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5G-NR MEASUREMENTS CAMPAIGN AND CONNECTIVITY ANALYSIS

Master's thesis

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5G-NR MÕÕTMISED JA ÜHENDUVUSE ANALÜÜS

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Author’s declaration of originality

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

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Abstract

5G is the fifth generation of mobile networks that is standardized by 3rd Generation Partnership Project (3GPP). 5G enables higher data rates, smaller latency times and connecting of massive amount of devices to the network. This enables new services that are defined by 3GPP. The three major use cases for 5G are Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC) and Ultra–Reliable and Low Latency Communications (uRLLC).

This thesis concentrates on eMBB and 3GPP Release 15. The aim of this thesis is to measure commercial 3.5 GHz 5G networks with commercial scanner and mobile phones. For coverage and signal quality assessment square analysis is used. As an outcome, a process for evaluating performance of 5G network is composed.

The measurement results show that the coverage areas of 5G networks develop at a fast pace, but that does not necessarily mean better overall network performance and hence user experience. As with denser network the interference level increases and in addition to this, also the amount of users grows, it is vital to have more focus on network optimisation.

This thesis is written in English and is 45 pages long, including 5 chapters, 32 figures and 6 tables.

Annotatsioon

5G-NR mõõtmised ja ühenduvuse analüüs

5G on viienda põlvkonna mobiilsidevõrk, mis on standardiseeritud 3GPP poolt. 5G võimaldab suuremat andmeedastuse kiirust, väiksemat viiteaega ja suure hulga seadmete ühendamist mobiilsidevõrku. Seega on võimalik võtta kasutusele uusi teenuseid, mis on 3GPP poolt välja pakutud. 5G jaoks on välja pakutud kolm põhilist kasutusvaldkonda ning nendeks on edasiarendatud mobiilne lairiba (*Enhanced Mobile Broadband,* eMBB), ulatuslik masintüüpi kommunikatsioon (*Massive Machine Type Communications,* mMTC) ning eriti töökindel ja madala viiteajaga kommunikatsioon (*Ultra–Reliable and Low Latency Communications*, uRLLC).

Antud lõputöö keskendub eMBB ja 3GPP standardile *Release 15* ning selle eesmärgiks on mõõta sagedusel 3.5 GHz töötavaid 5G kommertsvõrke, kasutades selleks kommertskasutamiseks mõeldud skännerit ja mobiiltelefone. Mobiilsidevõrkude katvuse ning signaali kvaliteedi hindamiseks kasutatakse ruuduanalüüsi. Lõputöö tulemusena koostatakse protsess, millega on võimalik 5G võrkude toimivust hinnata.

Mõõtmistest selgub, et 5G võrkude leviala laieneb küll kiiresti, kuid see ei pruugi otseselt näidata võrgu head toimivust ja sellest tulenevalt ka head kasutajakogemust. Kuna võrgu tihenemisega interferentsi tase tõuseb ning lisaks sellele tuleb juurde uusi kasutajad, on tähtis veelgi enam keskenduda võrgu häälestamisele.

Lõputöö on kirjutatud inglise keeles ning sisaldab teksti 45 leheküljel, 5 peatükki, 32 joonist, 6 tabelit.

List of abbreviations and terms

3G	3rd Generation of mobile technologies
3GPP	3rd Generation Partnership Project
4G	4th Generation of mobile technologies
5G	5th Generation of mobile technologies
5G–NR	5G New Radio
BBR	Bottleneck Bandwidth and Round–Trip Time
CN	Core Network
dB	Decibel
dBm	Decibel-Milliwatts
DC	Dual Connectivity
DMRS	Demodulation Reference Signal
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
EPSG	European Petroleum Survey Group
Exabyte	10^{18} bytes
FDD	Frequency Division Duplex
FR1	Frequency Range 1
FR2	Frequency Range 2
Gbps	Gigabits per second
GHz	Gigahertz
GIS	Geographic Information System
gNB	Next Generation NodeB/base station
GSCN	Global Synchronization Channel Number
GSM	Global System for Mobile Communications
HD	High Definition
IP	Internet Protocol
kbps	Kilobits per second
LAN	Local Area Network
LTE	Long Term Evolution
Mbps	Megabits per second
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
mMTC	Massive Machine Type Communications

mmWave	Millimeter–wave
NR	New Radio
NR–ARFCN	New Radio Absolute Radio Frequency Channel Number
NRSRP	New Radio Reference Signal Received Power
NRSRQ	New Radio Reference Signal Received Quality
NSA	Non–Standalone
OFDMA	Orthogonal Frequency Division Multiple Access
PBCH	Physical Broadcast Signal
PCI	Physical Cell Identity
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PRACH	Physical Random Access Channel
PRB	Physical Resource Block
PSS	Primary Synchronisation Signal
PUCCH	Physical Uplink Control Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RE	Resource Element
RMSI	Remaining Minimum System Information
RSSI	Received Signal Strength Indicator
RTT	Round–Trip Time
SA	Stand–Alone
SIM	Subscriber Identity Module
SISO	Single Input Single Output
SS	Synchronization Signal
SSB	Synchronization and Broadcast Signal Block
SSS	Secondary Synchronization Signal
TCP	Transmission Control Protocol
UDP	User Datagram Protocol
UE	User Equipment
UMTS	Universal Mobile Telecommunications Service
uRLLC	Ultra–Reliable and Low Latency Communications

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1 Introduction

The demand for always available data connection and higher data rates is increasing with every year. Current technologies (4G) can provide good data speeds for services that are used every day, like web browsing, downloading large files from the Internet and even watching HD videos, but as the number of users and their expectations to services continues to grow, newer technologies are needed. Currently, next generation (5G) of mobile networks are rolled out to support the growing demand and also to provide new services.

The number of mobile subscriptions at the end of 2020 is 7.9 billion and it is estimated to be 8.8 billion in 2026, where 7.5 billion will be smartphone subscriptions. More than 100 new 5G networks have been opened including standalone (SA) networks. With the growing number of 5G networks also the number of 5G subscriptions has increased and it is forecasted to be 220 million by the end of 2020 and this growth has been faster than it was for 4G. In 2019 the population coverage of 5G was only 5%, one year later in 2020 the coverage is estimated to increase to 15% and in 2026 it should reach to 60% of global population. At the same time the number of 5G subscriptions will be 3.5 billion at it will make 40% of all the mobile subscriptions. The amount of data consumed worldwide in every month is estimated to grow from 51 exabytes in 2020 to 226 exabytes in 2026. Most of the data traffic is generated by smartphones (95%) and video streaming and the data traffic originating from smartphones continues to grow. In 2026 more than half of the data traffic will be transmitted through 5G networks [1].

In 5G new frequencies are available that have never before been used in mobile communications, namely Frequency range 1 (FR1) and Frequency range 2 (FR2). FR1 covers frequencies from 410 MHz – 7.125 GHz and FR2 frequencies 24.250 – 52.600 GHz and even higher frequencies (up to 114.25GHz) will be supported in FR2 in the future [2]. The pathloss on FR2 frequencies, that are also named millimeter wave (mmWave) frequencies, is very high and therefore the service range will be limited. At the same time high throughput can be achieved due to higher bandwidth. FR1 frequencies will be used for traditional mobile traffic [3].

1.1 3GPP Release 15

Besides traditional call and data services that are already used today 5G introduces new services and use cases. Different services may have different requirements, for example some services need very high data rates and at the same time they have no restrictions on latency, in contrary to other services where very low latency is of critical importance. 3GPP has defined three major categories for 5G use cases: Enhanced Mobile Broadband (eMBB), Massive Machine Type Communications (mMTC) and Ultra–Reliable and Low Latency Communications (uRLLC) [4].

The first phase of 5G standards is dedicated to eMBB and its aim is to support services that require high data throughput and low latency, for example mobile broadband and virtual reality [4]. eMBB supports different scenarios like hotspot and wide area connection, where in former case many low mobility users that generate a lot of traffic are concentrated in a small location and in latter case, less users with high mobility are present [5].

mMTC, as the name states, provides machine types communication services. These types of devices generate low amount of traffic that is not time critical and due to low energy consumption can be easily implemented everywhere [5].

Very low latency and very high reliability describe uRLLC type of communication. uRLLC type of services are predominantly machine type communications like driverless or remotely controlled cars, wireless production process and other services that require very good response times and reliability [5].

Release 15 defines minimum requirements that are applicable for eMBB and selection of them are listed in Table 1.

Table 1. Minimum requirements defined in 3GPP Release 15 [4].

Key Performance Indicator	Downlink	Uplink
Maximum data throughput	20 Gbps	10 Gbps
Datarate per user (Dense urban)	100 Mbps	50 Mbps
User plane latency	4 ms	4 ms
Connection density	10^6 per km^2	

1.2 Non–standalone and standalone 5G

Mobile service operators have the option to choose whether to implement 5G only network from the beginning or 5G–4G coexisting network, where the first option is called standalone (SA) and the second option non–standalone (NSA). 3GPP has defined several possible combinations for NSA and SA, with configuration numbers ranging from 1 to 7 [6]. Next, the option 3 (NSA) and option 2 (SA) are described, since the former one is easier to implement, hence attractive to operators and latter one represents 5G only alternative.

In NSA mode (Figure 1 (a)), in addition to 5G base stations, also the 4G base stations and 4G core network are present. In this case, 4G base station acts as an anchor. With this approach the operator can start using the benefits of new 5G air interface without the need to implement new core network. The 5G will use either FR1 or FR2 frequencies and the LTE anchor frequencies below 2.7 GHz. In NSA dual connectivity (DC) mode the user equipment (UE) can send and receive data simultaneously on 5G and 4G and therefore notably increase the throughput [7]. In option 3 the LTE base station is the master node and it takes care of the control signalling [6].

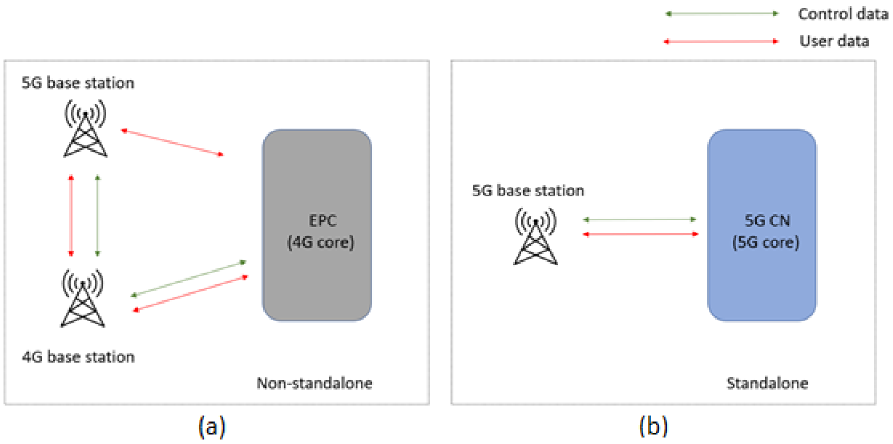

Figure 1. (a) Non–standalone and (b) standalone 5G [6].

SA mode option 2 comprises of 5G base stations and 5G core network (Figure 1 (b)). The throughput may initially be lower when only one lower band carrier is used for SA, compared to the case where multiple LTE carriers are used for NSA. However, the latency will be smaller in SA configuration, especially if no low latency features are utilized in LTE access network. Option 2 SA networks are possible candidates for dense urban environments where more capacity is needed along with low network latency. In order to minimize handovers between different technologies and thereby provide better service, carrier aggregation with at least one low band Frequency Division Duplex (FDD) carrier is needed [6].

1.3 5G parameters

In this chapter, an overview is given for 5G specific parameters starting with the description of the subcarrier spacing, then the synchronization signal block (SSB) is described along with the channel number that corresponds to it.

Orthogonal frequency division multiple access (OFDMA) that is used in 5G divides the available carrier into smaller parts named subcarriers. The bandwidth of one subcarrier is called subcarrier spacing (numerology). The advantage of dividing one big carrier into multiple smaller carriers is that it helps to reduce the effect of frequency selectivity. In multipath propagation the received signal may not have the same power over all bandwidth and therefore using subcarriers can help to reduce this effect [8].

The subcarrier spacing is inversely proportional to symbol duration and by using different subcarrier spacings it is possible to satisfy different requirements of Quality of Service (QoS). For example, for URLLC services that require very low latency, shorter symbol period and therefore wider subcarrier spacing can be used. On the contrary to provide larger service area, longer symbol duration (and narrower subcarrier spacing) can be used [8].

In 5G multiple subcarrier spacings (Table 2) are possible compared to 4G where only 15 kHz subcarrier spacing is used. In lower band (FR1) 15, 30 and 60 kHz numerologies are available whereas 60, 120 and 240 kHz numerologies exist for higher band (FR2). It is also possible to combine different numerologies on same carrier frequency – this is known as bandwidth parts [9].

Table 2. Subcarrier spacings in 5G [8].

Index μ	Subcarrier spacing Δf [kHz]	Cyclic prefix
0	15	Normal
1	30	Normal
2	60	Normal, extended
3	120	Normal
4	240	Normal

Bandwidth part is a subset of contiguous common resource blocks for a given numerology on a given carrier. A UE can have maximum four bandwidth parts configured and only one of them can be active at a given time. This applies for both downlink and uplink [10]. Having different bandwidth parts available may be useful in situations where user devices with different requirements to the service and also with different capabilities can be assigned appropriate amount from available bandwidth. For example, there may be simultaneously in the network user devices (for instance high end smartphone) that require full bandwidth for data transfer and at the same time devices with lower complexity and high requirements for energy saving, that need smaller part of it. Another example could be a mobile phone that is connected to network. When in idle mode, only low throughput and narrow frequency band is required to retrieve the system information and listen to paging information, but after switching to connected mode higher throughput and more bandwidth is needed. Due to different bandwidth parts it is possible to dynamically switch between them when state of the mobile phone changes [8]. Based on 3GPP Release 15 a carrier may be comprised of up to 3300 subcarriers and therefore the carrier bandwidth depends on the subcarrier spacing – in case of 15 kHz subcarrier spacing, the maximum bandwidth can be 50 MHz, for 30 kHz maximum 100 MHz, for 60 kHz 220 MHz and for 120 kHz subcarrier spacing maximum 400 MHz. With carrier aggregation it is possible to increase the bandwidth even further [11].

