FACULTY OF INFORMATION TECHNOLOGY AND ELECTRICAL ENGINEERING
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MASTER'S THESIS

COVERAGE MEASUREMENTS OF NB-IOT TECHNOLOGY

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ABSTRACT

The narrowband internet of things (NB-IoT) is a cellular radio access technology that provides seamless connectivity to wireless IoT devices with low latency, low power consumption, and long-range coverage. For long-range coverage, NB-IoT offers a coverage enhancement (CE) mechanism that is achieved by repeating the transmission of signals. Good network coverage is essential to reduce the battery usage and power consumption of IoT devices, while poor network coverage increases the number of repetitions in transmission, which causes high power consumption of IoT devices. The primary objective of this work is to determine the network coverage of NB-IoT technology under the University of Oulu's 5G test network (5GTN) base station. In this thesis work, measurement results on key performance indicators such as reference signal received power (RSRP), reference signal received quality (RSRQ), received signal strength indicator (RSSI), and signal to noise plus interference (SINR) have been reported. The goal of the measurement is to find out the NB-IoT signal strength at different locations, which are served by the 5GTN cells configured with different parameters, e.g., Tx power levels, antenna tilt angles.

The signal strength of NB-IoT technology has been measured at different places under the 5GTN base station in Oulu, Finland. Drive tests have been conducted to measure the signal strength of NB-IoT technology by using the Quectel BG96 module, Qualcomm kDC-5737 dongle and Keysight Nemo Outdoor software. The results have shown the values of RSRP, RSRQ, RSSI, and SINR at different locations within several kilometres of the 5GTN base stations. These values indicate the performance of the network and are used to assess the performance of network services to the end-users.

In this work, the overall performance of the network has been checked to verify if network performance meets good signal levels and good network coverage. Relevant details of the NB-IoT technology, the theory behind the signal coverage and comparisons with the measurement results have also been discussed to check the relevance of the measurement results.

Keywords: NB-IoT, CE, 5GTN, RSRP, RSRQ, RSSI, SINR.

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FOREWORD

This thesis has been carried out as a partial requirement for the completion of the master's degree program in Wireless Communication Engineering at the Centre for Wireless Communication (CWC), University of Oulu.

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I would like to thank my parents and elder brother for their continuous inspirations for my studies. I am also thankful to all my friends living here and in my home country for their continuous moral encouragement and support throughout my studies. I would like to dedicate this thesis to my parents and elder brother for their unconditional love, encouragement, and wonderful support.

Oulu, January 14, 2022

Md Sanaullah

LIST OF ABBREVIATIONS AND SYMBOLS

1G	1st Generation Mobile Network
2G	2nd Generation Mobile Network
3G	3rd Generation Mobile Network
3GPP	3rd Generation Partnership Project
4G	4th Generation Mobile Network
5G	5th Generation Mobile Network
5GTN	5G Test Network
AS	Access Stratum
AT	ATtention
Bps	Bits per Second
CE	Coverage Enhancement
CINR	Carrier to Interference Plus Noise Ratio
CRS	Cell Specific Reference Signal
CSV	Character Separated Value
CWC	Centre for Wireless Communications
DCI	Downlink Control Information
dB	Decibel
dBi	Decibel Relative to Isotropic
dBm	Decibel Milliwatt
DL	Downlink
DMRS	Demodulation Reference Signal
DRX	Discontinuous Reception
EDGE	Enhanced Data rates for GSM Evolution
eDRX	Extended Discontinuous Reception
EGPRS	Enhanced GPRS
EIRP	Effective Isotropic Radiated Power
eNB	Evolved Node B
EPS	Evolved Packet System
E-RAB	EPS Radio Access Bearer
E-UTRA	Evolved Universal Terrestrial Radio Access
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPRS	General Packet Radio Service
GPS	Global Positioning System
GSM	Global System for Mobile Communications
HD-FDD	Half Duplex-FDD
HPBW	Half Power Beamwidth
HSPA	High Speed Packet Access
I2S	Inter-IC Sound
IoT	Internet of Things
IoT-GW	IoT Gateway
IP	Internet Protocol
ISO	International Standards Organization
Kbps	Kilobits per Second

kHz	Kilohertz
Km	Kilometre
KPI	Key Performance Indicator
LoRaWAN	LoRa Wide Area Network
LPWA	Low Power Wide Area
LPWAN	Low Power Wide Area Network
LTE	Long Term Evolution
LTE-M	LTE-Machine Type Communication
LTE-FDD	LTE-Frequency Division Duplexing
LTE-TDD	LTE- Time Division Duplex
M2M	Machine to Machine
MAC	Medium Access Control
MCL	maximum Copling Loss
MCS	Modulation and Coding Scheme
MHz	Megahertz
MIB-NB	Narrowband Master Information Block
MME	Mobility Management Entity
mMTC	Massive Machine Type Communication
ms	Millisecond
MTC	Machine Type Communication
NAS	Non-Access Stratum
NB CIoT	Narrowband Cellular IoT
NB-IoT	Narrowband-Internet of Things
NB-LTE	Narrowband-Long Term Evolution
NB-M2M	Narrowband-Machine to Machine Communication
NB-OFDM	Narrowband-Orthogonal Frequency Division Multiplexing
NFV	Network Function Virtualization
NLOS	Non-Line of Sight
NPBCH	Narrowband Physical Broadcast Channel
NPDCCH	Narrowband Physical Downlink Control Channel
NPDSCH	Narrowband Physical Downlink Shared Channel
NPRACH	Narrowband Physical Random-Access Channel
NPSS	Narrowband Primary Synchronization Signal
NS	Network Slicing
NSSS	Narrowband Secondary Synchronization Signals
NPUSCH	Narrowband Physical Uplink Shared Channel
NR	New Radio
NRS	Narrowband Reference Signal
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OSI	Open Systems Interconnection
PAP	Password Authentication Protocol
PCI	Physical Cell Identity
PDU	Protocol Data Unit
PGW	Packet Data Network Gateway
PHY	Physical Layer
PIFA	Planar Inverted-F Antenna
PPP	Point to Point Protocol

PRB	Physical Resource Block
PSD	Power Spectral Density
PSM	Power Saving Mode
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RACH	Random Access Channel
RAN	Radio Access Network
RAP	Random Access Procedure
RB	Resource Block
REs	Resource Elements
RF	Radio Frequency
RRC	Radio Resource Control
RSRP	Reference Signal Received Power
RSRQ	Reference Signal Received Quality
RSSI	Received Signal Strength Indicator
RU	Resource Unit
SCEF	Service Capability Exposure Function
SC-FDMA	Single Carrier Frequency Division Multiple Access
SF	Subframe
SF0	First Subframe
SGW	Serving Gateway
SI	System Information
SIB	System Information Block
SIM	Subscriber Identification Module
SINR	Signal to Noise Plus Interference
SMS	Short Message Service
SMT	Surface Mount Technology
SNR	Signal to Noise
SPI	Serial Peripheral Interface
TAU	Tracking Area Update
TBS	Transport Block Size
TCP	Transmission Control Protocol
UART	Universal Asynchronous Receiver Transmitter
UCI	Uplink Control Information
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UL-SCH	Uplink Shared Channel
UMTS	Universal Mobile Telecommunications System
USB	Universal Serial Bus
WUS	Wake Up Signal
$N_{ID}^{(1)}$	NSSS provides cell identities values
$N_{ID}^{(2)}$	NPSS provides cell identities values
N_{ID}^{cell}	Physical cell identity
Ω	Ohm

1 INTRODUCTION

Beyond the 5th generation mobile network (5G), which promotes more applications of machine-to-machine (M2M) communications [1], [2], [3], [4]. Internet of Things (IoT) is an implementation of M2M. IoT dramatically extends the internet's scope from people-operated computers to autonomous smart devices [5], [6], [7], [8]. There were 7.6 billion active IoT devices at the end of 2019; it is expected to grow approximately 24.1 billion in 2030 [9]. So, the massive number of IoT devices require network coverage to connect to the internet. Though, existing cellular networks offer very good area coverage. However, many IoT devices are in remote areas, far away from the cellular base station. If there is weak coverage, the IoT device transmitter requires more power to operate. In addition, cellular networks are not optimized to transmit a small amount of data application which means cellular networks do not support power-saving mechanisms [10]. The cellular network is designed for various services such as mobile voice, messaging, and high data transmission. On the other hand, IoT applications have some requirements, such as low speed, reliable data transfer, very low energy consumption, cost-effectiveness, and long communication range. Therefore, the requirement of IoT applications leads to the emergence of a low power wide area network (LPWAN), which ensures low energy consumption, long transmission range and low-cost deployment. Some LPWAN technologies examples are Sigfox, LoRa wide area network (LoRaWAN), and narrowband Internet of Things (NB-IoT) [10], [11].

