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MASTER'S THESIS

5G NEW RADIO PERFORMANCE ASSESSMENT

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ABSTRACT

Each decade, a new generation of wireless cellular technology presents a step-change in what cellular wireless systems can do compared to the previous generation. It is the beginning of new wireless technology in mobile phone networks called 5th Generation Mobile Phone Network (5G), a robust technology from its predecessors. 5G New Radio (5G NR) is the first step in adapting the 5G wireless technology to the existing cellular infrastructure.

This thesis analyzes the 5G NR performance as part of the 5G test network (5GTN) deployed at the University of Oulu. The architecture of the 5GTN is a so-called non-standalone (NSA) network where the 4G Long-Term Evolution (4G-LTE) cellular network provides the control plane of the network. The performance of the 5G NR was obtained by measuring a few primary Key Performance Indicators (KPI) and data transmission measurements to observe the mobile network strength.

This thesis first described the importance of 5G and its history, the deployment timeline, the basic architecture of adaption and synchronization process with the current mobile network, and future possibilities. After that, the main KPI parameters, deployed software, and the test case environment are described, and the 5GTN architecture is also covered. Later, the test results are presented, and lastly, a brief discussion of the outcome of the test result is provided. Finally, a comparison between the 5G NR BTS cells within the test environment network is provided.

Performance measurements have been performed at the Linnanmaa campus of the University of Oulu and the surrounding premises under the 5GTN, the broadest open-access test network of 5G. The test cases were created during the time of field testing. The measurement key performance indicators (KPIs) have been carefully chosen for these test case scenarios, where the recorded result's output were analyzed and represented clearly through this study.

Data throughput tests have been performed parallelly during the field testing within the network to assess the 5G performance in terms of data rate. Along with the KPI parameter and throughput tests, there is a clear indication that 5G NR offers the fastest connection as part of the existing mobile network infrastructure.

Keywords: 5G, 5GTN, LTE, 5G NR, NSA, SS-RSRP, SS-RSRQ, SS-SINR, Throughput, real-time measurement.

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FOREWORD

This thesis has been conducted as a preferential requirement for accomplishing the degree towards the master's program in Electronics and Communications Engineering at the Centre for Wireless Communications (CWC), University of Oulu, Finland.

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Md Muksudul Alam

LIST OF ABBREVIATIONS AND SYMBOLS

2G	Second Generation Mobile Phone Network
2.5	A version of the 2G Network
3G	Third Generation Mobile Phone Network
3.5G	A version of the 3G Network
3GPP	Third Generation Partnership Project
4G	Fourth Generation Mobile Phone Network
4GC	4G Core
5G	Fifth Generation Mobile Phone Network
5GC	5G Core
5G NR	5G New Radio
5GTN	5G Test Network
ACK	Acknowledgement
AI	Artificial Intelligence
APN	Access Point Name
ARIB	Association of Radio Industries and Businesses
ATIS	Alliance for Telecommunications Industry Solutions
Bi	Beam index
BLER	Block Error Rate
BPSK	Binary Phase Shift Keying
BTS	Base Transceiver Station
CA	Carrier Aggregation
CCSA	China Communications Standards Association
CP	Control Plane
cmW	Centimetre Wave
CN	Core Network
CSI	Channel State Information
CSI-RS	Channel State Interference – Reference Signal
CU	Centralized Unit
CUPS	Control and User Plane Separation
dB	Decibel
dBm	Decibel Referenced to Milliwatt
dBi	Decibel Referenced to Isotropic Radiator
DL	Down Link
DMRS	Demodulation Reference Signal
DU	Distributed Unit
DUT	Device Under Test
EDGE	Enhanced Data for Global Evolution
eMBB	enhanced Mobile Broadband
eNB	evolved Node B
EPC	Evolve Packet Core
ETSI	European Telecommunications Standards Institute
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency-Division Duplexing
F-OFDMA	Flexible-Orthogonal Frequency Division Multiple Access
fps	frame per second
FR I	Frequency Range I
FR II	Frequency Range II

Gb	Gigabit
Gbps	Gigabit per second
GHz	Giga Hertz
gNB	5G Node B
GPRS	General Packet Radio Service
GPS	Global Positioning System
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSPA(Plus)	A Version of HSPA
HSUPA	High-Speed Uplink Packet Access
Hz	Hertz
IoT	Internet of Things
KPI	Key Performance Indicator
LDPC	Low-Density Parity-Check
LTE	Long Term Evolution
LTE-A	LTE-Advance
Mbps	Megabit per second
MEC	Multi-access Edge Computing
MNOs	Mobile Network Operators
MIMO	Multiple Input Multiple Output
mmW	Millimetre Wave
mMIMO	massive Multiple Input Multiple Output
ms	millisecond
NACK	Negative Acknowledgement
NAS	Non-Access Stratum
NFV	Network Function Virtualization
NPNs	Non-Public Networks
NR-ARFCN	New Radio-Absolute Radio Frequency Channel Number
nRPCI-bi	new Radio Physical Cell ID-beam index
NSA	Non-Stand Alone
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OP	One Plus
PBCH	Physical Broadcast Channel
PC	Personal Computer
PCI	Physical Cell ID
PDCCH	Physical DL Control Channel
PDN	Packet Data Network
PDSCH	Physical DL Shared Channel
PDV	Packet Delay Variation
PRACH	Physical Random-Access Channel
PRB	Physical Resource Block
PSS	Primary Synchronization Signal
PTRS	Phase Tracking Reference Signal
PUCCH	Physical UL Control Channel
PUSCH	Physical UL Shared Channel
QAM	Quadrature Amplitude Modulation
QoE	Quality of Experience
QoS	Quality of Service

QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RAN	Radio Access Network
RAT	Radio Access Technology
RB	Resource Block
RE	Resource Elements
RF	Radio Frequency
RRC	Radio Resource Channel
RSSI	Received Signal Strength Indicator
SA	Stand Alone
SB	Symbol Block
SC-FDMA	Single Carrier-Frequency Division Multiple Access
SDN	Software Defined Network
SHCCH	Shared and Control Channel
SRS	Sounding Reference Signal
SS	Synchronization Signal
SSB	Synchronization Signal Block
SSS	Secondary Synchronization Signal
SS-RSRP	Secondary Synchronization -Reference Signal Received Power
SS-RSRQ	Secondary Synchronization -Reference Signal Received Quality
SS-SINR	Secondary Synchronization -Signal to Interference-Noise Ratio
TDD	Time-Division Duplexing
TSC	Time-Sensitive Communication
TSDSI	Telecommunications Standards Development Society
TTA	Telecommunications Technology Association
Tx	Transmitter
UE	User End
UHD	Ultra High Definition
URLL	Ultra-Reliable Low Latency
URLLC	Ultra-Reliable Low Latency Communication
UL	Up Link
V2X	Vehicle to Anything
vCore	virtual Core
ViLTE	Video over LTE
vIMS	virtual IP Multimedia Subsystem
VNF	Virtual Network Function
VoLTE	Voice over LTE
VoWiFi	Voice over Wi-Fi
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WTTx	Wireless to The Anything
ZC	Zadoff-Chu

1 INTRODUCTION

In the mobile phone network system, the 5th generation of mobile network (5G) is an advancement in wireless technology. Wireless technology has led the industry to consumer satisfaction since first introduced. The wireless technology for mobile phone networks from 1st generation of mobile networks (1G) to 5G is a transaction to achieve different aims and goals for each generation. It has been seen that each generation maintained a decade of lifespan, and to meet the increasing consumer demand, wireless technology does enter in next generation. For example, the 2nd generation mobile network (2G) was introduced back in the 1990s, focusing on the data transmission part General Packet Radio Service (GPRS), and then the Enhanced Data for Global Evolution (EDGE) part was launched later. However, mobile phone networks have been mostly related to voice and mobility, mentioned as 1G. Later in the first phase of the millennium century, 3rd generation of mobile network (3G) was introduced by launching High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA) combinedly presented as High-Speed Packet Access (HSPA). Then, the High-Speed Packet Access Plus (HSPAP) was launched, which is the advancement of HSPA and succeeded in providing ten times faster data transmission speed than the original release. 3G was mixed with voice and data services advancements from its previous generation of wireless technology. In 2010, wireless technology entered a new generation named the 4th generation mobile phone network (4G) to support the increasing consumer demand. It has been noticed that 4G is mostly data-centric technology to cope with the increasing data traffic demand by providing the fastest internet with lower latency [1].

Using Carrier Aggregation (CA) and Orthogonal Frequency Division Multiplexing (OFDM) techniques, 4G was later known as Long Term Evolution (LTE) [1] [2]. As wireless technology advancement happened during each generation change, different consumer types with different demands also appeared during this generation adaptation. At the same time, due to different types of consumer addition, it has been seen that the growth of data transmission dependent technology like Internet of Things (IoT), Machine to Machine (M2M), Device to Device (D2D) type communication has already been growing fast. Therefore, wireless technology has entered a more data-centric performance to fulfill that increasing demand to provide a more stable mobile network named 5G. It is being conceived that 5G will increase IoT-based capacity for various consumers with high data rates compared to its predecessor. Moreover, 5G will be able to deliver an Ultra-Reliable Low Latency Communication (URLLC) centric mobile network where mission-critical services like vehicle systems, healthcare, mining, robotics, Artificial Intelligence (AI), etc., are included [3].

With the IoT ecosystem where all possible devices like cars, several types of home appliances, sensors, real-time interacting robots, and media devices will be connected through the internet, 5G surpasses its predecessor due to its fast and flexible connectivity. Moreover, 5G brings a new level of performance by focusing on data transmission through a more responsive connection with real-time interactivity and less network congestion. So, it will be possible to get higher network speeds even in densely populated areas as it has been seen that each generation of cellular network technology has enabled breakthrough improvements and new opportunities for researchers and industry, so doors are open. Furthermore, due to its flexible connectivity, it can be expected that 5G will provide seamless integration of virtual networks also.

According to Release-15 from the 3rd Generation Partnership Project (3GPP), responsible for the 5G specifications, 5G New Radio (5G NR) technology is the first stage of initial 5G deployment. 5G NR will be linked through a new architecture named Non-Standalone (NSA), where existing evolved Node B (eNB) from 4G will collaborate with the new 5G Node B (gNB) and deliver 5G experience partially without having any significant changes on existing infrastructure [3]. eNB and gNB are technical terms defining base stations in 4G and 5G, respectively.

In this thesis, 5G Test Network (5GTN) has been used to assess the performance of the 5G NR through indoor and outdoor measurement from 5G NR enabled Base Transceiver Station (BTS) or equivalently gNB to the wirelessly connected measurement device. In addition, Nemo Handy [4] (a real-time measurement tool) has been used to measure the performance of 5G NR. Furthermore, a post-processing tool called Nemo Analyze [5] has been used for the measured data file post-processing. Finally, an Android platform-based free version mobile application named Speed Test by Okla [6] has been used to measure the data throughput of the 5G NR signals.

At the beginning of this thesis, technical aspects of 5G have been reviewed and described in parts relevant to this thesis, and a discussion on the importance of the 5G new radio, structure and architecture is conducted. The real-time test drive data, individual test case data, and the throughput test data of this thesis have been presented in the measurement chapter. In the result chapter, the main goal of this thesis is fulfilled by comparing the outcome of the two separate measurement test cases and the theoretical specification.

1.1 Objectives

This thesis aims to evaluate the 5G NR performance in indoor and outdoor scenarios from one of the 5G NR-enabled BTS of 5GTN, situated at the University Oulu Linnanmaa campus. As this study is a performance evaluation assessment, the goal is to measure, analyze, and present the performance results of the 5G NR. The concept is to obtain the best possible signals from 5G NR enabled BTS of 5GTN through a real-time measurement tool and performed the throughput tests within the coverage of 5GTN. Also, partially make a cumulative comparison between the cells in terms of measured data obtained during the test.

1.2 Radio Channel Phenomena

The architectural choice of the 5GTN in these measurements is the NSA architecture, where the architecture system itself may pose some limitations to measurements. As 4G-LTE is used as an anchor for 5G NR (i.e., the control channels of the 5G cellular system are 4G control channels), where 4G-LTE BTS coverage will not be available or is unreachable or even if it remains down, then the 5G connection will not be provided due to its dependency on the NSA architecture system. However, the 4G-LTE anchor channels are typically on lower frequencies, thus providing higher coverage and making this problem very specific. Secondary phenomena is the noise generated in the receiver antenna and the front-end part of the receiver, which directly affects the receiver sensitivity and, together with signal propagation loss, is a determining factor of the achievable link distance. Thirdly, the interference level stemming from other users and adjacent cells will be high if the network is not optimized precisely [7] [8].

2 THEORETICAL BACKGROUND

2.1 Concepts

The next generation 5G is more capable than the previous generation 4G, in supporting new technologies. The massive Internet of Things (mIOT), smart cities, massive sensors, driverless cars, and even remote surgery need higher data transmission rates and higher capacity [7]. Due to the need for higher data rates/capacity is one of the reasons why wireless cellular technology was developed into 5G. 5G provides an easily modifiable network for widespread connectivity to connect anyone and anything at anywhere [7]. According to 3GPP for 5G specification, 5G NR is the new global standard for 5G air interface [9]. It uses both Time Division Duplexing (TDD) and Frequency Division Duplexing (FDD), which were also used in the previous generation. However, in TDD, it has been seen that allocation for the Up-Link (UL) time slot and Downlink Link (DL) time slots ratio offer more capacity and a high-performance mobile network [10]. Therefore, 5G commonly uses TDD technology, which brings a new scalable and highly flexible wireless cellular network.

2.1.1 Evolution of 5G

The evolution of the 5G is being agreed upon in 3GPP, where new standard releases appear every 18 months on average. The first 5G standard release was 3GPP Release-15 (Rel. 15). We know that 5G focuses on digital data transmission, and nowadays, mobile networks and data transmission are used in different areas with various types of needs [3]. For example, in some use cases, the amount of data and the transfer rate is critical, whereas latency is the main issue in some other use cases. Release-16 (Rel. 16) provides capabilities that offer smaller latencies. Thirdly, in some use cases, e.g., smart environment monitoring, smart cities, a massive number of devices need to communicate with up to one million devices in an area of 1 km^2, but at the same time, in some cases, there are fewer devices will be connected to the mobile network, but the high data rate is the primary concern [7]. Release-17 (Rel. 17) of 3GPP is soon targeting these massive machine-type communications use cases. Further releases will improve the capabilities of the 5G system, and it will eventually evolve into a 6G system.

2.1.2 5G Use Case

5G use cases have been divided into three different main categories. These three categories of 5G use cases are presented in Figure 1. These are mainly the enhanced Mobile Broadband (eMBB), where high data transmission rates are essential. Massive Machine-Type of Communications (mMTC), where the number of devices that need mobile network access is essential. Furthermore, Ultra-Reliable Low Latency (URLLC), where latency and reliability play a key role [7][11].

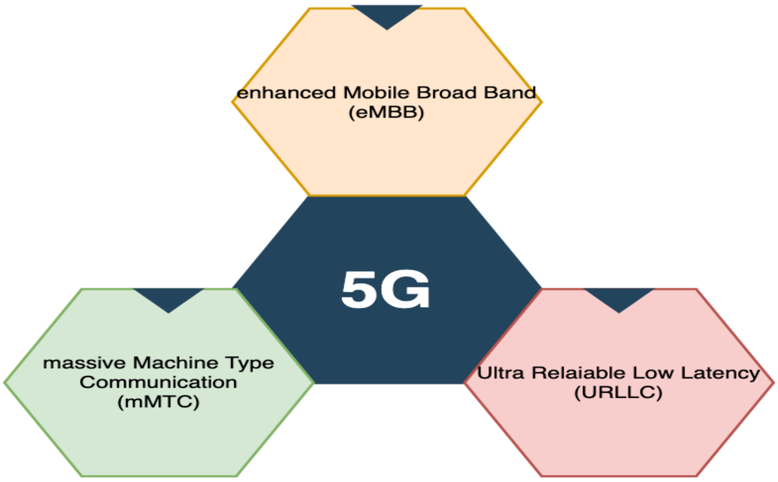

Figure 1. 5G use cases.

Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS), the European Union's flagship project on 5G, is partially funded under the seventh research framework programme (FP7) by the European Commission. It was initially introduced these three main use cases before the standardization of 5G. With 30 months of duration, this project was started in 2012 November. Later, ITU accepted these three different categories of use cases as the approach to 5G standardization [12]. Figure 2 signifies the possible 5G usage scenarios.

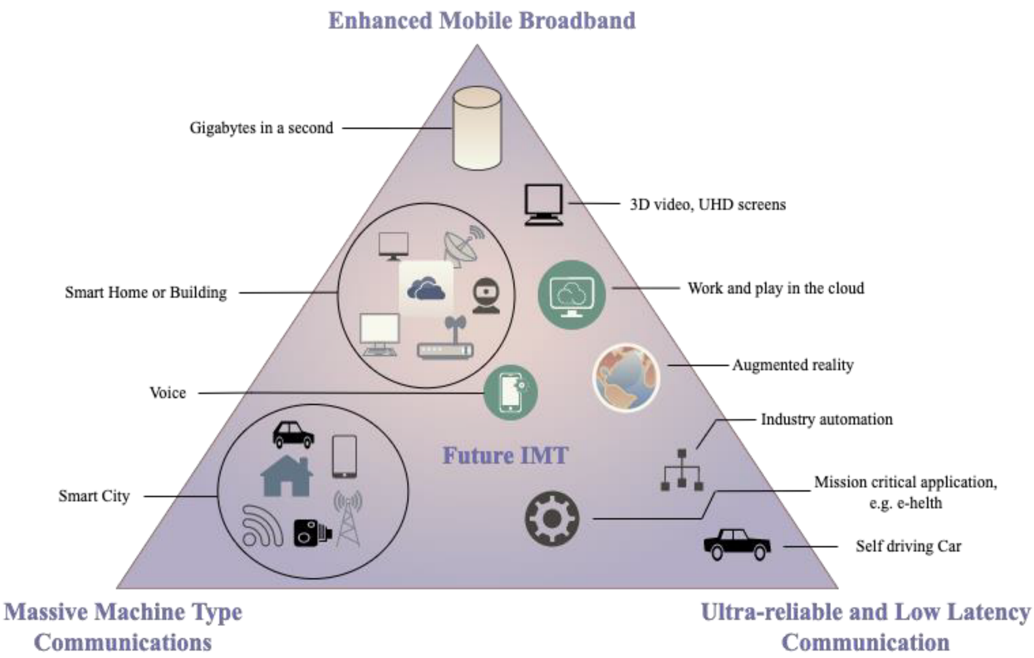

Figure 2. 5G Usage scenarios within the three main categories [13].

2.2 5G NR

5G NR is the new wireless standard and foundation of fifth-generation wireless technology. Moreover, this initial deployment of 5G was named New Radio by the 3rd Generation Partnership Project (responsible for 5G specification) [14]. It is being developed as part of the continuous evolution of wireless broadband communication to meet the requirements of 5G as outlined by International Mobile Telecommunication Systems (IMT)-2020 or Future IMT, whereas LTE has been developed as part of IMT-2010 previously. IMT is known as International Mobile Telecommunication. New radio's target is to make the wireless network the same as the wireless line network with a fiber-like performance at a low cost-per-bit [15]. ITU is the combined platform of the ITU-T (Telecommunication standardization - network and service aspects), ITU-D [Promote and assist the extension of ICTs (Information and Communication Technologies) to all the world's inhabitants - narrowing the digital divide], and ITU-R (Global radio spectrum management and radiocommunication standardization) to develop global broadband multimedia and define the required concepts for the future cellular generation of international mobile telecommunication systems. ITU is committed to connect the world through its 193 member states, 874 sector members, 171 associates, 127 academia [13] and more than 20,000 professionals in the world of technology as a part of the global network [16].

2.2.1 Importance of New Radio

Nowadays, the data traffic pattern between uplink (user to base station) and downlink (base station to the user) is often unbalanced due to users' more download-centric habits compared to their less upload usage [17]. The higher-order MIMO such as 4x4 or the advanced features like 256-QAM modulation are limited for the uplink in FDD. On the other hand, TDD operates a similar frequency for each duplex direction, with frames containing separate time periods and slots for uplink or downlink communications. So, for the 5G usage, TDD is becoming an important duplex mode due to its flexibility over the same frequency [8]. Mid Bands between 2 to 8 GHz are suitable for coverage and capacity for the 5G usage, such as eMBB, URLLC and mMTC on the current network structure. 3.5 GHz (3.4 - 3.8 GHz) mid-band is targeted to support most 5G use case scenarios in high capacity and wide areas [17]. Propagation models are used in wireless network planning, where the 3.5 GHz band is significant among the sub - 6 GHz bands (below 6 GHz) to allow for wider carrier bandwidths while still maintaining good propagation characteristics [18]. As wireless technology is forwarded towards the 5G after LTE, it is impossible to upgrade to 5G overnight. That is why 3GPP concludes with a solution where users can utilize the benefit of 5G partially on the same existing network infrastructure through their release-15 and reveal a new standard air interface for primary 5G deployment. According to 3GPP, it is known as 5G NR [8][19] and the first generation new radio is 3.5 GHz based [18].

2.2.2 Timeline and Phase

3GPP covers mobile telecommunication technologies that describe cellular communication systems, including core networks, radio access, and service functions. It brings seven telecommunications standards development organizations together to provide a reliable reporting environment and specifications to its members, defining 3GPP technology [20]. These seven organizational partners are the China Communications Standards Association (CCSA) from China, the European Telecommunications Standards Institute (ETSI), the Telecommunications Standards Development Society (TSDSI) from India, the Association of Radio Industries and Businesses (ARIB), and the Telecommunication Technology Committee (TTC) from Japan, Telecommunications Technology Association (TTA) from Korea including Alliance for Telecommunications Industry Solutions (ATIS) from the United States of America [21].

The 3GPP is working and actively developing 5G specifications, and in this process, 3GPP includes other organizations (responsible for standards development of telecommunications) together on a common platform [20]. 3GPP has released two standard versions (Release-15 and Release-16) for 5G deployment. Release-17 is currently expected to be completed in 2022, with a freeze in March 2022 and protocol coding freeze and stable in June 2022, according to the current timetable [22] as depicted in Figure 3.