With the use of higher frequencies, the attenuation is increasing. As a result, obtaining sufficient signal to noise ratio and high throughput is becoming challenging. Thus, one possible solution would be using beamforming on next generation nodeB (gNB) and UE side, especially in line of sight conditions. In 5G, beamforming is used besides data transmissions also for initial access and for transmitting the broadcast signals [5].

When UE accesses the network, first it needs to search for a cell, then synchronize it and identify the cell and finally retrieve basic system information. Cell search procedure is also necessary to enable mobility of the device, for example for handovers and cell reselection. UE has to detect two synchronization signals (SS) in downlink: the primary synchronization signal (PSS) and the secondary synchronization signal (SSS). Basic system information can be retrieved in downlink from physical broadcast channel (PBCH) and the remaining minimum system information (RMSI) that is required to access the cell is retrieved from physical downlink shared channel (PDSCH) [5].

SS, PBCH and demodulation reference signal (DMRS) for PBCH form SS/PBCH block (SSB). That block is broadcasted periodically [5]. DMRS is used for channel estimation and power measurements [8]. Besides synchronization signals, Master Information Block (MIB) channels are also transmitted periodically and they are the only always-on signals in 5G [12].

SSB (Figure 2) is comprised of 20 physical resource blocks (PRB) (this is 240 subcarriers) in frequency domain and 4 orthogonal frequency division multiplexing symbols in time domain. The PSS and SSS are located in the middle of the first symbol and third symbols, respectively and both of them contain 127 resource elements (RE). PBCH and DMRS are situated in the second and fourth symbol (240 REs in each symbol) plus additional 48 REs in the beginning and end of third symbol. After the PSS and SSS are found by the UE, the frequency and relative timing of PBCH is also known. The placement of SSB is usually outside the center of carrier [13].

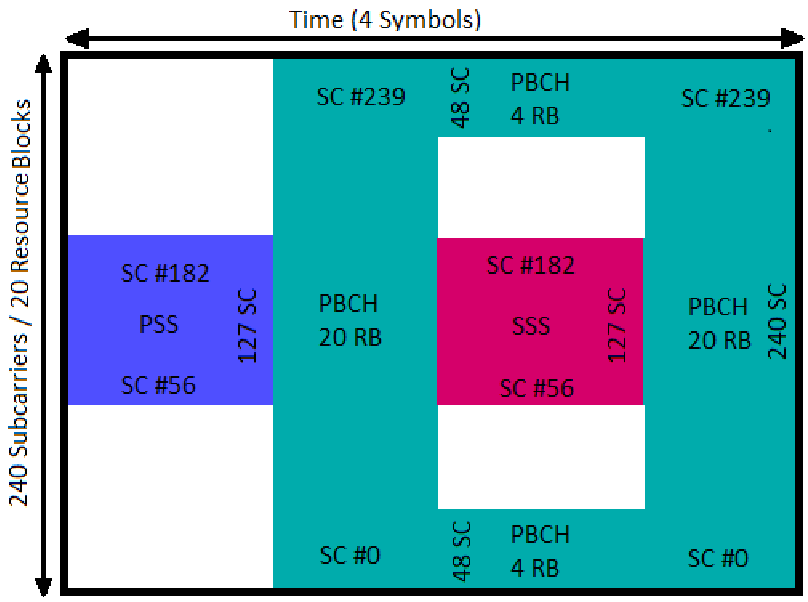

Figure 2. Structure of SSB [8].

Initially, when the mobile accesses the network, its direction is not known. Therefore, the beams that contain the signals that are necessary for initial access (Figure 3) procedure need to cover the whole sector. These signals are carried by SSB and their purpose is to provide time and frequency synchronization as well as basic system information on how to access the network, the physical cell identity (PCI) and where to find further information related to configuration. The beams that carry SSB form a SSB set and this set is then repeated with fixed periodicity. The periodicity for initial cell selection is 20 ms [5].

During accessing the network, if UE has no information about the location of the SSB, it starts searching the synchronization signals. As the channel raster granularity in 5G is only 5 kHz, compared to 100 kHz in LTE, it would be time consuming to find the SSB if it was placed in the center of the carrier. Therefore, the UE looks for the SSB in the locations determined by synchronization raster, that is sparser compared to channel raster. Global Synchronization Channel Number (GSCN) is related to global synchronization raster and it indicates the frequency of SSB. For FR1, different radio frequency channel raster spacings are present and therefore the frequency locations are at every 1.2 MHz with 15, 150, 250 kHz offset. In every band multiple GSCN locations are possible and the location is the center frequency of the SSB (NR-ARFCN). The channel raster depends on the band: for the bands where 5G and 4G are co–existing, channel raster of 100 kHz is used, in other bands where only 5G is present the channel raster is dependent on the subcarrier spacing. Unlike in LTE, where the location of the synchronization signals is in the center of the carrier, in 5G the location of SSB can be outside of the center of the carrier [13], [14].

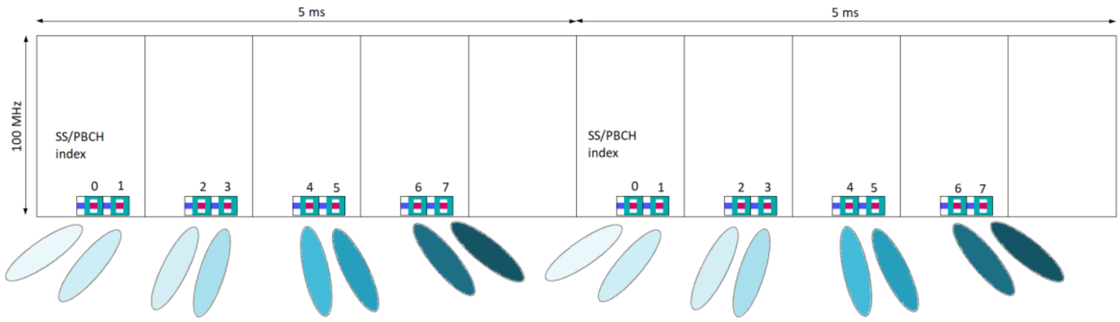

Figure 3. SSB transmitted on different spatial beams [8].

1.4 Motivation

The propagation of the radio waves is affected by the surrounding environment. The 3.5 GHz frequency has never before been used for mobile communications and likewise the number of measurements performed in this band is still very limited. Therefore, the motivation of this thesis is to provide additional information by providing new measurements in commercial 3.5 GHz 5G networks. Moreover, the results are analysed thereafter.

For coverage estimation the most straightforward approach would be calculating the average as well as maximum and minimum of measured points. As there may be variations in driving speed (due to traffic or road conditions) during the measurements, on some parts of the route more measurement points may be collected compared to other parts of the route. Calculating average values over measured points can lead to statistics that is distorted. Therefore, an alternative solution would be calculating signal strength values inside fixed geographical locations (squares). With this approach, it is possible to minimize the effect of multiple measurement points captured inside a small geographical area that could disfigure the final statistics.

In this thesis the measurements are carried out in commercial 3.5 GHz 5G network and a process is developed for performing the square analysis with open source software. With the results of square analysis the coverage areas are studied. Also, the data performance is examined.

2 State of the art

5G technology is still new and evolving hence little information can be found in literature specific to measurement campaigns and result analysis of commercial FR1 networks. Nevertheless, below an overview of related work is given.

In [15] the coverage of 5G at 3.5 GHz with massive Multiple Input Multiple Output (mMIMO) and beamforming is studied and compared with the propagation on 2.1 GHz (LTE). As the frequency increases, the pathloss also increases and therefore beamforming is a good remedy against this phenomenon. The measurements are carried out in an urban environment where one antenna array (5W micro cell prototype) is used. This antenna array is then installed to three different locations to simulate different scenarios: in first scenario the chosen location is on the wall of a building (8 m height to present micro cell case), in the second scenario the location is on top of the roof (20 m height to present macro cell case) and in third scenario the antenna array is installed on a mast that is on top of a small hill, to provide line of sight and open area coverage.

According to the measurements, very good coverage and downlink throughput can be achieved in the bore sight (+/- 60 degrees) and also some signal level is expected behind the building due to the reflections. In line of sight conditions up to 1.2 Gbps in downlink direction was measured. In non–line of sight scenario at the distance of 380 meters from the antenna the throughput of 200 Mbps was measured. In open area at the distance of 700 meters from the antenna throughput of 700 Mbps is possible as a best case, while 100 Mbps is possible at 1 km from the antenna in non–line of sight case. Next, the coverage predictions for indoors were made for older and newer building types and then compared with real life measurements. According to the authors, a good coverage is possible inside old buildings. 8 decibel (dB) was taken as outdoor to indoor loss for performing the predictions. For newer buildings, with energy saving glass, 22 dB was taken as outdoor to indoor loss. The measurements show that the estimated outdoor to indoor loss (8 dB for old building and 22 dB for modern building) is correct and sufficient signal level is possible inside buildings using 5G at 3.5 GHz.

In [16] the authors present link budget calculations to define the minimum required signal strength at the cell edge and the coverage area prediction based on that, for a 3.5 GHz 5G NSA suburban area in Sydney, Australia. After that, the prediction is compared with the measurements to assess its validity. Based on link budget calculations downlink throughput of 200 Mbps is assumed with signal strength -90.62 decibel–milliwatts (dBm). The antenna center line was at 27.77 m and electrical downtilt of 3 degrees was used, to minimize the interference between backlobes. At the same time, no mechanical downtilt was used. Antennas with 8 elements were used and also 8 SSB beams with beam indexes ranging from 0 to 7. As an example, a picture of 8 SSB beams was given in Figure 3.

Signal strength (NRSRP) and quality (NRSRQ) of the scanner and downlink throughput, uplink throughput, latency and NRSRP of the UE were captured. The NRSRP (SS–RSRP) is the linear average over the power contributions (in Watts) of resource elements of SSS. NRSRQ (SS-RSRQ) is the ratio of N*SS–RSRP/RSSI, where N denotes the number of resource blocks of the 5G NR carrier Received Signal Strength Indicator (RSSI) measurement bandwidth [17]. Measurements with the scanner were performed as drive test, data throughput tests were done stationary. More than 20 dB variations in signal strength close to the site were observed where due to multipath propagation fast fading is dominant. After applying Lee's method, the fast fading component is eliminated and slow fading component remains. With Lee's method,

Measurements showed that it is possible to reach 200 Mbps at signal strength of -91 dBm and also predicted signal strength values correspond to measured values after applying Lee's method. Finally, it was concluded that it is possible to use LTE planning techniques for 3.5 GHz 5G planning.

In [18] extensive LTE measurement campaign is described, where coverage, latency (user and control plane) and handover execution time are evaluated. The aim was to compare the performance of the LTE networks with the design requirements for LTE service and use the measurements to calibrate radio propagation prediction tool. Drive test route covered urban, sub urban and rural areas and commercial radio network scanners and smartphones were used to assess functioning of four different mobile operator networks in Denmark. The measurements reveal that the user plane latency is two times higher than the requirements for LTE and this comes mainly from the core network (and not radio network). At the same time observed control plane latency was within the required margins. The authors conclude that mobile edge computing and network slicing could help reduce Round Trip Time (RTT) in next generation (5G) networks. As handovers in LTE follow the “break before make” principle that causes interruptions in data transfer (measurements show median value of 40 ms), the authors find “make before break”, multi-cell-connectivity and synchronized handovers are necessary to support mission critical services in 5G. Simulation results showed that LTE coverage is adequate for most of the users, but for connected mobility denser network is required for 5G along with micro and macro diversity.

In [19] 5G mmWave and 2.5 GHz measurements are conducted in several locations in the USA in different operators networks. Different test cases are described: stationary and mobile testing, also application performance is evaluated. The measured average downlink throughput in mmWave networks was almost 2 Gbps while in 2.5 GHz network it was significantly lower, being around 500 Mbps. This was achieved with 8 parallel transfers, but with only one Transmission Control Protocol (TCP) connection the achieved throughputs were lower. At the same time uplink speeds were much lower being maximum 60 Mbps. As the measurements were conducted in NSA networks where 5G is on top of 4G, the RTT times stay on the same level as in 4G. The authors also find that 5G channel is shared between users as in 4G and therefore the maximum throughput may be only half in case of two devices transferring data at the same time.

In non line of sight cases the mobile phone made handovers from 5G to 4G due to high penetration losses on mmWaves and even the human body or hand can initiate handovers. Even rain can decrease data throughput on high frequencies when the distance is 50 meters from antenna (median throughput decreased 30%). At the distance of 25 meters, the effect on throughput was small. During mmWave walk test, the phone frequently made handovers between 4G and 5G that caused big variations in download speeds (between 0 and 954 Mbps) and the same thing happened in drive test, in contrast to 2.5 GHz where the variations were smaller. The authors also did location based throughput predictions and came to a conclusion it is difficult to predict the throughput due to high sensitivity of mmWaves.

Multiple key performance indicators like signal strength and quality, handover performance, data throughput and latency are studied in [20]. Besides these also quality of experience of services like 4K video and smartphone energy consumption is examined. The measurements are carried out in a campus 3.5 GHz 5G NSA network where 6 base stations are installed. Although 5G network is dense in given area, coverage holes still exist. The authors assume the reason for this is higher frequencies used. Testing shows that in dense urban environments the coverage radius in 5G network is 230 meters – this is the distance where mobile phone disconnects from network. The indoor and outdoor measurements reveal that on higher frequencies (3.5 GHz in 5G) the data throughput drop is more notable compared to lower frequencies (1.8 GHz in 4G), 50.59% versus 20.38%, respectively. The authors also find that the current handover strategy in 5G is not efficient as the quality after cell change may deteriorate. Also, the handover times in NSA case (5G to 5G) can be long compared to 4G–4G and 4G–5G cases due to abundant signalling process.

Next the data throughput for User Datagram Protocol (UDP) and TCP were analysed and RTT times were measured. The throughput for UDP remained around 900 Mbps in 5G throughout the day whereas in 4G at night the speeds increased from 130 Mbps to 200 Mbps. The explanation for this was more PRBs were assigned for measurement phone as there were less users in network at late night. With TCP different algorithms (Reno, Cubic, Vegas, Veno) were used and only one (Bottleneck Bandwidth and Roundtrip Time, BBR) gave high bandwidth utilization of 82.5%, when with some algorithms the bandwidth utilization was as low as 12.1%. The handover from 5G–4G and 5G–5G had high impact on data throughput and at the same time 4G–4G handover had significantly lower impact. The RTT times in 5G were lower than in 4G and the difference becomes smaller as the distance to the measurement server increases.