The challenge of cellular communication systems is the limited bandwidth. So, it is quite challenging to connect the huge number of IoT devices in the existing cellular technology with limited bandwidth. So, NB-IoT was introduced in cellular communication systems to connect many IoT devices to solve these challenges. NB-IoT uses a low bandwidth which has an excellent coverage performance. Besides, low-frequency bands have excellent propagation characteristics that improve indoor penetration. Some of the application fields are occupied by NB-IoT in agriculture, health care/ E-health, safety, and security automotive & logistics, manufacturing smart city energy & utilities retail smart home [10].

Huawei and Vodafone jointly applied for approval of the study item of the NB-M2M technology in the 3rd generation partnership project (3GPP) GREEN, which was finally approved in May 2014. In October 2014, Qualcomm submitted a proposal for another version of the NB-IoT technology named NB orthogonal frequency division multiplexing (NB-OFDM). In May 2015, Huawei and Qualcomm introduced air interface technologies where frequency division multiple access (FDMA) was used in the uplink, and orthogonal frequency division multiple access (OFDMA) was used in downlink. Then NB-M2M name was changed to narrowband Cellular IoT (NB CIoT). The three vendors Huawei, Qualcomm and Ericsson jointly started research of the narrowband IoT technology and later submitted the narrowband long-term evolution (NB-LTE) concept on August 10, 2015, GERAN Meeting. 3GPP accepted both NB-LTE and NB-CIoT as work items in release-13; therefore, the name was changed to NB-IoT in September 2015 [10].

1.1 Internet of Things

The internet of things (IoT) refers to anything that can be connected to the internet. In M2M communication, data communication occurs among devices without the need for human interaction. M2M communication is needed to support IoT. So, IoT mean interconnection and exchange of data among devices without human interaction [5], [10]. There are different kinds of usage of IoT applications in different fields such as IoT public, IoT industry, IoT appliance,

and IoT personal. Smart metering and smart garbage bins are IoT applications for public areas. Smart metering saves manpower by collecting gas meter, water, and electricity data over the cellular network. IoT applications in the industry help to improve industrial efficiency and general enterprise. IoT personal features low power wide area (LPWA) applications that create a personal area network for the purposes of information exchange for the user. Examples of IoT personal are wearable smart devices and smart bicycles [10].

1.2 Organization of the Thesis

This thesis work is organized as follows; in this first chapter, a brief introduction is given about the demand of NB-IoT, and NB-IoT standardization status is discussed. In Chapter 2, About NB-IoT technology is discussed. In Chapter 3, concepts of network coverage, key parameter indicators of network coverage are discussed. Chapter 4 provides a concise overview of the measurement devices, measurement software, measurement setup, measurement scenarios and measurement procedure. Chapter 5 evaluates the measurement results and analysis of the thesis work. Chapter 6 provides the discussion and difficulties faced while taking the measurement. Summary and references are presented at the end.

2 NB-IOT TECHNOLOGY

3GPP has introduced the NB-IoT standard in Release 13 [12], [13], [14], [15] compatible with the legacy long term evolution (LTE) [16] mobile networks. The design objectives of this technology are low user equipment (UE) device complexity, increased coverage, and long battery life. This chapter includes a brief description of NB-IoT technology according to release 13 [17], [18], [19], [20] such as network architecture of NB-IoT, NB-IoT channels and coverage enhancement of NB-IoT technology [21]. Besides that, this chapter also includes the features introduced in releases 14,15 and 16 related to network coverage.

2.1 Core Network

The design of NB-IoT is similar to that of LTE since they are both aimed to facilitate radio network evolution, development, and software solution over an existing LTE infrastructure. NB-IoT user equipment connects with evolved Node B (eNB) using the Uu air interface. eNB is connected to mobility management entity (MME) and serving gateway (SGW) via the S1 interface [1]. The S1 interface supports a many-to-many relation between MMEs or serving gateways and eNBs. The X2 interface allows eNBs to interconnect with each other [12]. Two signalling optimizations have been defined for evolved packet system (EPS) to allow the transmission of data to applications. Control plane cellular Internet of Things (CIoT) EPS optimization indicated in red and user plane CIoT EPS optimization indicated in blue shown in Figure 1 [1]. This architecture supports the transmission of infrequent and small data packets. The IoT uplink messages and data packets are transferred through the serving gateway (SGW) to the packet data network gateway (PGW) or service capability exposure function (SCEF) [1].

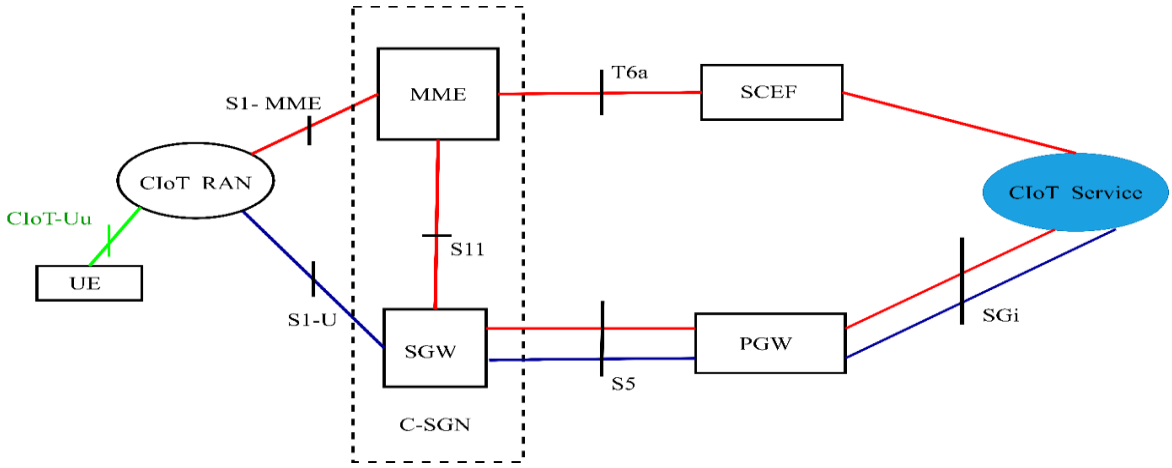

Figure 1. Network for NB-IoT data transmission.

2.2 Radio Protocol Architecture

The network protocol stack is a set of rules which is designed in a layered architecture for transmitting and receiving data or message. This layered architecture exchanges messages, packets, or protocol data units (PDUs) both in the upper and lower layer to provide and use the functions and services. Layered architecture is the reference model of open systems interconnection (OSI), developed by the international standards organization (ISO) as an international standard [7].

The physical layer (PHY) and medium access control (MAC) layers of OSI are called access stratum (AS) for NB-IoT. In the case of the NB-IoT, access stratum and air access methods and protocols remain in the MAC and PHY layers of the OSI model defined by 3GPP. Both layers are responsible for the handling and processing the physical transmission or reception. The physical media of NB-IoT uses wireless channels. So, application, session, presentation, transport, and network layers are called non-access stratum (NAS), unchanged in NB-IoT with respect to LTE defined by 3GPP. On the other hand, transport, and networking layers protocols such as transmission control protocol (TCP) or internet protocol (IP) can be used in NB-IoT as they exist in 3GPP protocols and layers [7], [8].

Layered architecture is separated into two planes: user plane and control plane. Radio resource control (RRC) is also defined in an additional control plane sublayer shown in Figure 2 where RRC executes some functions such as RRC connection management, resource block (RB) control, mobility functions, UE measurement reporting and control [7], [12].

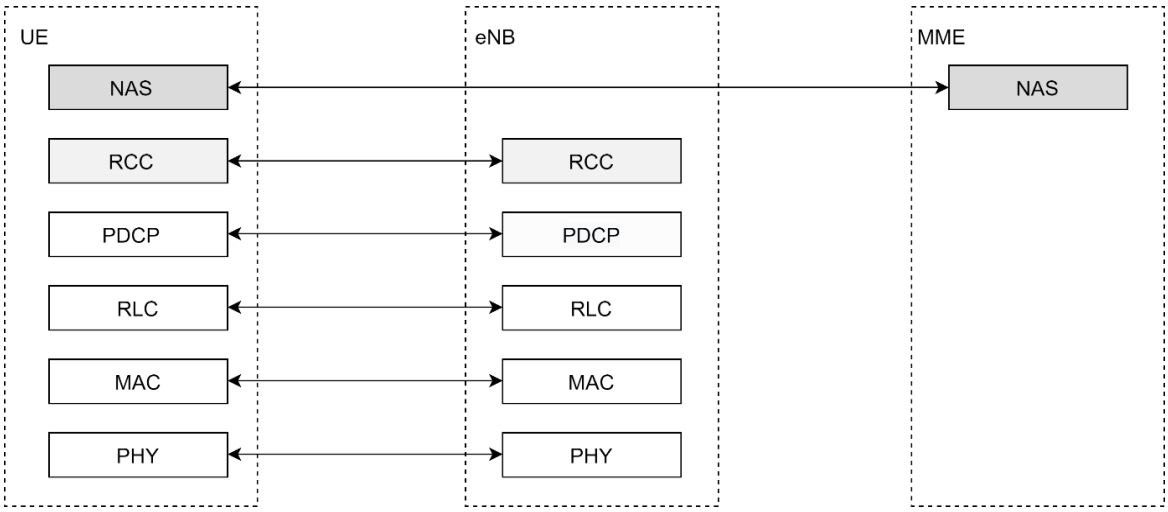

Figure 2. NB-IoT protocol stack for control plane.

