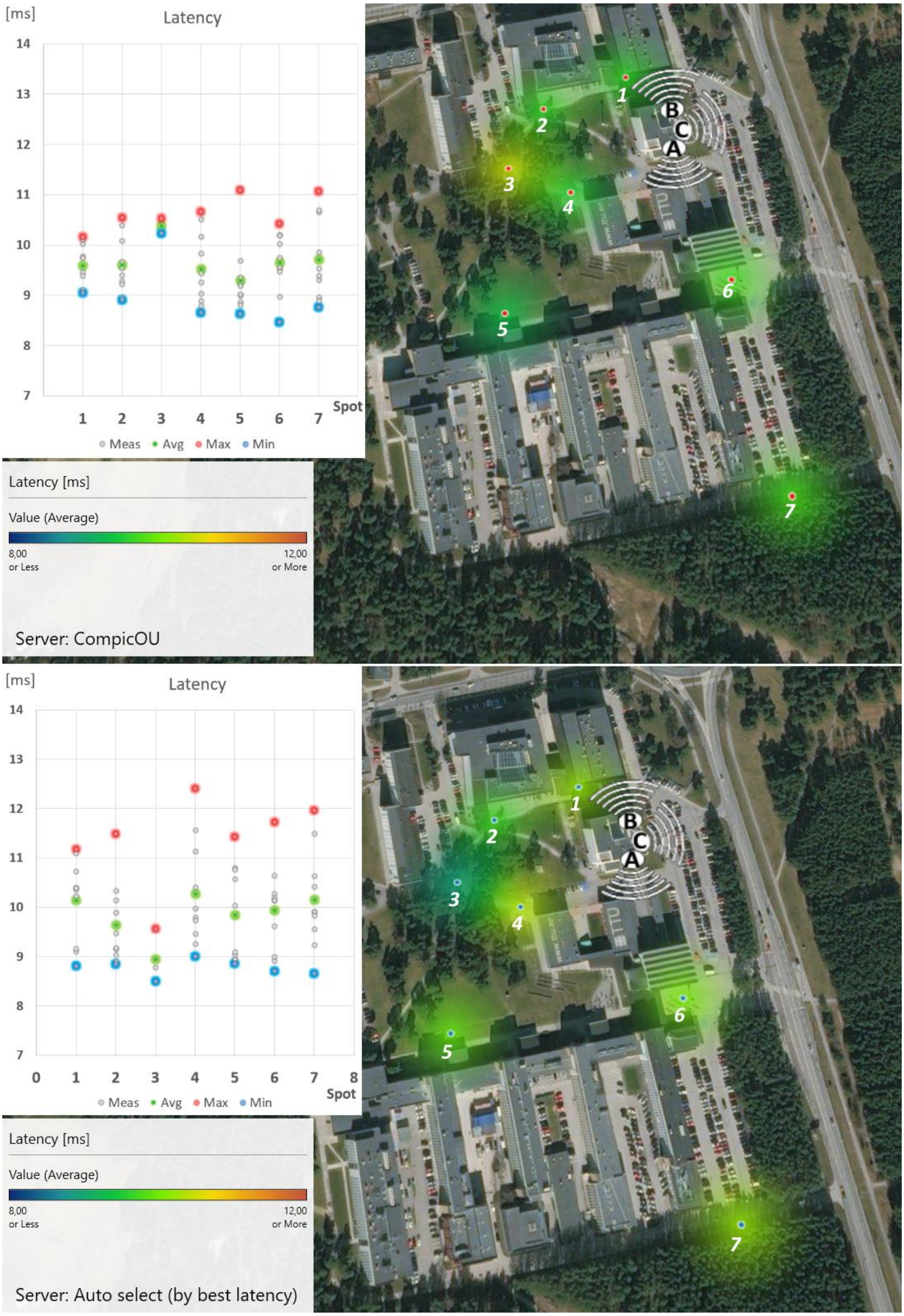


Figure 36. Heatmaps, based on average measured latency for the "CompicOU" server (top), and for the automatically picked servers (bottom).

While both server selection modes for the Speedtest application show insignificant differences in terms of average latency levels, the throughput measurement results show major differences. Figure 37 shows heatmaps for the measured downlink speed results for both manually selected server mode (top) and automatic server selection mode (bottom), with corresponding scatter diagram representation of the measured results. In case of the manually selected server, the used server always aims to provide the highest possible throughput, depending on the environmental conditions. Thus, the downlink speed measured for the manually selected server is showing stabile and possibly high results, only affected by nearby obstacles. In case of the automatic server selection mode, the Speedtest application is focused on the best achieved latency among all available servers, although, since the latency level for most of the available servers is nearly identical, the server pick in this mode is close to random. Since, the downlink and uplink capabilities provided by each server are significantly different, the random server pick leads to the random throughput results. This effect of significant throughput results float can be observed on the provided scatter diagrams.

Figure 38 shows heatmaps for the measured uplink speed results for both manually selected server mode (top) and automatic server selection mode (bottom), with corresponding scatter diagram representation of the measured results. As with the downlink speed measurement results, the uplink measurements for a manually selected server show stable and high uplink speed results for every particular spot, which differ expectedly at different locations with different environment. In case of automatically picked server, the uplink speed results are expected to be significantly different for every used server, although, since the uplink speed is significantly limited with ~110 Mbps at the base station level, most of the used servers in automatic selection mode are capable to provide this uplink throughput, and thus, the average uplink speed results are relatively close to manually selected server. Although, without the base station uplink speed limitation, the difference of average uplink speed results for both servers' modes are expected to be significant. Provided scatter diagrams illustrate the stability of the measured uplink throughput in case of the manually selected server compared to the automatic server selection mode. These throughput results were used to define the server selection mode and the server for the further throughput measurements within the TUT campus area at both ground and above ground altitudes, described in following chapters.