Phase-I is the 3GPP Release-15 was completed by September-2018. It addresses the most urgent and commercial needs. Non-Stand Alone (NSA) architecture for the core functionality was standardized, and Stand-Alone (SA) architecture was introduced. The 5GTN has followed the NSA architecture during this study. The main feature of Release-15 is 5G deployment which is mostly related to the eMBB part. URLLC, mMTC, mIoT. Mission Critical (MC) like High Reliable Low Latency Communication (HRLLC), Vehicle to Everything (V2X), and Wireless Local Area Network (WLAN), including unlicensed spectrums are also introduced, but the standardization of these features was and will be done in Release-16 and Release-17. All the commercial deployments are currently based on Rel-15, and it was frozen on 22 March 2019 [23].

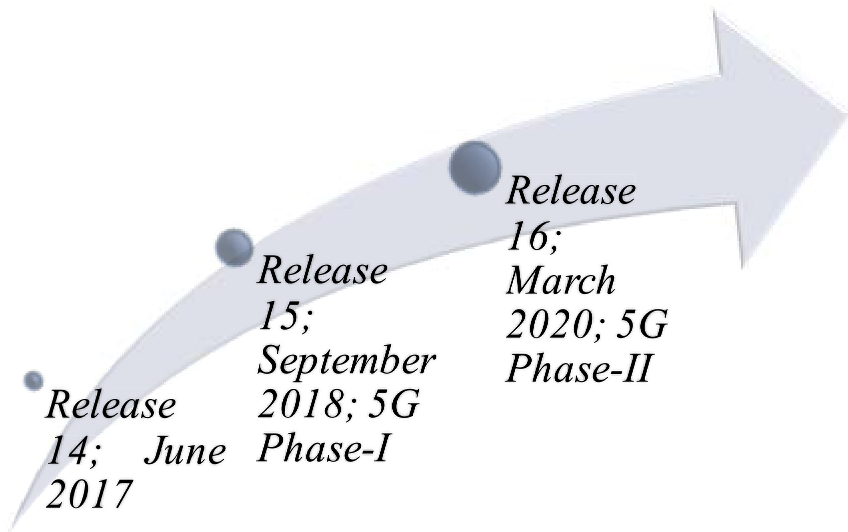

Figure 3. 5G adaption according to 3GPP phase timeline.

Phase II, 3GPP Release-16 was primarily completed in June 2020, with some parts in December 2020. The main features of Release-16 are URLLC, industrial IoT, Multiple Input Multiple Output (MIMO), NR operation for unlicensed spectrum [7], 5G Core (5GC), including approaches to reduce power consumption [22].

According to the current schedule, Release-17 reached in stage 3 with a functional freeze in March 2022, and coding protocol freeze and stable in June 2022. Rel-17 standardizes features such as URLCC enhancement, Multi Subscriber Identity Module (Multi Sim), Narrow Band

IoT (NB IoT), Industrial IoT (IIoT), enhanced Machine Type Communications (eMTC), Radio Access Network (RAN), and virtual RAN (vRAN) [22].

2.2.3 NSA and SA Architecture

There are two distinct architectures used for the 5G deployment. One is NSA, and another one is SA. Both are presented in Figure 4

- By using multiple radio access (4G and 5G) - NSA and
- With only one radio access technology (5G) - SA [24].

Most of the service providers will deploy the 5G by using NSA architecture to rely upon the strategy of backward compatibility to 4G and gradual upgrades towards the 5G mobile network. It is an economic architecture for service providers willing to offer high-speed connections to the customers with 5G-empowered gadgets, as the NSA architecture can straightforwardly build upon the existing 4G infrastructure. The existing 4G mobile network infrastructure can provide new end-to-end (E2E) 5G empowered services by offering the existing 4G control plane for setting up the connections. In short, NSA will provide faster data speeds at low investment. SA architecture will be a different choice for players who have set their goal in the long run to capture new markets such as the smart vehicle market, smart industries, smart hospitals, smart cities, or other vertical markets. Stand-alone architecture offers a new and typically virtualized network system of 5G, including a new RAN, new transmission Transport Network (TN) and new 5G core (5GC), and it can be run entirely separate from the 4G network and legacy. [14].

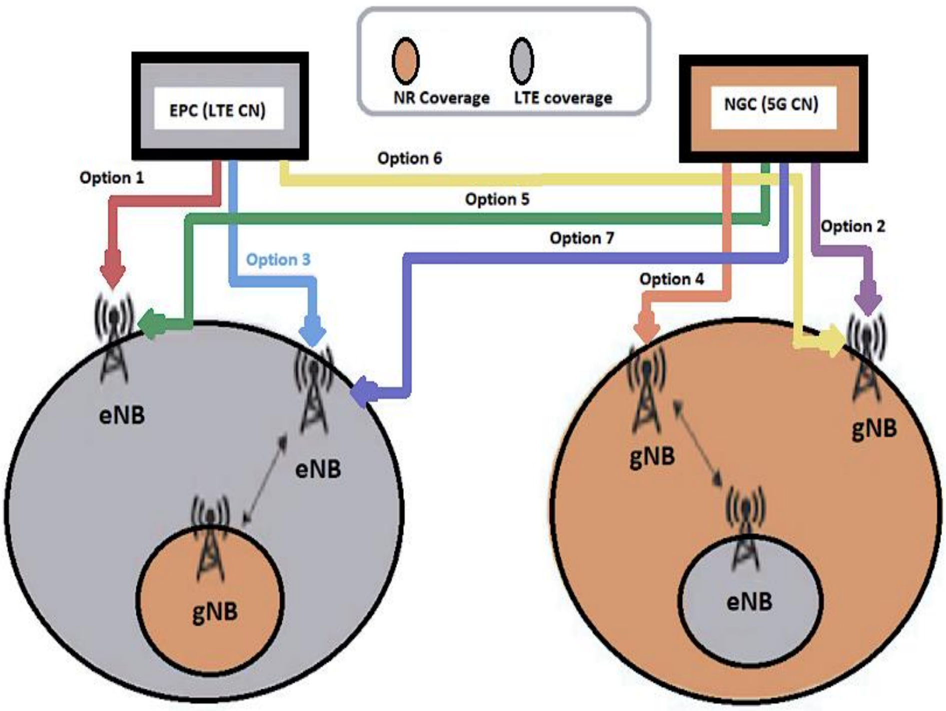

Figure 4. All the options for 5G network deployment [25].

Both access and core systems of 4G and 5G need to be combined in a meaningful and practical fashion. However, introducing 5G on top of the previous generation takes time and capital expenditure, and thus viable options are needed to perform the 5G inclusion. That is why the 3GPP introduces 5G NR NSA as a transition period toward the complete 5G network [23] [25] [26].

Non-Stand Alone enables the dual connectivity where 4G infrastructure supports connectivity to gNB (5G NR base station). Figure 5 shows a 5G gNB connected to a 4G Evolved Packet Core (EPC) at the data layer. 5G gNB does not connect to the mobility management entity (MME), but the gNB connects to the LTE eNB to receive activation and deactivation requests for the 5G bearer [25] [27].

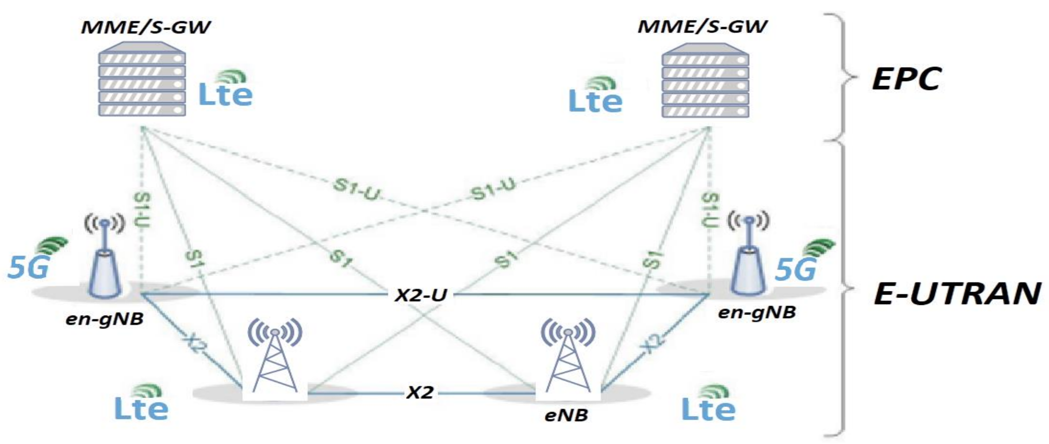

Figure 5. The NSA Architecture [23].

According to 3GPP, three variations for NSA have been defined in their published document, and these are presented in Figure 5 [23] and Figure 6.

- Option 3, here 5G Node B (gNB) will work as a secondary base station under the existing Evolved Packet Core (EPC), which is the core network of LTE, and the LTE evolved Node B (eNB) will act as the main base station providing the control plane for the connection [24] [27].

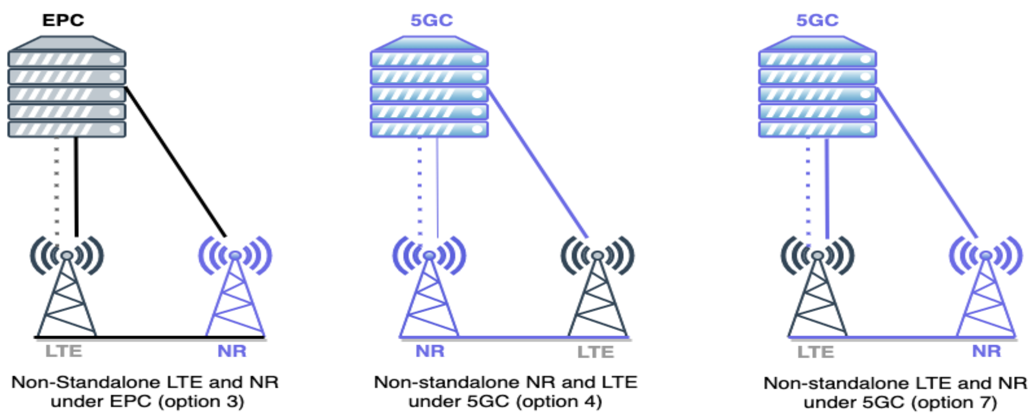

Figure 6. The difference between Non-Stand-Alone options [24].

- Option 4, in this variation, new 5GC and gNB work as a primary base station, and existing LTE eNB work as a secondary base station [24] [27].
- Option 7, here we have 5GC and an LTE eNB acts under 5GC as a primary base station, and gNB acts as a secondary base station [24] [27].

In Stand-Alone technology, NR cells will be operated directly without any help from LTE technology. So, during a new connection placement in this technology, gNB is independent to contact UE directly, and vice versa, without any dependency on 4G-LTE technology.

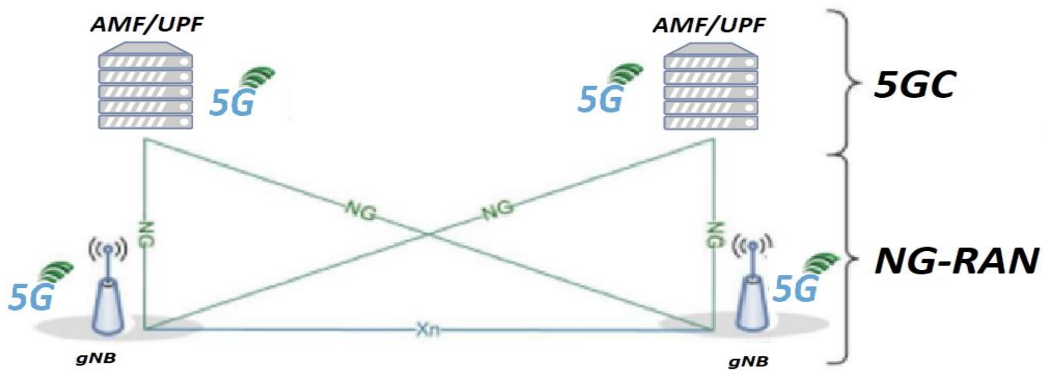

Figure 7. The SA Architecture[23].

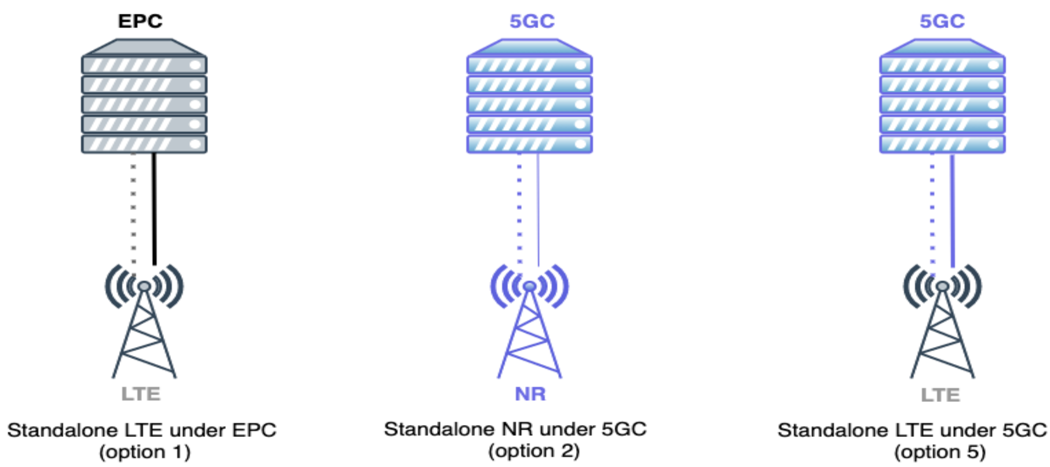

Figure 8. The difference between Stand-Alone options [24].

According to the 5G specification by 3GPP, three variations for SA are presented in Figure 7 [23] and Figure 8 and clarified below,

- Option 1, in the existing 4G LTE network, uses EPC with LTE eNB access [24].
- Option 2, here 5GC and NR gNB access will be used [24], and the last one is
- Option 5, where 5GC will be used as option 2 but only with LTE eNB access instead of NR gNB [24].

A technical comparison of the main options of NSA and SA system architecture is given in Table 1.

Table 1. The technical comparison between three 5G NSA and SA options [24]

	NSA		SA (Op. 2)
	Op. 3	**Op. 7**	
3GPP 5G specification	Rel-15 (' 17.12) – 1st prioritized,	Rel-15(' 18.6)	Rel-15(' 18.6)
5G spectrum	Sub - 6GHz and millimeter Wave (mmW) bands are feasible	Sub - 6GHz and mmW bands are feasible	The sub - 6GHz band is desirable
Core Network (CN)	EPC (Evolved Packet Core)	5GC (5G Core)	5GC
CN interworking	Not required	Not required	Required (with or without N26 [28] interface between 5GC and EPC)
Network slicing and 5G Quality of Service (QoS)	Not supported	Supported	Supported
UE impact (for 5G/LTE dual mode)	EPC-NAS (Evolved Packet Core -Non-Access Stratum)	5GC/EPC-NAS	5GC/EPC-NAS
Leverage of LTE	Full	Full	Partial (Reattach)
LTE upgrade	Required (eNB and 5GC)	Required (eNB and 5GC)	None or minor
Radio Access Network (RAN) interworking	EN-DC (Evolved Universal Terrestrial Radio Access Network New Radio-Dual Connectivity) [29][30]	NGEN-DC (Next Generation Radio Access Network Evolved Universal Terrestrial Radio Access Network-New Radio-Dual Connectivity)[29]	NR-DC (New Radio-Dual Connectivity) [30] [31] (Intra-RAT)
Inter-Radio Access Technology (RAT) data session continuity	MR-DC (Multi RAT – Dual Connectivity) [32] and intra-system handover [28]	MR-DC [32] and intra-system handover [28]	Inter-system handover (N26) [28]
Forward compatibility with SA or Release-16 onwards	Low	Mid	High

2.2.4 5G NR Physical Layer

2.2.4.1 Channels and Signals

The physical layer of 5G NR is presented in this section in detail, using 3GPP 5G NR specifications describing different physical layer properties. The used 3GPP specifications are listed below in
Table 2.

Table 2. Versions of 3GPP specifications for 5G NR [9]

Specifications	**Versions**	**Title**
38.201	V 15.0.0 (2017-12)	General Description
38.202	V 15.4.0 (2018-12)	Service Provided by the Physical Layer
38.211	V 15.4.0 (2018-12)	Physical Channel and Modulation
38.212	V 15.4.0 (2018-12)	Multiplexing and Channel Coding
38.213	V 15.4.0 (2018-12)	Physical Layer Procedures for Control
38.214	V 15.4.0 (2018-12)	Physical Layer Procedure for Data
38.215	V 15.4.0 (2018-12)	Physical Layer Measurements

According to these 3GPP specifications, 5G NR physical channels and signals from the user plane to the control plane are presented below in Figure 9 where DL denotes the Down Link, and UL denotes the Up Link [3] [33].

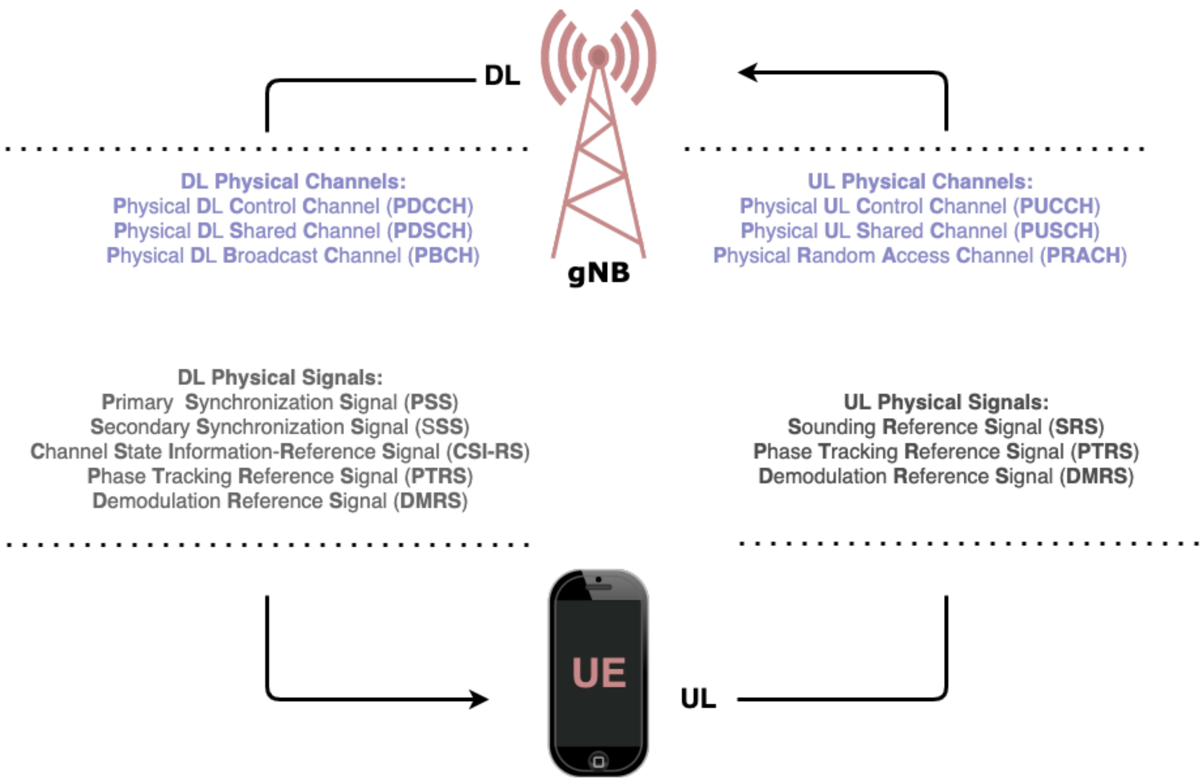

Figure 9. 5G NR physical channels and signals [33].

LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) technology, a new extension of OFDM, wherein each user is scheduled to a distinct part of the spectrum. The modulation in downlink (BS → UE) works in such a way that the signal subcarrier values (of all users) are generated and mapped directly onto the OFDM subcarriers. In the uplink direction, single carrier-frequency division multiple access (SC-FDMA) modulation is used, with a lower peak-to-average power ratio, meaning lower cost amplifiers and less power usage. Therein, the user data is mapped only to the subcarriers scheduled for the user for uplink traffic.

5G NR uses Flexible Orthogonal Frequency Division Multiple Access (F-OFDMA) technologies. F-OFDMA is an extension of the OFDMA architecture. In principle, it is the same technology as OFDMA but deployed in a more flexible way where subcarrier spacing, cyclic prefix length, and symbol duration are not constant[34] [10] [35].

As in this thesis study, the 5G NR NSA Option-3 architecture has been followed through the 5GTN, where the LTE plays a key role in 5G NR network strength measurements. A comparison between LTE and 5G NR in terms of each physical channel and signal is given below as a table. SHCCH indicates the shared and control channel as an example based, and the below

Table 3 observation will provide a good understanding and distinguish between the two standards [33] [35].

Table 3. Channels and signals: NR vs. LTE [9] [33]

		LTE	**NR**
Bandwidth	SHCCH	From 1.4 to 20 MHz	From 4.32 to 400 MHz
Type of Coding	PDSCH (Physical Down Link Shared Channel)	Turbo	LDPC (Low-Density Parity-Check)
	PDCCH (Physical DL Control Channel)	TBCC (Tail Bitting Convolution Codes)	Polar
	PBCH (Physical DL Broadcast Channel)	TBCC	Polar
	PUSCH (Physical Up Link Shared Channel)	Turbo	LDPC
	PUCCH (Physical UL Control Channel)	Block	Polar/Block
Type of SS sequences	PSS (Primary Synchronization Signal)	ZC (Zadoff-Chu)	m-sequence
	SSS (Secondary Synchronization Signal)	m-sequence	Gold sequence
	DMRS (Demodulation Reference Signal)	Gold sequence (DL), ZC (UL)	Gold sequence
	CSI-RS (Channel State Information-Reference Signal)	Gold sequence	Gold sequence

	PTRS (Phase Tracking Reference Signal)	NA	Gold sequence
	SRS (Sounding Reference Signal)	Gold sequence or ZC	Gold sequence
	PRACH (Physical Random Access Channel)	ZC	m-sequence
	PUCCH (Physical UL Control Channel)	ZC [e.g., ACK (Acknowledgement) / NACK (Negative Acknowledgement)]	ZC (e.g., ACK/NACK)
Type of Modulation	PDSCH	Up to 256 QAM (Quadrature Amplitude Modulation)	Up to 256 QAM
	PDCCH	QPSK (Quadrature Phase Shift Keying)	QPSK
	PBCH	QPSK	QPSK
	PUSCH	Up to 64 QAM	$\pi/2$-BPSK (Binary Phase Shift Keying) and up to 256 QAM
	PUCCH	BPSK / QPSK	BPSK / QPSK

2.2.4.2 Frame Structure of 5G NR

As 5G uses more flexible OFDMA technology than LTE, the frame structure for 5G NR will be slightly different and more advanced. Figure 10 below portrays the details of the 5G NR frame structure. The frame structure of 5G NR consists of 10 subframes ($N_{Subframe}^{frame} = 10$) where each subframe duration is 1ms. [33][10]. Each subframe of 5G NR can be divided into an even number of slots according to $N_{slot}^{subframe,\mu} = 2^{\mu}$, $\mu = 0, 1, 2, \ldots$ (showed in Figure 10). Subsequently, the duration of a slot period is equivalent to $1ms/2^{\mu}$. Furthermore, the subframe consists of either 14 or 12 OFDM symbols in each slot for normal/extended cyclic prefix denoted by N_{sym}^{slot}. Now depending on that frame structure for normal/extended cyclic prefix in the time domain, symbol duration for each is equal to 1 ms / ($2^{\mu} \times 14$) or (1 ms / ($2^{\mu} \times 12$)) [33][36].