2.3 Operation modes

NB-IoT technology operates based on existing LTE functionalities, reusing the same eNB hardware and spectrum without coexistence issues. NB-IoT occupies LTE physical resource carrier [3], [4]. It can be designed in three different operation modes shown in Figure 3.

- **Stand-alone operation:** It uses one dedicated carrier of global system for mobile communications (GSM) frequencies. In this mode, one carrier uses 180 kHz bandwidth with a guard interval of 10 kHz on both sides [1].
- **Guard band operation:** This operation uses the unused resource blocks within the guard band of an LTE carrier [1], [3].
- **In-band operation:** It uses one physical resource block (PRB) within the guard-band of LTE carrier with the total bandwidth of 180 kHz [1].

To avoid the interference between the NB-IoT PRB and LTE PRB, the difference of power spectral density (PSD) should not be more than 6 dB for both in-band and guard band operation modes [10].

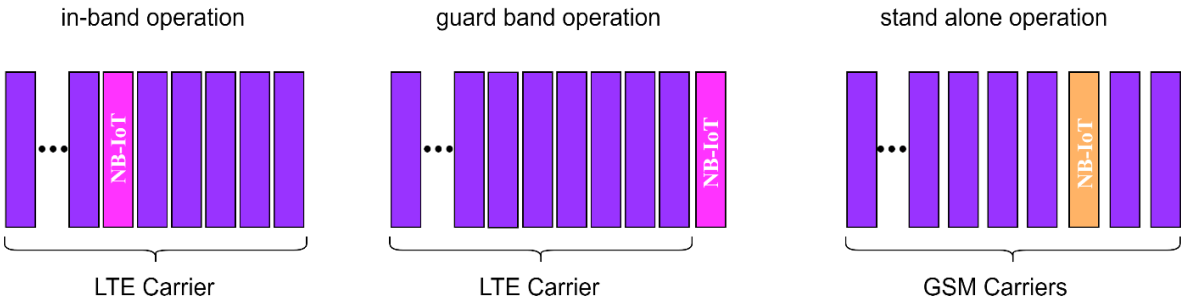

Figure 3. NB-IoT operation modes.

NB-IoT is designed to operate in LTE operating bands 1, 2, 3, 5, 8, 12, 13, 17, 18, 19, 20, 26, 28 and 66 which are defined in Table 1 [13]. The NB-IoT system operates in frequency-division duplexing (FDD) based on 3GPP release 13. Both downlink and uplink transmissions are separated in the frequency domain. The eNB and the UE will transmit in one frequency band and receive in another. NB-IoT system at the UE side operates in a type B half-duplex FDD (HD-FDD) mode. This transmission mode is useful for the low power, low complexity, and low processing capacity of NB-IoT hardware. Downlink and uplink transmissions are separated in both frequency and time in HD-FDD transmission mode shown in Figure 4. There is guard time between transmission from eNB and NB-IoT UE. NB-IoT UE first receives a downlink signal from the eNB, then transmits uplink transmission after a guard time and finally attends for the next downlink transmission after another guard time. So, there is at least one guard subframe (SF) between every switch from downlink to uplink or vice versa. UE uses this guard time to switch its transmitter and receiver chain [1], [14], [21].

Table 1. Frequency bands for NB-IoT [13]

Band Number	**Uplink frequency range /MHz**	**Downlink frequency range / MHz**	**Duplex Mode**
1	1920-1980	2110-2170	FDD
2	1850-1910	1930-1990	FDD
3	1710-1785	1805-1880	FDD
5	824-849	869-894	FDD
8	880-915	925-960	FDD
12	699-716	729-746	FDD
13	777-787	746-756	FDD
17	704-716	734-746	FDD
18	815-830	860-875	FDD
19	830-845	875-890	FDD
20	832-862	791-821	FDD
26	814-849	859-894	FDD
28	703-748	758-803	FDD
66	1710-1780	2110-2200	FDD

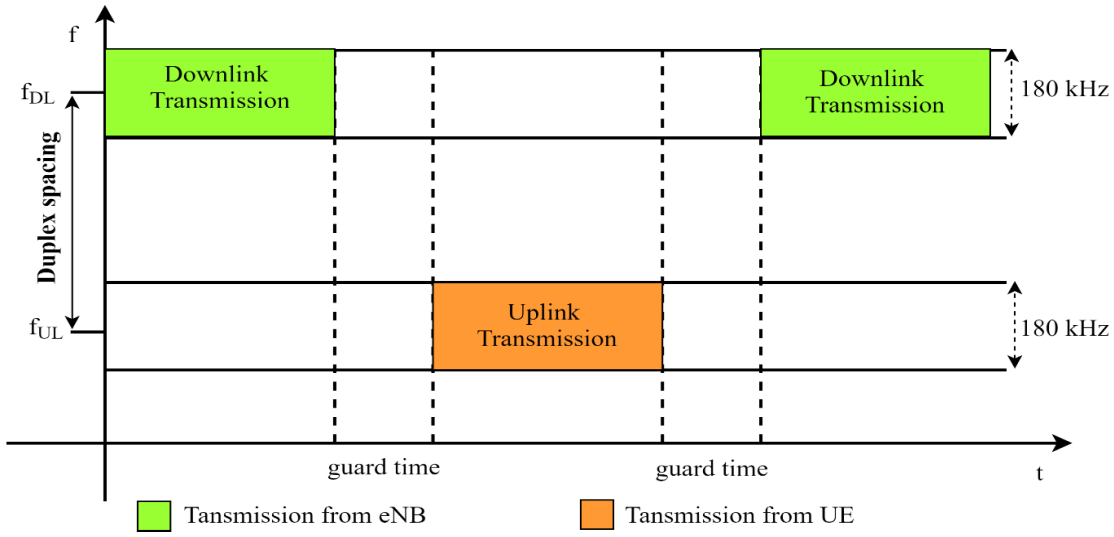

Figure 4. Illustration of type B half-duplex frequency-division duplexing.

2.4 Frame and slot structure

NB-IoT uses the bandwidth of 180 kHz for both downlink and uplink transmission. OFDMA is applied in the downlink of NB-IoT, which allocates data both in the time and frequency domain. Slot, SF, and frame durations of downlink are 0.5 ms, 1 ms, and 10 ms, respectively. One downlink SF consists of 12 × 14 resource elements (REs) where the total number of subcarriers are 12, and orthogonal frequency division multiplexing (OFDM) symbols are 14. One PRB consists of 12 subcarriers, which with 15-kHz subcarrier spacing correspond to the bandwidth of 180 kHz in downlink [1], [8], [15], [21].

Single carrier frequency division multiple access (SC-FDMA) is applied in the uplink of NB-IoT. Uplink of NB-IoT uses 15 kHz subcarrier spacing, 0.5 ms slot and 1 ms subframe like LTE using SC-FDMA in multi-tone transmission, which acquires the best coexistence performance with LTE in the uplink. In single tone transmission, both 15 kHz and 3.75 kHz carrier spacing are used. Based on the number of subcarriers, the single tone and multi-tone transmission are possible in the uplink of NB-IoT shown in Table 2. Resource unit (RU) represents the smallest unit during uplink transmission. In NB-IoT, every SF has a duration of 1 ms with two-time slots of 0.5 ms each, while 10 SFs create each frame with a duration of 10 ms each shown in Figure 5 [1], [8], [12], [21].

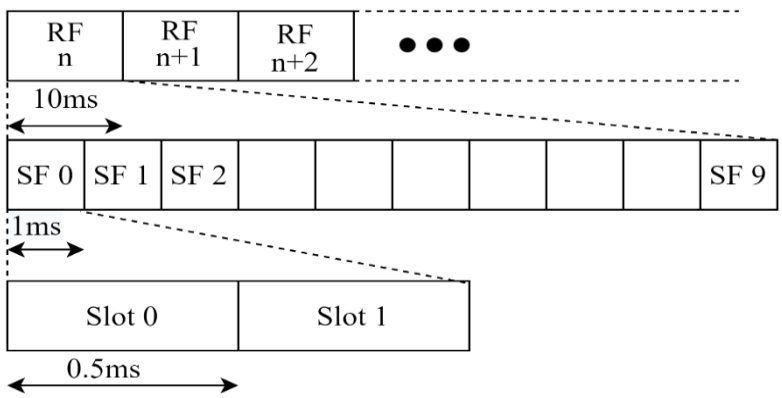

Figure 5. Frame structure for NB-IoT DL and UL with 15 kHz subcarrier spacing.