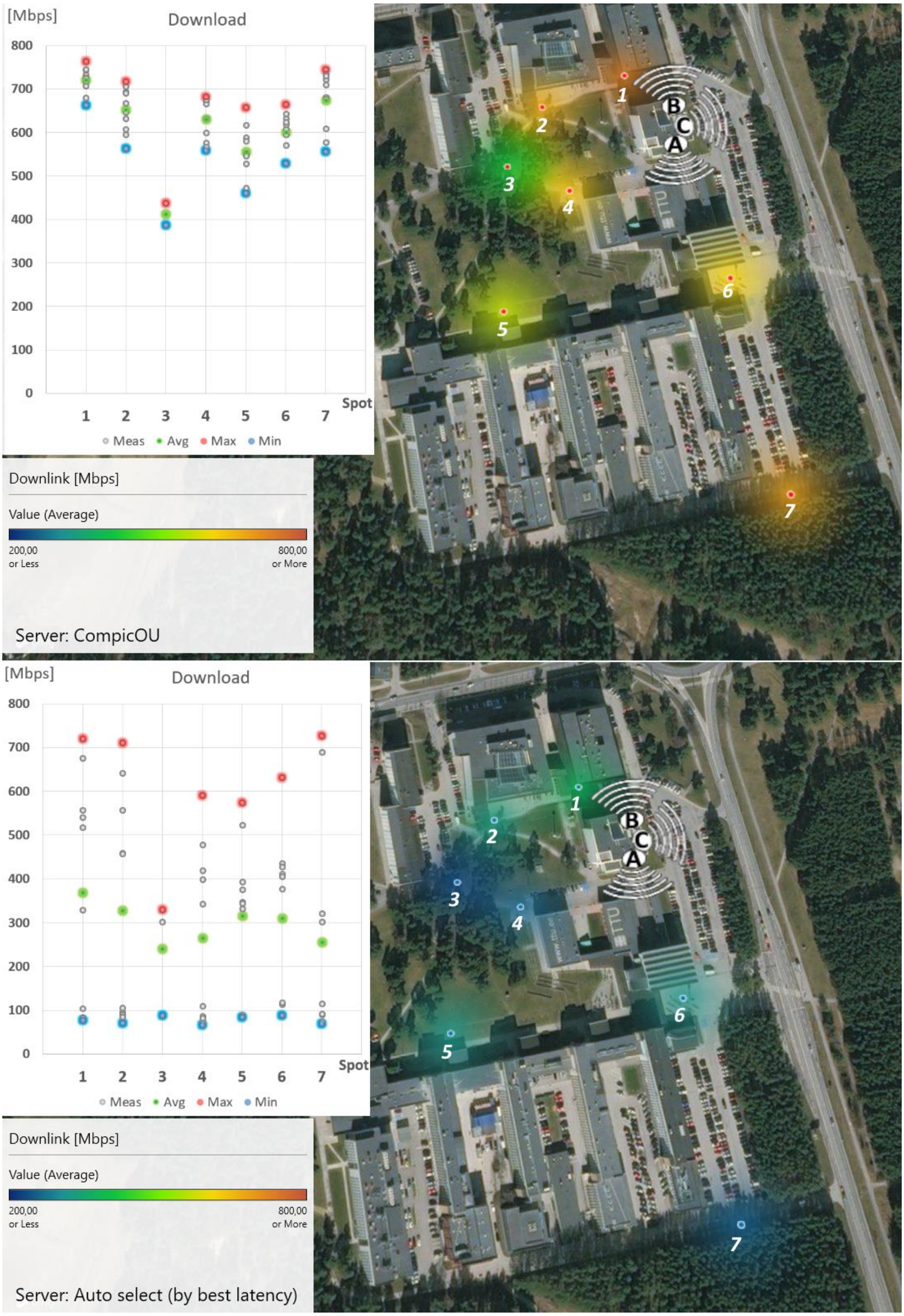


Figure 37. Heatmaps, based on average measured downlink speed for the "CompicOU" server (top), and for the automatically picked servers (bottom).

Figure 38. Heatmaps, based on average measured uplink speed for the “CompicOU” server (top), and for the automatically picked servers (bottom).

5.2.3 Throughput and coverage at different altitudes

To investigate the 5G behaviour at different altitudes, the coverage and throughput measurements were also performed at different altitudes by using a commercial drone DJI MATRICE 600 Pro briefly described in a subchapter 4.2.4 as a carrying platform for the testbed. For this work it was decided to perform signal quality and both uplink and downlink throughput measurements at altitudes of 10, 20 and 30 meters above the ground level in accordance with the measurement plan shown on a Figure 31 in chapter 5.1. Preliminarily, the same measurement procedures were performed at the ground level for a larger number of key spots. In both cases of measurements at the ground and above ground altitude levels, there were performed five throughput measurements including the latency measurements. The signal quality measurements were performed continuously in parallel with the throughput measurements. Obtained results were used to generate the corresponding heatmaps for different altitudes and parameters.

Figure 39 shows two SS-RSRP based heatmaps of the 5G signal quality within the TUT campus area at ground level (top), and 10 m altitude (bottom). Measurement spots are marked with dots, and the encircled dots represent measurement spots with too weak 5G signal. For this reason, at these spots the testbed was using LTE band instead, and thus, the obtained results are not listed. These designations are applied to all heatmaps provided within this subchapter. The overall coverage and signal quality at the ground level has exactly the same dynamic and steadily higher signal quality measurements compared to the coverage measurement results shown on a Figure 32 in subchapter 5.2.1. Unlike the coverage measurement results described in mentioned subchapter, the coverage results shown in the current case were measured by a fully static testbed, which demonstrates an overall received signal quality decrease caused by moving UE. As expected, the overall signal strength is the highest in front of the base station antennas, and slightly decreases with the distance. More significant signal strength decrease can be observed within areas without direct line of sight with the base station antenna.

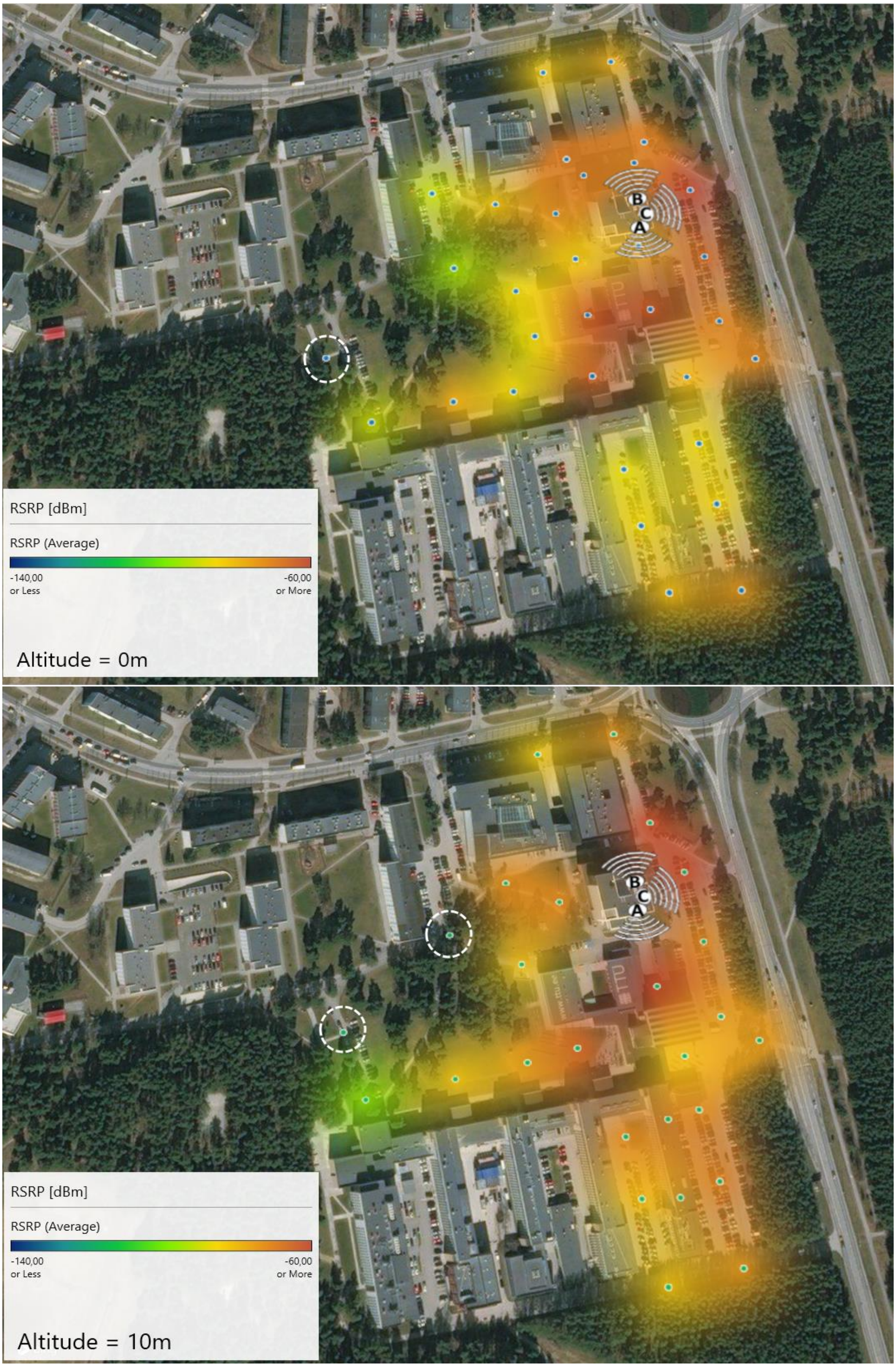


Figure 39. 5G signal coverage heatmaps based on the measured SS-RSRP within TUT campus area at the ground level (top), and 10 m altitude (bottom).