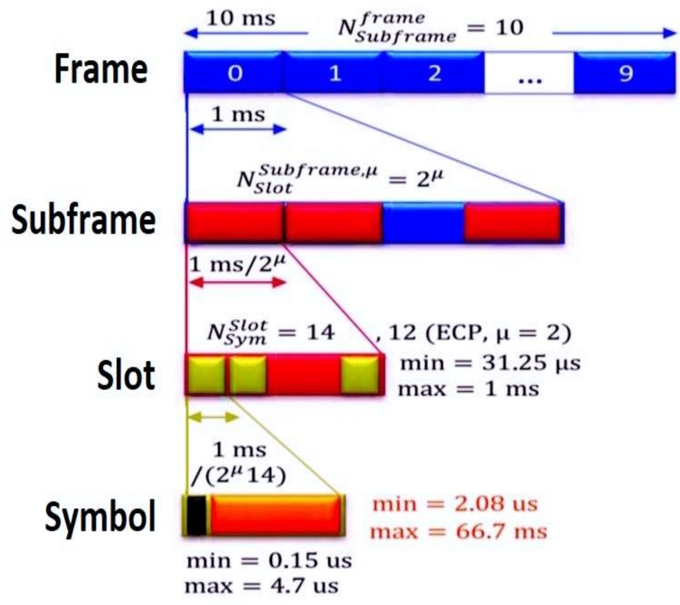

Figure 10. 5G NR frame structure [33].

A Resource Block (RB) consists of 12 adjacent subcarriers in the frequency domain where subcarrier spacing is denoted by Δf. A parameter μ was given for 5G NR in the time domain definition. In the frequency domain, Δf is flexible and depends on the used numerology (μ). So now,

$$\Delta f = 2^{\mu} \times 15 \ kHz \tag{1}$$

In the control plane (in time-frequency structure), next focuses on the 5G synchronization block, which is also denoted by the Synchronization Signal Block (SSB) of Synchronization Signal/ Physical Broadcast Channel (SS/PBCH) of 5G synchronization architecture. For SSB, resource allocation is described in Table 4, where v equals N_{ID}^{Cell} mod 4 and the corresponding PCI denotes by N_{ID}^{Cell}.

Table 4. SS/PBCH block resource allocation [[9], Tab. 7.4.3.1-1], ***l*** and **k** are relative to the SS/PBCH block [33]

Channel or Signal	**OFDM Symbol (*l*)**	**Subcarrier (k)**
PSS (Primary Synchronization Signal)	0	56, 57, …, 182
SSS (Secondary Synchronization Signal)	2	56, 57, …, 182
Set to 0	0	0, …, 55, and 183, …, 239
	2	48, …, 55, and 183, …, 191
PBCH (Physical DL Broadcast Channel)	1, 3	0, 1, …, 239
	2	0, …, 47, and 192, …, 239
Demodulation reference signals (DMRS) for PBCH	1, 3	0 + v, 4 + v, …, 236 + v
	2	0 + v, 4 + v, …, 44 + v, and 192 + v, 196 + v, …, 236 + v

According to Table 4 and Figure 11, the SSB specification is summarized as follows,

- In NR, Synchronization Signal (SS) combines Primary Synchronization Signal (PSS) + Secondary Synchronization Signal (SSS), and PBCH is transmitted through the same 4 Symbol Block (SB) [33].
- SSB contains 240 contiguous subcarriers, which means 20 resource blocks [33].
- Within the SSB, the subcarriers are maintained by number and increasing order from 0 – 239 [33].

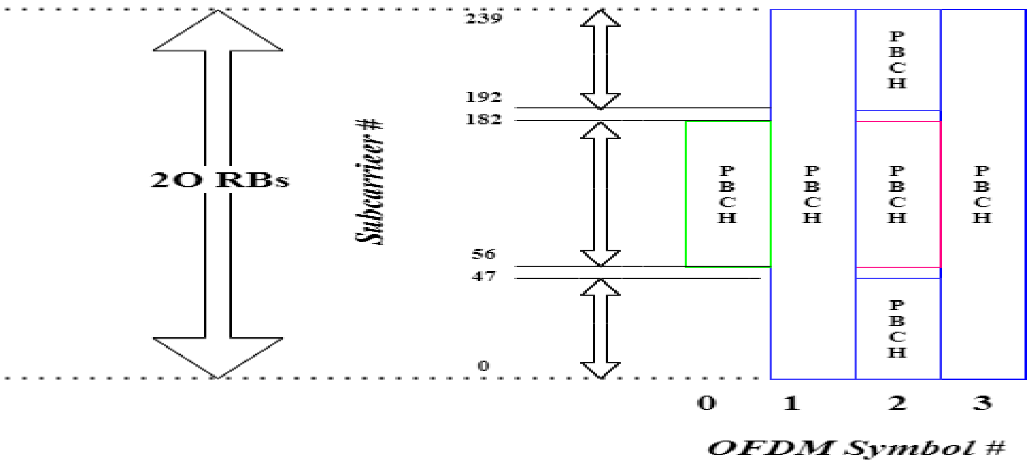

Figure 11. SSB resource allocation [33].

2.2.4.3 5G Flexible Physical Layer

Physical layer flexibility is another important feature of the 5G flexible network where subcarrier spacing plays a key role. It has been seen that in LTE, there is one subcarrier spacing which is 15KHz. However, in 5G, it is denoted by Δf, and from the equation (1) 'μ' is known as flexibility where μ = 0, 1, 2, 3, 4. Below, Table 5 will give a detailed clarification of μ and subcarrier spacing.

Table 5: Sub Carrier Spacing upon flexibility in 5G physical layer

Flexibility (μ)	**Sub Carrier Spacing (kHz.)**
0	15
1	30
2	60
3	120
4	240

It has been seen that in LTE, the mainframe of 10 ms time duration (in the time domain), whereas the subframe has 1ms of time duration, having two slots of 0.5 ms, and each slot consists of 7 OFDM symbols. So, in 1ms, LTE provides 14 OFDM symbols. As in 5G, each sub-frame of 1ms time duration has one slot, consisting of 14 OFDM symbols, and these symbols are constant for the sub-frame. As 5G has multiple combinations in the time domain, it is possible to increase slots through flexibility (μ). For example, according to equation (1) when μ = 1 it will be $2^{\mu} \times 14 = 2^1 \times 14 = 28$ OFDM symbols. It means the time duration of that

OFDM symbol has been reduced. So, it corresponds to latency, which provides quick data transmission within the same time duration delivered earlier in LTE [37].

2.2.5 Synchronization

In 5G NR, the control plane and user plane synchronization procedure are based on a new technology called beam management [33]. 5G NR system uses reference signals during beam management. During the IDLE mode, system uses PSS/SSS/PBCH DMRS (i.e., SSB). During the connected mode, it uses CSI-RS and SRS for downlink and uplink, respectively [38]. This management is done with four consecutive procedures [33],

- **Beam sweeping** refers to the coverage of a spatial area with a set of beams transmitted and received according to a pre-determined interval and direction [38][39].
- **Beam measurement** refers to the evaluation of the received signal quality at the gNB or UE. Various metrics such as RSRP, RSRQ, and SINR or SNR can be used [38][39].
- **Beam determination** means selecting the appropriate beam at the gNB or UE according to the measurements obtained by the beam measurement procedure [38][39] and
- **Beam reporting** means selecting the appropriate beam at the gNB or UE according to the measurements obtained by the beam measurement procedure[38][39].

Furthermore, it also includes initial access, which permits a physical link connection from UE to gNB for idle users, beam tracking, which maintains handover, recovery procedure of radio link failure, and beam adaptation. Altogether, it is called beam management operation [36] [40] [41].

2.3 5G Features and Network Flexibility

eMBB, URLLC, and mIOT are the primary three use case classes in 5G. Each use case class varies significantly depending on the user's category, traffic, and requirements. The deployment of 5G spectrum bands had been categorized to 1) sub to 1 GHz, 2) 1 GHz to 6 GHz, and 3) above 6 GHz. Each spectrum category is different with respect to capacity and coverage. In use cases such as IoT service support and extended mobile broadband coverage related to, e.g., sub-urban, deep in buildings and rural areas, the sub-1 GHz spectrum is suitable as it provides better coverage due to better propagation properties of lower frequency bands. In the case where high capacity is needed, the spectrum above 6 GHz is preferable - e.g., urban hotspot in mmW spectrum. In a typical outdoor urban case spectrum, from 1 GHz to 6 GHz is preferred due to the balanced ratio in capacity and coverage [24] [42].

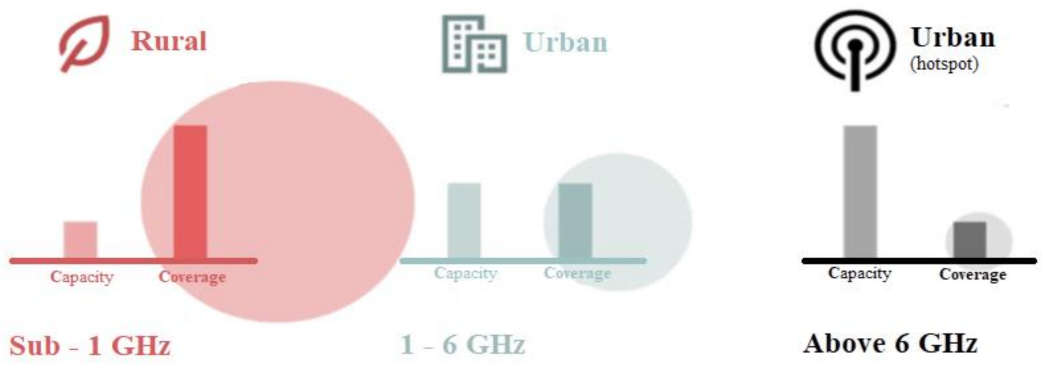

Figure 12. Capacity and coverage consideration of spectrum categories [24].

It has been seen that several types of research are ongoing (in sub-related areas such as mMIMO, cm Wave, and mmWave to deliver a better advance with a reliable and flexible network) to increase the capacity in terms of coverage area in rural areas and near-end urban cases as well as balanced and more flexible network support. Moreover, network development possibilities have opened to the future [25] [43].

2.4 Definitions of Measurements Signals

In 5G NR, the measurement of reference signals is used for cell selection/reselection, mobility, handover, and beam management. During the idle mode, the 5G NR system uses PSS, SSS, and PBCH DMRS (i.e., SSB), and during the connected mode, CSI-RS (DL) and SRS (UL) are used [38]. So, the UE measurements are performed based on Synchronization Signal (SS) and Channel State Information (CSI) instead of Cell-Specific Reference Signal (CRS) [36].

During the test case, LTE Band 7 (outdoor) and LTE Band 28 (indoor) were used as an anchor for the 5G NR n78. Table 6 shows the Uplink and Downlink operating ranges of the n78 band. As the 3GPP specification uses two main frequency bands: FR1 and FR2 [25] so, according to 3GPP, 5G NR n78 belongs to FR-1, and for the UE measurements, Table 7 expresses that below 6GHz, the UE is likely to have a single antenna, and for mmW, the UE has an antenna array.

Table 6. UL and DL operating band range for n78 [26]

NR Operating Band	**Uplink (UL) operating band BS receives UE transmit**	**Downlink (DL) operating band BS transmits UE receives**	**Duplex Mode**
n78	F (UL low) – F (UL high)	F (DL low) – F (DL high)	TDD
	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	

Table 7. UE measurement in terms of Frequency Range-1 and Frequency Range-2 [44]

NR Frequency Range-1	NR Frequency Range-2
410 MHz to 7.125 GHz	24.25 GHz to 52.6 GHz
In this case, the measurement will be the antenna connector of the UE as a reference point.	In this case, the measurement will be done based on the collective signal of the antenna components relative to the given receiver branch

2.4.1 RSSI

The 5G UE calculates Synchronization Signal Reference Signal Received Power (SS-RSRP), Synchronization Signal Reference Signal Received Quality (SS-RSRQ), and Secondary Synchronization Signal to Interference Noise Ratio (SS-SINR) using the power received from secondary synchronization signals (SSS). The NR Carrier RSSI does not specifically use the power of the SSS but is associated with other 5G NR reference signal measurements.
RSSI is defined as the total received wideband power measured by the UE over its entire bandwidth. RSSI is not reported to the eNB. RSSI is also power, and dBm is its measurement unit.
RSSI = Serving Cell Power + Neighbour Co-Channel Cells Power + Thermal Noise
Under full load conditions, the RSRP (dBm) = RSSI - 10*log (12*N), where N represents the resource block number.

2.4.2 SS-RSRP

Secondary Synchronization Reference Signal Received Power (SS-RSRP) is the linear average power of single resource elements which carry the SS signal. UE conducts SS-RSRP measurements for mobility procedures, power control, and beam management [45]. To calculate SS-RSRP, the 5G UE measure the PBCH-DMRS signal. DMRS and SSS are transmitted simultaneously at the same power to get an average result. When performing SS-RSRP measurements for L1, the UE may be configured for CSI-RS measurements. The CSI-RS may be transmitted with a transmission power different from the synchronization signal (SS) and PBCH-DMRS. In this case, the gNB provides information about the offset to the UE so that it can be taken into account in the measurement [46]. The SS-RSRP and CSI-RSRP at the L1 reporting range are defined as -140 dBm to -40 dBm with a 1 dB resolution in Table 8 [47]. The L1 measurement requires a 7-bit payload to present the 128 RSRP-mapped values in dB. Reporting range values 0 to 16 and 113 to 127 are invalid for L1 measurement. In Table 8, the reported value of 17 means SS-RSRP is greater than or equal to -156 dB, and the reported value of 112 means SS-RSRP is less than or equal to -45dBm [46][48].

Table 8: Reporting range of single-valued SS-RSRP and CSI-RSRP [47].

Reported value	**Measured quantity value** (L3 SS-RSRP)	**Measured quantity value** (L1: SS-RSRP and CSI-RSRP)	**Unit**
RSRP_0	$SS - RSRP < -156$	Not valid	dBm
RSRP_1	$-156 \leq SS - RSRP < -155$	Not valid	dBm
RSRP_2	$-155 \leq SS - RSRP < -154$	Not valid	dBm
RSRP_3	$-154 \leq SS - RSRP < -153$	Not valid	dBm
RSRP_4	$-153 \leq SS - RSRP < -152$	Not valid	dBm
RSRP_5	$-152 \leq SS - RSRP < -151$	Not valid	dBm
RSRP_6	$-151 \leq SS - RSRP < -150$	Not valid	dBm
RSRP_7	$-150 \leq SS - RSRP < -149$	Not valid	dBm
RSRP_8	$-149 \leq SS - RSRP < -148$	Not valid	dBm
RSRP_9	$-148 \leq SS - RSRP < -147$	Not valid	dBm

RSRP_10	$-147 \leq SS - RSRP < -146$	Not valid	dBm
RSRP_11	$-146 \leq SS - RSRP < -145$	Not valid	dBm
RSRP_12	$-145 \leq SS - RSRP < -144$	Not valid	dBm
RSRP_13	$-144 \leq SS - RSRP < -143$	Not valid	dBm
RSRP_14	$-143 \leq SS - RSRP < -142$	Not valid	dBm
RSRP_15	$-142 \leq SS - RSRP < -141$	Not valid	dBm
RSRP_16	$-141 \leq SS - RSRP < -140$	Not valid	dBm
RSRP_17	$-140 \leq SS - RSRP < -139$	$\leq SS - RSRP <$	dBm
RSRP_18	$-139 \leq SS - RSRP < -138$	$\leq SS - RSRP <$	dBm
- - -	- - -	- - -	- - -
RSRP_111	$-46 \leq SS - RSRP < -45$	$\leq SS - RSRP <$	dBm
RSRP_112	$-45 \leq SS - RSRP < -44$	$\leq SS - RSRP <$	dBm
RSRP_113	$-44 \leq SS - RSRP < -43$	Not valid	dBm
RSRP_114	$-43 \leq SS - RSRP < -42$	Not valid	dBm
RSRP_115	$-42 \leq SS - RSRP < -41$	Not valid	dBm
RSRP_116	$-41 \leq SS - RSRP < -40$	Not valid	dBm
RSRP_117	$-40 \leq SS - RSRP < -39$	Not valid	dBm
RSRP_118	$-39 \leq SS - RSRP < -38$	Not valid	dBm
RSRP_119	$-38 \leq SS - RSRP < -37$	Not valid	dBm
RSRP_120	$-37 \leq SS - RSRP < -36$	Not valid	dBm
RSRP_121	$-36 \leq SS - RSRP < -35$	Not valid	dBm
RSRP_122	$-35 \leq SS - RSRP < -34$	Not valid	dBm
RSRP_123	$-34 \leq SS - RSRP < -33$	Not valid	dBm
RSRP_124	$-33 \leq SS - RSRP < -32$	Not valid	dBm
RSRP_125	$-32 \leq SS - RSRP - 31 <$	Not valid	dBm
RSRP_126	$-31 \leq SS - RSRP$	Not valid	dBm
RSRP_127	Infinity	Infinity	dBm

A rough estimate of the RSRP value can be made with the following formula,

RSRP value = Reported value -156
RSRP in dBm = 18 -156 = -138 dBm

In L1, UE is forced to report the RSRP measurements for each antenna beam, and this is a considerable amount of data. According to the 3GPP specification, simplified relative measurements of single value RSRP and CSI-RSRP is presented as differential values in Table 9 [46][48]. The reporting range of differential SS-RSRP and CSI-RSRP for L1 is defined from 0 dBm to 30 dB with a 2 dB resolution [47].

Table 9: Reporting range of differential valued SS-RSRP and CSI-RSRP [47].

Reported value	**Measured quantity value** (Difference in measured RSRP from strongest RSRP)	**Unit**
DIFFRSRP_0	$0 \geq \Delta RSRP > -2$	dB
DIFFRSRP_1	$-2 \geq \Delta RSRP > -4$	dB
DIFFRSRP_2	$-4 \geq \Delta RSRP > -6$	dB
DIFFRSRP_3	$-6 \geq \Delta RSRP > -8$	dB
DIFFRSRP_4	$-8 \geq \Delta RSRP > -10$	dB
DIFFRSRP_5	$-10 \geq \Delta RSRP > -12$	dB
DIFFRSRP_6	$-12 \geq \Delta RSRP > -14$	dB
DIFFRSRP_7	$-14 \geq \Delta RSRP > -16$	dB
DIFFRSRP_8	$-16 \geq \Delta RSRP > -18$	dB
DIFFRSRP_9	$-18 \geq \Delta RSRP > -20$	dB
DIFFRSRP_10	$-20 \geq \Delta RSRP > -22$	dB
DIFFRSRP_11	$-22 \geq \Delta RSRP > -24$	dB
DIFFRSRP_12	$-24 \geq \Delta RSRP > -26$	dB
DIFFRSRP_13	$-26 \geq \Delta RSRP > -28$	dB
DIFFRSRP_14	$-28 \geq \Delta RSRP > -30$	dB
DIFFRSRP_15	$-30 \geq \Delta RSRP$	dB

2.4.3 SS-RSRQ

Secondary Synchronization Reference Signal Received Quality (SS-RSRQ) is also used for cell selection and delivery if the SS-RSRP is not sufficient. SS-RSRQ defines the precision of the reference signal (RS) over the system bandwidth. SS-RSRQ is a value calculated by SS-RSRP, and NR carrier RSSI is the measurement of signal and interference. It is similar to the RSRQ parameter of LTE networks. The main difference is that in 5G networks, synchronization signals (SS) and channel state information (CSI) are used instead of reference signals (RS) [46][48]. It is emphasized below through the mathematical expression,

SS-RSRQ = N × SS-RSRP /NR carrier RSSI,

Where both (numerator and denominator) belong to the same set of resource blocks, N defines as the number of RB in the NR carrier RSSI bandwidth estimation. RSSI is the total power received from all sources, including serving and non-serving cells, adjacent channel interference and thermal noise [44]. RSSI is measured in symbols other than SSS. So, according to 3GPP, the reporting range of SS-RSRQ is different from RSRQ, and it is presented in Table 10. The SS-RSRQ range is defined from -43 dB to 20 dB with 0.5 dB resolution.

Table 10: Reporting range of SS-RSRQ [47].