Table 2. Transmission option in uplink based on RU duration [21]

Subcarrier spacing	**Subcarrier number**	**Slots number**	**Resource elements number**	**SC-FDMA symbols number**	**RU duration**
3.75 kHz	1	16	112	112	32 ms
15 kHz	1	16	112	112	8 ms
	3	8	168	56	4 ms
	6	4	168	28	2 ms
	12	2	168	14	1 ms

2.5 Connecting to eNB

When UE is powered on, UE needs to know the basic information about the eNB. For this purpose, the system information (SI) transmits all necessary information and parameters about the eNB to UE. There are two types of system information messages: narrowband master information block (MIB-NB) and system information blocks (SIBs). After receiving the SI messages, the UE can perform cell selection and reselection tasks and monitor the paging channel. MIB-NB defines the essential information about the physical layers of eNB required for receiving further system information such as downlink system bandwidth, number of transmit antennas and system frame number. SIBs carry information about cell access and selection, and radio resource configuration [1], [2].

After receiving the MIB-NB and SIBs, the UE initiates the RACH stands for Random Access Channel, the first message from UE to eNB when the UE is powered on. RACH procedure occurs at the MAC layer, which provides uplink synchronization and obtains an uplink grant for starting the RRC connection establishment [7]. There are four steps in the contention-based random-access procedure (RAP) [1], [8]. In the first step, UE transmits a random-access preamble to eNB. After getting random access preamble, eNB transmits a random-access response. UE gets two pieces of information by receiving access response, timing advance command and scheduling of uplink resources used for the third step. UE transmits a scheduled message (msg3) in the third step to start the contention resolution process. Finally, eNB transmits a contention resolution message essential for solving the contention problem due to multiple transmissions of the same random-access preamble by different UEs in step 1 [1], [7], [8], [19].

2.6 Downlink Channels

Downlink transmission of the NB-IoT system is in the PHY and MAC layer design. In NB-IoT, the MAC layer performs several tasks, such as scheduling all PHY layer channels and signals. NB-IoT downlink scheme uses many concepts from LTE architecture. Compared to LTE, NB-IoT uses only three downlink channels and three downlink signals, where LTE uses more according to the 3GPP release 13 [1], [14]. The channels and signals used in NB-IoT are given below:

- Narrowband physical broadcast channel (NPBCH)
- Narrowband physical downlink control channel (NPDCCH)
- Narrowband physical downlink shared channel (NPDSCH)
- Narrowband reference signal (NRS)
- Narrowband Primary synchronization signal (NPSS)

- Narrowband Secondary synchronization signals (NSSS)

2.6.1 Narrowband physical broadcast channel

NPBCH is the first essential channel that carries 34 bits MIB-NB. The total MIB-NB is divided into eight blocks, and NPBCH transmits the whole MIB-NB over a time of 640 ms. NPBCH is transmitted in the first subframe (SF0) of each frame in-band operation mode. It repeats SF0 for next seven consecutive radio frames to cope with extreme coverage conditions [1], [6], [21]. MIB-NB carries essential information for NB-IoT devices to operate in the network. The MIB-NB provides some specifics information to UE, such as cell-specific reference signal (CRS) information, SIB scheduling, and the operation mode [1], [6].

2.6.2 Narrowband physical downlink control channel

The NPDCCH is the responsible transmission of control information between eNB and UE. There are two narrowband control channel elements (NCCEs) for NPDCCH; NCCE0 and NCCE1. The repetition of NPDCCH transmissions is vital for achieving coverage enhancement (CE). In NPDCCH, there is also a logical block called downlink control information (DCI) carrying the control information: N0, N1 and N2. Two formats are used in NB-IoT for NPDCCH: format 0, format 1 [1], [6], [18], [21].

The use of any of the two formats depends on the search space defined in Table 3. Type1 common search space is dedicated to the transmission of paging information in NPDCCH. The Type2 common search space is responsible for transmitting control information related to random access messages. Moreover, the UE specific search space is used for the transmission of control information related to data [1], [6], [17], [18], [21].

Table 3. Relation among search space, NPDCCH formats and DCI [21]

Search space types	**NPDCCH formats**	**DCI types**
Types1 common	Format 1	N2
Types2 common	Format 2	N0 & N1
UE-specific	Format 0 & 1	N0 & N1

2.6.3 Narrowband physical downlink shared channel

The NPDSCH is used for data transmissions in NB-IoT UE and transmit SIBs with maximum transport block size (TBS) of 680 bits. NPDSCH carries SIB1-NB data, which is the second important information block after MIB-NB. SIB1-NB carries additional information such as scheduling information to receive other system information blocks. NPDSCH scheduling is always handled by a DCI of type N1 [1], [6], [14], [18], [21].

2.6.4 Narrowband reference signal

It is present in every frame except containing in NPSS or NSSS. The NRS is mapped over the 6th, 7th, 13th, and 14th OFDM symbols of each subframe. NRS is dedicated to channel estimation in the frequency domain [14], [16], [21].

2.6.5 Synchronization signal

The base station transmits both NPSS and NSSS in the 5th and 9th subframes, respectively, used to determine the NCellID. Three different cell identities values 0 to 2 are used for the NPSS denoted by $N_{\mathrm{ID}}^{(2)}$, which are orthogonal. The NSSS gives a cell-identity group number from 168 possible cell identities denoted by $3N_{\mathrm{ID}}^{(1)}$, a pseudo-random sequence. A physical cell identity (PCI) is defined in equation (1) [8], [14], [16].

$$N_{\mathrm{ID}}^{\mathrm{cell}} = 3N_{\mathrm{ID}}^{(1)} + N_{\mathrm{ID}}^{(2)} \tag{1}$$

2.7 Uplink Channels

Uplink transmission is a part of NB-IoT system in PHY, and MAC design which illustrates the transmission chain at the NB-IoT UE and eNB side. Compared to LTE, NB-IoT uses only two uplink channels and one uplink signal, where LTE uses more according to the 3GPP release 13 [14], [16], [21]. The channels and signals used in NB-IoT are given below:

- Narrowband physical uplink shared channel (NPUSCH)
- Narrowband physical random-access channel (NPRACH)
- Demodulation reference signal (DMRS)

2.7.1 Narrowband physical uplink shared channel

The NPUSCH transmits data and control information from the NB-IoT UE side towards eNB. For this reason, two formats are defined. NPUSCH format 1 is responsible for uplink transport channel data over the uplink shared channel (UL-SCH). NPUSCH format 1 uses multi-carrier transmission. NPUSCH format 2 carries uplink control information (UCI) which is used for signalling acknowledgement for NPDSCH. The DCI format N0 indicates a UL grant for transmission on the NPUSCH. The NPUSCH transmissions are scheduled by the NPDCCH through a DCI of type N0 or N1. When UE has uplink data for transmission, eNB will send a DCI of type N0 to schedule the NPUSCH transmission. On the other hand, when UE transmits control information, then eNB will send a DCI of type N1 with the scheduling information [1], [12], [14], [17], [21].

2.7.2 Narrowband physical random-access channel

NPRACH transmits the NB-IoT preamble towards eNB. This preamble is the first transmitted signal from UE towards eNB to request access to the network. The coverage area of the eNB is divided into several zones called coverage CE levels. Configuration of NPRACH transmissions depends on the CE levels of eNB, such as CE0, CE1 and CE2 levels. The CE levels of eNB depend on the position of UE from eNB [1], [14], [21].

2.7.3 Demodulation reference signal

DMRS are transmitted in the 4th block of a slot responsible for channel estimation in the frequency domain for uplink transmissions. In uplink, the DMRS is transmitted only in the NPUSCH subframes [1], [14], [21].

2.8 Connection Control

Handover is not needed in NB-IoT technology while UE is connected to eNB. When eNB change is required, UE must first go to the idle state and select another eNB [1]. RRC has only two states: RRC idle state or RRC connected state. The UE toggles between these two states. Initially, the UE is in an idle state. UE is first powered on in the idle state. By establishing a connection to eNB, UE moves to a connected state from an Idle state. By releasing the connection to eNB, the UE moves the Idle state again. After Idle state, UE goes into the energy-saving mechanism is known as power-saving mode (PSM). UE remains registered with the network during the PSM [1], [7].

2.9 Coverage Enhancement

The most critical attribute of NB-IoT technology is offering significant coverage extension beyond existing cellular technologies. When UEs are in remote areas or challenging areas where the signal is hard to reach, the coverage extension feature of NB-IoT technology is handy. NB-IoT system has 20 dB more maximum coupling loss (MCL) than general packet radio service (GPRS), which gives a path loss of 164 dB to serve UE in deep coverage. Several modifications have been made to the different LTE protocol layers for achieving this significant gain. Several solutions were used to make these modifications: repeating the same transmission several times, assigning variable bandwidth in multi-tone transmission, cross-subframe channel estimation and frequency hopping [22], [23]. Among them, using the repeated transmission of data and control signalling, reliable coverage enhancement is achieved. Increasing the number of repeated transmissions reach 128 repetitions for the uplink communications and 2048 for the downlink. These repetitions increase the signal-to-noise (SNR) ratio at the receiver end. Repetitions occur in both downlink channels (e.g., NPDCCH) and uplink channels (e.g., NPRACH) and they are determined by the eNB. Signal transmission can be configured to repeat for a specific number of times in order to achieve desired coverage level. Three coverage enhancements (CE); CE level 0: normal coverage, CE level 1: robust coverage, CE level 2: extreme coverage can be configured by the network. The major effect of these three different CE levels is the repetition of messages for a different number of times. If the device stays in the CE level 0 with lower path loss, then the number of signal repetitions is less. However, the number of configured repetitions is higher for the device at the CE level 2 shown in Figure 6. The list of power thresholds for the received reference signals of the CE levels is broadcasted and configured by the network. The device identifies its initial CE level by measuring the reference signal received power (RSRP). The devices experiencing high RSRP are attributed to the lowest CE level, low RSRP is attributed to the higher CE level. The transmit power consumption at the CE1 level is doubled compared to the CE0 level, while the power consumption at the CE2 level is thrice compared to the CE0 level. So, CE1 and CE2 always use maximum transmit power, while in CE0, the transmit power control mechanism is employed [22], [23].