At the 10 m altitude overall signal strength slightly decreases, which is caused by a significant initial tilt of the deployed 5G antennas. A more significant 5G signal strength decrease can be noticed in park area measurement spots surrounded by trees. Measurement spots without the line of sight of 5G bases station antenna on the ground level, on the contrary, show an expected signal strength increase and alignment with neighbour spots caused by getting above the main obstacles.

Figure 40 shows two SS-RSRP based heatmaps of the 5G signal quality within the TUT campus area at 20 m altitude (top), and 30 m altitude (bottom). With the increasing altitude to 20 and 30 meters, the overall 5G signal strength proceeds with the slight decrease. As expected, the influence of urban obstacles partially blocking the line of sight with the base station antenna can be barely noticed on the 20 m altitude, and fully disappears at the 30 m altitude. It is remarkable, that in several measurement spots the lower signal strength at the 20 m altitude experience a slight signal strength increase at 30 m altitude. It may be caused by the testbed getting into the range of 5G antenna side lobes. This effect can be observed best at the westernmost measurement spot in park area, at which the signal strength results gradually decrease with the increasing altitude from 0 m to 20 m until the signal becomes too weak to be used at 20 m altitude. Although, at 30 m altitude in the same spot the signal reappears with relatively high strength.

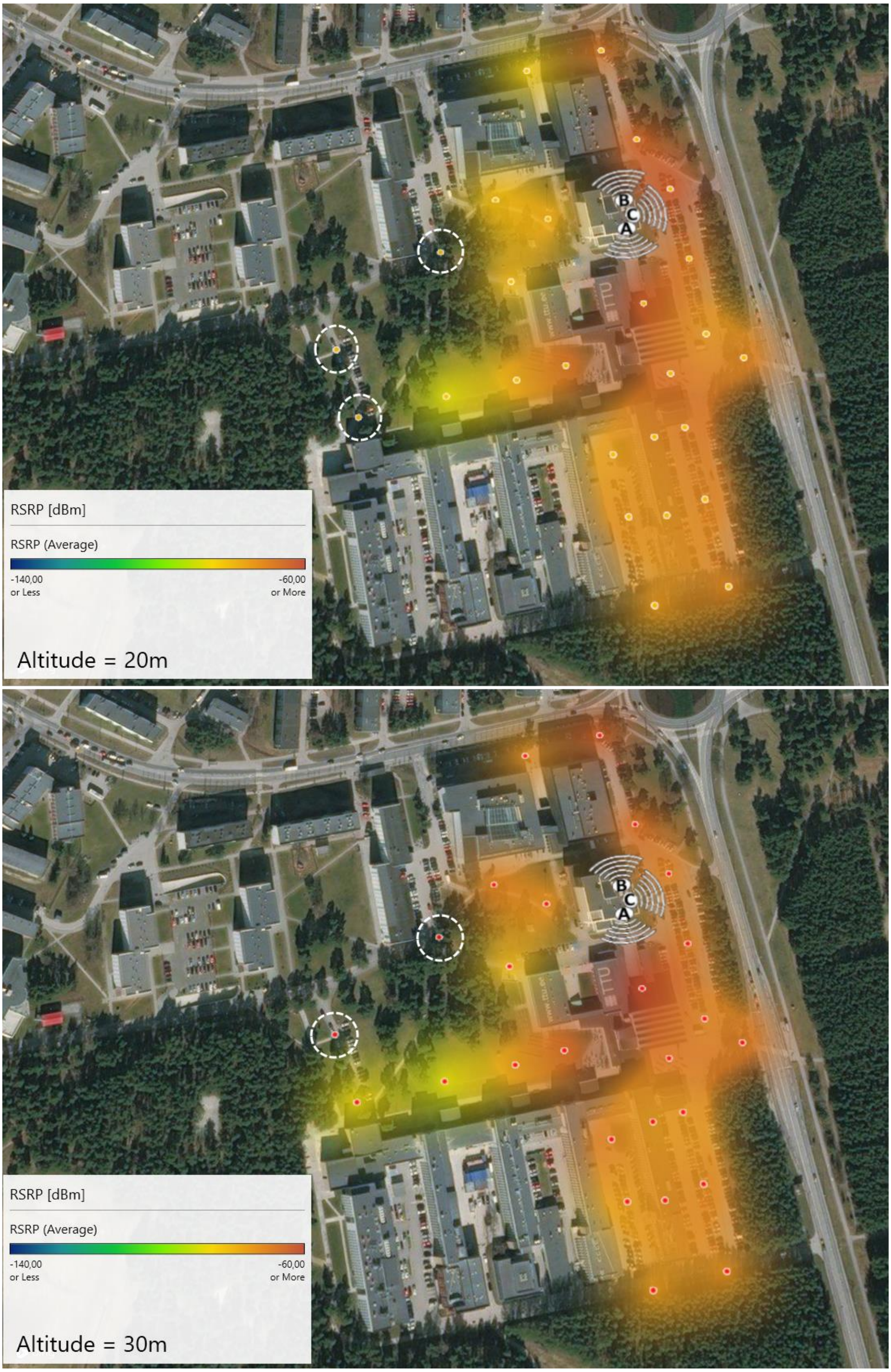


Figure 40. 5G signal coverage heatmaps based on the measured SS-RSRP within TUT campus area at the 20 m altitude (top), and 30 m altitude (bottom).

Figure 41 shows two heatmaps based on the measured average downlink transmission speed for 5G band within TUT campus area at the ground level (top), and 10 m altitude (bottom). As it can be seen, the downlink speed significantly depends on the environmental conditions, and case of moving 5G receiver has a noticeable impact on the downlink speed. Various obstacles, and especially trees also cause a significant downlink throughput. Results displayed on a top heatmap on a Figure 41 demonstrate a predominantly high average downlink speed capabilities of 600–700 Mbps at the ground level depending on the environmental obstacles with few single decreases in blind areas of deployed 5G antennas, as well as within the campus park area.

Although, in case of measurements performed at 10 m altitude, the obtained results shown on a bottom heatmap of the Figure 41 demonstrate a significant downlink speed decrease at most of the areas located aside from the direction of each antenna. The most noticeable downlink speed decrease is observed in open area of the campus park and the front parking area. None of three deployed 5G antennas are directed to both mentioned areas, which indicates that the deployed 5G antennas were installed and set up to provide a proper coverage and performance at the ground level, although, the performance out of the main antenna beam experiences a significant downlink speed decrease. The peak values of measured downlink speed are 777 Mbps at the ground level, and 775 Mbps at the altitude of 10 m.