Reported value	Measured quantity value	Unit
SS-RSRQ_0	$SS - RSRQ < -43$	dB
SS-RSRQ_1	$-43 \leq SS - RSRQ < -42.5$	dB
SS-RSRQ_2	$-42.5 \leq SS - RSRQ < -42$	dB
SS-RSRQ_3	$-42 \leq SS - RSRQ < -41.5$	dB

SS-RSRQ_4	$-41.5 \leq SS - RSRQ < -41$	dB
SS-RSRQ_5	$-41 \leq SS - RSRQ < -40.5$	dB
SS-RSRQ_6	$-40.5 \leq SS - RSRQ < -40$	dB
- - -	- - -	- - -
SS-RSRQ_121	$17 \leq SS - RSRQ < 17.5$	dB
SS-RSRQ_122	$17.5 \leq SS - RSRQ < 18$	dB
SS-RSRQ_123	$18 \leq SS - RSRQ < 18.5$	dB
SS-RSRQ_124	$18.5 \leq SS - RSRQ <19$	dB
SS-RSRQ_125	$19 \leq SS - RSRQ <19.5$	dB
SS-RSRQ_126	$19.5 \leq SS - RSRQ <20$	dB
SS-RSRQ_127	$20 \leq SS - RSRQ$	dB

2.4.4 SS-SINR

SS-SINR is the short form Secondary Synchronization Signal to Interference Noise Ratio. The ratio of the linear average power of a single resource element carries the SS signal to a linear average of the interference-noise power contribution over the same RE (resource elements) carrying the SS Signal through the same frequency bandwidth [44]. It is emphasized below through the mathematical expression,

SS-SINR = S/(I+N),

where S represents useful signal power in watts is divided by the summation of interference (I) and noise (N) measured over the same resource element. With 0.5 dB resolution, the reporting range for SS-RSRP starts from −23dB to 40 dB defined in Table 11.

Table 11: Reporting range of SS-SINR [47].

Reported value	Measured quantity value	Unit
SS-SINR_0	$SS - SINR < -23$	dB
SS- SINR _1	$-23 \leq SS - SINR < -22.5$	dB
SS- SINR _2	$-22.5 \leq SS - SINR < -22$	dB
SS- SINR _3	$-22 \leq SS - SINR < -21.5$	dB
SS- SINR _4	$-21.5 \leq SS - SINR < -21$	dB
SS- SINR _5	$-21 \leq SS - SINR < -20.5$	dB
SS- SINR _6	$-20.5 \leq SS - SINR < -20$	dB
- - -	- - -	- - -
SS- SINR _121	$37 \leq SS - SINR < 37.5$	dB
SS- SINR _122	$37.5 \leq SS - SINR < 38$	dB
SS- SINR _123	$38 \leq SS - SINR < 38.5$	dB
SS- SINR _124	$38.5 \leq SS - SINR < 39$	dB
SS- SINR _125	$39 \leq SS - SINR < 39.5$	dB
SS- SINR _126	$39.5 \leq SS - SINR < 40$	dB
SS- SINR _127	$40 \leq SS - SINR$	dB

2.4.5 Throughput for Downlink/Uplink

Throughput is the measurement of data transferred from source to destination in a given time interval [49]. It is defined by the ratio of data transferred per unit of time. This test verifies that a maximum number of bits in the DL-SCH transport block is correctly decoded and delivered to higher levels (for downlink throughput) which indicates the data transmission strength of any network [50]. When calculated by the user end, downlink (speed) broadband (gNB to UE) refers to the download speed, while uplink (speed) broadband (UE to gNB) is calculated by the control plane (CP), which refers to the upload speed [50][51]. Due to various technical issues such as latency, jitter and loss, throughput may vary. Ping is a unit of measurement for the delay that is measured in milliseconds. It refers to the device's response time, which indicates how soon it receives a response after delivering a request. The variability of the ping over time is referred to as jitter. It calculates the change in packet delay or PDV (Packet Delay Variation), which influences buffering and other data transmission interruptions. The loss, on the other hand, is the proportion of packets lost during transmission over the radio channel [52].

3 DESCRIPTION OF EMPLOYED SOFTWARES AND PLATFORM

3.1 Nemo by Keysight

Keysight or Keysight Technologies has several types of equipment and software platforms for measuring electronic tests in a network system. Nemo wireless networking solution is known for its versatile convenience and management. Nemo stands for Network Mobility of RF Network Solution, which optimizes and automates the wireless networking process to provide a better network experience. These tools can also be synchronized with Keysight's cloud-based solution, which provides real-time monitoring and control of the product review and analysis fleet. The Nemo tool Wireless Network Solution can be used in all phases, such as implementation and optimization, benchmarking, monitoring and control, data post-processing, and wireless network life cycle analysis [53].

3.1.1 Nemo Handy

Nemo Handy is an ARM chip-based testing software tool that supports Exynos and Qualcomm variants. It offers the best visualization of a real-time measurement experience in terms of portability [54]. Figure 13 shows us the main interface of Nemo Handy on the One Plus Phone.

(a) Back view of OP 7 (b) Initial login interface (c) Primary interface of the application

Figure 13. Primary interface of Nemo Handy tools on One Plus phone.

3.1.2 Nemo Outdoor

Nemo Outdoor is a mobile network monitoring test tool for laptops or variants. It is a complete unit testing solution for the mobile wireless network testing process. It provides detailed functionality beyond the limits of Nemo Handy. Nemo Outdoor can be used with scanning receivers to conduct 5G NR drive test measurements with the demodulation of 5G NR reference signals and makes simultaneous measurements of 2G, 3G, 4G, and 5G NR spectrum scan and frequency scan [54]. Figure 14 shows Nemo Outdoor box, including the virtual registry key and USB stick which contains all the setting information.

Figure 14. Nemo Outdoor box including registry key and USB stick.

3.1.3 Nemo Analyze

The Nemo Analyze, drive post-processing solution is a compelling and customizable testing platform focused on driving test data for benchmarking, integrated troubleshooting and statistical reporting. It can tie with other Nemo equipment through a fully automated data processing chain from raw measurement data to automatically generated results in a workbook format. It supports all the latest 3GPP network technologies, including 5G NR, LTE/LTE-Advance (LTE-A) Carrier Aggregation (CA), IoT, Voice over LTE (VoLTE), Video over LTE (ViLTE), and Voice over Wi-Fi (VoWiFi) [54]. Figure 15 shows the Nemo Analyze box, including the virtual registry key and USB stick which contains all the setting information.

Figure 15. Nemo Analyze box including registry key and USB stick.

3.2 5G Test Network

In the northern city of Oulu, Finland, the 5G test network offers the possibility to test 5G wireless technology, modules, or new services in real-time. With two locations at the University of Oulu and the VTT-technical research center of Finland. 5GTN meets the most demanding 5G testing requirements, such as the use of devices with 5G connectivity, different frequency bands, orchestration features, and system test tools. A real-time network test for the 5G NR BTS was performed at the University of Oulu, Linnanmaa, as part of the 5GTN for this thesis [55].

3.2.1 Coverage Map

Globally, 5GTN is the broadest fifth-generation open-access test network for research purposes. The comprehensive 5G test framework enables specific test possibilities ranging from experimental products to complete system solutions in a controlled environment, from technology to software and utilities.

Figure 16 shows the full coverage map of 5GTN, including the two sites where some core areas overlap. It also shows two specific locations of the test network where the position of the blue color (65.05696, 25.45594) identifies on the google map indicating the VTT premises, and red (65.06035, 25.46826) indicates the premises of the University of Oulu [56]. Information about two 5G NR BTSs belonging to 5GTN is presented in Table 12.

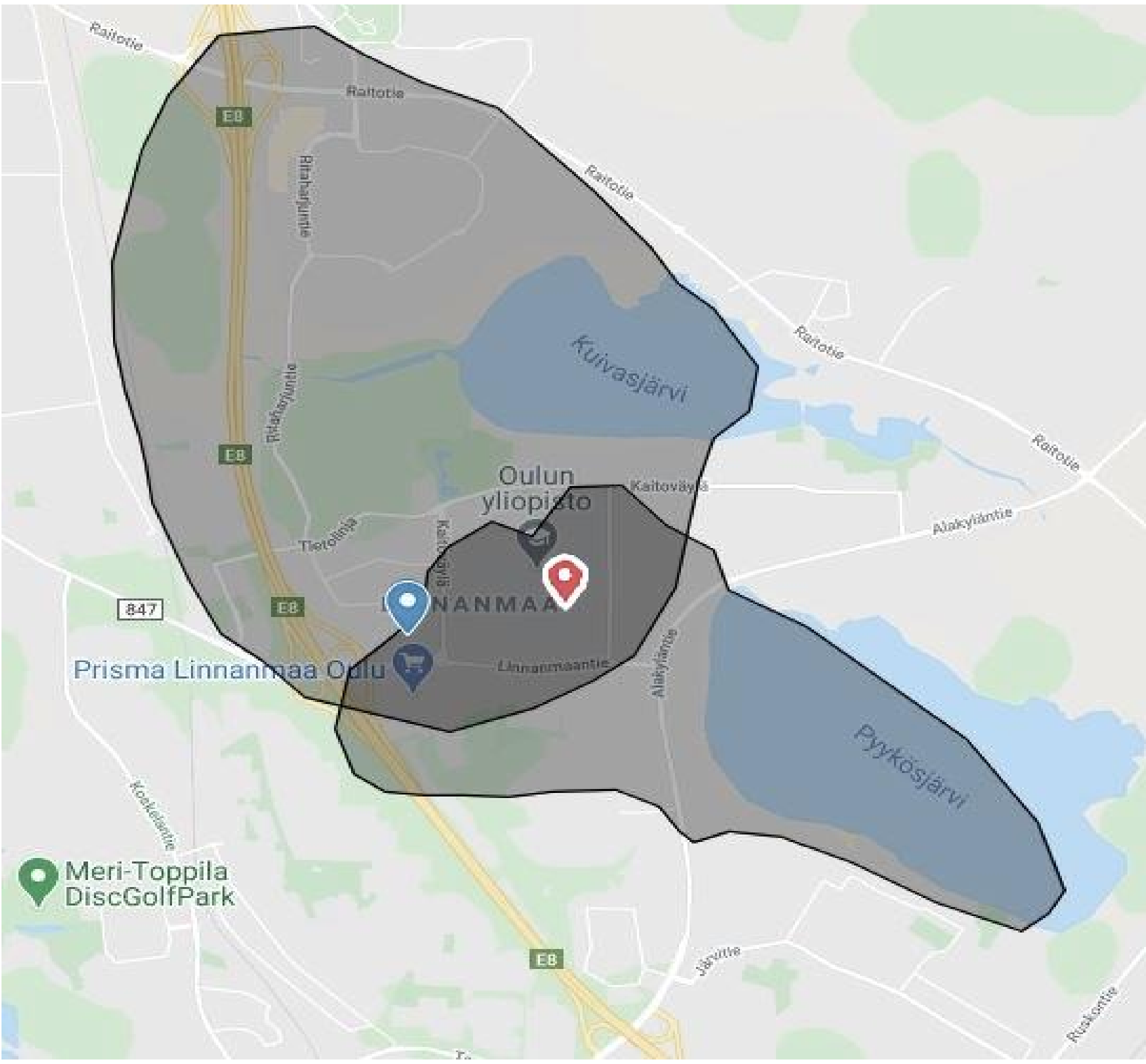

Figure 16. 5GTN coverage map of two sites [56].

Table 12. Information about two 5G NR BTS of the 5GTN [56]

Location	VTT premises	University of Oulu premises
Name	5G NR BTS (VTT rooftop)	5G NR BTS (Tietotalo 1 rooftop)
Band	43	42
Range	3700 - 3760 MHz	3500 MHz
BW	60 MHz	60 MHz

3.2.2 5G NR BTS at the University of Oulu

Based on the 5GTN specification, measurements were taken at the University of Oulu's Linnanmaa campus. Here, 5G New Radio BTS covers existing LTE coverage in two directions, facing south and north, covering a radius of 5 kilometers to Idea Park and Syynimaa. LTE B7/PCI 2 is an anchor for NR n78/PCI 76 (north), and LTE B7/PCI 70 is an anchor for NR n78/PCI 74 (south). Figure 17 shows the 5G NR coverage area at Oulu University and anchor information [55].

Figure 17. Anchoring information and coverage area of 5G NR in the University of Oulu.

Below, Figure 18 and Figure 19 present the 5G NR BTS information where NR Cell Id is 633984 for north-facing PCI and for south directed is 638016, respectively. In addition, Table 13 has information about two cells of 5G NR BTS at Linnanmaa campus (University of Oulu) premises from Figure 18 and Figure 19.

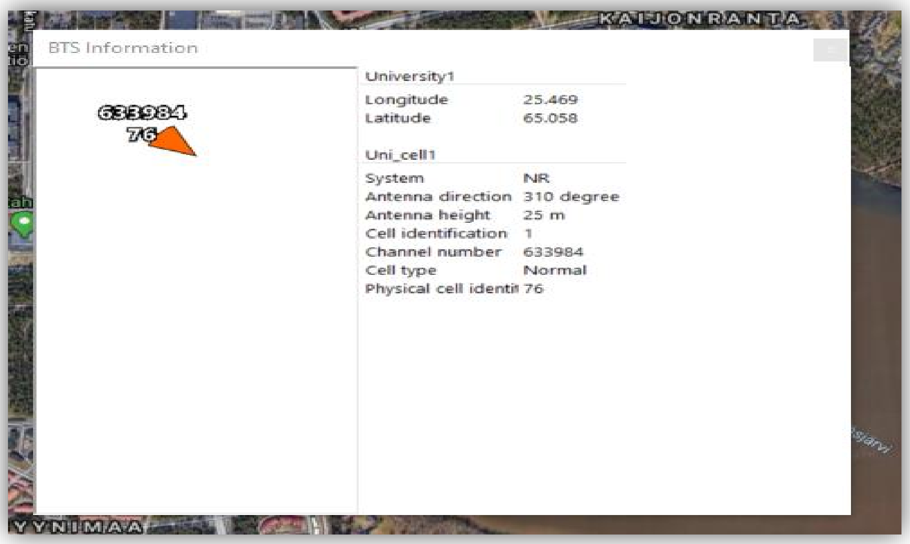

Figure 18. 5G New Radio BTS information (north).

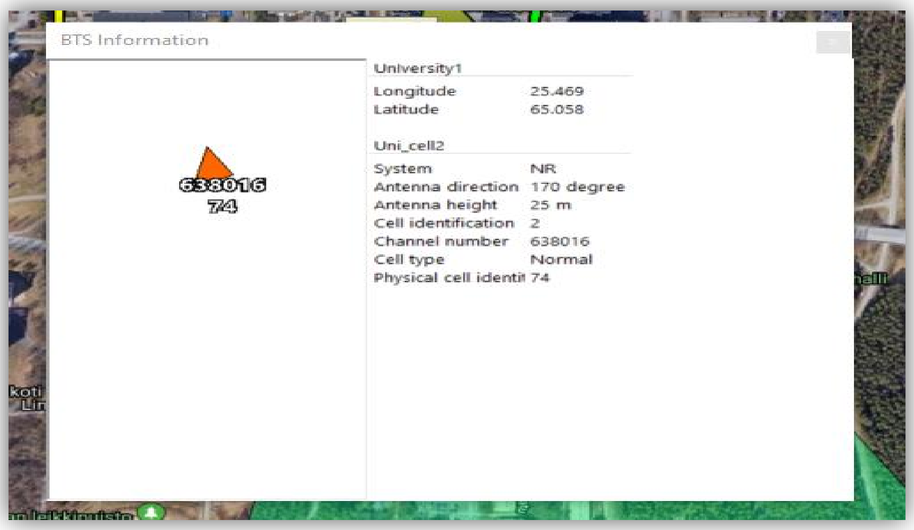

Figure 19. 5G New Radio information (south).

Table 13. Information about two cells of 5G NR BTS at Linnanmaa campus (University of Oulu) premises

Parameters	**Uni_cell1**	**Uni_cell2**
Longitude	25.469	25.469
Latitude	65.058	65.058
System	NR	NR
Antenna azimuth	310 degrees	170 degrees
Antenna direction	North	South
Antenna height	25 meters	25 meters
Cell identification	1	2
Channel number	633984	638016
Cell type	Normal	Normal
Physical cell identity	76	74

4 MEASUREMENTS

The 5G NR performance evaluation can be carried out by performing related measurements in the indoor premises of the University of Oulu, which covers the main corridors of the Linnanmaa campus where the 5G NR BTS is located, and the outdoor premises, which cover the surrounding University area of Linnanmaa campus. In the first steps, three variants of measurement software tools from the Nemo Wireless Network Solution platform were used for this measurement. In addition, an application based on the Android platform, SPEEDTEST, was used for the throughput tests to check the downlink and uplink speed in this measurement process. The main feature of this measurement is as follows,

- Signal power measurement, signal quality check, and interference noise ratio measurement through the Nemo Handy at the user end.
- And finally, data throughput measurement as a parallel test at the UE end.

4.1 Indoor

Nemo Handy and Nemo Outdoor are two different devices but use a similar measurement technique. Indoor measurement has been performed with Nemo handy for its hand-held mobility facilities. Before starting the measurements, a route has been settled which covers the main indoor premises of the Linnanmaa campus. In this real-time measurement test, 42 reference spots have been set on this route to understand the possible impact of performance on the measurement zone. Figure 20 shows the measurement zone with the planned route, and reference points are marked red from 0 to 41. For indoor measurements, LTE B7/PCI 2 has been configured as an anchor for 5G NR n78/PCI 76 on the north, and LTE B7/PCI 70 has been configured as an anchor for 5G NR n78/PCI 74 on the south.

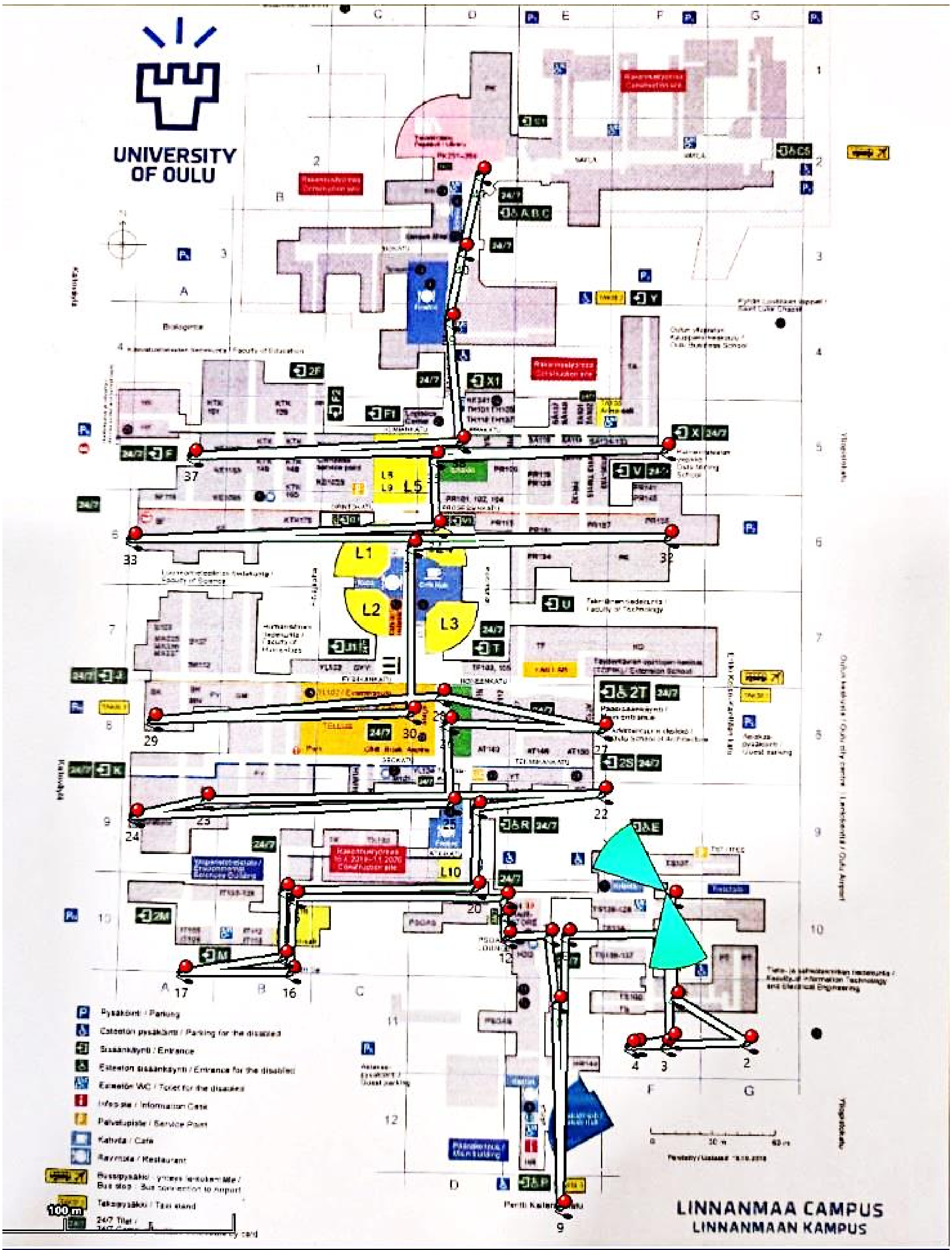

Figure 20. Indoor ground floor map at University of Oulu with measurement route.

4.2 Outdoor

The outdoor measurement has also been performed by Nemo Handy due to the mobility facility. Before starting the measurement procedure, a path has been planned that covers the area surrounding the University of Oulu's Linnanmaa campus. The measurement was initiated before the R-gate and covering the surrounding area, it has stopped at the E-gate. In this real-time measurement test drive, there are 16 reference points that have been used to better assess the possible impact of the performance on the measurement zone. The whole measurement path is portrayed in Figure 21, with reference spots indicated in red from 0 to 15. LTE B28/PCI 50 has been configured as an anchor for 5G NR n78/PCI 76 on the north, and LTE B28/PCI 46 has been configured as an anchor for 5G NR n78/PCI 74 on the south for outdoor measurement.