In [21] 7 pre–commercial 3.5 GHz 5G base stations and UE prototypes are used. The maximum measured downlink throughput was 2.84 Gbps with 64 QAM and 3.79 Gbps with 256 QAM. In both cases eight data streams were used. Measured maximum throughputs were lower compared to theoretical values due to the interference between parallel data streams and as a result coding rate and modulation order are decreased. For comparison, maximum downlink throughput in 2.6 GHz 4G network was 110 Mbps using 64 QAM and two spatial layers. With 16 UE’s spread across a cell, peak data rate of the cell was 4 Gbps and that is 100 times higher than in 4G. In the uplink maximum throughput was 388 Mbps using 64 QAM and four data streams. The maximum service radius of a base station was determined by the distance where PBCH, Physical Downlink Control Channel (PDCCH) and Physical Uplink Control Channel (PUCCH) connection was lost. In 3.5 GHz 5G this happened at 676 meters and in 2.6 GHz LTE at 452 meters. The service radius in 5G was bigger because 3D–MIMO and beam sweeping were used.

Besides 5G measurements, papers can be found where 4G measurements are described. The performance of on operator's LTE network on different types of roads in Croatia was measured and the compared to the standards in [22]. The measured values (received signal level, quality or RTT) were divided into four categories: Excellent, Good, Mid Cell, Edge Cell. On the highways and state roads the downlink throughput, received signal strength and quality and ping times were well below expected values, for example the average downlink speeds varied between 5.27 Mbps and 17.48 Mbps and the average signal strength was below -90 dBm. On local roads higher average downlink throughput was measured, reaching up to 40.18 Mbps. The authors come to a conclusion that the service of the LTE network does not meet the reference values specified in LTE standards.

In [23] measurements are conducted in LTE 1800 MHz network in Kosovo to estimate the penetration loss of a vehicle. 6 mobile phones were used, where three of them were placed inside and other three outside the vehicle and signal strength, block error rate, data rate and quality of service of 3G and 4G networks were measured. The penetration loss in urban environment was between 1.88 and 3.83 dB, while in suburban and rural environments it was between 2.13 and 4.38 dB and even higher in some cases. The variations in penetration loss were caused by the orientation of the car and also by multipath propagation.

In literature papers can be found that describe mobile network measurements, both for precommercial 5G networks and operational 4G networks. The information on commercial 3.5GHz 5G network measurement campaigns, where both commercial measurement scanner and mobile phones are used, is still limited.

3 Measurement setup in FR1

In this chapter an overview is given on how the equipment was set up and how the measurements were performed. First, the equipment that is used for mobile network benchmarking is introduced. Next, a general overview of the measurements is given along with the description of how the equipment was set up and after that information is provided on what parameters were configured for scanner. A more detailed explanation on these parameters can be found in Chapter 1.3. Also, a brief summary is given of the capabilities of the scanner. Then the structure of the measurement scripts is provided that are necessary to carry out testing with mobile phones.

3.1 Equipment used in measurement campaigns

General approach for benchmarking mobile networks is to use a scanner and mobile phones. Scanner is used for coverage measurements and it does not require SIM card for operating, therefore it is network independent. It allows to scan multiple technologies (GSM, UMTS, LTE, 5G) and frequencies simultaneously. As there are limitations in scanner's scanning capabilities it is good to measure only these technologies that are necessary in given measurement campaign. This way more scanning resources are available for systems of interest and no resources is spent on scanning unnecessary technologies.

In 5G, with scanner it is possible to measure always on signals, namely PBCH, PSS and SSS. To measure rest of the channels that are related to UE, a mobile phone is needed. The channels related to mobile phone can be for example PUCCH, Physical Uplink Shared Channel (PUSCH), Physical Random Access Channel (PRACH) [24].

3.2 Overview of the measurements

The measurements were done as drive test in operational commercial 5G networks in Finland. Two operators were measured simultaneously. For this, two commercial mobile phones (OnePlus 7Pro 5G) were used to evaluate RTT, downlink and uplink speeds, signal strength (SSB-RSRP) and quality (SSB-SINR) for both operators. At the same time, signal strength (SSB-RSRP) measurements were done with the scanner.

The drive test was performed for the first time in May 2020 and it was repeated the same year in September. The measurement route was located in urban environment of Turku, Finland, concentrating on areas where the two operators had advertised their 5G coverage on their coverage maps. These coverage maps can be found on both operator’s web pages.

The terrain in measured area has no drastic elevation differences and the buildings have mostly less than 10 floors (Figure 4). A river flows through the city that divides the measurement route into two parts.

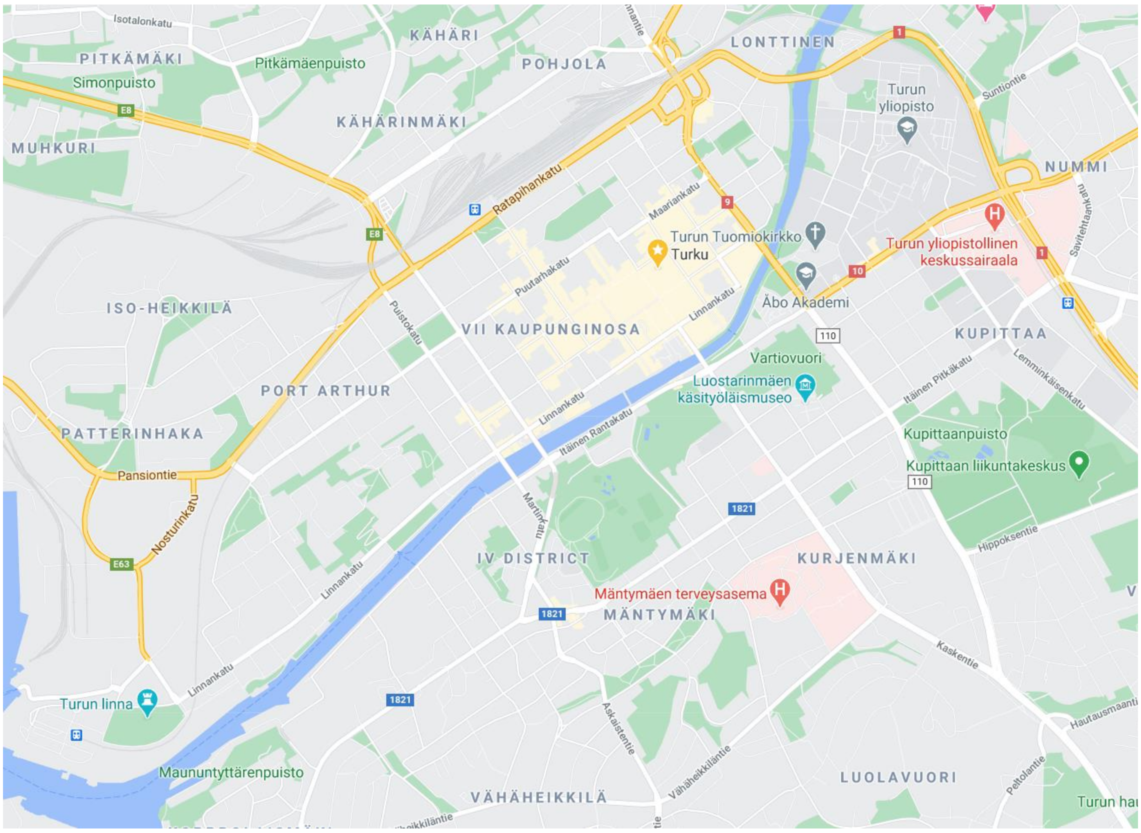

Figure 4. Measurement area.

3.3 Overview of measurement equipment setup

The measurement equipment consisted of 5G capable scanner from Rohde&Schwarz (model TSME6) with Nemo Outdoor measurement software and two mobile phones that had measurement software (EchoOne) by Enhancell installed. The scanner and phones were used simultaneously during the measurement campaign. A laptop (Dell Latitude 5400 with Windows 10 operating system) was used to control the scanner and to see current measured values. At the same time, the phones performed data test and operated independent of each other. The measured downlink and uplink speeds and signal strengths were visible on phone’s screens. The scanner had an omnidirectional RF antenna for signal strength measurements and a GPS antenna for assigning the coordinates to measured values.

Laptop was connected to scanner via LAN port using Cat5 patch cable. The antennas were placed on top of the roof of measurement bus leaving at least one wavelength from the corners of the roof (Figure 5).

Figure 5. GPS (left) and RF (right) antenna of the scanner on the roof of measurement bus.

As for the frequency 3500 MHz the corresponding wavelength is approximately 10cm, this was chosen as the minimum distance from the corners [25].

The phones were installed on the window (Figure 6) inside the measurement bus to provide best possible radio conditions and also to ensure sufficient signal for positioning.

Figure 6. Placement of the mobile phones on window and USB hub (inside yellow box).

The measurement software used for scanner and phones was the most up to date available by the time of measurement campaigns. Besides that, the latest operating system available for the phones (Android 10 Oxygen OS 10.0.5.GM27BA in May and Android 10 Oxygen OS 10.0.7.GM27BA in September) had also been installed to ensure best performance possible. Earlier versions (Android 9) caused mobile phone to make frequent handovers between 5G and 4G and also in some cases the serving system was wrongly detected by measurement software. The UE's were commercial off the shelf mobile phones.

Inside the measurement bus four base station backup batteries were installed in parallel to provide electricity for devices (Figure 7). Power inverter was used to transform the direct current from batteries to alternating current. Through the USB hub two phones were fed with power.

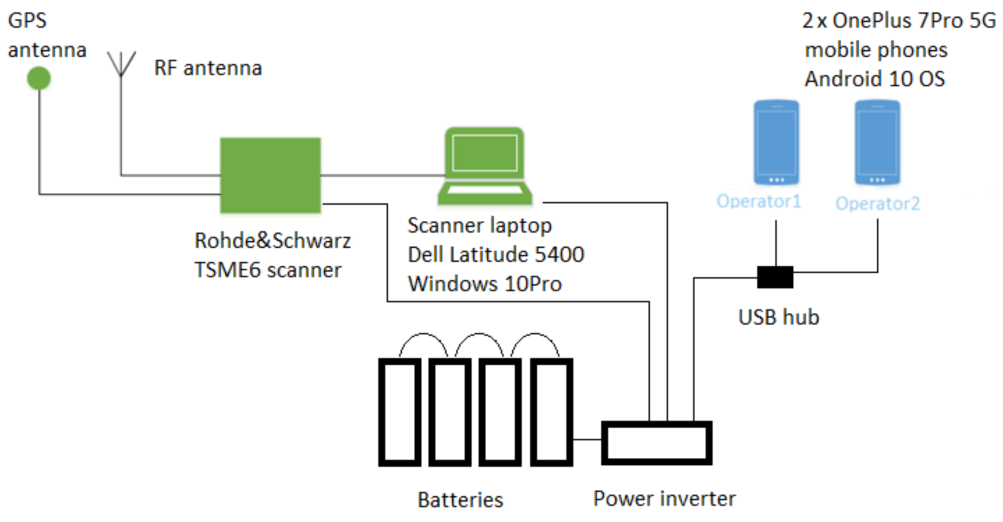

Figure 7. Measurement equipment setup.

3.3.1 Initial setup of the laptop

Before connecting the scanner to the laptop, the laptop with Windows 10 OS had to be configured. For this, in operating system's LAN adapter settings 9k Jumbo frame packets option was selected. Next, the scanner was connected to the laptop and in network card properties window the IP address and subnet mask for the laptop were assigned: 192.168.0.1 and 255.255.255.0, respectively. The IP address 192.168.0.2 was avoided as it is the default IP address for the scanner [26]. To prevent any conflicts the firewall and antivirus were switched off.

3.3.2 Capability of the scanner

During measurement campaign a 5G capable scanner from Rohde&Schwarz (model TSME6) was used. The purpose was to collect signal strength information (SSB-RSRP).

Given device supports FR1 measurements with the possibility of Multiple Input Multiple Output (MIMO) and mmWave measurements after hardware and software upgrade. During given measurements only one antenna and receiver (Single Input Single Output (SISO)) was used [27].

Depending on the license, it is possible to scan multiple technologies concurrently and for 5G, for example parameters like signal strength, PCI, beam index number, Layer3 signalling (MIB, System Information Block 1, System Information Block 2) can be captured. Besides regular signal strength measurements, it is possible to execute band scan tests in cases where channel numbers are not known [27].

The measurement uncertainty of the device is up to 1.5 dB and it is recommended to calibrate the scanner once every two years, to verify the accuracy stays within given range [27].

3.3.3 Parameters for configuring the scanner

Before the start of the actual measurements a band scan was carried out to find broadcasted channel numbers of both operators. For this, frequency band n78 was selected from measurement software to perform band scan. The locations for this kind of measurement were selected based on the coverage maps where each operator had advertised its 5G availability. With newer version of Nemo Outdoor it is possible to perform band scan while doing measurements and automatically add new channels to channel list. At the time when these measurements were carried out this feature was not available.

After the band scan completed (Figure 8), channels that were found along with the subcarrier spacing were inserted to measurement software. As there may be different subcarrier spacings (numerologies) used in the network it is important to select the correct numerology before measurements. The default measurement period of 20 ms was used. Description of channel number New-Radio Absolute Radio Frequency Channel Number (NR-ARFCN) and subcarrier spacing is given in Chapter 1.3.