Figure 42 shows heatmaps of measured downlink speed at altitudes of 20 m (top), and 30 m (bottom). As it can be seen, the altitude increase to 20 and 30 meters leads to a uniform downlink speed decrease. At the altitude of 20 m, a noticeably higher downlink throughput was measured in front of the northern antenna named as “C”, which may indicate that the corresponding antenna is less tilted down compared to other two antennas. At 30 m altitude, the downlink speed measurements demonstrate even more uniform and lower results. The observed peak values of measured downlink speed are 781 Mbps and 739 Mbps at the altitude levels of 20 m and 30 m, respectively.

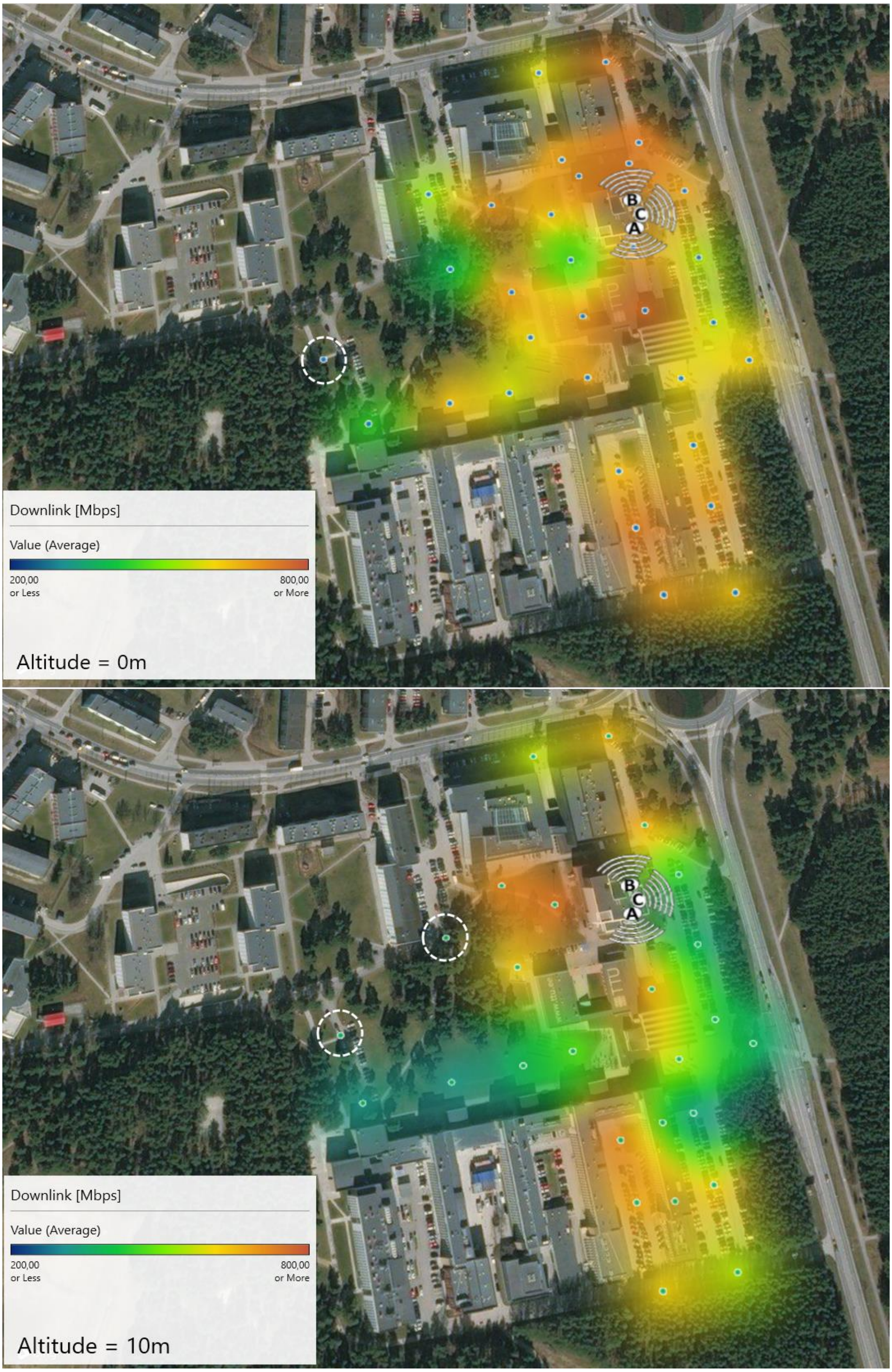


Figure 41. Heatmaps based on the measured downlink speed for 5G band within TUT campus area at the ground level (top), and 10 m altitude (bottom).