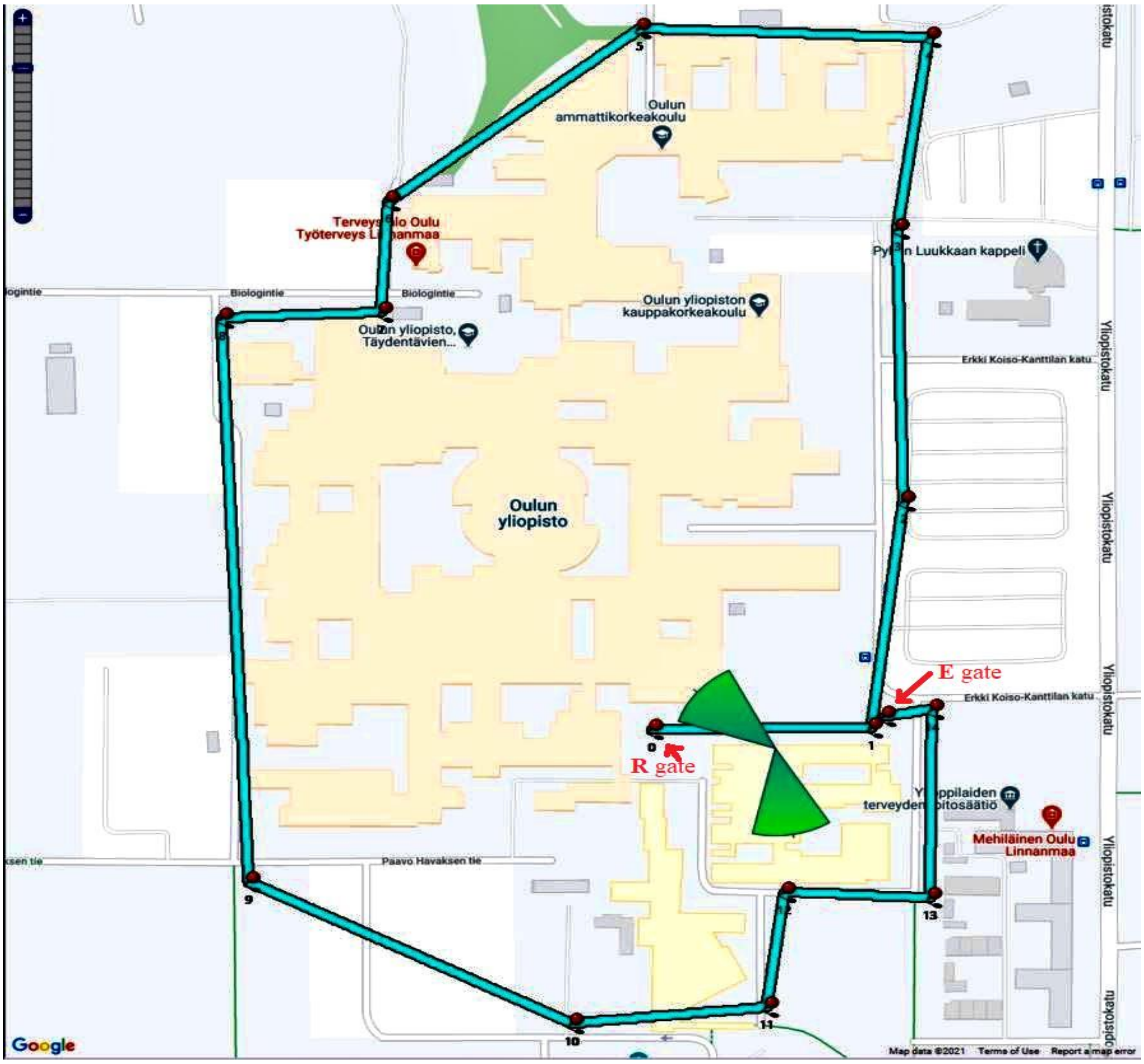

Figure 21. Outdoor map of University of Oulu with measurement route.

4.3 Key Performance Metrics

4.3.1 From SS-RSRP Aspects

SS-RSRP, SS-RSRQ, and SS-SINR are the key metrics that provide accurate information on network coverage and quality to assist the 5G NR performance assessment. So, SS-RSRP has been chosen as the first KPI parameter in this measurement. SS-RSRP indicates the signal strength in the 5G network in terms of power. Figure 22 shows the total of 3080 real-time measurements encountered during the indoor test, and Figure 23 shows the total of 3545 real-time measurements encountered during the outdoor test. 42 (for indoor) and 16 (for outdoor) reference spots are assigned for complete test observation, and SS-RSRP is measured in dBm units at each reference point.

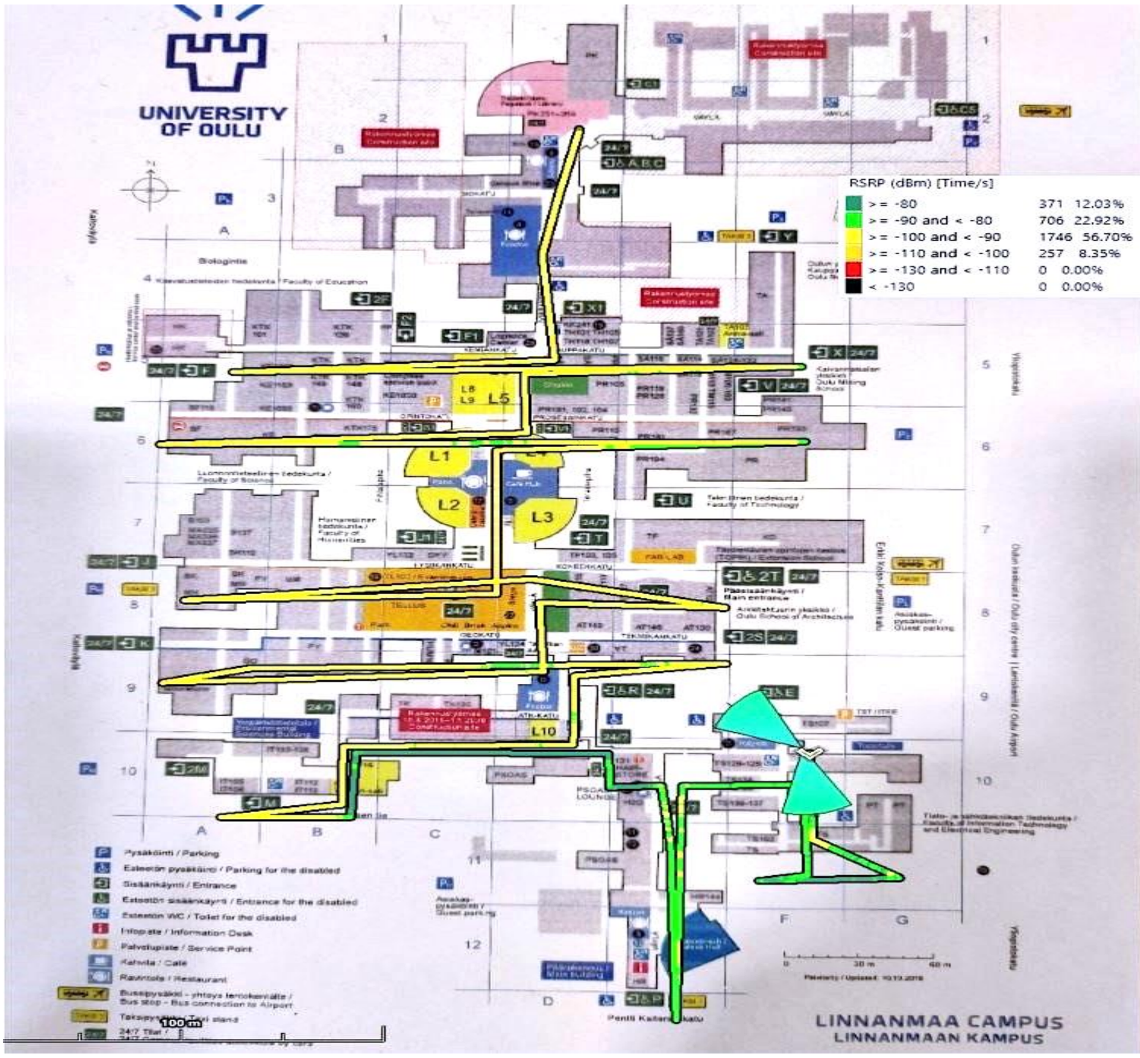

Figure 22. SS-RSRP route at indoor measurement.

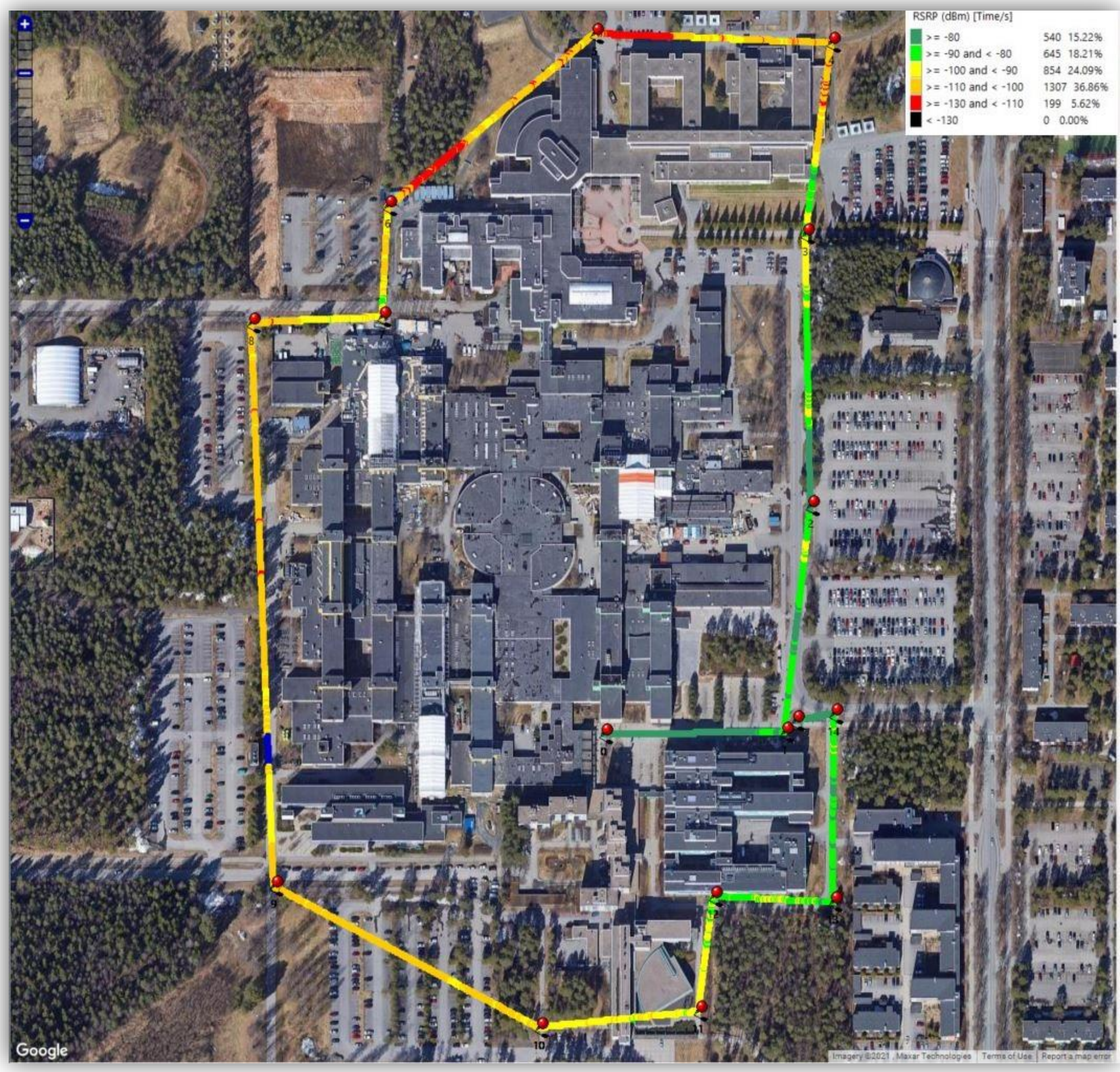

Figure 23. SS-RSRP route for outdoor.

In addition, alongside the primary measurement, nR PCI_bi, NR-ARFCN and PCI have been taken where nR PCI_bi indicates the strongest signal strength with SSB index can be identified by the user end. This strongest signal strength is the best beam at that particular reference spot, measured by the UE [57]. NR-ARFCN is a code that specifies a pair of reference frequencies in the radio system. It is used for transmission and reception purposes in radio systems. As downlink and uplink frequencies are different in the FDD system, two NR-ARFCN are required. But for the TDD system, one NR-ARFCN is required due to remaining the same frequency for downlink and uplink [58]. Moreover, PCI denotes the cell ID of any BTS, which indicates the possible location and direction of UE. Furthermore, for downlink synchronization, PCI is required. PCI = PSS + three x SSS and 5G NR supports total 1008 PCIs [59]. This PCI ensures that the test result SS-RSRP of the transmitting signal comes from the specific 5G NR BTS. Table 14 presents those 42 values taken on the reference spots (indoor), and Table 15 presents the values taken on the 16 reference spots (outdoor).

Table 14. SS-RSRP value at Indoor reference point

Reference Point	**SS-RSRP (dBm)**	**nR PCI_bi**	**NR-ARFCN**	**Physical cell index (PCI)**
0	-86	74_5	636000	74
1	-95.3	74_0	636000	74
2	-79.1	74_5	636000	74
3	-79.5	74_5	636000	74
4	-79.6	74_5	636000	74
5	-84.8	74_5	636000	74
6	-80.6	74_5	636000	74
7	-84.6	74_5	636000	74
8	-90.8	74_0	636000	74
9	-84.3	74_5	636000	74
10	-83.6	74_0	636000	74
11	-85.6	74_5	636000	74
12	-76.4	76_3	636000	76
13	-81.8	76_3	636000	76
14	-75	76_5	636000	76
15	-78.5	76_5	636000	76
16	-74.3	76_4	636000	76
17	-97.1	76_5	636000	76
18	-96.8	76_0	636000	76
19	-95.1	76_5	636000	76
20	-91.7	76_5	636000	76
21	-92.6	74_0	636000	74
22	-95.8	76_4	636000	76
23	-91.8	76_5	636000	76
24	-102	76_4	636000	76
25	-96.6	76_4	636000	76
26	-92.5	76_4	636000	76
27	-95.3	76_4	636000	76
28	-94.8	76_4	636000	76
29	-97.7	76_4	636000	76
30	-100	76_4	636000	76
31	-102.1	76_4	636000	76
32	-88	76_4	636000	76
33	-102	76_4	636000	76
34	-98.1	76_4	636000	76
35	-97.7	76_4	636000	76
36	-87.8	76_4	636000	76
37	-90.7	76_4	636000	76
38	-95	76_4	636000	76
39	-96.5	76_4	636000	76
40	-98.2	76_4	636000	76
41	-98	76_4	636000	76

Table 15. SS-RSRP of the outdoor reference point

Reference Point	SS-RSRP (dBm)	nR PCI_bi	NR-ARFCN	Physical cell index (PCI)
0	-63.2	76_5	636000	76
1	-83.8	76_2	636000	76
2	-78.3	76_2	636000	76
3	-87.5	76_0	636000	76
4	-109.6	76_0	636000	76
5	-102.5	76_1	636000	76
6	-101.5	76_2	636000	76
7	-95.4	76_2	636000	76
8	-105	76_3	636000	76
9	-106	74_1	636000	74
10	-100.8	74_0	636000	74
11	-96.8	74_5	636000	74
12	-87.9	74_0	636000	74
13	-78.2	74_5	636000	74
14	-82.8	76_5	636000	76
15	-73.9	76_5	636000	76

4.3.2 From SS-RSRQ Aspects

SS-RSRQ is used to measure the signal quality between radio channels and check the network's quality. Measurement of SS-RSRQ is required in call selection-reselection, and mainly at the cell edge for handover procedures. So, SS-RSRQ has been chosen in this measurement along with the SS-RSRP as the second KPI parameter to understand the received signal quality from 5G NR BTS. During the test, there were a total of 3079 (indoor) and 3545 (outdoor) encountered real-time measurements presents in Figure 24 and Figure 25, respectively. 42 (indoor) and 16 (outdoor) reference locations are chosen for the observation of these real-time measurement tests. Throughout the test, the SS-RSRQ is measured in decibels (dB).

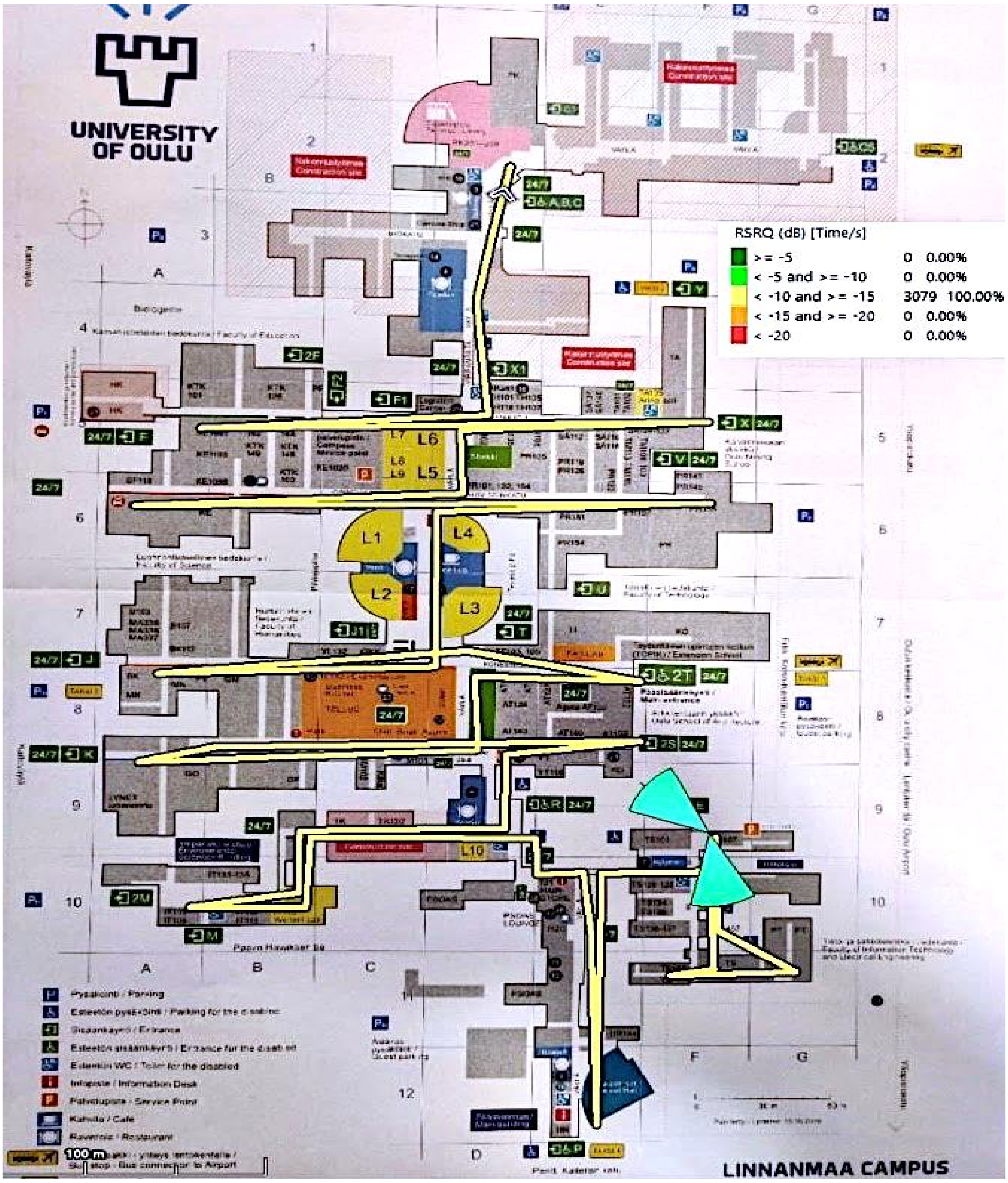

Figure 24. SS-RSRQ route at indoor measurement.

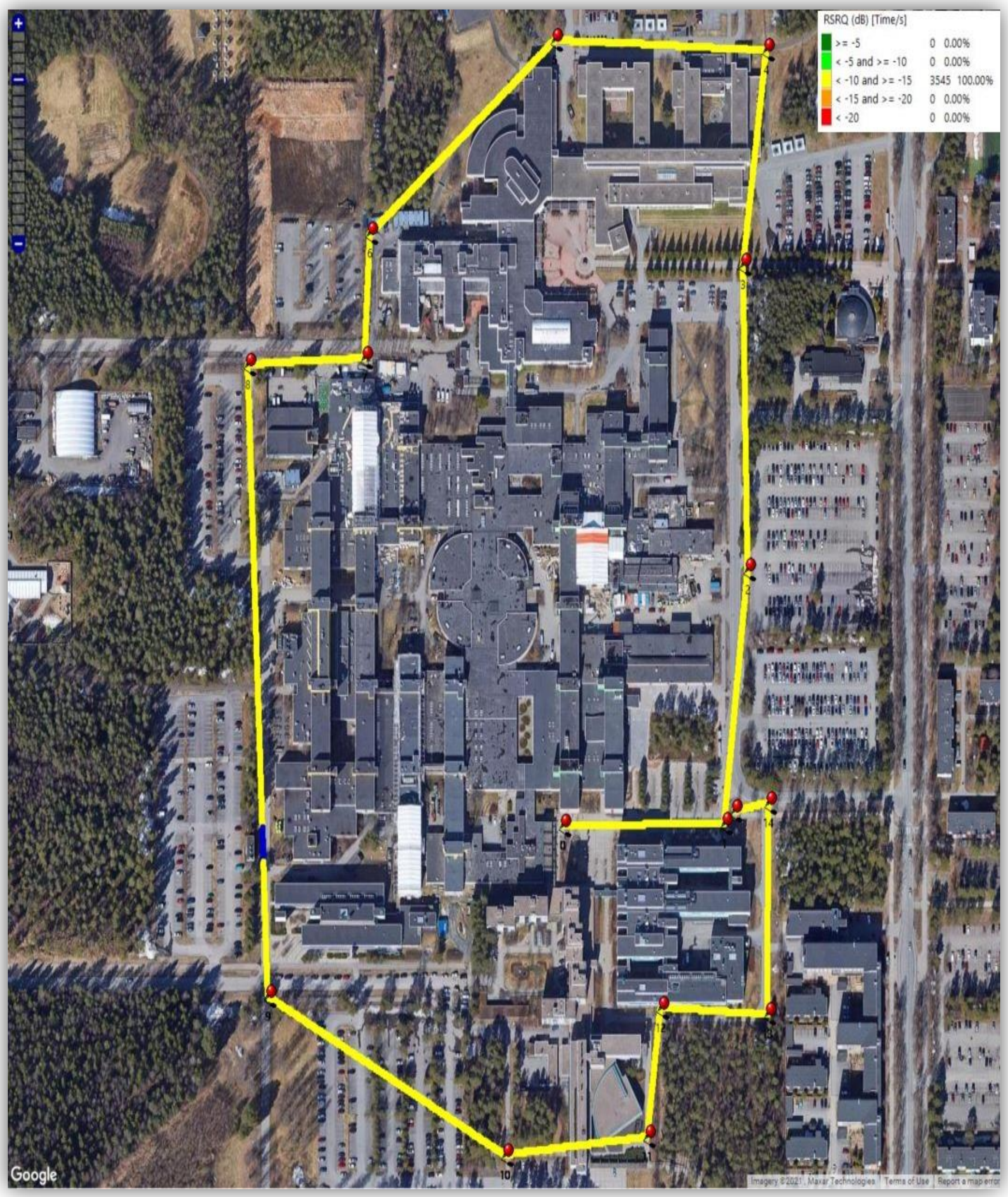

Figure 25. SS-RSRQ route for the outdoor.