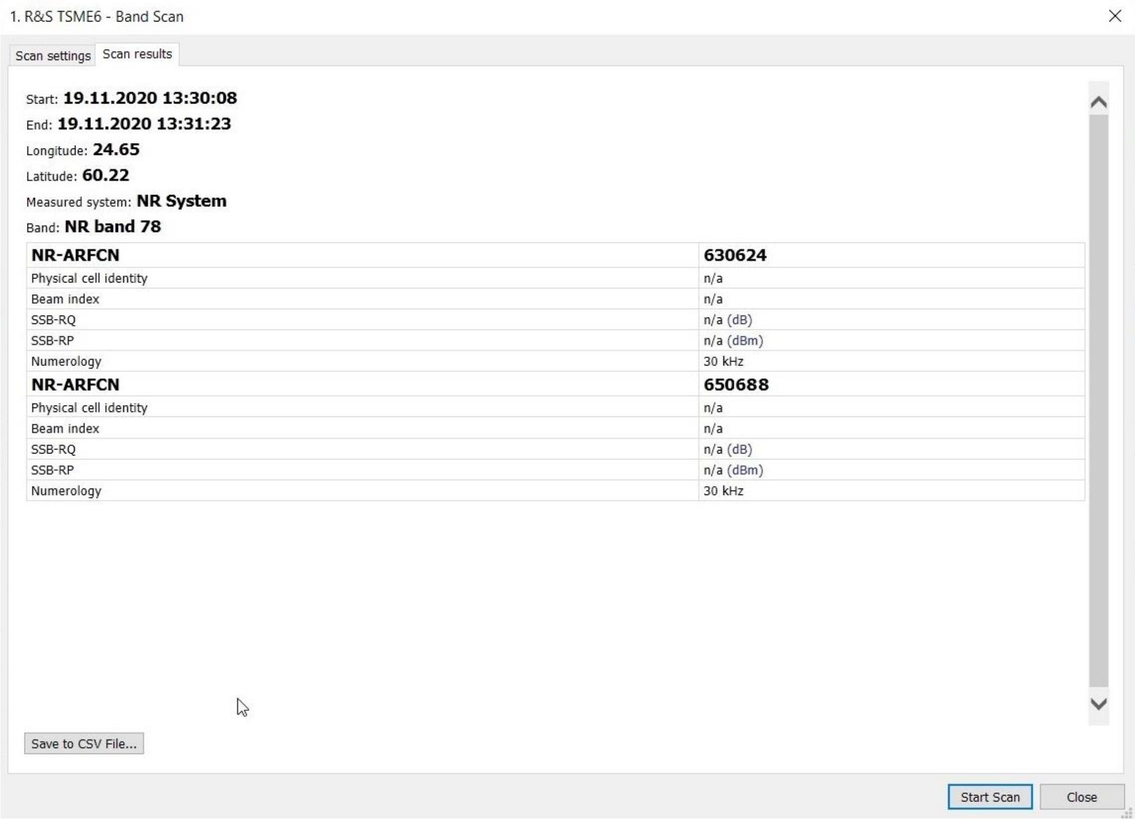

Figure 8. Example of band scan results with TSME6 scanner.

As the band scan results do not contain operator names (only channel numbers are visible), the phone's measurement software was examined in order to associate the channels that were found with operator names.

3.3.4 Measurement phones configuration and measurement server

For collecting downlink and uplink throughput data as well as RTT times and key performance indicators like signal strength and quality, mobile phones with measurement software (EchoOne) were used. With given software it is also possible to see cell related information, for example PCI, serving and neighbouring channel numbers, base station number and Layer3 signalling and to record all the information to log files for analysing later in post–processing software (Echo Studio).

Both phones used the same settings to ensure comparable results between the operators. The phones were locked to 4G and 5G technology to avoid handover to UMTS or GSM hence making handover back to 5G more difficult. While locked to 4G and 5G, phones were readily able to handover between LTE and 5G–NR systems. Notifications of data transfer and ping failures as well as notification of lost GPS signal were switched on in order to enable to take action when any problems occur. All the settings (for example, Smart 5G and locking only to 2G or 3G) in Android OS were switched off that could constrain phones performance during measurements and always on screen was switched on to avoid the situation where phones display would turn off in the middle of measurements.

During network performance test, data tests were conducted against dedicated server. Beforehand data server maximum throughput was determined to avoid the situation where server throughput would be the limiting factor. It was also confirmed on field by selecting locations where both operators could potentially simultaneously have high throughput speeds. In order to keep the latency as low as possible the data server location was chosen to be in Finland.

3.3.5 Measurement scripts

To evaluate the performance of the mobile network, data tests were made. For this, one measurement script (Figure 9) was prepared for each phone. The purpose of the measurement script was to follow a certain test routine – predefined measurement processes were performed and then repeated throughout the whole drive test.

Measurement scripts were almost identical with the only exception being different port number – different port number was assigned to different phone to grant access to the server.

The number of parallel transfers for downlink and uplink data transfer was determined by using trial and error – the number of parallel transfers was increased as long as the throughput increased. Once the maximum throughput was achieved the count of parallel transfers was inserted into measurement script. The highest throughput was obtained with 8 parallel streams.

For downlink and uplink testing iPerf3 was used, which is described in more detail in the next section.

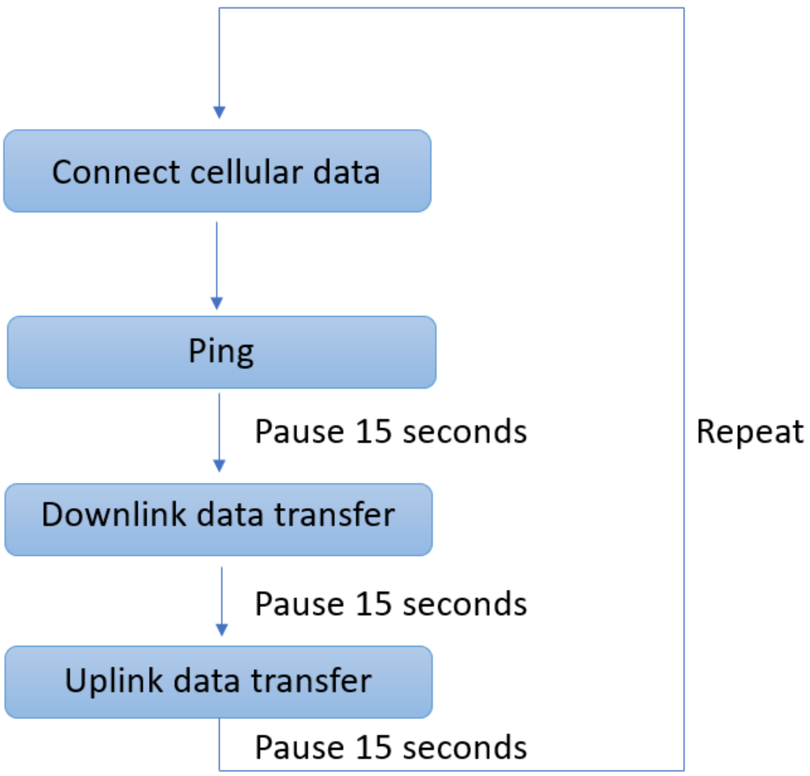

Figure 9. Block diagram of the measurement script.

3.3.6 iPerf for data throughput evaluation

iPerf3 is a tool for measuring maximum achievable throughput of IP networks. It allows the user to perform TCP or UDP test, set the buffer size, UDP bandwidth, measure delay jitter and other parameters [28]. In order to test the bandwidth of the network, both the client and the server side need to be installed. During data transfer the server listens for the requests sent by the client and sends data as fast as possible. The statistics captured during the session is then returned. iPerf can be configured using command line or graphical user interface named JPerf. As no files are stored locally when transferring the data, it is not necessary to do any file clean up afterwards [29].

During 5G measurements iPerf was used to evaluate the downlink and uplink speeds. TCP was chosen as the transmission protocol. In downlink direction the payload transfer time was 100 seconds and in the uplink directions it was 20 seconds as this time period was sufficient to mitigate the effect of TCP slow start. When using downlink and uplink transmission intermittently it makes it also possible to gauge for example data setup time and success.

In this chapter an overview was given of the measurement campaign and the setup of the equipment. In the next chapter the process of the preparation of measurement data for performing square analysis is described and after that the results are analysed.

4 Measurement results

After the measurements data was collected, the next step was to analyse the results. For coverage assessment the square analysis was performed and statistics for downlink and uplink speeds and RTT of the UE’s were calculated. The benefit of using square analysis for coverage evaluation is the fact that it is possible to minimize the effect of multiple measurement points captured inside a small geographical area, for example when stopping in traffic jam or waiting at the traffic lights, as these points may distort the final statistics. Therefore, the square analysis was used on the data captured by both, scanner and the mobile phones and it was carried out using QGIS that is open source GIS (Geographic Information System) software.

As can be seen in Figure 10 (a), inside each square multiple measurement points are present with each having different measured value, where dark green represents the strongest signal, light green strong and yellow medium signal strength.

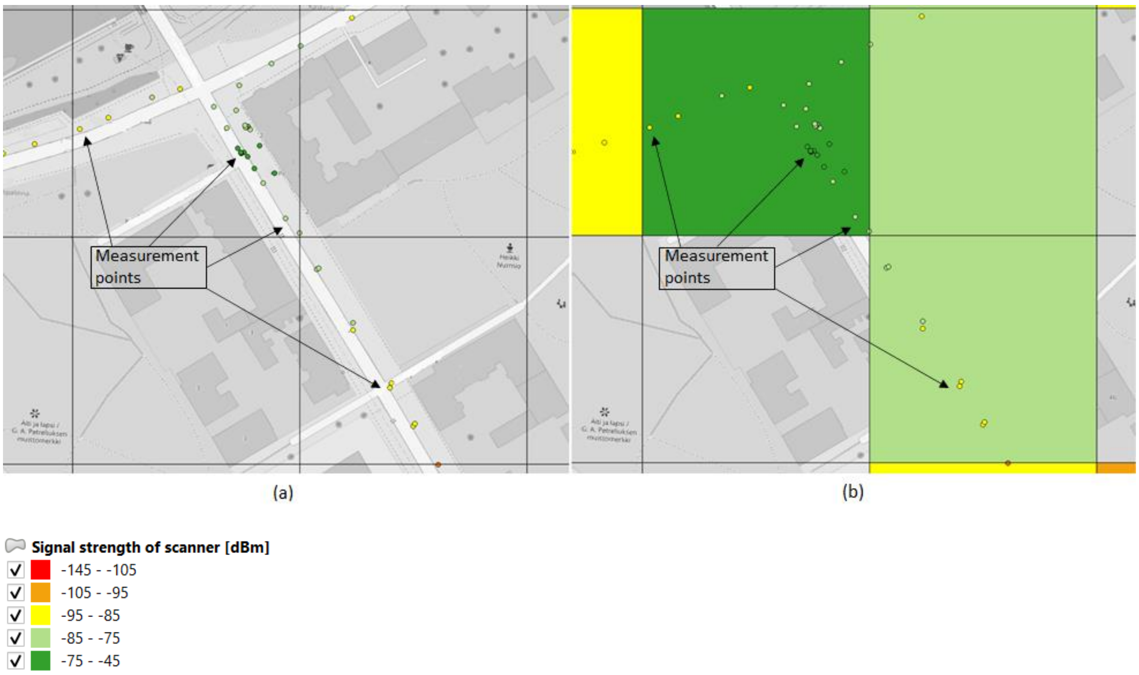

Figure 10. Multiple measurement points: (a) inside grid, (b) resulting squares.

Top right and bottom right squares have two and eight measurement points, respectively, whereas more than ten points are inside the square in top left that have been collected when waiting at the crossroad to make a turn. During square analysis (Figure 10 (b)) the strongest measured value inside each square is assigned to given square and in case a square contained no points then no value was assigned to corresponding square, like the square on bottom left. Assigning maximum value instead of mean value can be considered as first best signal level inside square or in another words, the strength of the potential serving signal.

In the following section the process of exporting the results containing downlink and uplink throughput and ping values is described first and the preparations and square analysis process of UE and scanner data after that.

4.1 Exporting and processing data captured by mobile phones

Downlink, uplink speeds and RTT values show the performance of the network from the user's perspective, but besides that key performance indicators like signal strength and quality give valuable information of the extent of the service area. With analysis software (Echo Studio) throughput and ping results along with signal strength were observed for any missing data or anomalies before exporting them for post processing using spreadsheets. Also, measurement route was visually checked on map to verify the integrity of coordinates.

With Echo Studio it is possible to export the collected raw data into spreadsheet files. Furthermore, if spreadsheet contains macros it is possible to automatically process the exported data and minimize the risk of errors caused by manual work.

In order to export data, parameters to be exported need to be selected using KPI editor. It is possible to define parameters by user as well as use predefined ones. If necessary, it is also possible to apply filter, for example to select only data throughput values collected when phone was served by 5G network.

During measurements, phones were locked to 4G and 5G NSA technology and therefore it was possible to gather data from 4G and 5G. During exporting, information related to 4G was filtered out and only 5G specific information remained. Key performance indicators that were exported were signal strength (SSB-RSRP), signal quality (SSB-SINR), downlink and uplink throughput and ping.

After data was exported to spreadsheet files, next step was to calculate the statistics of throughputs and RTT. As raw radio link data rate was measured during data testing, the exported downlink and uplink data contained some information even if no data transfer or ping was active (throughput of less than 100 kbps was present even in idle mode). Hence, measured values under certain threshold were discarded. 100 kbps was selected as the base as this was the value that guaranteed that real data (RTT times) was not discarded. After redundant information was removed, maximum, average and sample count were calculated for downlink and uplink throughputs. For RTT average, median, minimum and sample count were determined.

4.2 Exporting scanner data and preparations for the square analysis

The software used by the scanner and mobile phones do not provide square analysis capability and also their file format has limited support, so it was mandatory to export the results in a format suitable for processing the data in some third party software. The results were exported as comma separated values as this format is widely supported and it makes easy to explore the data to find any missing values. During exporting from scanner, it was already known which channel belongs to which operator, so separate export profile was created for each operator and they contained only these results that correspond to selected channel number. As a next step exported scanner values were processed with Microsoft Excel where for every measured point/location maximum (first best) signal strength value was found. Assigning maximum value for every recorded location point was necessary, because it is common to capture simultaneously more than one signal (originating from different sectors) in every location point by the scanner. Selecting the strongest signal (maximum signal value) in particular location gives the first best server or in another words, it gives the signal strength of potential serving signal. In rare cases, some measurement points have missing coordinates or the measured value is missing – in this case, these points were discarded, to avoid conflicts when doing square analysis. After initial data cleaning was finished it was suitable to start preparing the square analysis.

4.3 Square analysis

For the square analysis open–source geospatial software from QGIS was used. First, the exported signal strength and quality values were imported to QGIS and shapefiles were created using the default coordinate reference system EPSG 4326 (WGS 84). Next, these shapefiles were reprojected to EPSG 3067 coordinate reference system that is suitable for Finland map data. After that, a grid that covers the whole measured route (Figure 11) and consists of 50x50 meters squares was created using the same EPSG 3067 coordinate reference system.