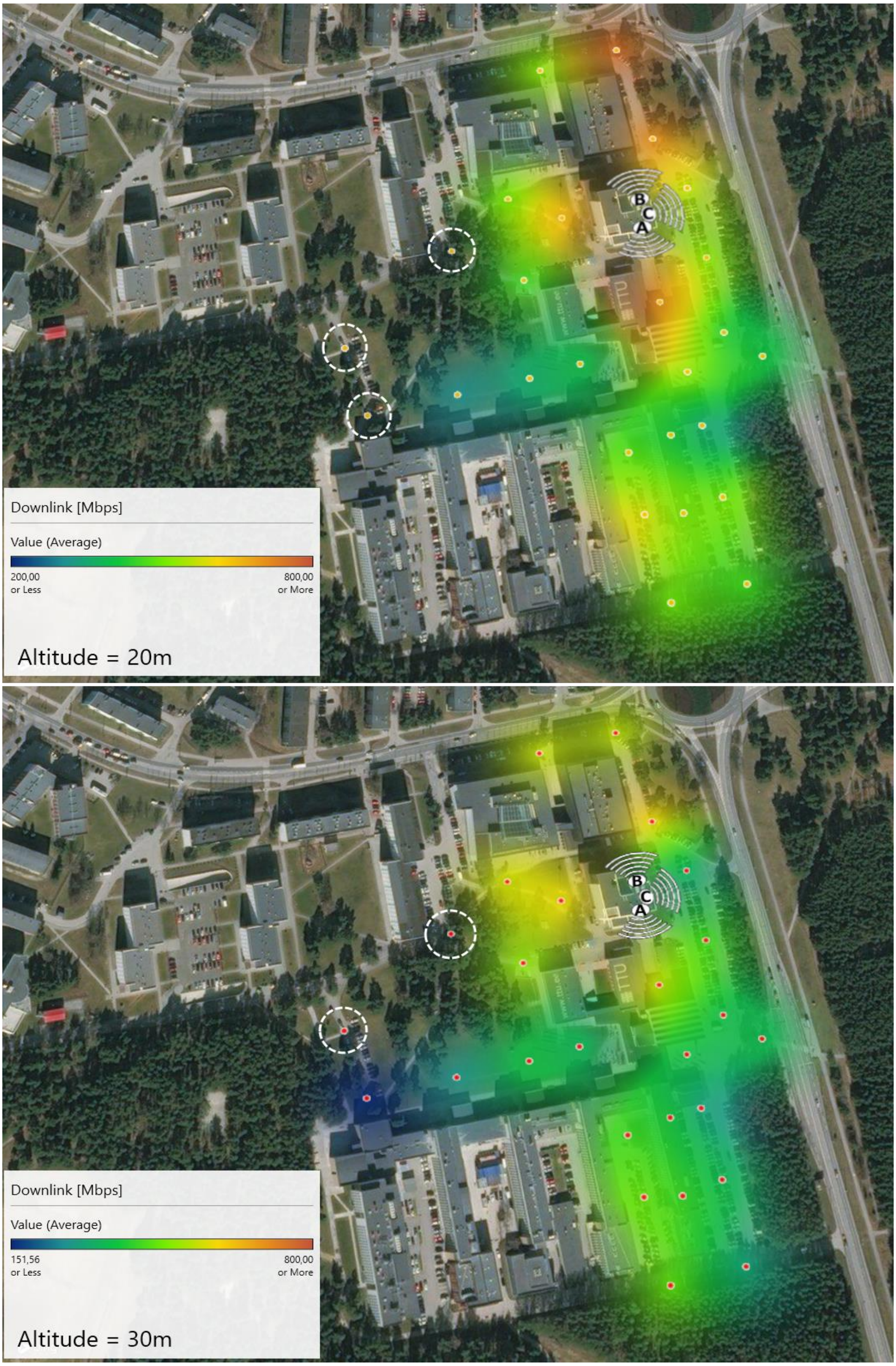


Figure 42. Heatmaps based on the measured downlink speed for 5G band within TUT campus area at the 20 m altitude (top), and 30 m altitude (bottom).

In case of the uplink measurement, the closest environment to the UE and the direct line of sight paly a defining role of the uplink performance. Since the uplink transmission is based on the UE output signal strength capabilities, which in its turn is significantly inferior compared to the base station capabilities, the nearby obstacles are capable to significantly interfere the uplink transmission.

The uplink speed measurement results at the ground level (top), and 10 m altitude (bottom) are shown on a Figure 43. As it can be seen on the top heatmap, the uplink speed is dramatically decreased outside of the antenna line of sigh regardless of the distance to it. In case of both southern parking areas, the line of sight with the antenna is completely blocked by two-storey building, significantly reducing the uplink speed capabilities. Different environmental obstacles, and especially trees, located near the current position of the transmitting UE also affect the uplink capabilities, while in the areas with direct line of sight with the base station antenna, the uplink throughput show the highest and stable results. The measured peak values of uplink speed at the ground level and the altitude of 10 m are accordingly 105 Mbps and 108 Mbps.

At the higher altitude levels, with considerably lower number of different obstacles, the uplink speed capabilities of the UE become significantly higher and uniform. Thus, at the 10 m altitude, the testbed is located above the two-storey building roof level and has a direct line of sight with the base station antenna, which leads to the sharp increase of the uplink throughput capabilities. On the bottom heatmap of the Figure 43 there can be seen only two spots with lower uplink speed measurement results, located near the higher buildings.

The uplink throughput measurement results at 20 m and 30 m altitudes represented as heatmaps are shown on a Figure 44 respectively on top and bottom. Uplink speed measurement results performed at the altitude of 20 m show a minor change compared to the 10 m altitude. At the altitude of 30 m, the performed measurements indicate a slight decrease of the uplink throughput capabilities, since the testbed setup attached to the drone was located above the base station antenna level. Additionally, at all above ground altitudes, the testbed was experiencing a noticeable uplink speed decrease in enclosed areas directly in front of the antenna “A”. The measured peak values of the uplink speed are 107 Mbps at 20 m altitude and 108 Mbps at 30 m altitude.

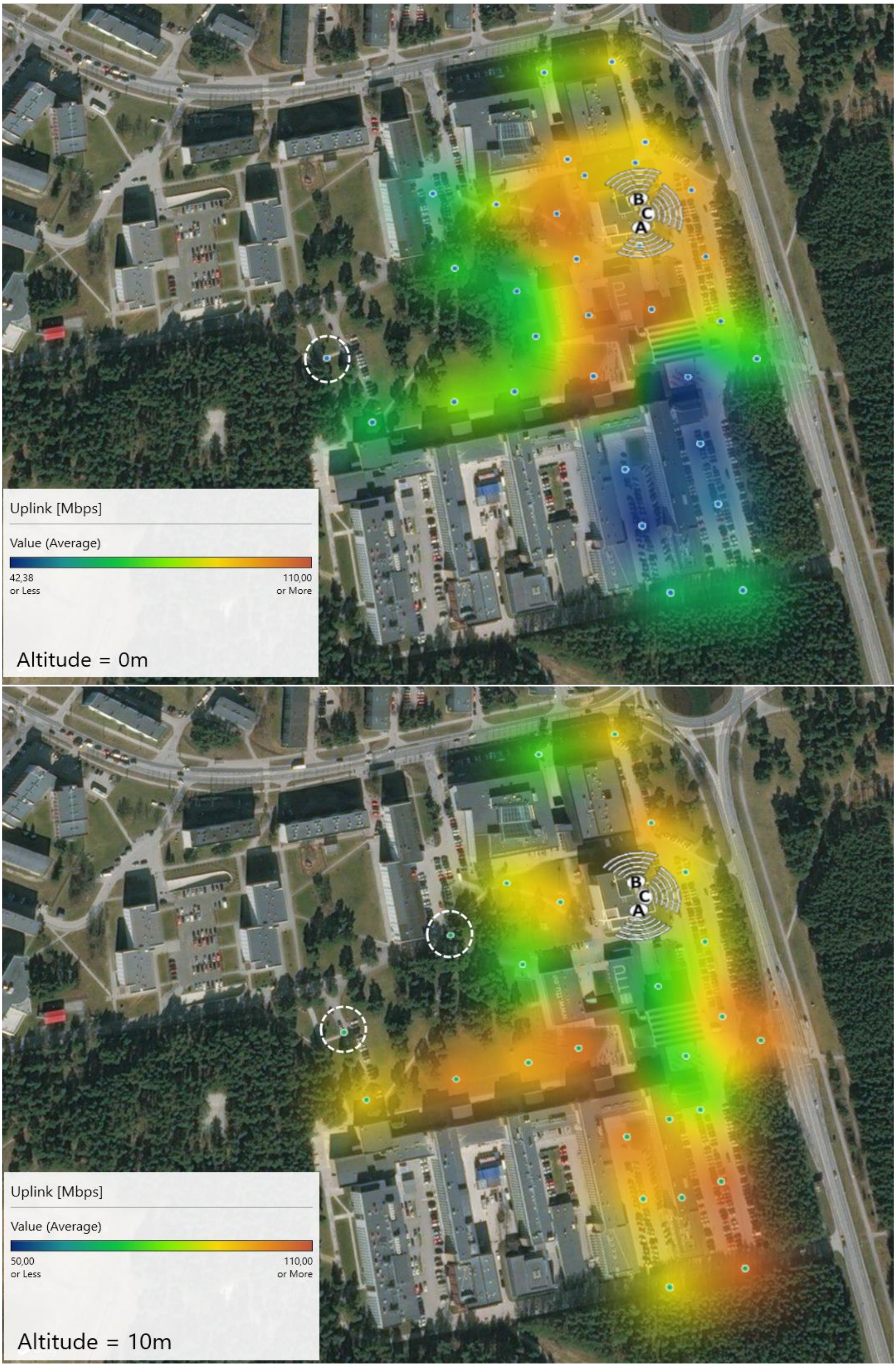


Figure 43. Heatmaps based on the measured uplink speed using 5G band within TUT campus area at the ground level (top), and 10 m altitude (bottom).