Along with the primary measurement, nRPCI_bi, NR-ARFCN, and PCI have also been taken. Here PCI indicates that the desired SS-RSRQ has been taken from the 5G NR BTS of 5GTN at Linnanmaa and not interrupted or mixed by neighboring cells. nRPCI_bi is responsible for explaining the best beam at each reference spot, and NR_ARFCN confirms the transmission and reception of 5G NR signals in the radio system. Table 16 and Table 17 shows the SS-RSRQ data taken at the reference spots during the real-time measurements at indoors and outdoors, respectively.

Table 16. SS-RSRQ value at Indoor reference point

Reference Point	**SS-RSRQ (dB)**	**nR PCI_bi**	**NR-ARFCN**	**Physical cell index (PCI)**
0	-10.9	74_5	636000	74
1	-12.4	74_4	636000	74
2	-10.8	74_5	636000	74
3	-10.8	74_5	636000	74
4	-10.9	74_5	636000	74
5	-10.9	74_5	636000	74
6	-10.8	74_5	636000	74
7	-11	74_5	636000	74
8	-11	74_0	636000	74
9	-10.9	74_0	636000	74
10	-10.9	74_0	636000	74
11	-10.9	74_4	636000	74
12	-10.8	76_4	636000	76
13	-10.9	76_4	636000	76
14	-10.8	76_5	636000	76
15	-10.8	76_5	636000	76
16	-10.8	76_5	636000	76
17	-10.9	76_5	636000	76
18	-10.9	76_5	636000	76
19	-10.9	76_5	636000	76
20	-10.9	76_5	636000	76
21	-11.1	74_0	636000	74
22	-10.9	76_5	636000	76
23	-10.8	76_4	636000	76
24	-10.9	76_4	636000	76
25	-10.9	76_4	636000	76
26	-10.8	76_4	636000	76
27	-10.9	76_4	636000	76
28	-10.8	76_4	636000	76
29	-10.8	76_4	636000	76
30	-10.9	76_4	636000	76
31	-10.9	76_4	636000	76
32	-10.8	76_4	636000	76
33	-10.9	76_4	636000	76
34	-10.9	76_5	636000	76
35	-10.8	76_4	636000	76
36	-10.8	76_4	636000	76
37	-10.8	76_5	636000	76
38	-10.8	76_4	636000	76
39	-10.8	76_4	636000	76
40	-10.8	76_4	636000	76
41	-10.9	76_5	636000	76

Table 17. SS-RSRQ of the outdoor reference point

Reference Point	**SS-RSRQ (dB)**	**nR PCI_bi**	**NR-ARFCN**	**Physical cell index (PCI)**
0	-10.8	76_5	636000	76
1	-10.8	76_2	636000	76
2	-10.9	76_5	636000	76
3	-10.8	76_1	636000	76
4	-11	76_0	636000	76
5	-10.9	76_1	636000	76
6	-10.9	76_2	636000	76
7	-10.8	76_2	636000	76
8	-10.9	76_3	636000	76
9	-11.2	74_1	636000	74
10	-10.9	74_0	636000	74
11	-10.8	74_5	636000	74
12	-10.8	74_0	636000	74
13	-10.8	74_5	636000	74
14	-10.9	76_2	636000	76
15	-10.8	76_5	636000	76

4.3.3 From SS-SINR Aspects

As the third KPI component in this measurement, SS-SINR assesses signal quality. It indicates the strength of the desired signal in comparison to unwanted interference. All kinds of interference-noise are reported through this SS-SINR value. The signal quality is determined by the throughput, which may be increased by delivering the signal at a higher power or by limiting interference from the transmitted signal. High SS-SINR means less interference, and less interference means higher QAM modulation. Higher QAM modulation provides higher data rates, which specifies higher throughput. So, SS-SINR is directly involved with the throughput. Figure 26 represents 3079 real-time samples of data collected during the indoor test, whereas Figure 27 represents 3545 real-time sample of data collected during the outside test. For the overall test case observation, 42 (indoor) and 16 (outdoor) sample spots are chosen. During the test, the SS-SINR is measured in decibels (dB).

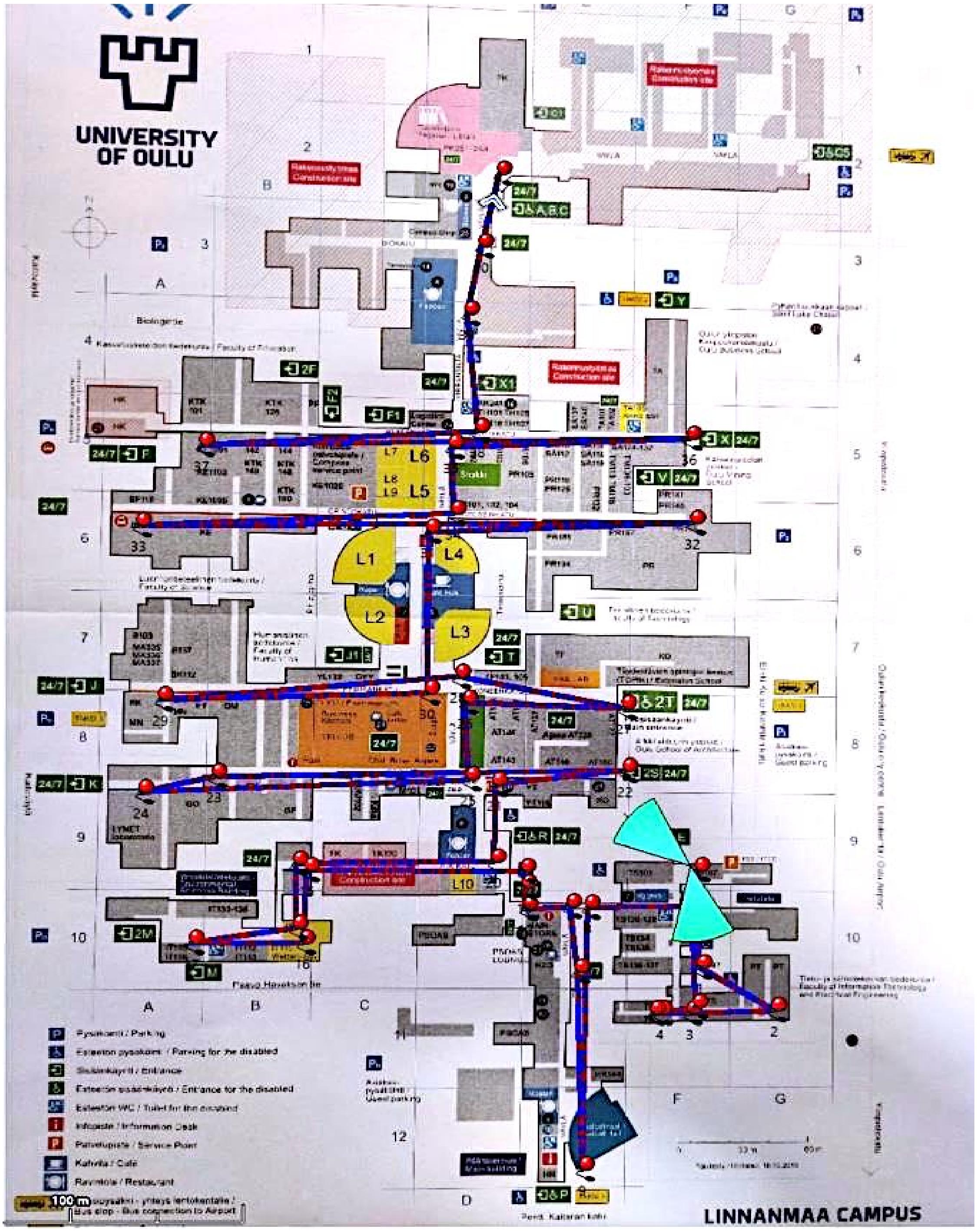

Figure 26. SS-SINR route at indoor measurement.

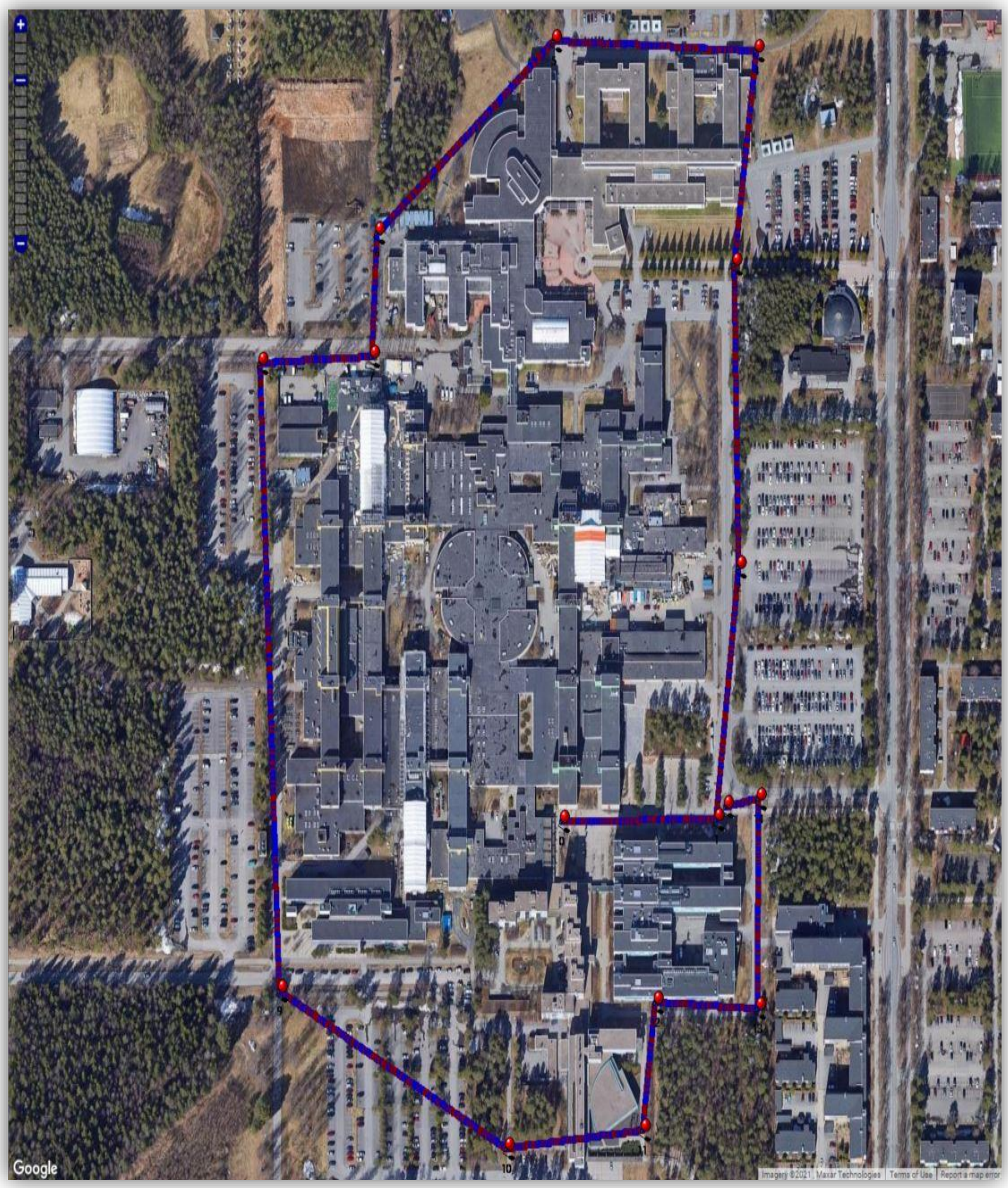

Figure 27. SS-SINR route for the outdoor.

Table 18 (indoor) and Table 19 (outdoor) below represent the SS-SINR data taken at benchmarks during real-time measurement. Along with the table's primary measurement (SS-SINR), PCI indicates that the measured SS-SINR were from the 5G NR BTS (at Linnanmaa) of 5GTN and not interrupted or mixed by neighboring cells. nRPCI_bi is responsible for explaining the best beam at each reference point, and NR_ARFCN confirms the transmission and reception of 5G NR signals in the radio system.

Table 18. SS-SINR value at Indoor reference point

Reference Point	SS-SINR (dB)	nR PCI_bi	NR-ARFCN	Physical cell index (PCI)
0	18.9	74_5	636000	74
1	4.9	74_0	636000	74
2	19.9	74_5	636000	74
3	19.3	74_5	636000	74
4	18.9	74_5	636000	74
5	18.5	74_5	636000	74
6	19.3	74_5	636000	74
7	11.7	74_5	636000	74
8	16.5	74_0	636000	74
9	12.6	74_5	636000	74
10	17.7	74_0	636000	74
11	12.4	74_5	636000	74
12	21.9	76_3	636000	76
13	18.5	76_3	636000	76
14	20.3	76_5	636000	76
15	21	76_5	636000	76
16	21.1	76_4	636000	76
17	17.6	76_5	636000	76
18	12.5	76_0	636000	76
19	19	76_5	636000	76
20	17.6	76_5	636000	76
21	11.1	74_0	636000	74
22	15.5	76_4	636000	76
23	20.9	76_5	636000	76
24	17.4	76_4	636000	76
25	18.7	76_4	636000	76
26	20.6	76_4	636000	76
27	18.1	76_4	636000	76
28	19.2	76_4	636000	76
29	20	76_4	636000	76
30	17.4	76_4	636000	76
31	16.8	76_4	636000	76
32	21.6	76_4	636000	76
33	18.1	76_4	636000	76
34	18.8	76_4	636000	76
35	19.7	76_4	636000	76
36	22.1	76_4	636000	76
37	21.2	76_4	636000	76
38	19.5	76_4	636000	76
39	19.6	76_4	636000	76
40	19.4	76_4	636000	76
41	17.8	76_4	636000	76

Table 19. SS-SINR of the outdoor reference point

Reference Point	**SS-SINR (dB)**	**nR PCI_bi**	**NR-ARFCN**	**Physical cell index (PCI)**
0	19.5	76_5	636000	76
1	20.4	76_2	636000	76
2	19.1	76_0	636000	76
3	19.1	76_1	636000	76
4	13	76_0	636000	76
5	17	76_1	636000	76
6	19	76_2	636000	76
7	19.9	76_2	636000	76
8	16.8	76_3	636000	76
9	10.1	74_1	636000	74
10	15.1	74_0	636000	74
11	19.8	74_5	636000	74
12	19.8	74_0	636000	74
13	21.3	74_5	636000	74
14	13.7	76_2	636000	76
15	19.6	76_5	636000	76

4.3.4 From Throughput Aspect

A throughput test was performed using OCLA's Speedtest mobile application to assess the data throughput by calculating download and upload speeds between radio channels. This test was performed only at the 58 reference spots, where 42 were indoor tests and 16 were the outdoor tests. Here, the throughput is presented in Mbps and ensures higher peak data rates. Throughput may vary due to various technical issues such as ping, jitter, and loss. Ping is related to latency and is measured in milliseconds. It refers to the reaction time indicating how quickly the device receives a response after sending a request. Jitter is the variability of the ping over time. It measures the change in packet delay or PDV (Packet Delay Variation), which affects buffering and other interruptions in data transmission. On the other hand, the loss indicates the percentage of packet loss for the packets sent over the radio channel. Over the selected reference spots, Table 20 shows the indoor and Table 21 shows the outdoor throughput test.

Table 20. SPEED TEST performed at the indoor reference point

Reference Point	**Downlink speed (Mbps)**	**Uplink speed (Mbps)**	**Ping (ms)**	**Jitter (ms)**	**Loss (%)**
0	301	30.7	21	6	0.7
1	305	7.4	21	4	0
2	123	7.78	21	4	0.7
3	286	7.84	20	2	0
4	115	0.45	20	2	0
5	118	0.9	21	4	0
6	312	28	22	6	0.3
7	290	19	20	2	0
8	322	26.9	22	6	0.3
9	321	33.1	20	4	0
10	323	29.4	20	2	0
11	254	5.4	21	1	0
12	314	18.9	21	3	0.8
13	324	29.2	22	6	0
14	310	12.5	20	4	2
15	17.2	1.66	20	8	21.6
16	19	1.6	19	8	21.8
17	1.4	0.06	40	74	96.2
18	18	1.9	18	8	21.9
19	17.4	1.6	21	8	21.5
20	300.9	21.94	19	2	0.3
21	324	35.7	19	5	0.7
22	330	8.72	21	2	0
23	301	11.5	25	697	2.7
24	299	7.39	21	4	0
25	312	5.36	34	200	0
26	337	13.5	19	1	0
27	50.2	27.8	30	6	0
29	13.1	0.81	45	63	19.2
30	219	0.54	22	2	0
31	41.2	6.44	34	2	0
32	328	12	22	3	1.9
33	1.99	0.02	45	78	94.3
34	59.4	0.23	22	2	0
35	206	1.43	25	14	0
36	244	3.42	21	3	0
37	16.7	0.44	38	10	0
38	47.2	6.55	30	51	0
39	47.2	6.55	30	51	0
40	23.8	3.29	38	1	0
41	39.2	6.51	27	2	0

Table 21. Speed test performed at outdoor reference Point

Reference Point	**Downlink speed (Mbps)**	**Uplink speed (Mbps)**	**Ping (ms)**	**Jitter (ms)**	**Loss (%)**
0	314	30.3	24	2	0
1	309	36	21	2	1.5
2	315	28.1	19	2	0.7
3	327	13.3	20	2	0
4	220	1.8	19	3	0
5	226	4.02	20	5	0
6	314	5.26	21	6	0
7	169	0.7	20	3	0
8	226	0.71	20	4	0
9	216	5.3	21	2	0
10	313	16.7	20	3	0
11	329	18.5	24	7	1.4
12	324	29.1	20	2	0
13	325	8.21	23	5	0
14	308	30.8	21	2	0.5
15	308	30.8	21	2	0.5

5 RESULTS

The total measurement results have been collected in two separate test drives, indoor and outdoor. This chapter presents the post-processing outcome of both measurements. It also presents the obtained values through the measurements, which will help compare indoor-outdoor measurements and the theoretical perspective.

5.1 Practical Highlights

5.1.1 Indoor Attributes

A total of 3080 data samples were collected during these real-time measurements, based on four different KPIs. In terms of RSRP, 12.03 percent was found to be Excellent, 22.92 percent was found to be Good, 56.70 percent was found within Mid-Cell range, and 8.35 percent was found at the Cell-Edge range. Table 22 shows the total number of samples counted throughout the measurement.

Table 22. SS-RSRP sample count with the range at the indoor

Legend	Colour	Range (dBm)	Sample Count (3080)	Percentage (%)
Excellent		-80 or above	371	12.03
Good		-90 to -80	706	22.92
Mid-Cell		-100 to -90	1746	56.70
Cell-Edge		-110 to -100	257	8.35
Worst		-130 to -110	0	0
Missing		-130 or below	0	0

Figure 28 is the graph view presentation of all SS-RSRP sample values, where the x-direction shows the time interval and the y-direction shows the value in dBm. The bar view graph has plotted the 42 SS-RSRP values from Table 14 in Figure 29 where each bar indicates the active new Radio Physical Cell Id beam index (nR PCI_bi) from the table with its unique color. It represents the best beam at that particular reference spot, measured by the UE. In Figure 29 the x-direction shows the 42 reference spots from 0 to 41, and the y-direction shows the value of SS-RSRP in dBm.

Through this measurement, −90.43 dBm has been calculated as an average value, −74.3 dBm as the highest value, and −102.1 dBm as the lowest value at the reference points from the 5G NR BTS. The average SS-RSRP −90.43 dBm belongs to the mid-cell range. As −90.43 dBm is close to −90 dB, this level of SS-RSRP will provide a strong signal with fair data speed.

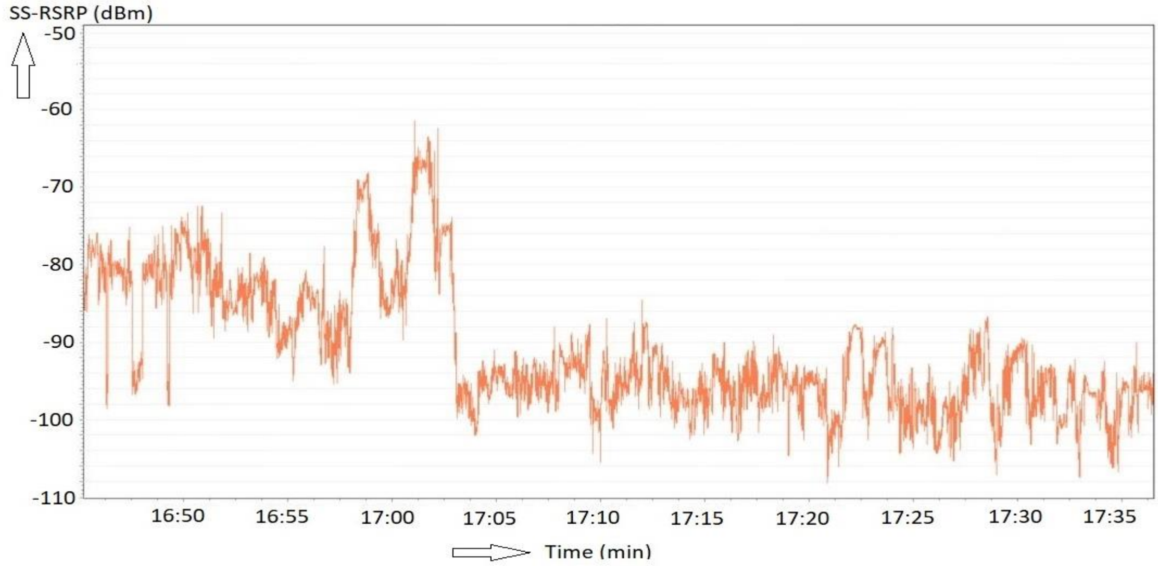

Figure 28. Indoor SS-RSRP presentation through graph view.