Figure 11. 50x50 meters squares covering measurement route (in green).

When the shapefiles and grid were created with correct coordinate reference system, a square analysis model was constructed from blocks using graphical modeler (Figure 12). A separate model was created for signal strength and quality square analysis. These models take two inputs: a 50x50 meters grid and measurement points. The main function of the created analysis model is “Join attributes by location” that selects all squares that contain at least one measurement point and as a result outputs summary of sum, mean, maximum, minimum and median values for every square. In order to get accurate results it is necessary to use same coordinate reference systems (EPSG 3067) for measurement points and grid layer when doing calculations. To make distinguishing between squares that contain measurement points from squares that have no points easier, it is possible to discard non matching squares so that only matching squares remain. The created model selected maximum measured value inside each square and this value then was assigned to given square and after that the resulting squares were classified into signal strength or quality intervals with the size of 5 decibels or 3 decibels, respectively using pre-defined formulas. For example, the value -88 dBm is in range "maxRSRP">=-90 AND "maxRSRP"<-85. For the signal strength model the ranges between -130 dBm and -20 dBm were created, while for quality model ranges between -20 dB and +40 dB were used.

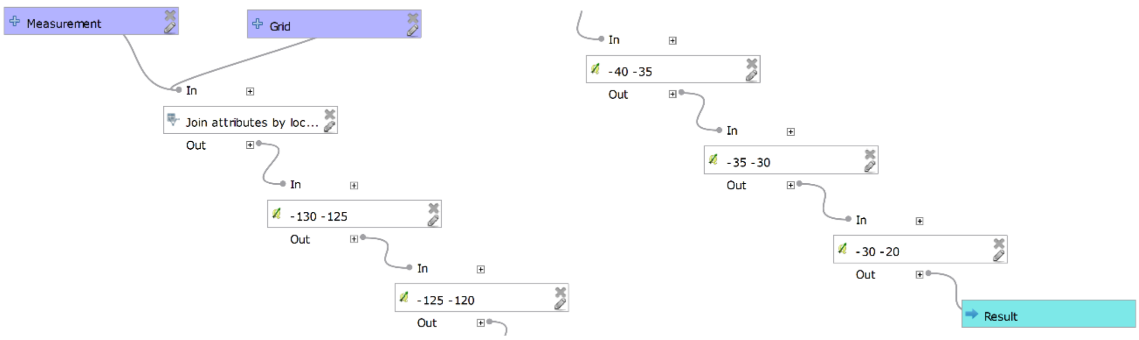

Figure 12. Square analysis model created with QGIS (end and beginning shown).

After the calculations had finished, a summary table was created with the coordinates of each square and corresponding sum, mean, maximum, minimum and median values. As can be seen in Figure 13, for every square that is on separate row value “1” is assigned depending on the value interval it falls in. For example, first square (on row one) with left, top, right and bottom coordinates has the value between -80 dBm and -75 dBm and second square has the value between -75 dBm and -70 dBm.

	left	top	right	bottom		-80 -75	-75 -70	
1	312400.174743000...	6663642.7160...	312500.17474...	6663542.7160...		1	0	
2	312400.174743000...	6663542.7160...	312500.17474...	6663442.7160...	○○○	0	1	○○○
3	312400.174743000...	6663442.7160...	312500.17474...	6663342.7160...		1	0	
4	312400.174743000...	6663342.7160...	312500.17474...	6663242.7160...		1	0	

Figure 13. Result (SSB-RSRP) of square analysis (coordinates and two corresponding signal ranges).

The results were saved to shapefile format and for easy storing and accessing the files later they were also stored in comma separated value format.

The values “1” were summed for every column (value interval) using spreadsheet processing program to get the total amount of the squares for every category. A template containing tables and graphs was created where the final results were inserted.

4.4 Measurement results

In current chapter the results of the square analysis and summaries calculated from downlink and uplink throughputs and ping times are analysed. The route was driven for the first time in May 2020 and then again in September 2020. Although the driven route was not identical it still gives an overview of the coverage areas of the operators and how they have improved over time.

In Figure 14 for every given signal strength class the corresponding amount of 50x50 meters squares is given on vertical axis. The dashed line illustrates square counts for the measurements performed in May whereas solid line shows the situation in September. The results for both operators are presented in the same graph to make the comparison between them easier.

In given measurement area the signal strength values for Operator1 has slightly increased when comparing with the measurements performed in spring and in autumn (Figure 14). This can be seen by looking at the solid line that has slightly moved towards stronger signal levels (to right) and also a small amount of squares with high signal levels (signal level > -75 dBm) have been added, compared to the dashed line. This can be a sign of a new base station introduced in the area. This assumption will be confirmed later when pictures Figure 18 and Figure 19 are analysed. Less squares with Operator1 and also the higher concentration on lower signal levels is the indication of smaller coverage area (less base stations).

Compared to Operator1, in spring Operator2 had more squares with high signal values, especially in range -70 dBm and -45 dBm and later in the year the difference became even more notable. From the measurements performed in autumn it can be seen that a lot of squares (almost 90 squares) are concentrated around -70 dBm and this shows that new base stations have been added in the area. With signal levels like this good mobile network performance can be expected.

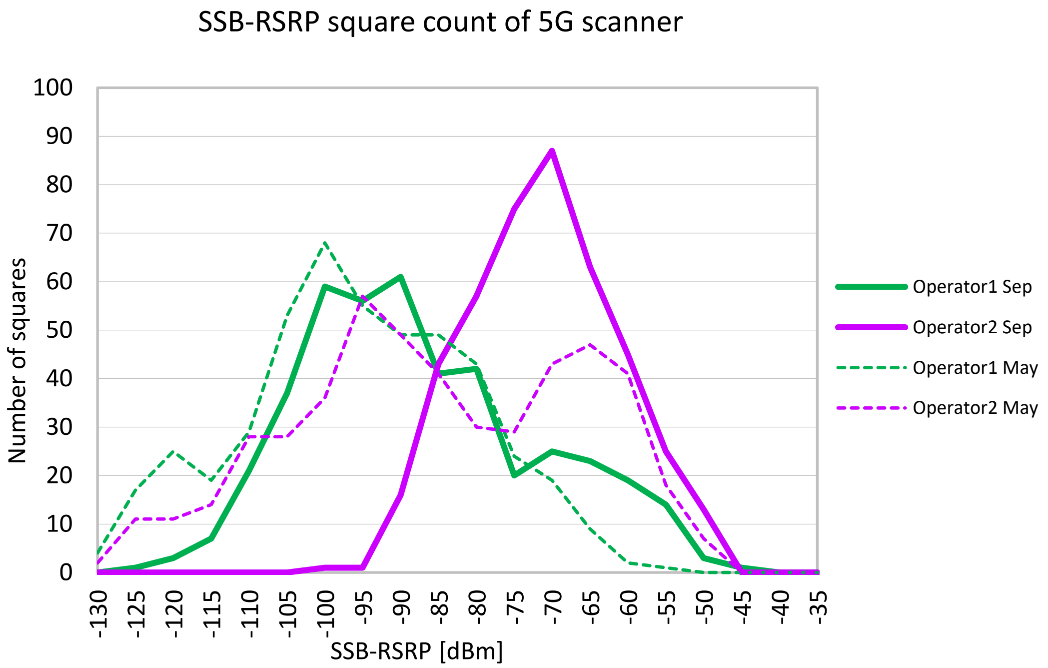

Figure 14. Square count of scanner in May (dashed line) and in September (solid line).

Also, in cumulative graph (Figure 15) both of the operators are displayed concurrently for easier comparison. On vertical axis total amount of the squares can be seen. In spring, the count of squares of Operator1 and Operator2 was higher compared to the measurements in autumn. It can be stated that the difference is caused by dissimilarity of the driven routes. For comparison measurements it would be good to follow exactly the same route, but in real world measurements it may not always be possible, for example due to closed roads.

The cumulative graph also shows slight improvement of signal strengths for Operator1, where solid line has moved to the right. The total amount of squares in second measurement is almost the same for both operators and it shows that at least some level of 5G service should be possible in both networks. In closer inspection it can be seen that higher signal levels are offered by Operator2 and only in a few occasions signals levels fall below -85 dBm.

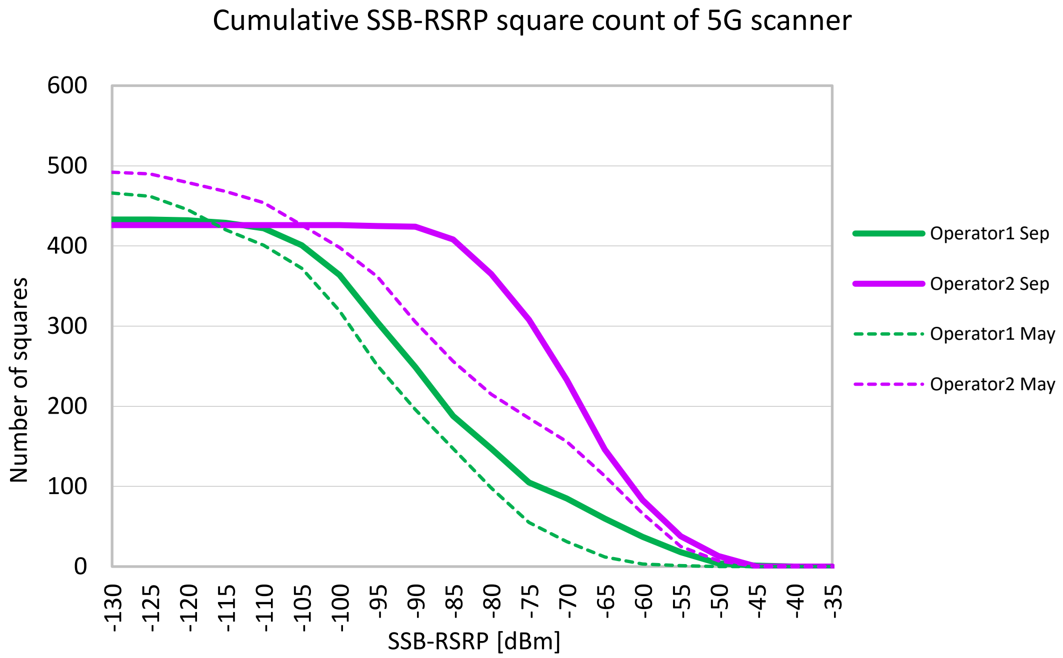

Figure 15. Cumulative square count of scanner in May (solid line) and in September (dashed line).

Next, the signal strength (Figure 16) results of the mobile phones are introduced. Compared to the scanner, mobile phones have no external antenna and consequently the measured signal levels can be lower due to the attenuation from the measurement vehicle. The testing showed, that inside the vehicle the signal strength was approximately 5 dB lower compared to the signal strength that was measure outside the vehicle. This explains the lower signal levels in Figure 16. Also, the signal level differences come from accuracy of the devices: for scanner, the signal level uncertainty is approximately +/- 1 dB, while for mobile phone it is +/- 3 dB.

The notable increase in square count for Operator2 in September shows that the coverage area has increased and therefore the mobile phone connects to 5G more frequently. At the same time the improvements for Operator1 have been modest.

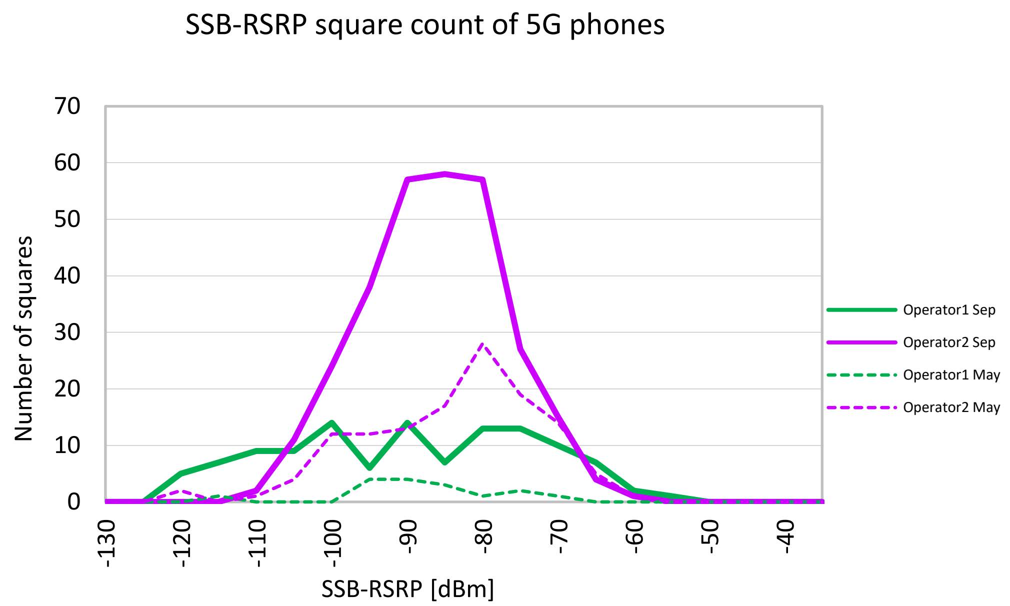

Figure 16. Square count of mobiles in May (dashed line) and in September (solid line).

When looking at the total number of squares on cumulative graph (Figure 17) of mobile phones it gives an indication of how easily the UE can access the network. It can be seen that in spring the UE of Operator1 attached to 5G network only for a very short period of time while most of the time it was served by 4G. One of the reasons for this could be a small 5G coverage area and hence low signal levels or it could also be a sign of shortcomings in the software of the mobile phone. In autumn, the UE square count of Operator1 had increased multiple times but at the same time, according to scanner graph (Figure 15), no major changes in coverage area had taken place. So, this could lead to second assumption, that the short time spent in 5G network was caused by inefficient algorithm of mobile phones software that were mentioned in Chapter 3.3.

The total square count (Figure 17) of Operator2 had also increased between spring and autumn and the reason for this is the addition of new base stations. It can be seen in scanner's cumulative graph (Figure 15) that the solid line of Operator2 has moved towards higher signal levels and therefore the reason for more time spent in 5G is the expanded coverage area.