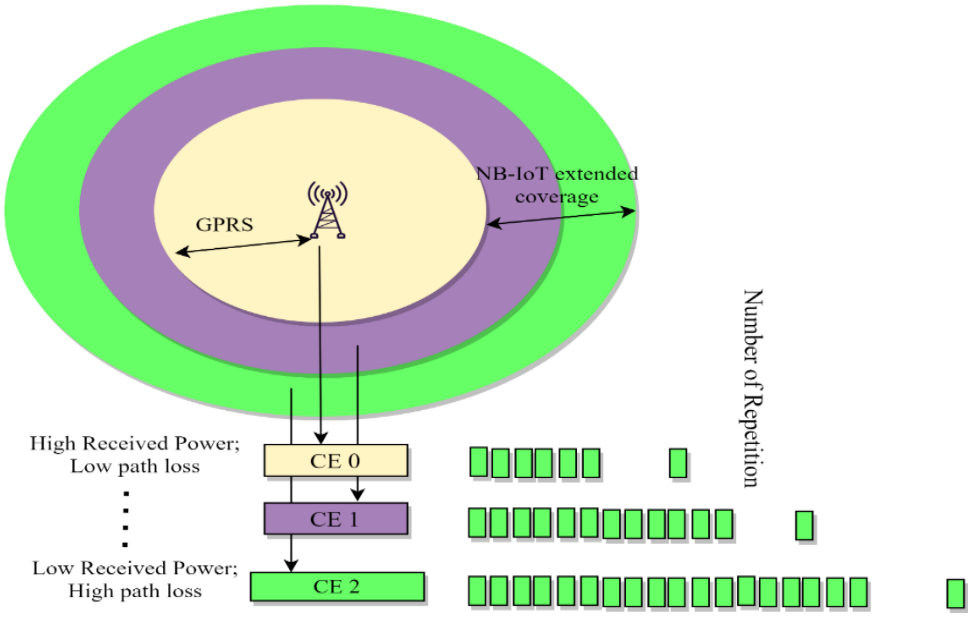

Figure 6. Coverage enhancement levels and repetitions.

2.10 Release-13 Features

Release 13 specifies some significant key configurations and considerations for the development of NB-IoT.

2.10.1 Power Saving Mode

NB-IoT is designed for long-life devices with a battery life of several years. By reusing LTE's power-saving mechanisms and extending the timers, a longer battery lifetime is achieved. Like LTE, NB-IoT has two key power-saving mechanisms of communications between UE and the network. The eNB uses an Inactivity Timer to detect UE's inactivity after a data packet transfer. When UE does not send or receive any data during a certain period, UE goes in Idle mode. Inactive timer stays off for a certain amount of time, such as the 20s, 10s [4], [21], [24].

PSM is used to reduce the energy used by the UE. When PSM is activated in the device with the network, two preferred timers, T3324 and T3412, are provided. The difference between these timers T3412-T3324 determines PSM time. By using these values or a different set of values is known as tracking area update (TAU), PSM allows the UE in deep sleep where UE is unreachable by the network, but UE is still registered [4], [24].

2.10.2 eDRX

There are two discontinuous reception (DRX) cycles; short and long used in LTE. However, CE only uses long DRX cycles in NB-IoT during UE is in RRC Connected or RRC Idle. There are two phases in DRX cycles that configure the DRX, enabling UE to receive the PDCCH discontinuously [4], [24].

Extended discontinuous reception (eDRX) is an extension of DRX that can be used in conjunction with PSM or without PSM to obtain additional power savings. eDRX mode is only supported in the RCC Idle state, not supported in RRC connected state. NB-IoT uses it to reduce power consumption. eDRX is not providing the same levels of power reduction as PSM, and

however, for some cases, it may provide an excellent optimization between device reachability and power consumption [4], [21], [24].

2.10.3 Power Class

The power class determines the maximum transmission power of the NB-IoT device. NB-IoT devices adjust the power transmission to optimise power consumption. LTE networks have been planned to assume the UE can transmit up to 23 dBm. A change in output power from a UE will lead to a change in coverage. A reduction of coverage means the device enters CE1 or CE 2 level. This reduction of coverage may impact the signal repetitions level of some UEs. There are two power classes in release 13 that have been introduced. LTE device power level at 23 dBm refers to power class 3, and less power class output at 20 dBm refers to power class 5 in release 13, and lower power class output at 14 dBm refers to power class 6 [24].

2.11 Post Release Features

After release 13 implementation, further studies continue for advanced enhancements to improve the quality of service and coverage performance. In this consideration, 3GPP introduced more enhancement features in release 14, 15 & 16 to NB-IoT [21], [24], [25].

2.11.1 Release 14

- **Multicast Services:** Multicast service is an optimized process to send the data to a group of UEs simultaneously instead of sending data multiple times to separate devices. This multicast service reduces transmission latency and uses the communication resources in an optimized way [21], [24], [25].
- **New Transport-Block-Size Support:** A new NB-IoT device has been introduced in release 14, having enhanced TBS equal to 2536 bits which improve data rates [21], [24], [25].

2.11.2 Release 15

- **Latency Reduction:** The eNB sends the UE a 'wake-up signal' (WUS) to instruct the UE to monitor NPDCCH for paging and otherwise allows the UE to skip the paging procedures. NB-IoT supports new features for reducing power consumption and transmission delay for long transmission [24], [25].
- **Small Cell Support:** Improving the capacity with good coverage, NB-IoT supports small cell deployment in release 15. To avoid interference, UE can transmit less power than the configured maximum power [24], [25].

2.11.3 Release 16

- **Grant-Free Access:** It is expected that without an access grant, UE will transmit data in Idle mode through Msg3. A UE can transmit data with the control-less grant or without the grant in RCC connected state. In release 16, it has reduced the NB-IoT signalling overhead while providing the required quality of service. These features will reduce both latency and power consumption [25].

3 NETWORK COVERAGE

A telecommunication network [26], [27] system refers to the process of interconnecting devices to each other or a server. Typical examples of telecommunication networks are cellular and IoT networks [26]. A radio network [28], [29] served by cells in the geographical area is known as a cellular network or mobile network [29], [30]. The cellular network uses the frequency reuse technique to avoid interference [27] and increase the mobile network's capacity [31], [32], [33] and coverage. Based on the coverage range and capacity [34], [35] cells are different: macrocell, microcell, and picocell. Based on different technologies, the types of mobile network are different: The 1st Generation mobile network (1G), GSM refers to 2nd generation mobile network (2G), universal mobile telecommunications system (UMTS) refers to 3rd generation mobile network (3G), LTE refers to 4th generation mobile network (4G), and new radio (NR) refers to 5th generation mobile network (5G) [26], [27], [28], [30]. This chapter includes descriptions of network coverage concepts, method of measuring the network coverage, key performance indicator, impact of NB-IoT in coverage and some definitions related to this work.

3.1 Concepts of Network Coverage

The objective of network coverage planning is to provide better quality of service (QoS), increase network capacity and use the frequency reuse technique. Radio propagation depends on the speed of the mobile terminal, the topology of the network, operation frequency, and other dynamic factors like scattering, polarization, reflection, refraction, diffraction, and absorption. Doppler effect occurs in communication channels due to the speed of the mobile terminal. The Doppler effect results in a change of the apparent frequency of the signal, which affects radio propagation [27], [29], [30]. Using the frequency reuse technique, the cellular network propagates radio frequency over a specific geographical area so that neighbouring cells use the different frequency and distant cells use the same frequency. For this reason, many hexagonal cells are used to cover a large geographical area efficiently. Those cells propagate radio frequency over a large geographical area to connect the end-users within the network. The maximum power of the signal or radio frequency radiated from an antenna of a cell is known as effective isotropic radiated power (EIRP). It is calculated by the output power of the transmitter, cable loss and antenna gain. Since downlink receiver power is evaluated by EIRP and propagation losses. So, coverage of the network is mainly based on downlink receiver power from the cells [29], [30], [31].

3.1.1 Methods of Network Coverage Measurement

Network optimization goals are to optimize resource allocation, adjust network parameters, and make networks in the best cell coverage. There are two ways to estimate the cell coverage: drive test and field strength prediction.