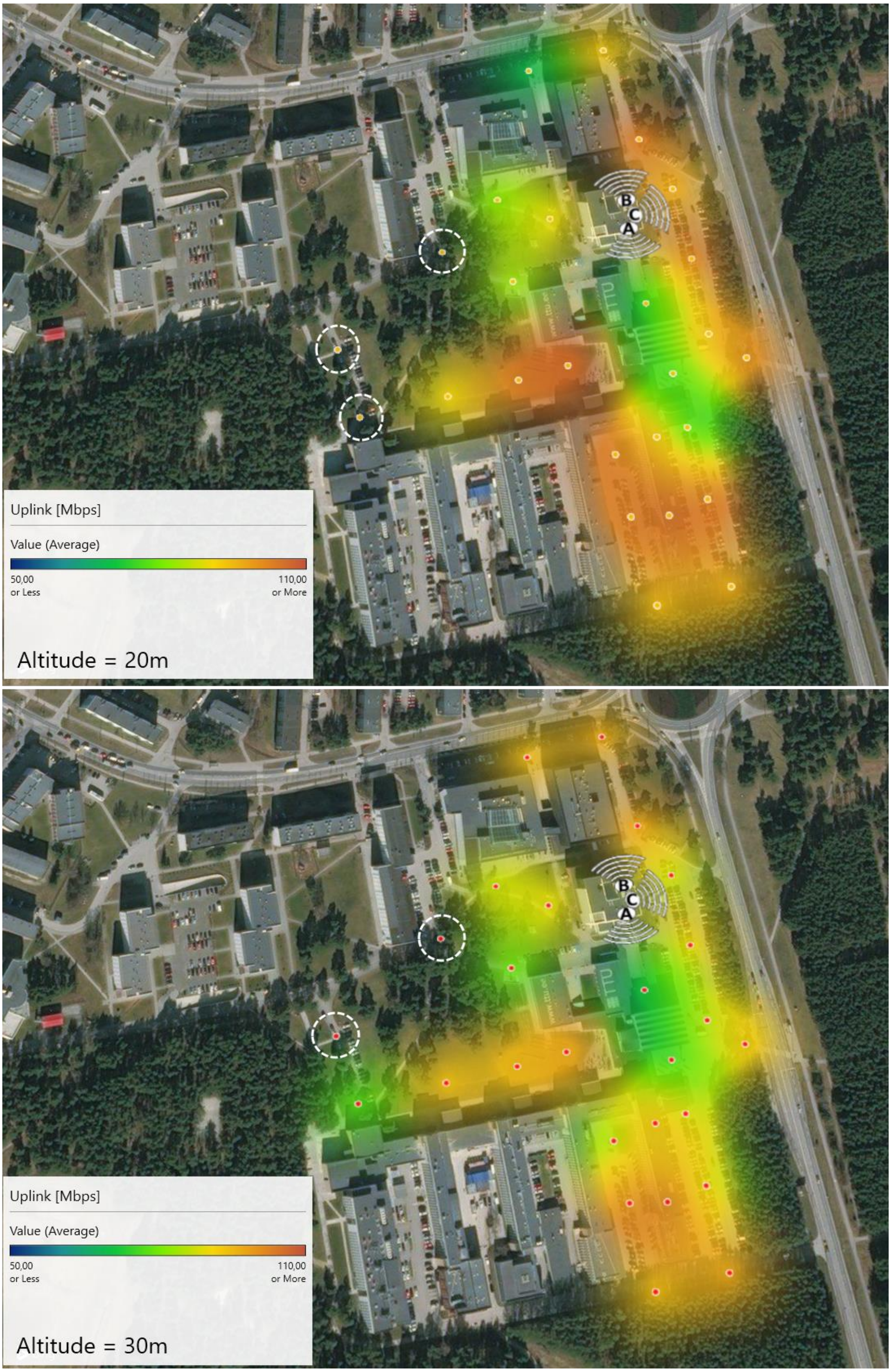


Figure 44. Heatmaps based on the measured downlink speed using 5G band within TUT campus area at the 20 m altitude (top), and 30 m altitude (bottom).

5.2.4 Drone influence on the performed measurements

In order to investigate the influence of a used drone on the aerial measurements compared to the ground measurements performed in the previous subchapter, it was decided to perform an additional set of control measurements with and without use of a drone. Measurements were performed possibly at the exact same position and height above the ground. First set of measurements was performed without use of a drone with the testbed placed at the height of ~1 m above the ground level and includes five performed throughput measurements and continuous signal quality measurements. The same measurements were performed afterwards with the testbed attached to the hovering drone, keeping the attached testbed at the same hight of ~1 m above the ground. For both measurement result sets there were calculated the average values of measured signal quality parameters, as well as measured latency, downlink speed, and uplink speed results. Calculated average values for both cases are shown on a Figure 45 as a column chart.