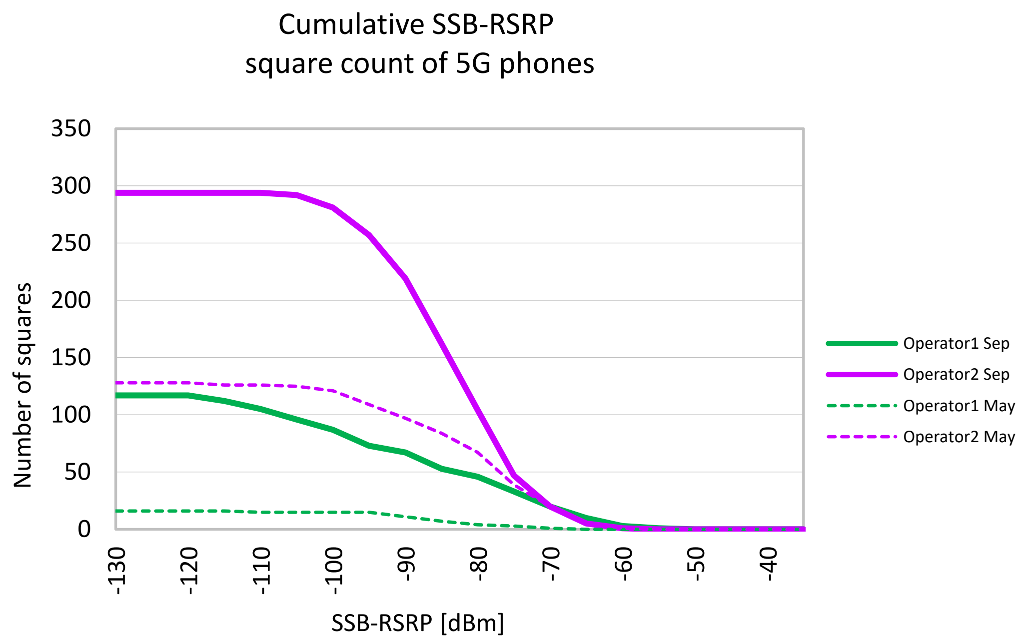

Figure 17. Cumulative square count of mobiles in May (dashed) and in September (solid line).

In Table 3 summary of the percentages of how many squares scanner had compared to mobile is shown. According to it, in May Operator1 UE connected to 5G network only briefly and although in September coverage had improved slightly, only about quarter of the time UE was served by 5G. For Operator2 the percentages were higher during both measurements, reaching to more than 2/3 of time in autumn when the phone was served by 5G.

Table 3. Percentage of scanner square count compared to mobile square count.

Squares	Operator1 May 2020	Operator1 September 2020	Operator2 May 2020	Operator2 September 2020
Scanner/mobile	3,4%	27,0%	26,4%	69,0%

In Figure 18 to Figure 21 square analysis results are depicted. Every 50x50 meter square is coloured according to the calculated signal level, where dark green stands for very good signal (signal level higher than -75 dBm) and red very weak signal (signal level lower than -105 dBm). For every signal range corresponding square count is presented in square brackets on the legend.

In Figure 19 it can be seen that Operator1 has added a new base station in the area that is situated below the river dividing measured region, where the square values are above -75 dBm now, compared to previous measurements in Figure 18 where the coverage was provided by surrounding base stations and the signal levels were below -105 dBm. The total amount of squares in autumn was 433 and square count with strongest signal values (dark green) increased from 55 to 105, as can be seen when looking at the values in square brackets.

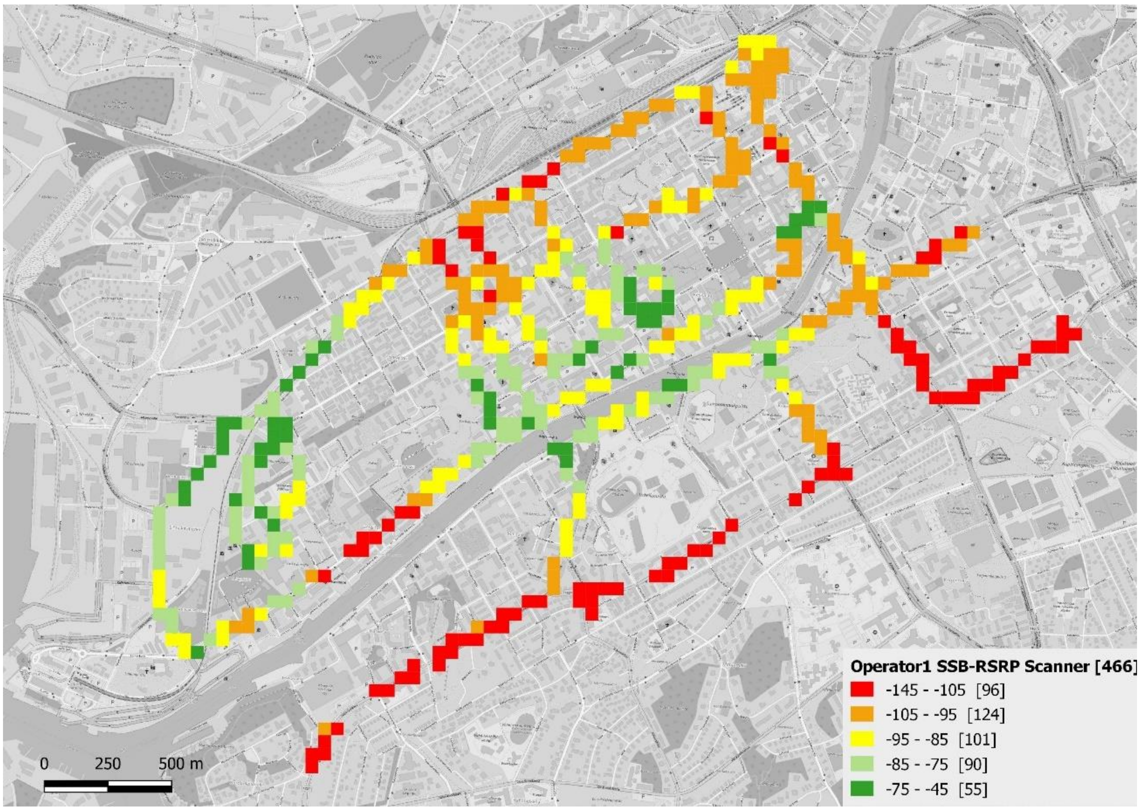

Figure 18. Operator1 SSB-RSRP of scanner in May 2020.

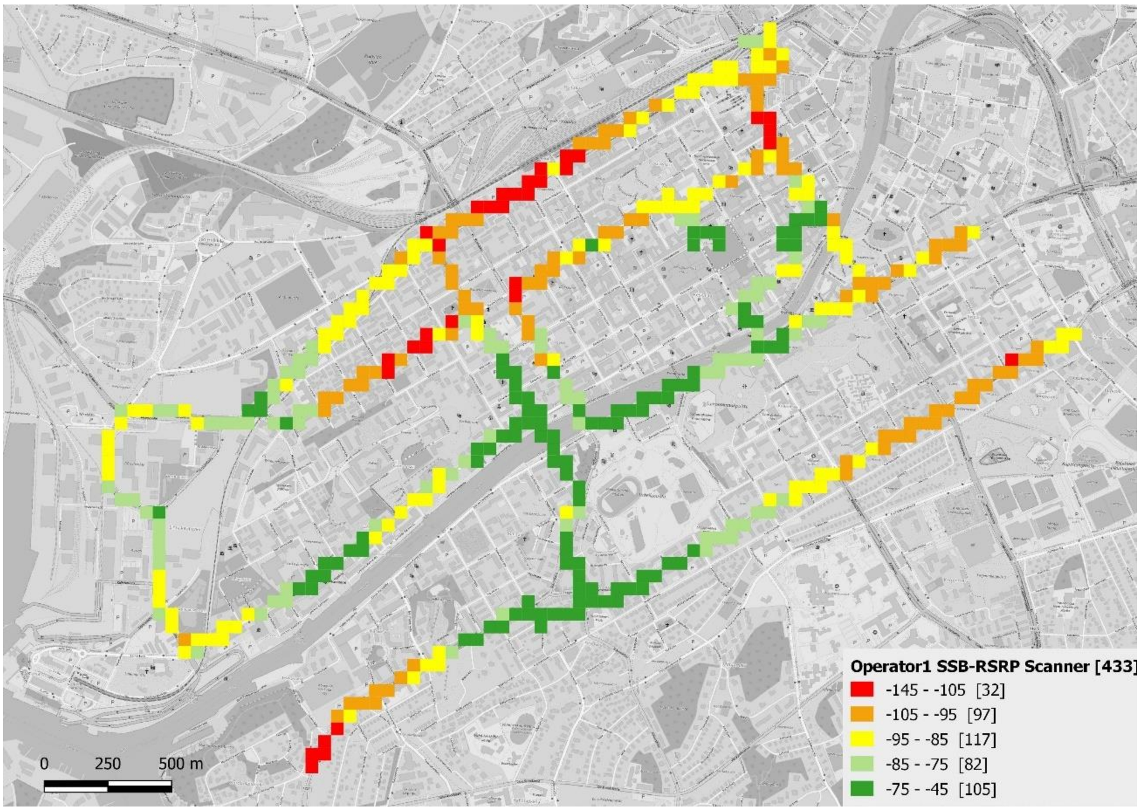

Figure 19. Operator1 SSB-RSRP of scanner in September 2020.

In Figure 20 Operator2 network was providing good (light green) or very good (dark green) signal levels already in spring but in autumn (Figure 21) more base stations have been added and now most of the area is covered with strong signal levels that is essential for good data performance. Therefore, the assumption that was made before about new base stations is valid.

The calculated square analysis figures for mobile phones are given in Appendix 2.

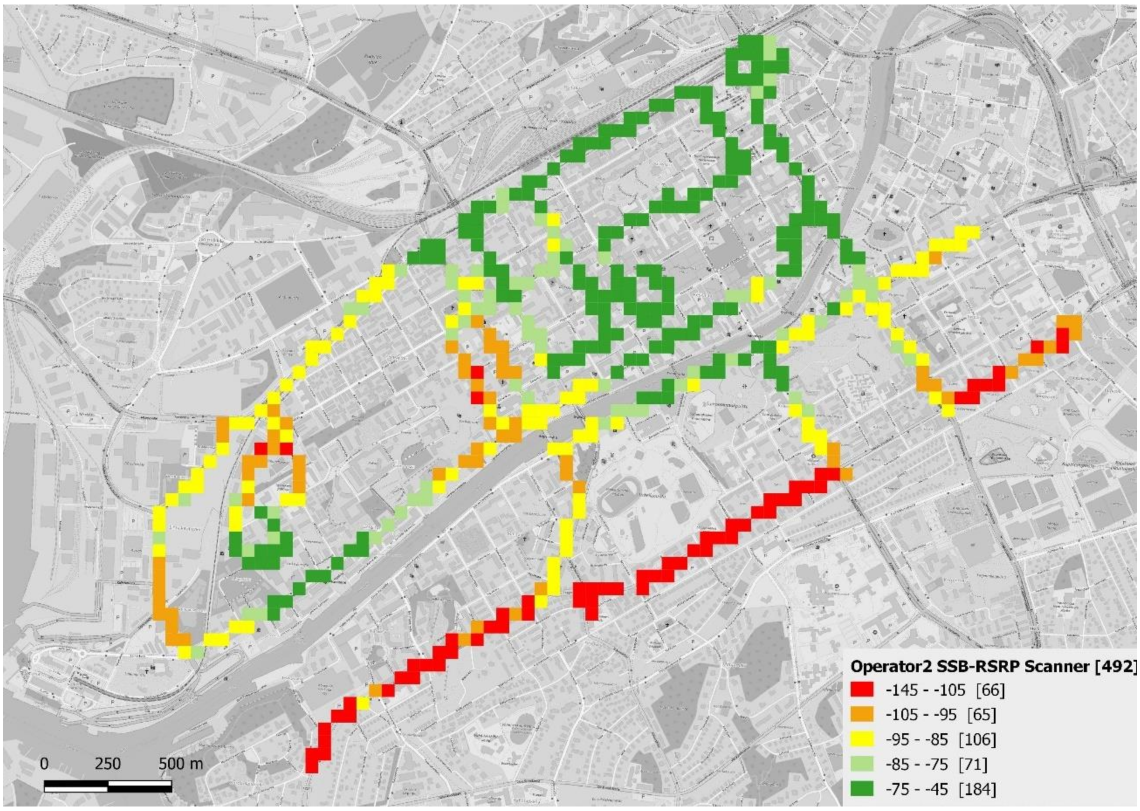

Figure 20. Operator2 SSB-RSRP of scanner in May 2020.

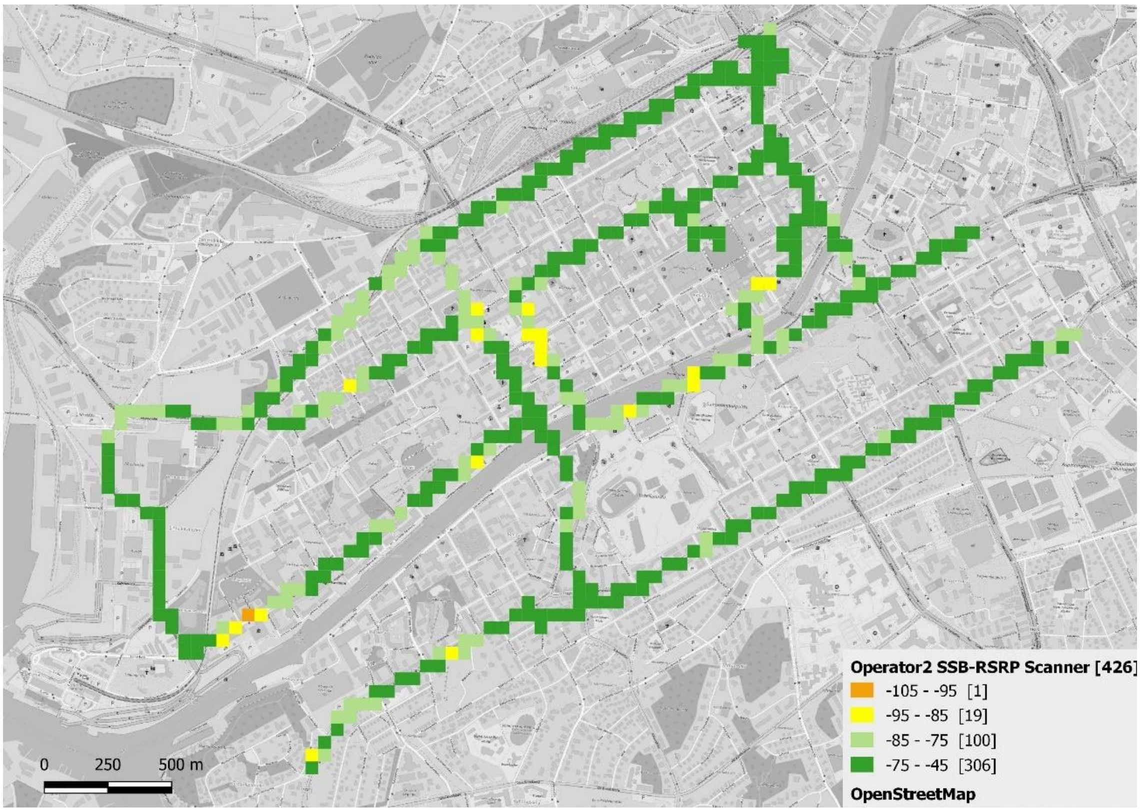

Figure 21. Operator2 SSB-RSRP of scanner in September 2020.