3.1.1.1 Field Strength Prediction

The prediction is an empirical method based upon a large database of field strength and path-loss measurements in the geographic information system (GIS) of mobile-cellular networks. Field strength algorithms such as the Okumura model are used to predict the field strength of a network coverage area. In these algorithms, to conform to the accurate condition of the network,

it is necessary to measure and analyse the field data along with a proper propagation model [35].

3.1.1.2 Drive Test

Drive testing of a particular network provides a real scenario of the radio frequency (RF) environment. Drive test measures a particular route's field strength or intensity under a particular serving cell using network coverage test equipment and software. This testing is done by using a car or on foot. The main benefit of drive testing is that it measures the actual network coverage and performance that a user on the actual drive route would experience [32], [35].

There are two ways of drive testing; both have their characteristics with drawbacks and benefits: UE-based and receiver-based. In the LTE network, network intelligence and traffic management have moved from core to the eNBs; as a result, radio resource management is in eNBs. UE-based drive test measures field strength under a particular serving cell within network-controlled constraints in the physical layer using the instrumented smartphones and tablets known as test engineering phones. It provides end-user experience, actual network performance, mainly RF coverage and quality, by measuring RSRP and reference signal received quality (RSRQ) in LTE. RSRP and RSRQ provide the signal strength and quality of reference signals, respectively, which are the most crucial parameters where UE keep on the current cell or hand over to an adjacent cell [32].

A receiver-based drive test refers to monitoring the entire frequency spectrum to obtain the raw view of the RF environment by using the scanning receivers. This measurement system does not provide the end-user experience but is helpful for network coverage estimation and band clearing. It provides the spectrum clearing activities to confirm that no rough interfering signals are left from the other technologies before deploying new communication technology [32].

3.1.2 Importance of Network Coverage

It is essential to connect every user equipment and IoT device to the network within a specific area. For this purpose, good network coverage is essential. Good network coverage offers better signal strength, and quality means good RSRP, RSRQ and received signal strength indicator (RSSI) with less interference and noise. Less interference offers higher signal strength and throughput; as a result, it provides the excellent performance of the network to the end-user. In the case of NB-IoT, poor network coverage increases the number of repetitions in transmission, leading to high power consumption in higher CE levels. The optimized network coverage is vital to reduce the battery usage of user equipment and power consumption. Since user equipment search for a good signal causes excessive battery usage under poor network coverage. So, providing a reliable, secure, and available network is very important [2], [22].

3.2 Definitions

In this section, antenna and antenna tilt theories have been described, which are related to this measurement work.

3.2.1 Antenna

An antenna is a device that converts radio waves into radiating waves which is transmitted in the free space [27]. The antenna radiation pattern refers to the direction of energy radiation in

the far-field from the antenna. There are three types of lobes in radiation pattern: main lobe, side lobe and back lobe. The angle of maximum radiation is known as the main lobe. Beamwidth is the angle from where most energy is radiated. The term half-power beamwidth (HPBW) is an angular width in the main lobe. Low beamwidth angle changes the transmission pattern with high antenna gain that covers a small coverage area with strong signal strength. On the other hand, a high beamwidth angle provides low antenna gain that covers a large coverage area with weak signal strength [27].

3.2.2 Antenna Tilt

The cellular network performance depends on the correct adjustment and configuration of the radiation patterns of the antenna. The antenna tilt refers to the angle or the inclination of the antenna to the horizontal plane. So, tilt is the angle of the antenna main beam below or above the horizontal plane. Based on the angle of the main beam, there are two types of tilt: downtilt and uptilt, which represent the positive and negative angle, respectively. Generally, downtilt is used to receive stronger signals from the eNB. The extreme downtilt angle may reduce the coverage of cells [27], [34].

There are two ways of adjusting the antenna tilt: mechanically and electrically. Mechanical tilt refers to the physical rotation around the horizontal plane, which changes the radiation pattern. In mechanical tilt, there is no change in the phase of the input signal. Electrical tilt refers to modifying the phase of the input signals and switching the antenna elements without changing the physical rotation of the antennas. Antenna tilting is a common technique for increasing coverage and capacity, improving cell separation in cellular networks. Mechanical tilt with zero degrees provides the maximum coverage. Mechanical downtilt provides good coverage near eNB. So, for an efficient coverage environment, mechanical tilt is used to the base station antenna. To provide an efficient capacity of the base station, electrical tilt is a better option to use [27], [34].

3.3 Key Performance Indicator

Key performance indicator (KPI) refers to the parameters indicating the network's performance, which is used to assess the performance of network services to the end-users. In telecommunication, KPIs emphasize service availability, network performance, call failures, network development, network capacity, and network coverage enhancement. Different KPIs are used at different layers, such as the application, MAC, and PHY layers. The service availability, EPS radio access bearer (E-RAB) establishment success rate, handover procedure time are higher layer KPIs, e.g., application and network layer. RSRP, RSRQ, RSSI, and signal to noise plus interference (SINR) are the physical layer KPIs. The performance of the upper layers is interrelated to the performance of lower layer KPIs. Lower-level KPIs is the pre-requirement for the high performance of upper-level [2], [33]. The KPIs addressed in this study are described below:

- **RSRP:** RSRP refers to the linear average power over the contributions of the resource elements that carry NRS for specific cells within the considered measurement frequency bandwidth. The RSRP is the power of a single 15 kHz NRS. Specific resource elements carry the reference signal, which provides the reference point for the downlink power. Higher RSRP provides excellent channel quality; as a result, users get more resource blocks which means a higher bit rate [2], [33].

- **RSRQ and RSSI:** RSRQ refers to the pure reference signal power over the whole E-UTRA power received by the UE. RSRQ is derived from RSRP and RSSI value by the equation: RSRQ = N × RSRP/ (E-UTRA carrier RSSI). Here, N is the RBs over the measurement bandwidth by UE from co-channel serving and non-serving cells and adjacent channel interference. RSSI is the linear average of the total received power from the antenna, measured over the entire bandwidth, adjacent channel interference, including co-channel serving and non-serving cells, thermal noise, and other sources of noise [2], [33].
- **SINR:** SINR refers to the measurement of the unwanted part of the received signal. It is the ratio of all subcarriers' power that makes up a cell-specific reference signal to the power of the interference plus noise over the same subcarriers. A higher value of SINR will enable higher throughput because a higher-order modulation and coding scheme (MCS) allow to boost the number of bits that can be transmitted per RE. It affects the network's throughput, coverage, and capacity, and ultimately the user experience [2], [33].

Path loss occurs in the radio channel due to scattering, reflection, refraction, diffraction, and absorption. Downlink receiver power at UE is calculated by using the output power of the transmitter and propagation losses. So, it is important to calculate the amount of noise and interference of serving and non-serving cells. Low levels of noise, interference and good levels of downlink power are expected for a good radio channel [2], [27], [29].

RSRP measures the downlink power of the reference signal within the channel bandwidth, thus characterizing the signal strength of cells. It is the information about downlink power at the UE end since it does not measure the noise and interference from the other cells. It is an essential measurement for cell selection, handover, mobility measurements, but it does not indicate the received signal quality [2], [33].

RSSI is the total downlink power of reference symbols, noise, interference power, and interference of serving and non-serving cells. As it is the measured received power of a signal thus the value of RSSI indicates the signal strength of the radio channel. The higher values of RSSI means better signal strength. It does not indicate the signal quality. On the other hand, the SINR characterizes the amount of noise and interference levels of the signal [2], [33].

Generally, RSRQ is the information about the quality of the received reference signal at the UE end. RSRQ values depend on the RSRP and RSSI since RSRQ is the ratio of two power based KPIs. Thus, RSRQ also indicates the information of noise and interference in the radio channel. Higher RSRQ characterizes a good radio channel and good user's communication performance. Each of the four KPIs is critical in order to measure the performance of network coverage, signal strength, quality of signal and radio channel, and user's communication performance [2], [33].

Higher levels of KPIs values are associated higher performance to the PHY layer, while low levels of KPIs values provide lower performance to the PHY layer. Signal level drops from excellent to poor level, while throughput changes from high to low level. Low throughput is attributed to maximum latency [2], [33].

3.4 Goal of This Work

The primary objective of the thesis work is to determine the network coverage area of NB-IoT technology using different PCIs at the University of Oulu's 5G test network (5GTN). This work is about measuring the coverage of three different PCIs in Oulu, Finland. Two NB-IoT supported devices are used to measure the network coverage area. The measurement locations

for measuring the coverage performance of PCI 50 in Oulu, Finland are: Linnanmaa, Pateniemi, Haukipudas, Ideapark, Ruskonniitty and Pyykösjärvi. The measurement locations for measuring the coverage performance of PCI 46 in Oulu, Finland are: Puolivälinkangas, Koskela, Välivainio, Hietasaari, Haapalehto, Kirkkokangas, Limingantulli and Finnkino Plaza Oulu. The measurement locations for measuring the coverage performance of PCI 60 in Oulu, Finland are: Oulu Public Library, Pikisaari, Hietasaari, Tuira, Isko, Rusko, Haapalehto, Kirkkokangas, Hiironen, Äimärautio, Kasarminranta and Heinäpää.