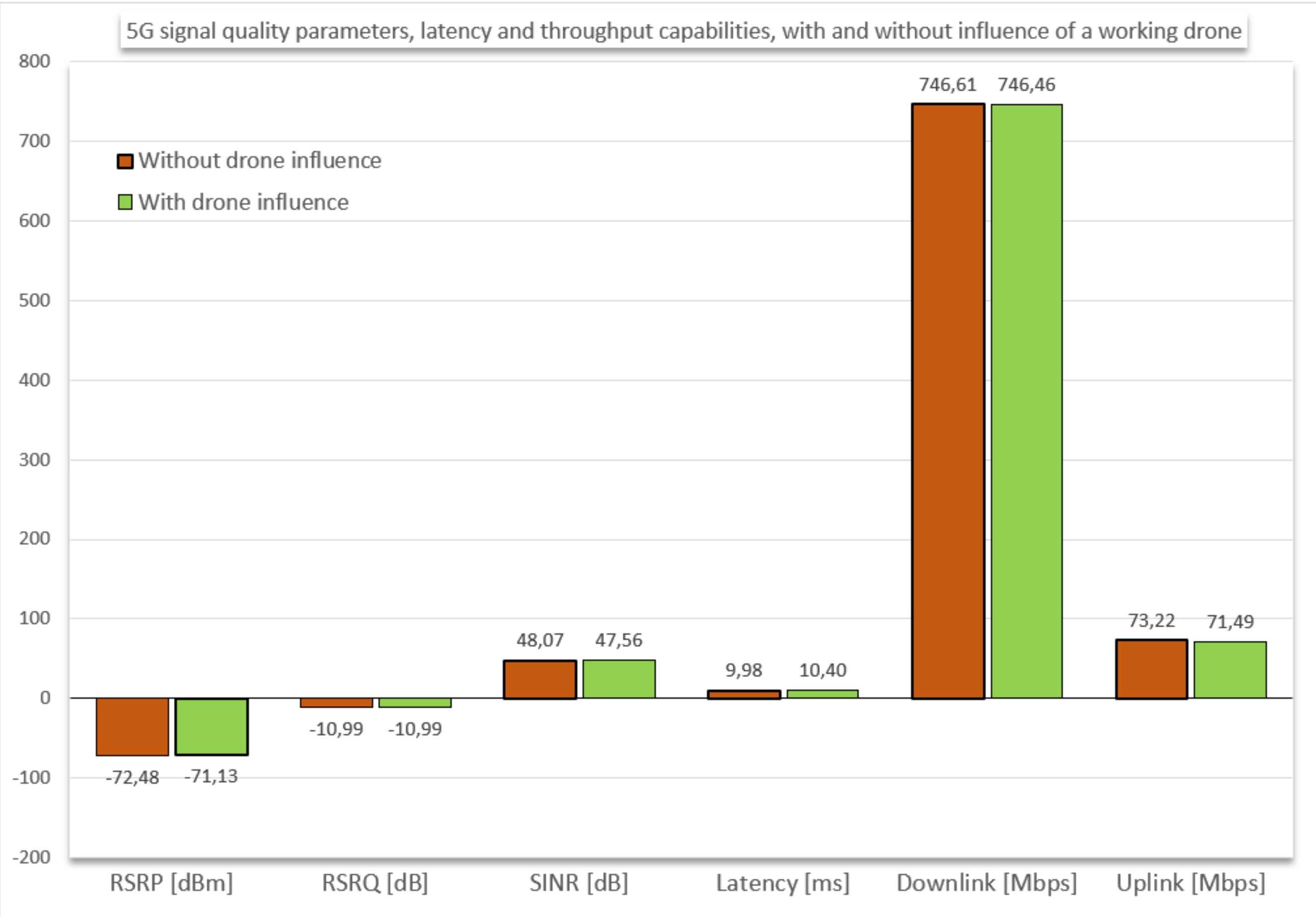


Figure 45. Column chart of the measured signal quality, latency, and throughput parameters with and without the possible influence of a drone.

As it can be seen, the working drone has a barely noticeable influence on the measured RSRP, RSRQ and SINR parameters of the 5G signal, which can be considered as a measurement errors in live environment. In case of the measured latency and throughput speeds, the observed drone influence has the same effect of ~0.5 ms average latency increase, ~0.5 Mbps downlink and ~1.5 Mbps uplink speed decrease, which can be also considered as live measurement errors. Thus, the measured drone influence on the performed aerial measurements is barely noticeable and can be neglected. The same conclusions on the possible drone influence on the 5G connection were made during the "Drone delivered 5G node" project in the city of Jordanstown, UK in 2017, described in the chapter 3.2.2.

5.2.5 Problems encountered

At the later stages of the 5G testbed implementation it was encountered an effect of operating 5G module interference on the GNSS dongle work. Once the 5G module is connected and recognized by processing device, the used GNSS dongle suddenly starts experiencing different errors with the position fixing. It is remarkable that during the interference from the 5G module, the GNSS unit often is still able to detect and receive signals from satellites in view, which is confirmed with the presence of corresponding NMEA $GPGSV sentences. At the same time, the NMEA $GPGSA sentence, which contains cumulative dilution of precision (DOP) information, remains totally empty until the 5G module is disabled.

According to the Intel research of the same effect at the 2.4 GHz frequency [30], while in use, the USB 3.0 connection is radiating a sensible amount of RF noise at high frequencies. Despite that USB 3.0 cables at their length usually are properly shielded, their connectors are not, which makes them RF noise leaking points. Since the GPS signal itself is quite weak and sensitive to surrounding noise, in combination with compact layout of the testbed for the drone, the influence of used USB 3.0 cable may be high enough to jam the GNSS module.

In order to confirm the presence of this effect it was used the USRP SDR receiver tuned to the used GPS L1 frequency of 1.57542 GHz, while the SDR device was placed ~20 cm away from the 5G module.

Before the 5G module was powered up and enabled, the SDR was receiving relatively weak GPS signal. Once the 5G module was enabled and the serial connection over USB cable was established, the previously received GPS signal was completely lost by nearby SDR. Figure 46 shows the spectrogram of the GPS frequency band measured with USRP SDR.

Upper half of the spectrogram represents the received GPS signal before the 5G module was enabled. Bottom half represents the spectrogram reading at the same frequency after the 5G was enabled. A significant spectrum change can be seen at the moment, when the USB connection was established, which indicates that in this case the present GPS signal was fully jammed. Disabling the 5G module removed the interference.

5G module was tested without SIM (Subscriber Identity Module) card and antennas connected, to prevent any attempt of wireless communication from the module side. This effect was noticed and mentioned by different users in various resources, as well as is named as a possible reason of GNSS units malfunctioning [31]. Possible solutions to reduce the radiated RF noise are to shield the USB connectors used by 5G modem, and to move the GNSS module possibly away from the noise source.

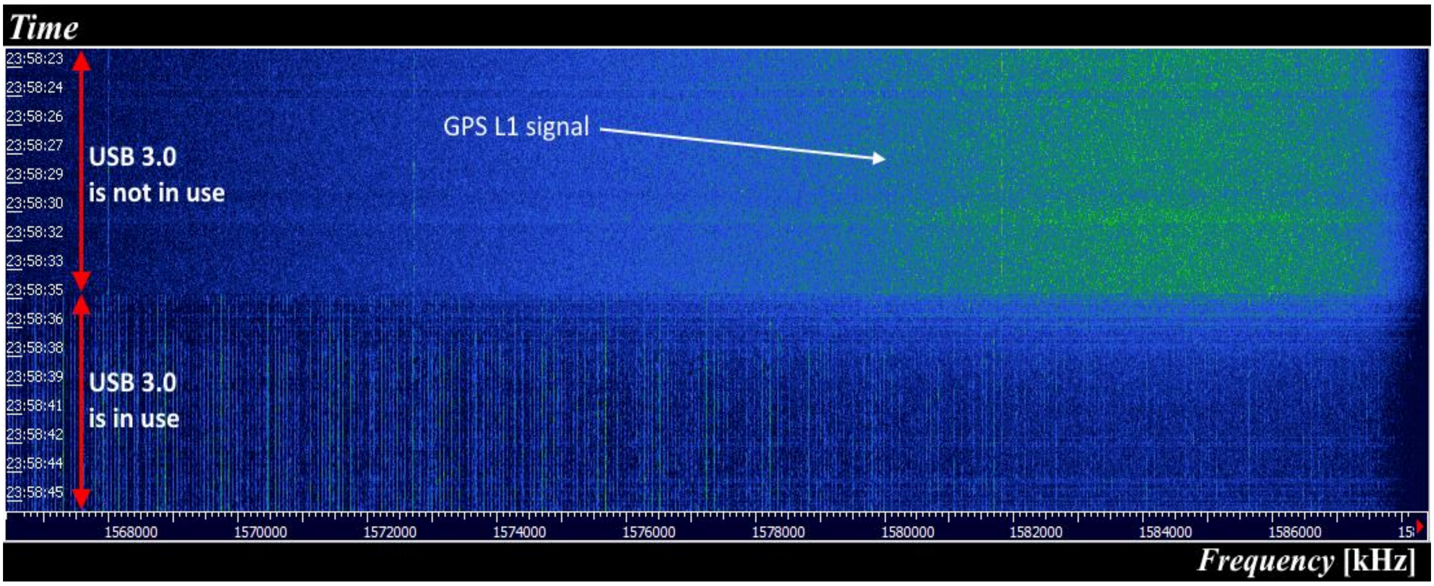


Figure 46. Spectrogram of the captured USB 3.0 RF interference at the GPS L1 frequency, displayed in HDSDR software environment.