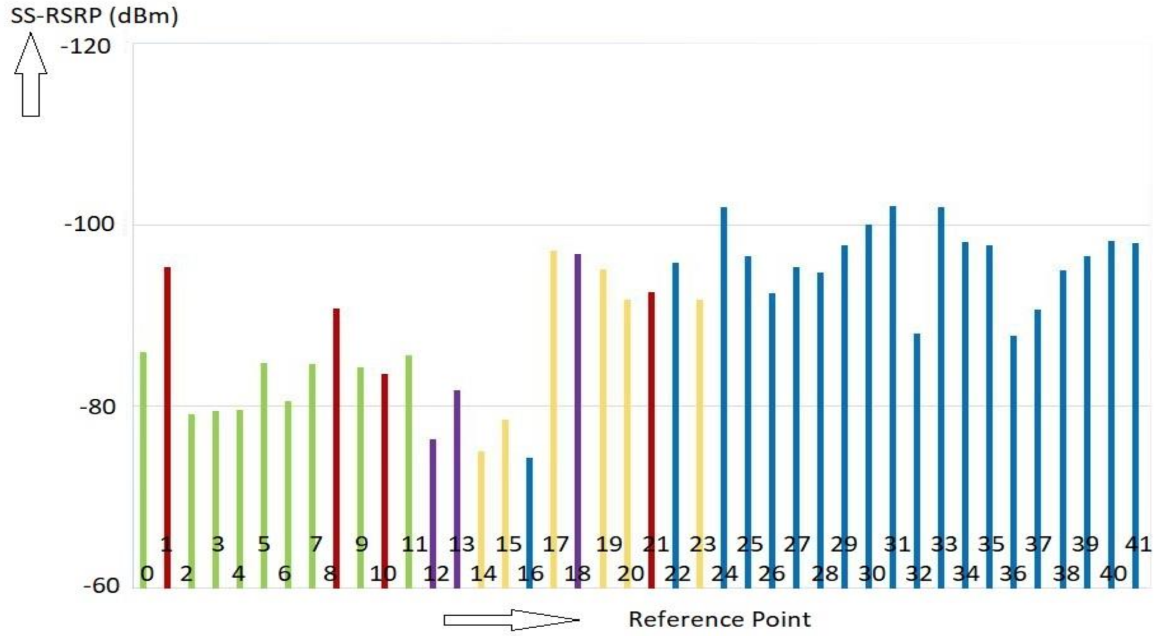

Figure 29. Bar view graph of indoor reference points (in SS-RSRP).

Similarly, SS-RSRQ has been measured parallelly, and all the measured data has been found in the mid-cell. There are 3079 samples of SS-RSRQ that have been counted during the test are presented in Table 23. Throughout this measurement, −10.90 dB has been calculated as an average value, −10.8 dB measured as the highest value, and −12.4 dB is the lowest at the reference points from the 5G NR BTS. For SS-RSRQ, the average value of −10.9 dB belongs to the mid-cell range. As −10.9 dBm is close to −10 dB, this level of SS-RSRQ will provide a strong signal level with fair data speed.

Table 23. SS-RSRQ sample count with the range at the indoor

Legend	**Colour**	**Range (dB)**	**Sample Count (3079)**	**Percentage (%)**
Excellent		-5 or above	0	0.00
Good		-5 to -10	0	0.00
Mid Cell		-10 to -15	3079	100.00
Cell Edge		-15 to -20	0	0.00
Worst		-20 to below	0	0.00

Figure 30 is the graph presentation of all the sample values of the SS-RSRQ that has been recorded during the test, where the x and y-direction show the time interval and value, respectively. The value of the 42 samples of SS-RSRQ from Table 16 has been plotted through the bar view graph in Figure 31 where each bar has its color identity. Each color indicates the active nR PCI_bi from Table 16, representing the best beam at each reference spot recorded by the UE, where the x-direction shows the reference points and the y-direction shows the SS-RSRQ value in dB.

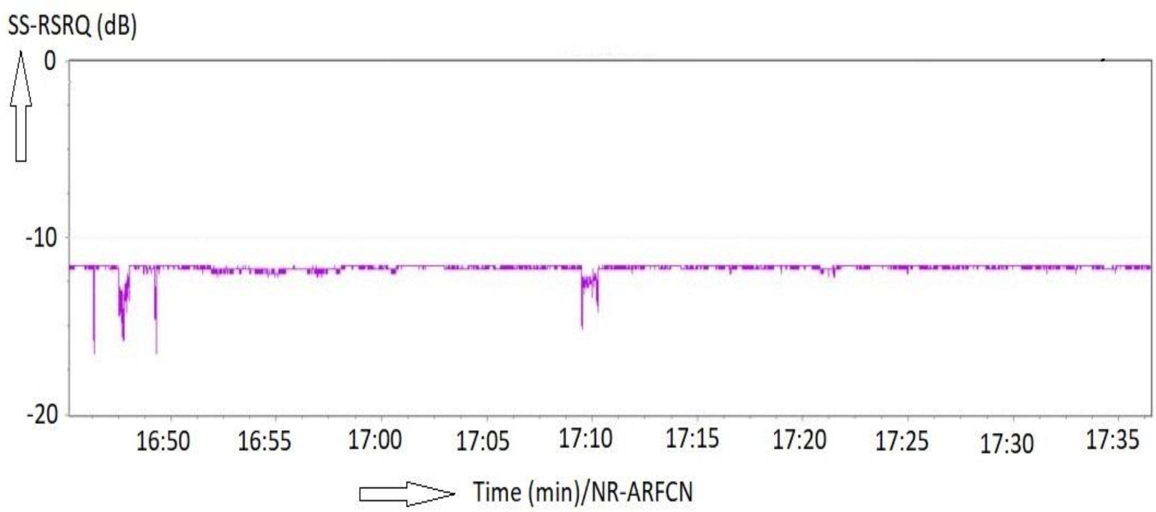

Figure 30. Indoor SS-RSRQ performance through graph view.

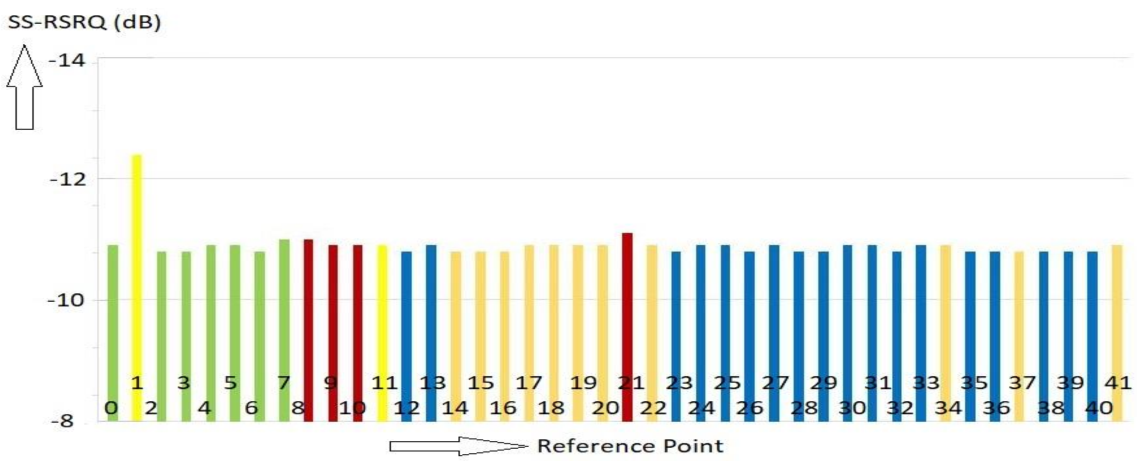

Figure 31. Bar view graph of indoor reference points (in SS-RSRQ).

According to the third KPI parameter SS-SINR, 22.1dB, 4.9 dB, and 17.94 dB have been listed as the highest, lowest, and average values, respectively, through this indoor real-time measurement. As the average SS-SINR of 17.94 dB belongs to the good (13 dB – 20 dB) range, this level of SS-SINR will provide a robust signal with reasonable data rates. The measured value of 42 reference samples from Table 18 has been presented through the bar view graph in Figure 33 where every bar has its specific color. Each color suggests the identity of active nR PCI_bi from Table 18, and it also represents the best beam on that particular spot. In Figure 33, the x-direction shows the number of reference points from 0 to 41, and the y-direction represents the recorded value of SS-SINR in dB during the test.

Table 24. Range of SS-SINR values in dB

Legend	**Colour**	**Range (dB)**
Excellent		20 or above
Good		13 to 20
Mid Cell		0 to 13
Cell Edge		0 to below

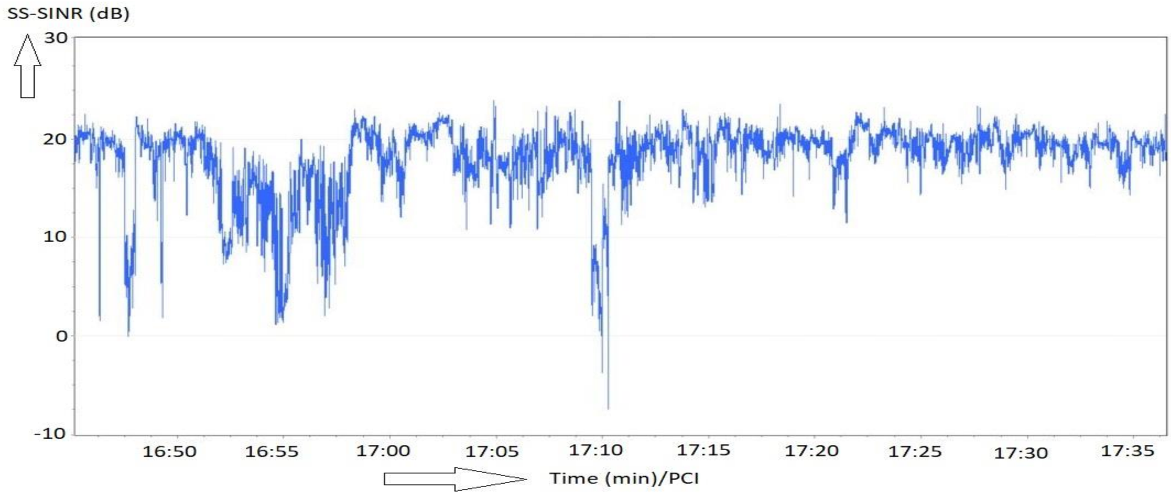

Figure 32. Indoor SS-SINR performance through graph view.

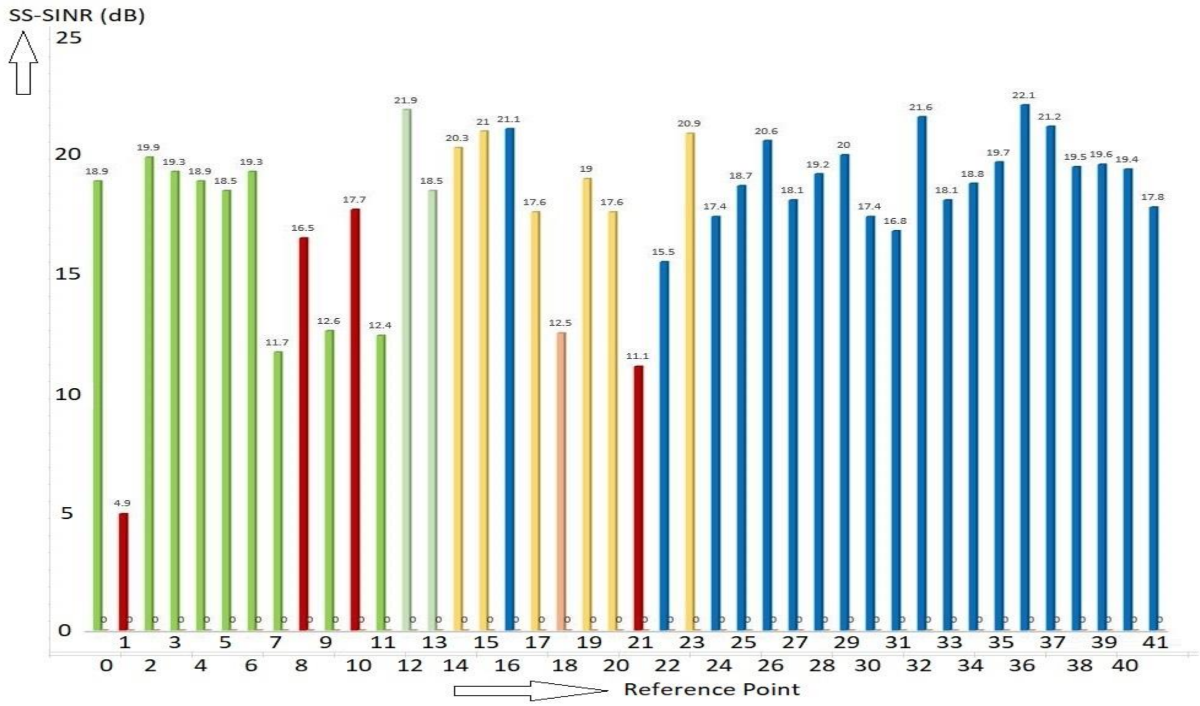

Figure 33. Bar view graph of indoor reference points (in SS-SINR).

Figure 34 shows the calculated downlink and uplink speed on each 42-reference point during the indoor measurement. The downlink speed (indoor route) remained between 337 Mbps to 206Mbps except the opposite of R-Gate corridors and before the central library. Therefore, the average downlink speed was reduced to 186.14 Mbps, and the average uplink speed was 10.84 Mbps. The peak downlink and uplink speeds were 337 Mbps and 35.7 Mbps, respectively. The ping varies between 19 to 40 milliseconds. The jitter varies from 2 to 7 milliseconds. Packet loss is close to zero except for a few values. All of this information leads to a good data-centric 5G cellular network system.

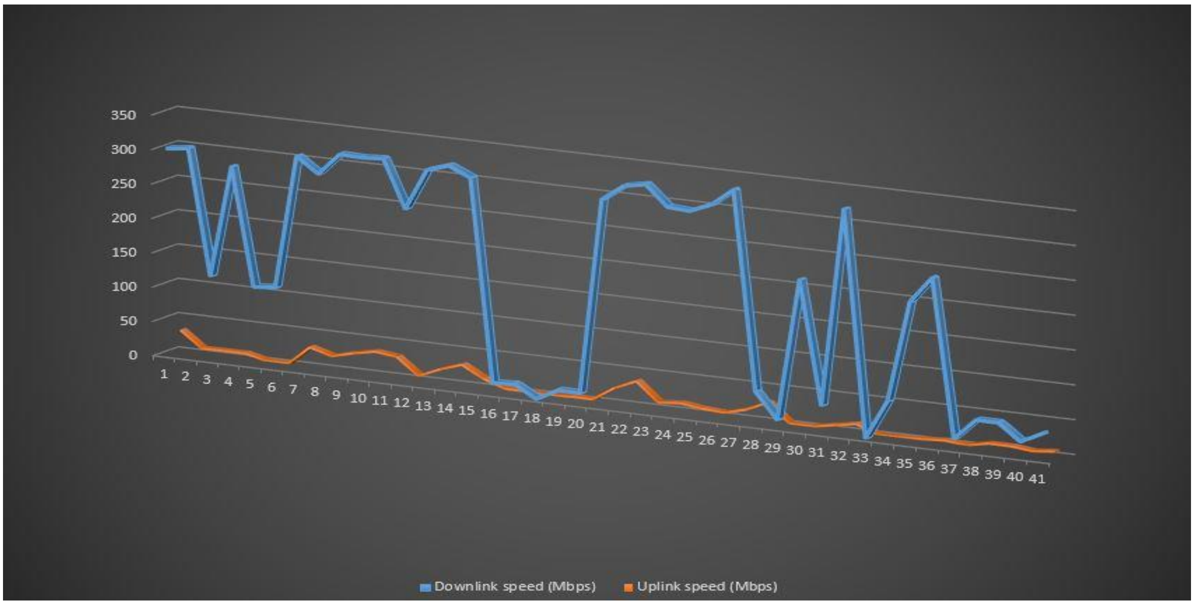

Figure 34. Indoor Throughput performance through graph view.

5.1.2 Outdoor Attributes

In terms of RSRP, 15.22 percent was found to be Excellent, 18.21 percent was found to be Good, 24.09 percent was recorded to be in the Mid-Cell range, 36.86 percent was found to be in the Cell-Edge range, and 5.62 percent was recorded to be in the Worst range. The total number of samples counted throughout the measurement are shown in Table 25. Across this measurement, the average value has been calculated as −90.83 dBm. −109.6 dBm has been found as the lowest and −63.2 dBm as the highest value at the reference points from 5G NR BTS of 5GTN. As −90.83 dBm is close to -90 dB, this level of SS-RSRP will provide a strong signal with fair data speed.

Table 25. SS-RSRP sample count with range for the outdoor

Legend	Colour	Range (dBm)	Sample Count (3545)	Percentage (%)
Excellent		-80 or above	540	15.22
Good		-90 to -80	645	18.21
Mid Cell		-100 to -90	854	24.09
Cell Edge		-110 to -100	1307	36.86
Worst		-130 to -110	199	5.62
Missing		-130 or below	0	0

Figure 35 is the graph view presentation of all the sample values of the SS-RSRP, where the x-direction shows the time interval and the y-direction shows the value. Figure 36 is the bar view graph of the 16 reference points from Table 15 where each bar indicates the nR PCI_bi from the table with its unique color. It represents the best beam at that particular reference spot, measured by the UE.

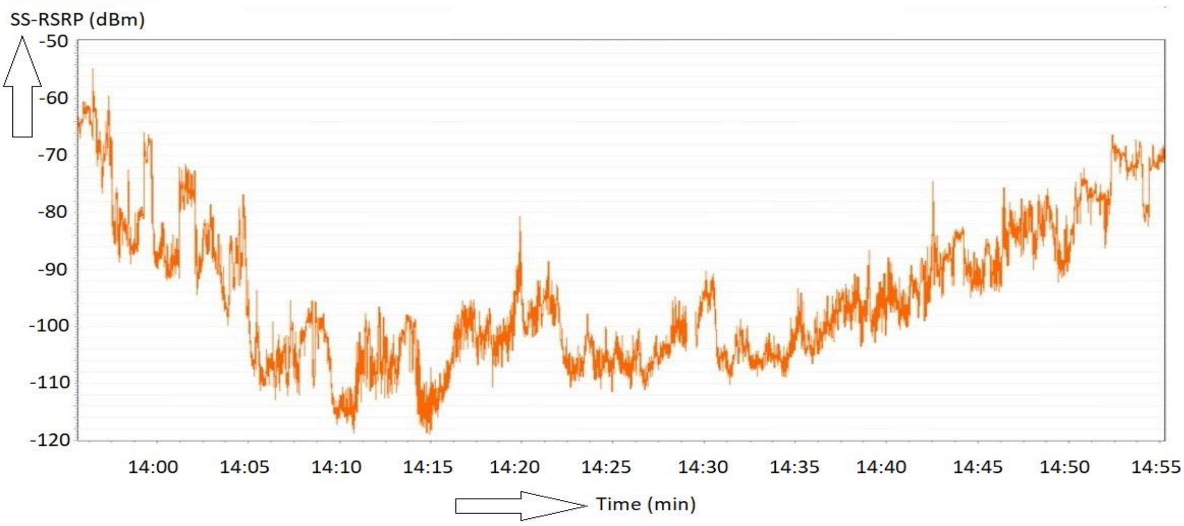

Figure 35. Outdoor SS-RSRP performance through graph view.

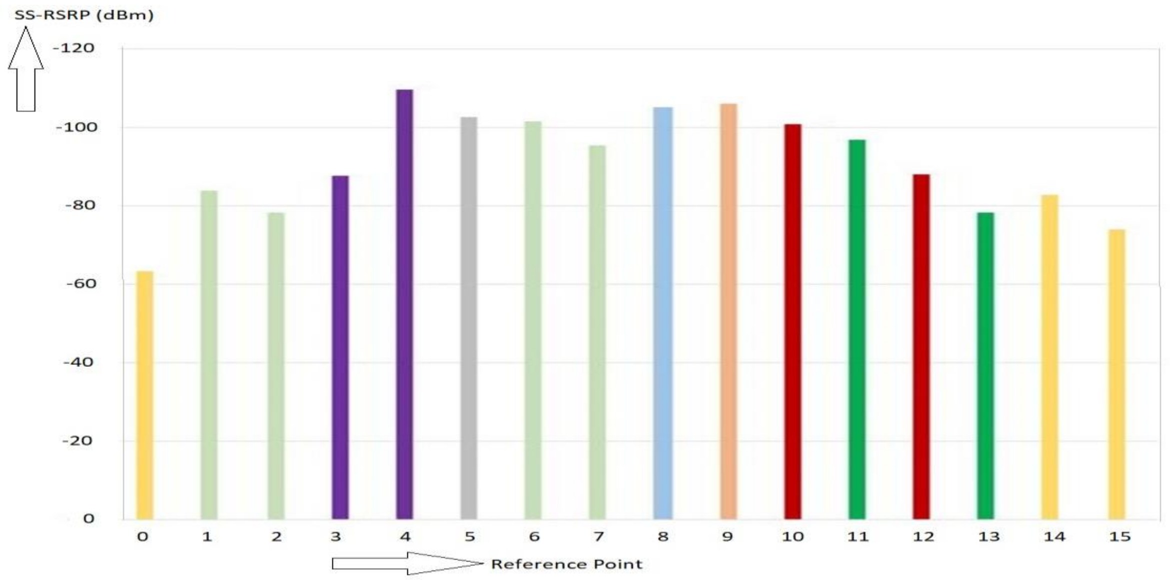

Figure 36. Bar view graph of outdoor reference points (in SS-RSRP).

During the outdoor measurement, it has been noted that 100% of recorded data of SS-RSRQ was found in the Mid Cell range. The total 3545 count samples are presented in Table 26 which indicates the different ranges of SS-RSRQ with color identification. Throughout the outdoor measurement, −10.88 dB, -10.8 dB, and −11.2 dB have been calculated as the average, highest and lowest values, respectively. The average value of -10.88 dB falls within the range of -10 to -15 dB, suggesting the mid-cell range. As −10.88 dB is close to −10 dB, this level of SS-RSRQ will provide a strong signal level with fair data speed.