The objective is to measure the network coverage performance in NB-IoT technology. Mainly RSRP, RSRQ, SINR and RSSI are the key parameters that will be the primary focus during the measurement work. Four KPIs are important for measuring the signal strength, quality, and noise levels at different locations. RSRP and RSSI parameters provide signal strength levels, SINR parameters provide interference and noise levels, and RSRQ parameters provide signal quality.

A drive test was arranged to collect the field data under specific cell coverage areas using Keysight Nemo handy IoT and Nemo outdoor software. Then, collected field data were analysed by using the Nemo analyzer software to find out some specific's outcomes of the measurement area. The primary objective of the field data analysis was to find out the signal strength at different locations of the different cells. Besides that, the objective of analysing the field data is to find out the best signal strength position in a specific cell area, good coverage, and a weak coverage or no coverage area at a specific cell. Location with best signal strength provides the best coverage location for using NB-IoT UE under a particular cell. Finally, the desired goal of this work is to check whether the overall performance of the network meets at least good signal levels and good network coverage.

4 MEASUREMENT DEVICES AND SOFTWARE

The measurements were conducted using different types of devices and software. In this chapter, a brief introduction about the used devices and software have been discussed. The measurements were performed at the different locations of the Oulu city and near to University of Oulu area.

4.1 Measurement Devices

The measurements were conducted using Quectel BG96 and Qualcomm kDC-5737 dongle devices. The measurements were performed in three different PCIs of the Oulu university 5GTN.

4.1.1 Quectel BG96

BG96 is an embedded IoT wireless communication module with a highly integrated, cost-effective, and compact surface-mount technology (SMT) form factor of 26.5mm × 22.5mm × 2.3mm. BG96 is LTE Cat M1 / LTE cat NB1 /EGPRS module that does not support receiver diversity. It supports Half-Duplex LTE-FDD and LTE-TDD wireless communication, providing data connectivity on LTE-TDD/FDD networks along with a voice interface and global navigation satellite system (GNSS). It is compatible with Quectel's LTE Standard module EG91/EG95, LPWA module BC95-G/BG95, UMTS/HSPA module UG95/UG96 and GSM/GPRS module M95 [36].

BG96 has six operating modes: normal operation, minimum functionality mode, airplane mode, sleep mode, PSM, and power-down mode. In the Idle mode of normal operation, the module is registered on the network, ready to send and receive data. In the data/talk mode of normal operation, power consumption by the module is decided by network setting and data transfer rate. During sleep mode, the module can still receive paging messages, SMS, voice call and TCP/ user datagram protocol (UDP) data from the network to reduce the power consumption to the minimal level [36].

The BG96 module provides three universal asynchronous receiver transmitter (UART) interfaces: UART1, UART2 and UART3. UART1 is used for AT command communication, and data transmission, which supports the default baud rate is 115200 bps. UART2 supports 115200 bps baud rate used for module debugging and log output. Furthermore, the UART3 interface is used for outputting GNSS data. BG96 provides one inter-IC sound (I2S) digital interface, one I2C interface and one serial peripheral interface (SPI) digital interface, multiplexed from UART3. BG96 includes a 50Ω impedance main antenna interface and a GNSS antenna interface [36].

The main features of the BG96 are highlighted as [36]

- Transmitting power of 23 dBm in class 3 for both LTE-FDD and LTE-TDD bands.
- It supports LTE Cat NB1 and LTE Cat M1 with a maximum of 375 Kbps in DL and 375 Kbps in UL. And for LTE Cat NB1 with a maximum of 32 Kbps in DL and a maximum of 70 Kbps in UL.
- It also supports GPRS with a maximum of 85.6 Kbps in DL and 85.6 Kbps in UL. Besides that, it supports enhanced data rates for GSM evolution (EDGE) with a maximum of 236.8 Kbps in DL and 236.8 Kbps in UL.
- It endorses TCP, UDP, point-to-point protocol (PPP) and password authentication protocol (PAP).

- It also endorses SMS services in the format of text and PDU [36].

4.1.2 Qualcomm KDC-5737

The kDC-5737 NB-IoT wireless data terminal from Knowyou technologies have been used for NB-IoT coverage measurement. The device is a dongle made with a Qualcomm chipset that supports multi-bands. So, the device supports bands 1, 2, 4, 5, 7 for LTE and band 28 for NB-IoT. It endorses the modulation technology QPSK, 16-QAM. It uses a planar inverted-F antenna (PIFA) with an omnidirectional pattern and is very useful in mobile wireless devices for its space-saving properties. The terminal has a rubber bar antenna with an antenna gain of 1.9 dBi [37].

4.1.3 5GTN

The 5G refers to 5th generation mobile networks that bring many new IoT and M2M communications possibilities. RAN, packet core, and applications of 5G typically run-in cloud environments. 5GTN refers to the 5G test network at the University of Oulu's Centre for wireless communications (CWC), including RAN operating on licensed LTE and 5G bands. The University of Oulu and VTT manage 5GTN, the realistic 5G network environment [38], [39], [40].

5GTN provides the machine type communication (MTC) system by integrating IoT to 5GTN using IoT gateway (IoT-GW). The gateway is operated by using network function virtualization (NFV). NFV supports any network function independent of hardware by using the software. To realize network slicing (NS), NFV is the key enabler, NS is the technological addition in cellular networks to overcome the 5th generation mobile network challenges. Network slicing is the methodology to deploy only the necessary network functions according to customer demand. So, it creates the logical partition into shared physical infrastructure, which provides multiple virtual networks. By using network slicing in 5GTN, it endorses IoT applications in the core network and radio access network (RAN) operating in the narrow band, bands 7, 28 and 42 [38], [39], [40].

There are three cell IDs 46,50, and 60 in 5GTN that is in the city of Oulu, Finland. Cell IDs 46 and 50 are in the base station on the 'Tietotalo' roof at CWC shown in Figure 7. Cell ID 46 is directed towards the South, and cell ID 50 is directed towards the North between the Ideapark shopping centre and Technopolis shown in Figure 7. The latitude of cell ID 46 and 50 are 65.058120 degrees in decimal, and longitude is 25.469035 degrees in decimal. The cell ID 60 is located on the roof of the city library and directed towards the Valkea shopping centre shown in Figure 7. The latitude and longitude of cell ID 60 are 65.015320 and 25.463216 degrees in decimal, respectively. The position of the cell or base station is shown in Figure 7 lower portion. The sectorizations of the cell are shown in Figure 7 upper portion. The sectorization refers to when cells are divided into different parts called sectors. The base station on the 'Tietotalo' roof at CWC is divided into two sectors: PCI 46 and PCI 50. The base station on the roof of the city library is into one sector named PCI 60 [40].

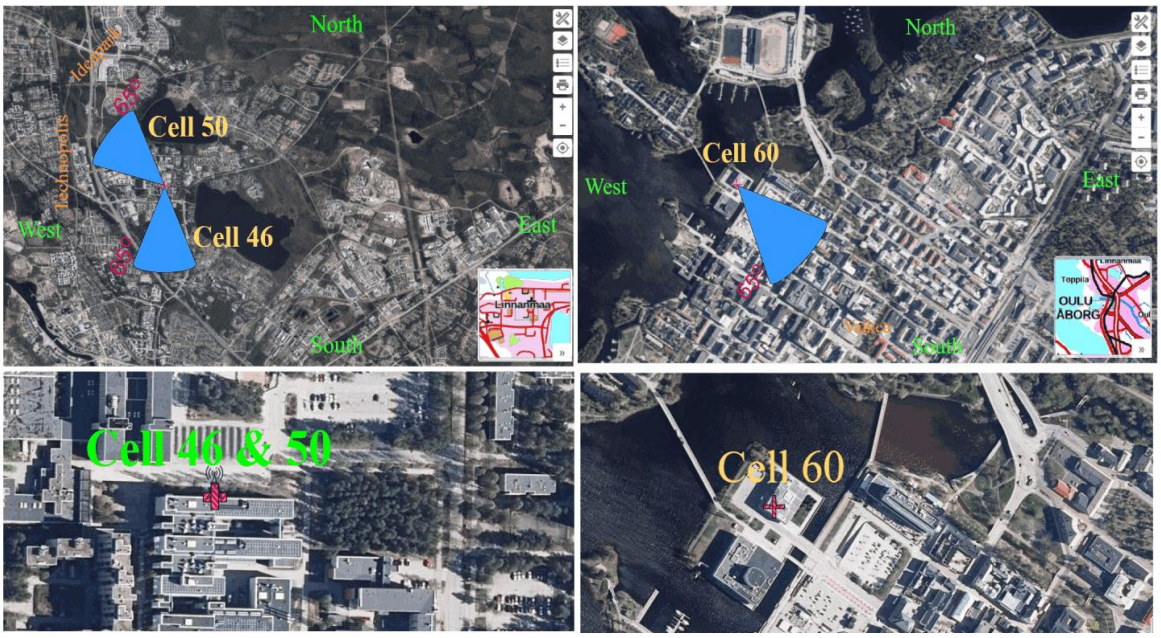

Figure 7. Location of Cell 46, 50 and 60.