The signal quality according to Figure 22 and Figure 23 of Operator1 show that the quality has improved to some extent. Because in May the phone connected to 5G network very briefly only 16 squares contain measurement results.

Figure 22. Operator1 SSB-SINR of phones in May 2020.

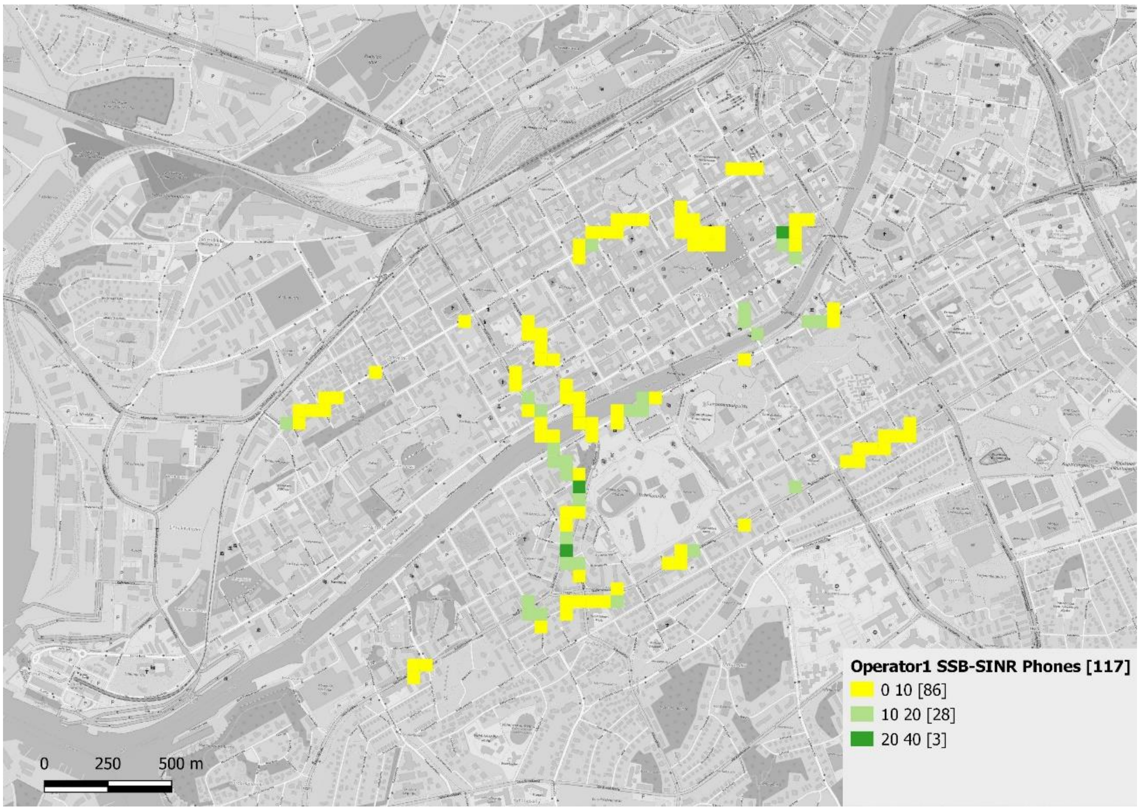

Figure 23. Operator1 SSB-SINR of phones in September 2020.

Figure 24 and Figure 25 also show that there have been no noteworthy changes in quality between the two measurements and most of the quality values are still between 0 and 10 dB.

Figure 24. Operator2 SSB-SINR of phones in May 2020.

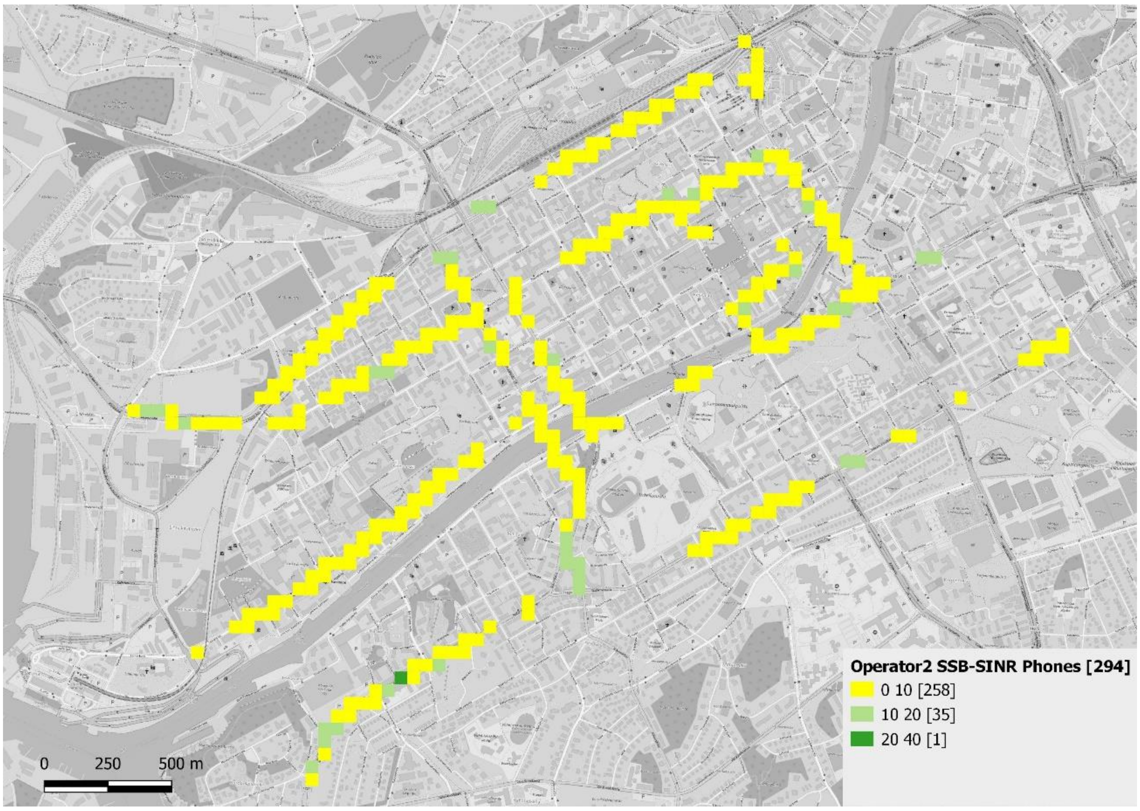

Figure 25. Operator2 SSB-SINR of phones in September 2020.

Next the summary of measured downlink and uplink throughputs as well as RTT times are presented. As with signal strength statistics, data transfer performance is also summarized for spring and autumn measurement campaigns. When looking at the measurement results of Operator1 the number of both the downlink (Table 4) and uplink (Table 5) points have increased. Probable reason for this is somewhat denser 5G network and in addition to this, it can also be newer phones software. The big difference between downlink and uplink points count comes from the measurement script: as shown in Chapter 3.3.5, the duration of downlink transfer was 100 seconds and for uplink it was 20 seconds. The downlink and uplink average speeds as well as maximum speeds of Operator1 have increased.

The downlink throughput speeds of Operator2 were higher already in spring compared to Operator1 but in autumn the speed has decreased. This could be caused by denser 5G network (and hence higher interference) and also increased number of users in network. The higher count of measurement points reveals larger 5G coverage area and mobile phones capability to connect to the network. High signal levels with controlled interference is one key factor for good data transfer speeds.

Table 4. Summary of downlink throughput tests.

Downlink throughput	Operator1 May 2020	Operator1 September 2020	Operator2 May 2020	Operator2 September 2020
Average [Mbps]	237,2	319,5	680,7	591,8
Count	503	1118	1001	1526
Maximum [Mbps]	871,3	956,8	1101,8	1103,3

There is no big differences in average uplink speeds when comparing the two operators with only exception speeds being higher in September compared to May.

Table 5. Summary of uplink throughput tests.

Uplink throughput	Operator1 May 2020	Operator1 September 2020	Operator2 May 2020	Operator2 September 2020
Average [Mbps]	21	31,5	25,4	29,2
Count	78	194	166	155
Maximum [Mbps]	48,9	60,6	42,2	90,1

The RTT times (Table 6) of Operator1 was lower in autumn and this could be the result of better 5G coverage. Ping times (as well as the average downlink speed) of Operator2 have worsened to some extent and this could be the result of more users in network and also the degradation of signal quality due to added new base stations.

Table 6. Summary of ping tests.

Ping	Operator 1 May 2020	Operator1 September 2020	Operator2 May 2020	Operator2 September 2020
Average [ms]	42,5	39,9	16,1	27
Minimum [ms]	15,7	18,4	13	12,1
Median [ms]	46,8	29,1	14,9	19,9

Next the scatter plots with linear trendline of both operators are given where the relationship between signal strength points (SSB-RSRP) and quality points (SSB-SINR) of the mobile phones can be seen. One measurement point corresponds to one measured value (both, signal strength and quality) of a measurement phone in a given location. Only the results from autumn measurements are presented as they contain more measurement points and therefore are more informative. The measurement route was presented in Figure 11.

When looking at the trendline in Figure 26, it can be seen that as the signal strength increases the corresponding signal quality gets better. The maximum measured quality value for Operator1 and Operator2 is between 25 dB and 30 dB and the resulting linear trendline maximum is around 10 dB. Even when the signal strength is less than - 100 dBm the quality remains above 0 dB. This is caused by measurement software that does not report values below 0 dB. After measurement campaign it was verified that with newer versions this shortcoming was eliminated.

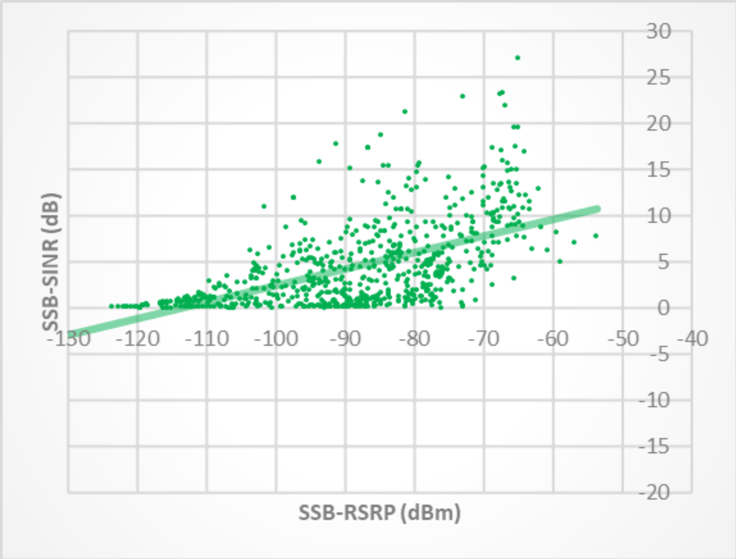

Figure 26. Scatter plot of Operator1 in September 2020.

For Operator2 it can also be seen that as the SSB-RSRP gets better SSB-SINR also improves (trendline in Figure 27). As can be seen, the measurement points of Operator2 are less scattered and this is due to more optimised handovers.

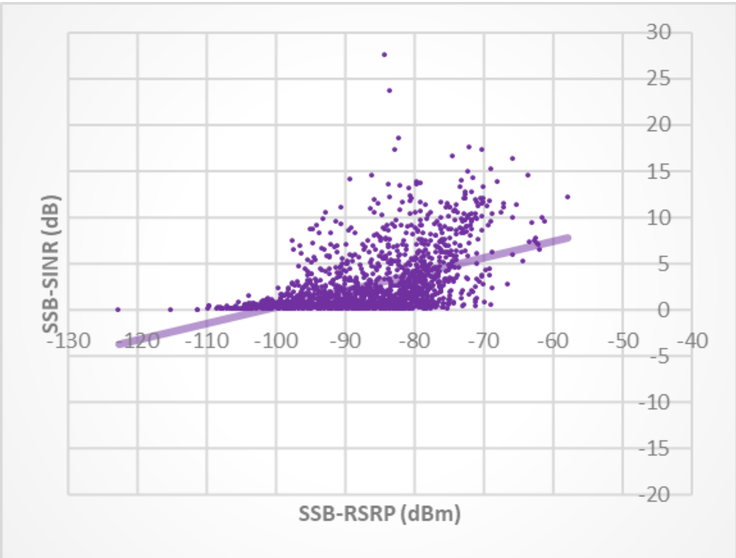

Figure 27. Scatter plot of Operator2 in September 2020.

For comparison, in Figure 28 the linear trendlines of both operators are depicted. The trendline should show the improvement in signal quality as the signal strength increases. When comparing the two trendlines it can be seen, that they are very similar. On the same signal levels Operator1 provides slightly better signal quality compared to Operator2, where the quality values are 2–3 dB higher. Operator1 has less base stations and therefore there is less intercell interference and in addition to this there can also be less users in the network. As Operator2 provides very good 5G coverage (with many base stations), it is recommended to put more emphasis on optimisation (for example, antenna tilting) to lower the interference and thereby improve the service quality.