Several different positioning solutions were tested during the testbed implementation process. Originally, it was planned to use the build-in GNSS feature of the used 5G module. Both modules developed by Quectel and SIMCom are declared to support the GNSS positioning, which could simplify the overall testbed setup in terms of both hardware and software. Nevertheless, both 5G modules have encountered the same problem of the inability to fix the current position of the device. In both cases there were performed different attempts to provide the optimal conditions for the GNSS module to work, including the use of the proper GNSS antenna, open outdoor area, and sufficient amount of time for the module to fix its position after the cold start. It also includes the actual consultation with the manufacturer and technical support and the module firmware update.

The effect of RF noise radiated by the USB 3.0, encountered at the later stages of the testbed implementation, and described earlier in this chapter, may explain the inability of the build-in GNSS module to work as well. Since the build-in GNSS of the 5G module is enabled after the modem connection is established over USB 3.0, it is highly possible for the GNSS signal to be jammed by the noise immediately after the module was started. Additionally, a very close positioning of the unshielded USB connector to GNSS antenna on the evaluation board increases the level of the RF noise received by GNSS antenna.

During the testbed implementation it was also tested the positioning service available in Windows. Although, this source of device positioning information significantly relies on different wireless access points including Wi-Fi and cellular nodes. Reducing number of access points within the area causes a significant drop of positioning accuracy up to hundreds of meters. Therefore, it was decided to use a separate and standalone USB GNSS dongle.

Nowadays, unmanned aircrafts in Estonia are being regulated by Estonian Civil Aviation Authority (CAA) in aerial security reasons. These regulations are intended to prevent an unauthorized drone flights in restricted areas in avoidance of aerial accidents and possible violations of state security. Many areas in Estonian airspace are counted as restricted or controlled, and drone pilots require corresponding permissions form the CAA to fly within these areas. One of those areas is located around the Lennart Meri Tallinn airport area to avoid any possible drone interference on the aircraft traffic of the airport. Part of this controlled "red" area is shown on a Figure 47. Tallinn University of Technology, marked on a Figure 47, is located right on the way of possible landing or taking off aircrafts, and therefore, in the controlled "red" zone. Within this area, all the UAV flights must be declared and accepted by CAA for a limited and declared period of time, flight area and maximal altitude. It allows CAA to consider all the potential aerial threats while managing the aircraft traffic. In case of this work, all the performed flights were approved by CAA and all the necessary permissions for drone flights within TUT campus area were received. Screenshot of the map of Tallinn with controlled "red" area, shown on a Figure 47 was taken in official "Drooni.app" environment of the CAA [32].

Figure 47. TUT location in the "red" controlled aerial zone of Tallinn [32].

6 Summary

5G is a promising evolution of currently used cellular technologies, which is intended to exponentially increase a throughput capability and decrease the transmission latency of the cellular connection, as well as significantly expand its areas of use covering IoT, real time applications, smart technologies, and massive industrial automation. Low latency and high throughputs, achieved by the 5G technology make it a perfect wireless solution for these areas. UAVs are another example of technology with fast growing popularity, especially in a civil sector, and in combination with only 5G it can lead to hundreds of various innovative solutions in divers' areas of the modern reality.

The purpose of this thesis was to implement an operational, autonomous, portable, and sub-6 GHz band supportive 5G testbed setup, suitable for drones' applications, as well as perform its testing by using an available 5G connectivity in Tallinn University of Technology. This goal was successfully achieved, and the testbed was successfully implemented by using available resources, and in accordance with autonomous operability and portability requirements. Implementation includes both hardware assembly of the testbed, as well as implementation of the specialized and adaptation of already available software.

Implemented testbed was also practically tested on a real deployed 5G live network in various circumstances and conditions to test its operability, as well as to obtain an additional data about the deployed 5G network for Telia. Performed practical tests include a throughput and latency measurements of different provider server selections, overall ground coverage of the 5G signal, as well as signal quality and throughput capability measurements of deployed 5G on ground level and several different altitudes by using a commercial drone.

Results, obtained during the performed measurement campaign indicate that despite the significant antenna tilt the deployed 5G network successfully covers the whole Tallinn University of Technology campus area with the proper 5G signal for the everyday use.

Different throughput capabilities of the 5G network can be achieved depending on the provider server used for the data transmission. While most of the available provided servers show minor differences in the measured latency results, their measured throughput capabilities differ significantly. Among others, the “CompicOU” server has shown the highest throughput speed results, close to 780 Mbps for downlink and 110 Mbps for uplink. Results of the performed aerial measurements show a minor signal quality decrease and significant downlink speed decrease with the increasing altitude, while the measured results of uplink speed indicate its high sensitivity to the environmental obstacles and minor negative influence of the increasing altitude.

With consideration of locally present throughput limitations, the results obtained during the performed measurement campaign are not inferior to results of other testbeds implemented and tested in other countries and mentioned in state-of-the-art chapter 3. Results of the drone influence on the performed measurements test have shown a barely noticeable and negligible interference, which can be considered as expected measurement error.

Testbed was designed flexible for a further upgrading, and thus, it can be expanded with various features and specialized equipment to support and fulfil a variety of additional tasks, which may be required during a further 5G applications and solutions development. Future testbed upgrading perspectives include an integration of various sensors and video cameras to perform additional measurements and recordings, as well as direct video or measured data streaming to the server, as well as remote testbed control over the established 5G connection. Future intentions also include measurements of the 5G signal quality and throughput capabilities on higher altitude levels up to allowed 60 meters within TUT area, as well as under different weather conditions, originally planned to be covered in the current work, which require proper and continuous rain or snowfall. In the later stages of the thesis, it was also received an offer to use the implemented testbed in another TUT project related to the indoor positioning, which can also be considered as another way of the further development.

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Appendix 2 – Source files of the implemented program available in OneDrive

The latest version 0.6.0 of the program specially written for the implemented testbed, with all its source files and code is available online in MS OneDrive file hosting service, and can be accessed by the following link:

https://livettu-my.sharepoint.com/:f:/g/personal/aleksei_fjodorov1_ttu_ee/EgYchZso37NKm7gVjryqD9MB0Vk17B5xIRyd4LOntQS8-w?e=mVckWp

Figure 48 shows the contents of the OneDrive folder accessible with the provided link. OneDrive folder contains the following files:

- .PreviousVersions folder – folder contains source files of several previous versions of the implemented program
- 5G.Testbed_0.6.0 folder – folder contains source files of the latest version of the program at the moment of May 5th 2021.
- 5G.Testbed_0.6.0.exe – compiled executable file of the latest version of the program at the moment of May 5th 2021.
- ookla.exe – copy of the Ookla Speedtest CLI application used in the implemented testbed.

Name	Modified	Modified By	File size	Sharing
.PreviousVersions	2 minutes ago	Aleksei Fjodorov	8 items	Shared
5G.Testbed_0.6.0	April 28	Aleksei Fjodorov	10 items	Shared
5G.Testbed_0.6.0.exe	April 28	Aleksei Fjodorov	138 KB	Shared
ookla.exe	March 21	Aleksei Fjodorov	1.82 MB	Shared

Figure 48. Contents of the linked OneDrive folder.