Table 26. SS-RSRQ sample count with range for the outdoor

Legend	**Colour**	**Range (dB)**	**Sample Count (3545)**	**Percentage (%)**
Excellent		-5 or above	0	0.00
Good		-5 to -10	0	0.00
Mid Cell		-10 to -15	3545	100.00
Cell Edge		-15 to -20	0	0.00
Worst		-20 to below	0	0.00

The value of 16 mentioned spots are shown through the bar view graph in Figure 38 where every bar has its unique color. Each color signifies the active nR PCI bi and other beams on that spot remain passive.

Figure 37 is the graph view of all the sample values of the SS-RSRQ, where towards x-direction shows the time interval and the y-direction shows the value of the SS-RSRQ.

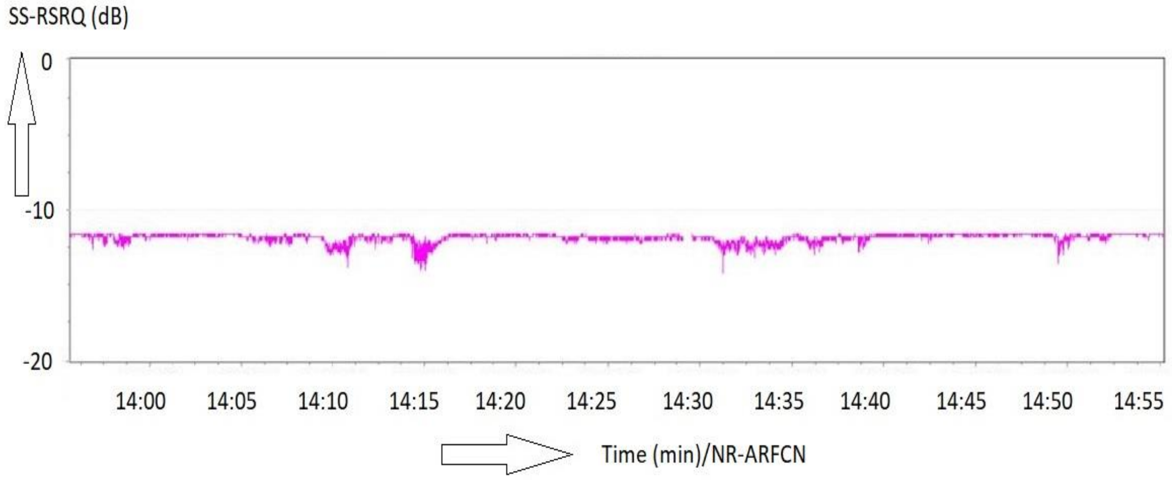

Figure 37. Outdoor SS-RSRQ performance through graph view.

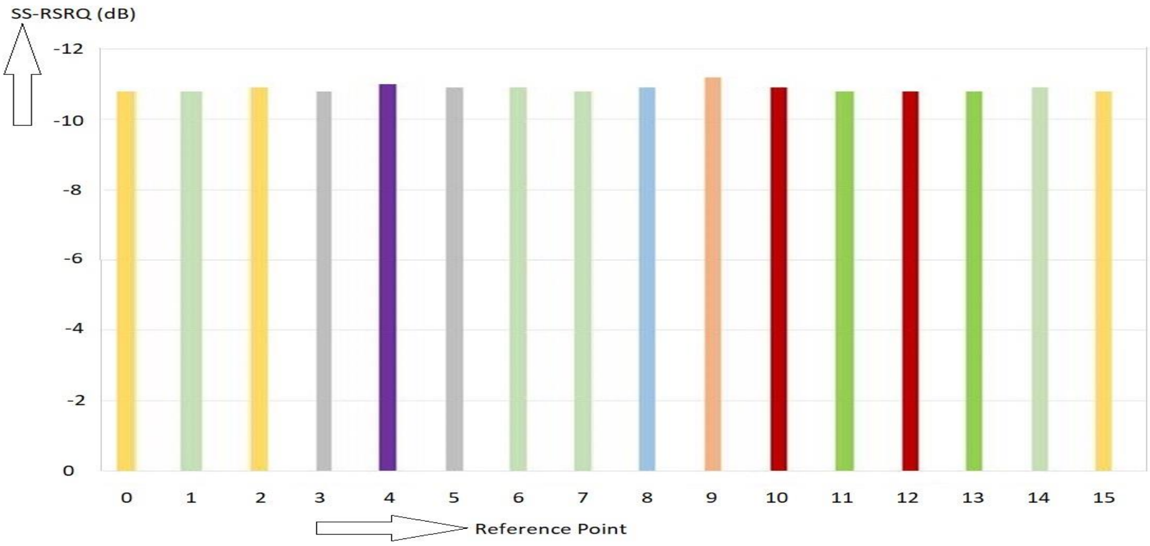

Figure 38. Bar view graph of outdoor reference points (in SS-RSRQ).

In this outdoor measurement test, an average value of 17.7 dB was determined for SS-SINR, with 21.3 dB being the highest value and 10.1 dB being the lowest. As the average SS-SINR of 17.7 dB belongs to the good range, this level of SS-SINR will provide a strong signal and good data speed. Figure 39 is the graph view presentation of 3545 sample values of the SS-SINR. The x and y-direction shows the time interval and measured value of SS-SINR in dB, respectively. The recorded 16 SS-SINR samples from Table 19 have been reflected through the bar view graph in Figure 40. Each bar color represents the uniqueness of the active nR PCI bi from Table 19, which measures the best beam on that specific spot. In Figure 40, the x-direction shows the number of reference points, and the y-direction indicates the calculated value in dB.

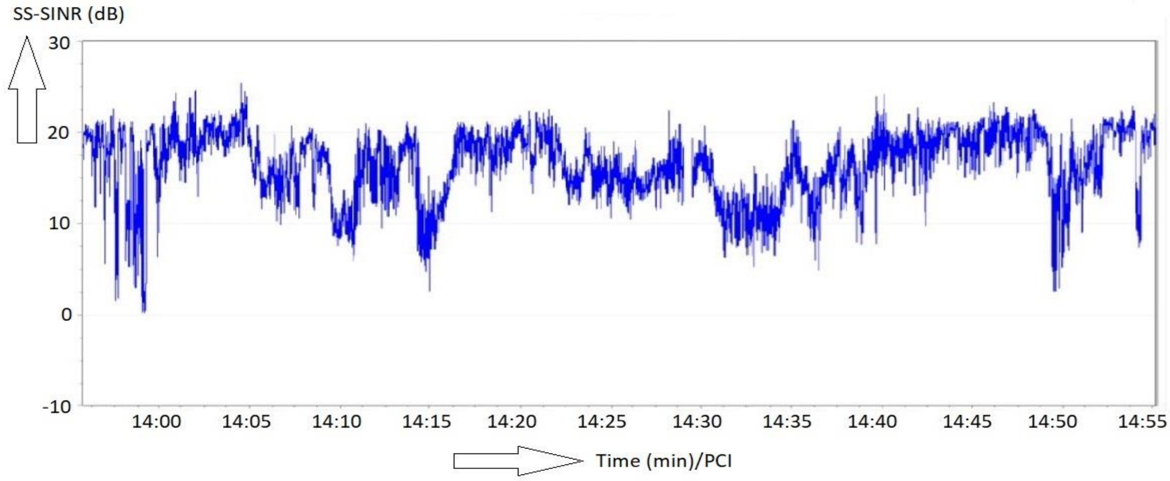

Figure 39. Outdoor SS-SINR performance through graph view.

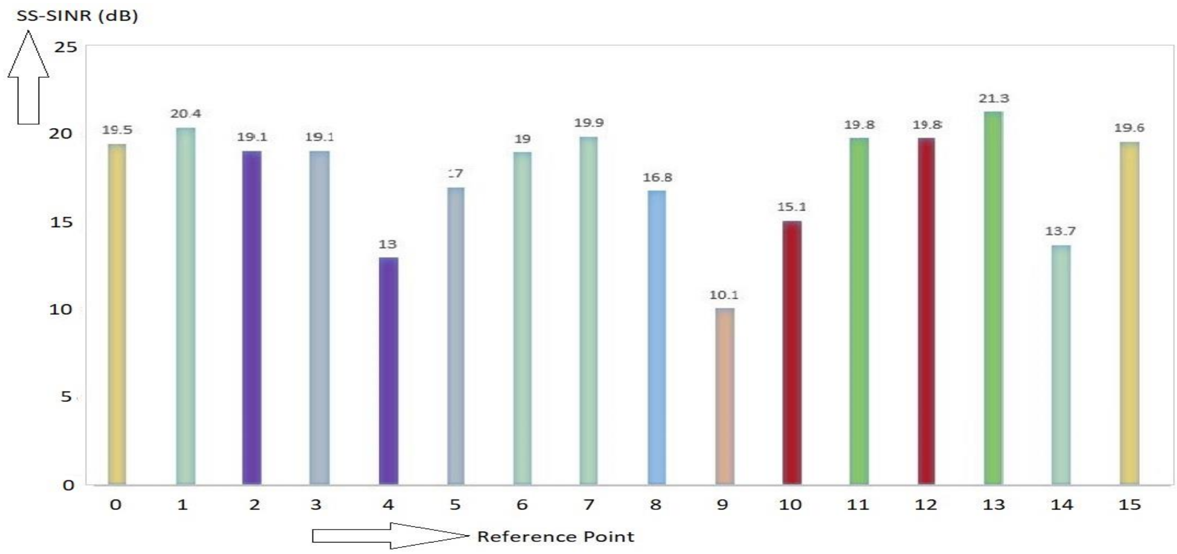

Figure 40. Bar view graph of outdoor reference points (in SS-SINR).

Figure 41 shows the calculated downlink and uplink speed of each 16-reference point during the outdoor measurement. It has been recorded that the downlink speed remained between 329 Mbps to 227Mbps except at point 7, where it was measured at 169 Mbps, and the uplink speed remained from 30.08 Mbps to 0.7 Mbps. Thus, average Downlink and Uplink speeds are 283.94 Mbps and 16.23 Mbps, respectively. Most of the time, the ping was around 20 milliseconds, and sometimes it was below 20 milliseconds. The jitter varies from 2 to 7 milliseconds. There is no packet loss except for one or two values. All of this data leads toward a good data-centric 5G cellular network system.

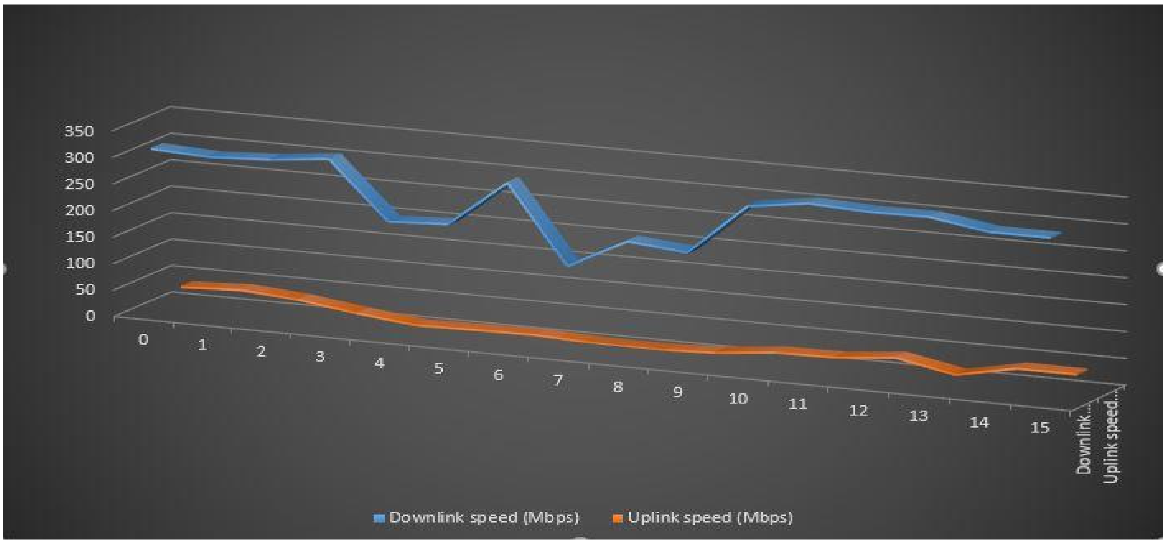

Figure 41. Outdoor Throughput performance through graph view.

5.2 5G NR Band Specifications

In this measurement process, the test has been performed indoors and outdoors to assess the performance of the 5G New Radio band n78. It is also known as the c-band of 5G, which refers to the 3.5 GHz band [60]. According to the 3GPP specification, Table 27 presents the 5G NR (n78) band specifications.

Table 27. 5G NR band specifications [9] [55]

5G NR Band name	n78 (TD 3500)
Duplex mode	TDD
Operating Band (MHz)	3300 to 3800 MHz
NR-ARFCN	620000 to 653333
Supported Channel Bandwidth	10 15 20 30 40 50 60 70 80 90 100
Modulation	64 QAM

5.3 Overall Comparison

At first, the indoor and outdoor real-time measurement samples were compared based on the reference signals. Analyzing the test data, it turns out that the average SS-RSRP values are −90.43 dBm (indoors) and −90.83 dBm (outdoors). Furthermore, the average SS-RSRQ values are −10.90 dB (inside) and −10.88 dB (outside). The observed value for SS-RSRP and SS-RSRQ are almost identical in both test cases. SS-RSRP and SS-RSRQ values are in the mid-cell range, indicating robust signals with decent data rates.

In terms of SS-SINR, there is a difference found in the test cases during the post-processing of test data. The average indoor SS-SINR value is 17.94 dB, and the average outdoor SS-SINR value is 17.70 dB. However, in both cases, the average SS-SINR is below 20 dB (from Table 24), which indicates a good reliable connection, but if the value approaches near 0 dB, the performance will reduce considerably. Therefore, marginal data rates with drop-out will not be avoidable.

Although the average SS-RSRP and SS-RSRQ values are inside the mid-cell range, SS-SINR is detected comparatively better at indoors than outdoors. So, it may be concluded that something (i.e., walls, buildings, trees, or other obstacles) is interfering with the 5G NR signals during transmission across the radio channel, reducing signal strength and causing signal propagation attenuation.

These studies and analyses have found one common factor for both practical cases. The SS-SINR is comparatively showing an average value even in the mid-cell range, and another thing was observed from Table 28 that 5G NR PCI 74 is slightly better optimized than 5G NR PCI 76. The transmitted signal power is essential when compared to the signal propagation attenuation and interference present in the system. So overall, transmit signal power needs to be increased slightly for 74 PCI than 76 PCI of existing gNB of 5GTN at the Linnanmaa campus. Figure 42 shows the 5GTN NR BTS at the University of Oulu, Linnanmaa campus, in front of the 'R' gate.

Figure 42. 5G New Radio BTS of 5GTN at the University of Oulu (Linnanmaa campus) on existing infrastructure.

Table 28. KPI table for existing 5G NR cells of 5GTN

Parameter		**PCI**							
		76				**74**			
		Indoor		**Outdoor**		**Indoor**		**Outdoor**	
		Nearest	**Longest**	**Nearest**	**Longest**	**Nearest**	**Longest**	**Nearest**	**Longest**
		12	41	0	5	0	21	12	9
SS-RSRP (dBm)		-76.4	-98	-63.2	-102.5	-86	-92.6	-87.9	-106
SS-RSRQ (dB)		-10.8	-10.9	-10.8	-10.9	-10.9	-11.1	-10.8	-11.2
SS-SINR (dB)		21.9	17.8	19.5	17	18.9	11.1	19.8	10.1
Throughput	**Downlink (Mbps)**	314	39.2	314	226	301	324	324	216
	Uplink (Mbps)	18.9	6.51	30.3	4.02	30.7	35.7	29.1	5.3

Throughput test was found as expected for 5G. The peak downlink speeds at indoor and outdoor are 328 Mbps and 327 Mbps, respectively. The peak uplink speeds are 35.7 Mbps and 36 Mbps at indoors and outdoors, respectively. The ping varies between 19 to 40 milliseconds. The jitter varies from 2 to 7 milliseconds. Except for a few values, the packet loss is close to zero. So, it can be concluded that if signal propagation attenuation and the interference could be reduced by increasing the transmit signal power, then higher data rates can be attainable with the existing wireless cellular system.

6 DISCUSSION

Non-standalone 5G NR is the first step toward deploying 5G on the current wireless cellular infrastructure. It is faster in terms of data rate than the fourth-generation LTE mobile network when compared to data transmission facilities. It represents the initial phase of 5G deployment and is based on 3GPP Release-15. With 5G user equipment operating at sub-6GHz frequencies, 5G NR has begun to be commercially adopted throughout the world.

The primary purpose of this thesis is to perform signal strength analysis on the 5G NR signal of 5GTN in two distinct environments, indoor and outdoor. The secondary purpose of this thesis is to use throughput tests to assess the fluctuation in data download and upload speed. The Nemo measuring solution tool was used in the test scenarios. It is a simple and useful app for determining the strength of a 5G NR signal. To perform these measurements, we need to fulfill the minimum computer hardware requirement and have 5G enabled UE equipment. Finally, we need throughput measurement software.

Nemo Handy was installed in the Oneplus-7 phone (capable of receiving 5G signals) to measure the reference signals, and Nemo-Outdoor was used. Here two measurement tests were performed. Since the outdoor route can be mapped with Global Positioning System (GPS), an automated route was generated throughout the test. Due to the lack of GPS support at indoor, a manual map has been prepared for the ground floor of the campus. A route has been drawn on that map to perform the test.

Many signal throughput measurement applications are available for mobile phones based on different platforms. However, since the phone used in this measurement was based on the Android platform. A free version of an Android platform-based mobile application called Speedtest by Okla was used to measure the signal throughput variation. It detects the speed of the data rate in Mbps at the reference points of the measurement route.

The test result was post-processed after the real-time measurement was completed. The deviation in the measurement routes was observed as a result of the distance and interference from the BTS to the reference spots (indoors and outdoors). Because of the construction of modern buildings, trees and other obstacles, the amount of interference on the outside is marginally higher than on the inside. Furthermore, the comparative distance between the two physical cell IDs of the 5G NR BTS and UE has been highlighted.

Section-5 presents the measurement results for both indoor and outdoor environments. According to the test results, the average SS-RSRPs are -90.43 dBm (indoors) and -90.83 dBm (outdoors). The average SS-RSRQs are -10.9 dB (inside) and -10.88 dB (outside). Both SS-RSRP and SS-RSRQ were found in the mid-cell range. So, it can be concluded that the 5G NR signals transmit at a good power level with sufficient signal quality. The third KPI parameter SS-SINRs averages are 17.94 dB (indoor) and 17.70 dB (outdoor). There is a slight deviation between indoor and outdoor SS-SINR due to interference, but the 5G NR performance was as expected.

Furthermore, the throughput test verifies the data transfer rate between the gNB and the UE across the radio channel. Indoor and outdoor average downlink speeds are 186.14 Mbps and 283.94 Mbps, respectively. Inside and outside the campus, the average uplink speeds are 10.84 Mbps and 16.23 Mbps, respectively. So, according to the 5GTN gNB, the 5G NR has been deployed for 5G purposes on top of the existing LTE wireless cellular infrastructure while maintaining the NSA Option 3 architecture.

7 SUMMARY

This thesis focuses on the 5G NR signal performance assessment within the 5G Test Network by performing real-time measurement tests with a signal assessment tool. The objectives of this thesis have been studied in the first chapter. The literature review discussed the adaptation of the 5G system to current cellular infrastructure, the variety of the 5G architecture, the relevance of 5G NR, the possibilities, and the development. The topic discussed in the literature review is the analyzed summary from various scientific articles, white papers, and several scientific web portals. 3GPP Release-15 is the basis of this literature review.

A theoretical background is required to understand the 5G wireless network, and the objectives of this thesis are provided in 1st Chapter. The details of the 5G wireless network with basic architectures, figures, tables, and equation contains in it. After studying several books, scientific papers, and relevant web portals, these descriptions are written. 2nd Chapter began by defining the 5G, its use cases, the significance of the 5G new radio, its architecture, 5G new radio physical layer, its frame structure, and the 5G NR synchronization process with beamforming technology. Discussion on different KPI metrics is included in this chapter 2. All those sections assist us in developing the theoretical concept.

3rd Chapter provides the basic information about the software, 5G test network, coverage area, and 5G new radio base stations are used in the test measurement for this thesis. There are many signal-measurement tools available in the industry. Nemo Wireless Network Solution was used during the measurement by Keysight Technologies and Okla's Speedtest mobile application.

The tests were performed using the Nemo Handy Network Solution mobile application and were carried out following the test specifications prepared for the measurements. The Measurements chapter presents two types of test cases, maps, test routes, and test data. SS-RSRP, SS-RSRQ, SS-SINR, and Throughput are the four main measurements used in this thesis.

The Nemo Analyze tool was used to post-processing the test data such as SS-RSRP, SS-RSRQ, and SS-SINR presented in the Result part. Throughput data was also analyzed and presented in terms of data transmission speed with ping, jitter, and loss parameters. In addition, a comparative comparison has been drawn between the two physical cell IDs of the 5G NR BTS in terms of distance from UE by using SS-RSRP, SS-RSRQ, SS-SINR, and Throughput test.

Based on the measurements and analysis, the average SS-RSRP and SS-RSRQ of 5G NR signals from gNB of 5GTN at the Linnanmaa campus were observed in the mid-cell range. The average SS-SINR was calculated within a tolerable range. According to experiential parameters (SS-RSRP, SS-RSRQ and SS-SINR) it can be concluded that the coverage of the 5G NR BTS at the Linnanmaa campus is maintaining the 5GTN planned area. The 5G NR signal is transmitted with good transmission power and good signal quality with an average SS-SINR level. Moreover, the throughput test ensures the data transmission rate over the radio channel between gNB and UE. The peak downlink speeds at indoor and outdoor are 337 Mbps and 329 Mbps, respectively. The peak indoor and outdoor uplink speeds are 35.7 Mbps and 36 Mbps, respectively. So, it can be concluded that the 5G NR synchronization over the existing 4th generation wireless cellular infrastructure has been achieved, and the NSA Option-3 architecture has been maintained.

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