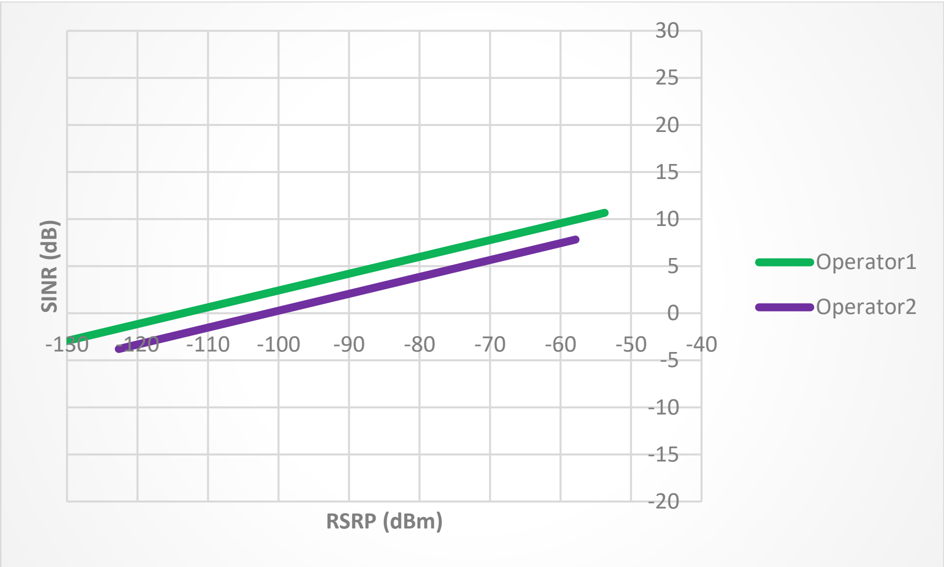

Figure 28. Comparison of the trendlines of Operator1 and Operator2.

5 Conclusion and future work

5G is currently the newest generation in mobile technologies. The motivation for newer technologies is the need for better connectivity and the support for new services and use cases. Also, as the amount of data consumed by the customers increases yearly, current mobile technologies are becoming saturated and new technologies are needed.

In Chapter 1 three main use cases of 5G were introduced: Enhanced Mobile Broadband, Massive Machine Type Communications and Ultra–Reliable and Low Latency Communications. Also, two connection modes, option 3 for NSA and option 2 for SA were described, as former allows the operators to implement the existing 4G core network with new access network of 5G and the latter case describes true 5G network, that consists of 5G access and core network. Moreover, 5G specific parameters were described, namely new sub carrier spacings, SSB and NR–ARFCN.

In Chapter 2 an overview was given of the works related to mobile network measurements and the analysis of the results. As 5G is still new, limited number of works can be found on the measurements that have been performed in commercial networks. Hence, the aim of this thesis was to carry out measurements in commercial networks with commercial measurement tools and to create a process for analysing the results. Chapter 3 gave an overview of the measurement campaign and introduced the setup of the equipment. The measurements were performed in commercial 3.5 GHz 5G networks and a commercial scanner with two off the shelf mobile phones were used. In chapter 4 the measurement results were analysed. For coverage and signal quality assessment square analysis was used, as this gives a more accurate overview of the coverage. The benefit of using square analysis is the fact that it mitigates the effect of multiple measurement points that have been collected in a small geographical area can have a negative impact on statistics.

Besides coverage analysis, data performance was studied. When comparing the measurements performed in spring with measurements performed in autumn, it can be seen that irrespective of the operator, the coverage areas of 5G have expanded, but still the networks are in different development phase. For Operator2 the growth has been more notable and now most of the measured area is covered with strong signal (signal level >= -75 dBm). At the same time, the average downlink speeds of Operator1 have increased from 237,2 Mbps to 319,5 Mbps, whereas for Operator2 they have decreased from 680,7 Mbps to 591,8 Mbps. Because Operator2 now provides a very good coverage, the interference between base stations has increased and likely there is more user in the network. As a result, this has had negative impact on the throughput. The average uplink speeds for both operators have slightly improved: the average speed measured in Operator1 network was 31.5 Mbps and Operator2 network it was 29.2 Mbps. Similarly to download speeds, the RTT of Operator1 has had minor improvement and for Operator2 it has deteriorated.

It can be affirmed, that square analysis is reasonable solution for evaluating operator network's performance and service quality and also for evaluating how network matures over development cycle. Furthermore, it can be stated that square analysis is suitable for visualizing coverage area.

Because the phones operating system as well as the measurement tools are still immature, it can happen that the serving system is not always correctly detected by the measurement software, as it was revealed when analysing the coverage area of mobile phones. For example, even if very high data throughput is measured, the measurement software still displays 4G as the serving system.

Consequently, the measurements need to be repeated with more established measurement software and the operating system of user equipment. Also, new measurements are recommended as the density of 5G networks continues to increase and along with it also the interference increases that degrades the performance of the network. Furthermore, to estimate the service area of a single 5G base station, plots with PCI's with strongest signal levels could be generated. Additionally, it would be possible to do cell based signal strength and quality trendline graphs to discover cells with low quality.

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Appendix 2 – Signal strength of mobile phones

In the following figures the results of the signal strength square analysis of the mobile phones are depicted. Similarly to scanner, results from spring and autumn measurements are given.

Figure 29. Operator1 SSB-RSRP of phones in May 2020.

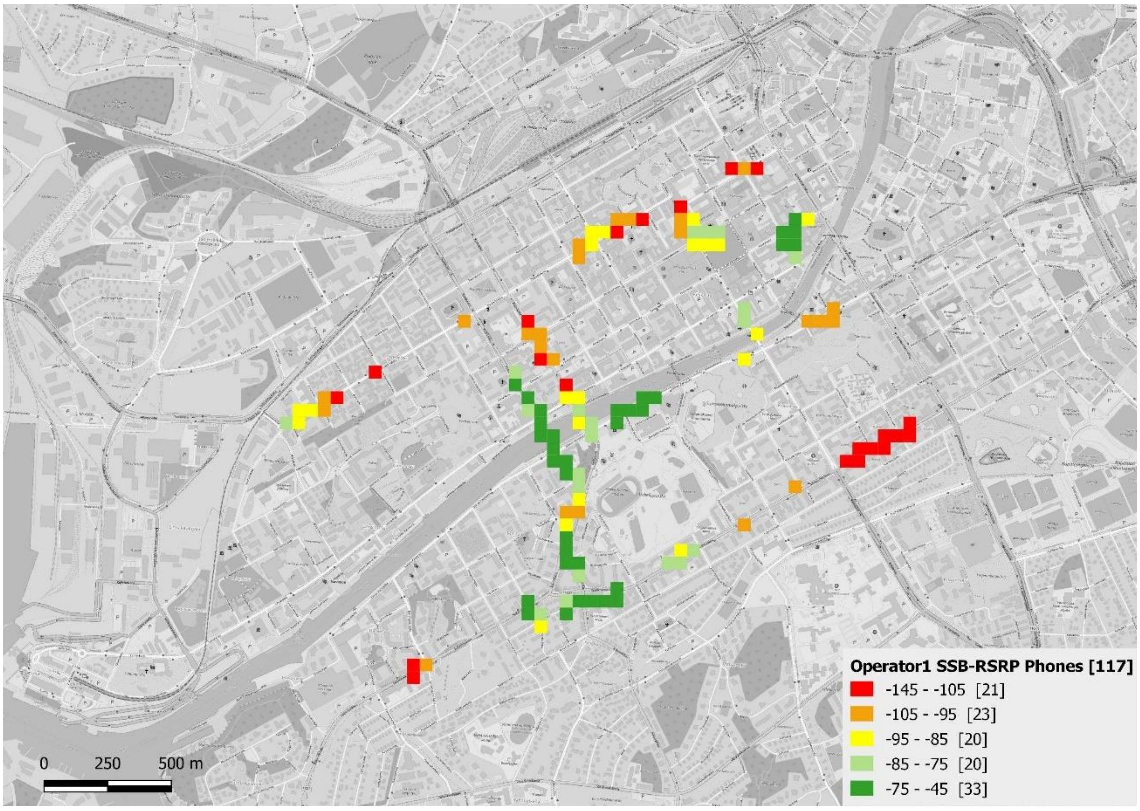

Figure 30. Operator1 SSB-RSRP of phones in September 2020.

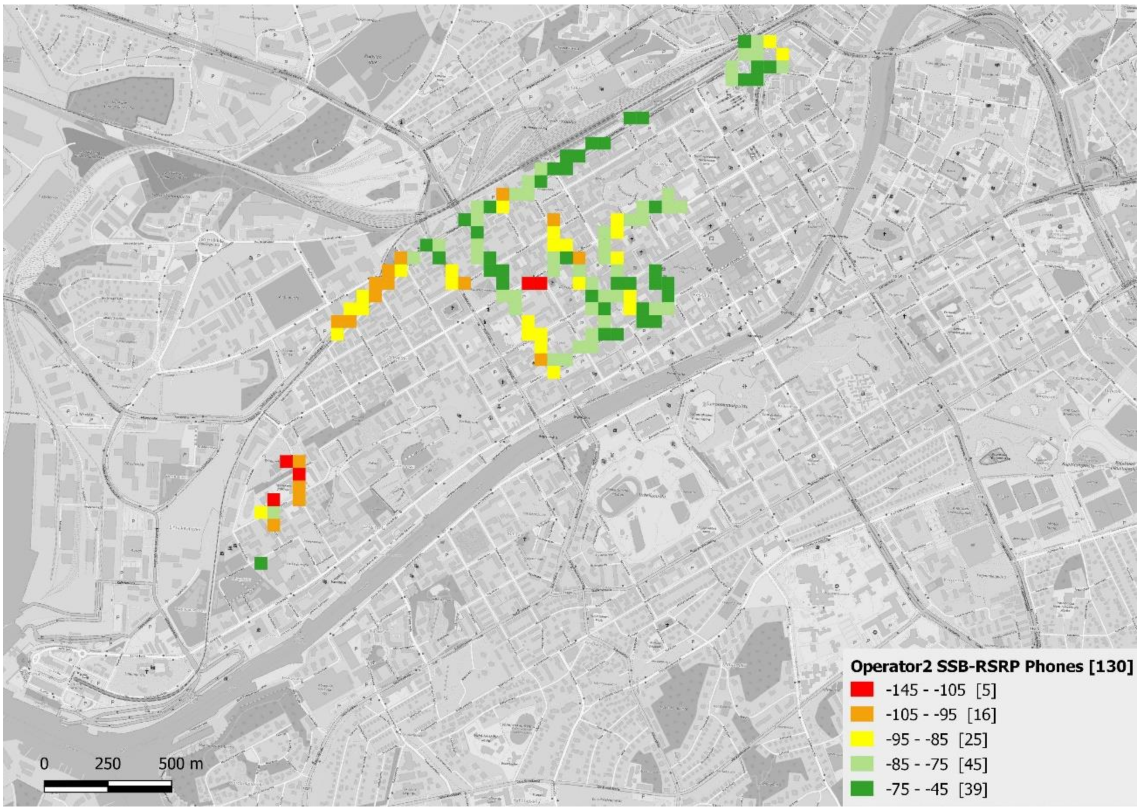

Figure 31. Operator2 SSB-RSRP of phones in May 2020.

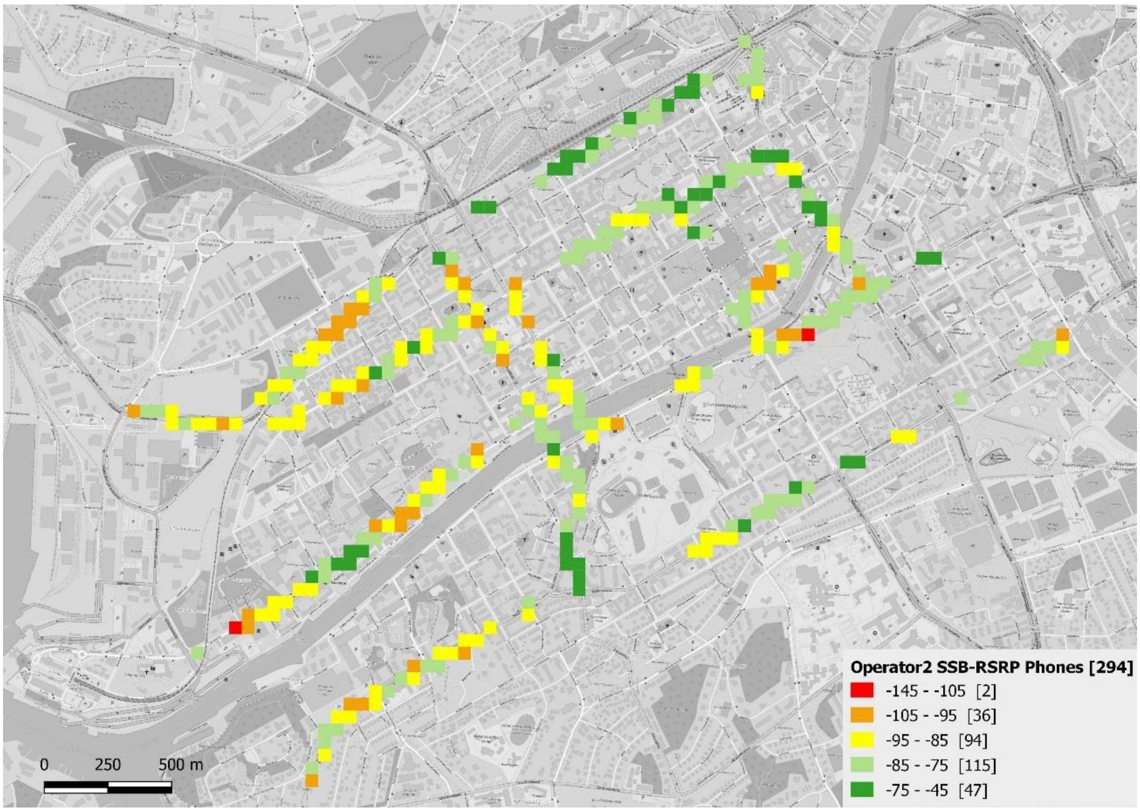

Figure 32. Operator2 SSB-RSRP of phones in September 2020.