4.2 Measurement Software

The measurements were conducted using Quectel QNavigator software, Nemo Outdoor and Nemo analyzer. Nemo analyzer is used for analysing the Nemo outdoor data. This section includes a brief description of that software.

4.2.1 Quectel QNavigator

QNavigator software tool is applicable for the Quectel modules. The program's main interface contains seven parts: menu, toolbar, selection for module test function, the functional interface of the module test, display area for the data sent and received via serial port, status, and hand control. Along with AT command, the tool has eight functions: Home, SMS, Voice Call, TCP/UDP, PPP, AT Command, QuecLocator and QCOM. The Quectel module provides the positioning service of a base station by using QuecLocator. GNSS provides the current location of satellite positioning information retrieved from the module and shows the module's current location, such as latitude, longitude. AT command function provides AT commands for the user to query, test, and learn. Keywords of AT commands are put in the send column to query the results, and the result will be displayed [41].

4.2.2 Nemo Outdoor

Nemo Outdoor from Keysight Technologies is expandable; modular structure supports drive testing measurement and optimization solutions for perfecting the air interface of wireless networks and QoS and benchmarking measurements on 5G NR, 2G, 3G, and 4G. This software is used for network planning, roll-out, tuning, verification, optimization, maintenance, and benchmarking purposes of the wireless network. The Nemo outdoor measurement system consists of a test mobile or module, a global positioning system (GPS) receiver with antenna, a PC or laptop with windows operating system, Nemo outdoor measurement software and connecting cables. It provides the drive test measurement results with the geographical

coordinates. Nemo outdoor software has three ways to start the device configuration: autodetection, load device configuration and manual. Nemo Outdoor provides an impressive set of IoT KPIs, and it has been used in multiple pilots and coverage measurements in IoT networks. It supports LTE/NB-IoT measurements, RSRP, RSSI, RSRQ, SINR and carrier to interference plus noise ratio (CINR) [42].

4.2.3 Nemo Analyzer

The Nemo Analyze is an analysis tool provided by Keysight Technologies for troubleshooting, performing benchmarking and statistical reporting based on drive test data. The benefit of using this tool is automating the entire data processing chain from a drive test data to an open workbook with analysis results. It analyses the full set of graphs, maps, and other data views with statistical reporting tasks for KPI reporting and analysis. This software tool supports the files of Nemo Outdoor, Nemo Autonomous Probe, Nemo Handy and Measurement data in character separated value (CSV). Nemo Analyze maps represent the cutting-edge of drive test data visualization; with a glance, the general picture of the network performance is on a particular measurement route [43].

4.3 Measurements Set-Up

The outdoor measurements were performed using Qualcomm kDC-5737 dongle and Quectel BG96, two different types of NB-IoT devices. Both measurements were done simultaneously in the same places. This section describes how the measurement devices have been set up for measurement work.

4.3.1 Quectel BG96 Setup

For this measurement purposes, first, it is needed to set up the Quectel BG96 device with the proper configuration parameters of the QNavigator software tool. One 4G supported sim card was inserted into the sim card connector. Then, the main antenna was connected to the PIN 60, which works as a receiving antenna. One universal serial bus (USB) cable was connected to the laptop to provide the necessary power supply to the device. The Quectel BG96 module used for measurement has shown in Figure 8.

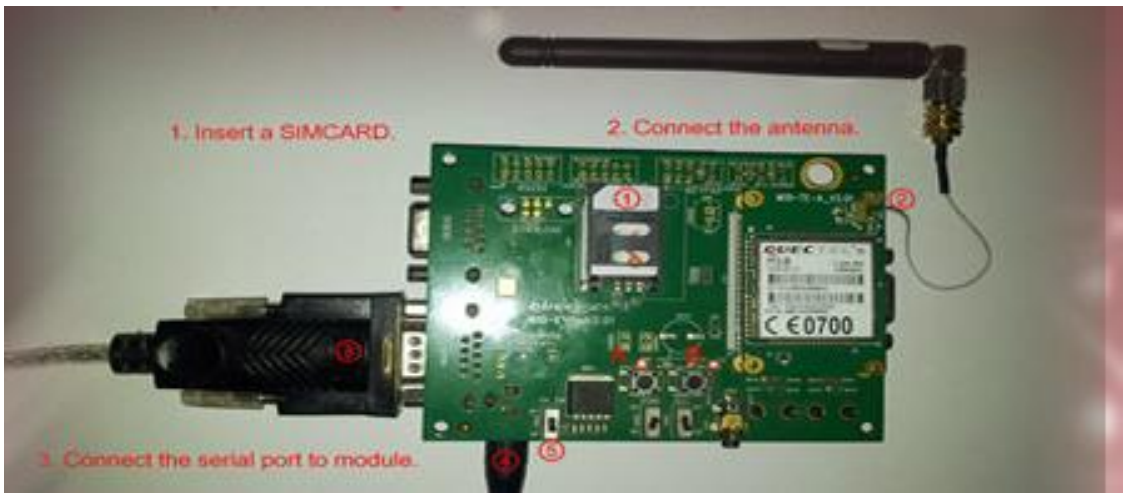

Figure 8. Device used for measurement.

The serial port of Quectel BG96 was connected to the QNavigator software, which was operating on the laptop. The Device Manager option was opened to confirm the serial port number, which was connected to the laptop properly. Then, some parameters of serial port setting were defined, shown in Table 4.

Table 4. UART parameter settings

Parameter	**Value**
Port	COM16
Baudrate	115200
Data bits	8
Stop bits	1
Parity	None
Flow ctrl	None

The switch of the Quectel device was flipped on, then the power of the device was turned on. Then PWRKEY button was pressed and held to activate the module. Then the STATUS indicator was turned on, and the NET_STA indicator light was flickered, indicating the network status. By clicking the 'connect to module' of the QNavigator tool, the BG96 module was initialized and prepared for AT command.

4.3.2 Qualcomm KDC-5737 Setup

A subscriber identification module (SIM) card has been used in the NB-IoT data terminal. The Qualcomm USB Host Driver was run, Setup.exe file was run for the installation wizard. After finishing the installation, the NB-IoT data terminal was connected to the laptop and was kept the NB-IoT data terminal at least 20 cm from the human body. Windows detected the new hardware and installed drivers and waited until the installation process was finished. Then the device set up was done and ready to use. Qualcomm kDC-5737 was connected to Nemo outdoor using the USB port of the laptop. After opening the Nemo outdoor software, the Qualcomm kDC-5737 was detected through autodetect functionality on the welcome page of this software. Trace port and modem port was selected according to the port settings of the laptop device manager.

4.4 Parameters Specification for Thesis

This measurement work was performed at three different PCIs with different parameters specifications, transmit power and electrical tilt, shown in Table 5. During the measurement, the PCIs were configured with different transmit power. Three PCIs have been used to compare the performance of NB-IoT network coverage with different parameters configurations.

Table 5. Specification for thesis parameters

Parameter	**Value**
Mechanical tilt for PCI 46	0 degree
Electrical tilt for PCI 46	2 degrees
Horizontal width for PCI 46	65 degrees
Transmit power for PCI 46	39 dBm
Mechanical tilt for PCI 50	0 degree
Electrical tilt for PCI 50	16 degrees
Horizontal width for PCI 50	65 degrees
Transmit power for PCI 50	39 dBm
Mechanical tilt for PCI 60	0 degree
Electrical tilt for PCI 60	2 degrees
Horizontal width for PCI 60	65 degrees
Transmit power for PCI 60	46 dBm

4.5 Use of Two Devices

The Quectel BG96 module was released on 28.04.2017 in version 1.4, supporting both LTE-M and NB-IoT. On the other hand, the Qualcomm kDC-5737 was released on 09.05.2018 in version 2, which supports only NB-IoT [36], [37].

The BG96 module has the feature of coverage enhancement CE0, CE1 and CE2 in NB-IoT. This device can operate in an extended coverage region under the network for this feature. So that, this device provides the maximum coverage even with low RSRP. This device is used to estimate how far the NB-IoT network coverage is available under any PCI. Qualcomm kDC-5737 device also supports CE levels [36], [37].

Network coverage performance can be presented in a more acceptable way by using two devices. Two devices have been used to compare their results and thus achieve some insight into how different they are and which of the two devices is better to use.

4.6 Measurements Procedure

Outdoor measurement was performed in different locations of Oulu city, Finland, during late spring 2019 using both Qualcomm kDC-5737 dongle and Quectel BG96 module at the same time. Those measurements have been taken under the three different PCIs coverage areas: 46, 50 and 60. For these measurements, band 28 have been selected. The measurement procedures of both devices were different since Nemo outdoor software has been used for the Qualcomm kDC-5737 device, and QNavigator software has been used for Quectel BG96. All measurements date were collected between 11:00 to 16:00 time intervals.

First, an approximate measurements path was chosen for each PCI. Since the drive test was conducted on a drive test vehicle, the drive test's measurements path was selected on the roadway or highway. During the drive test, the vehicle was driven according to the speed limit of the roadway and highway. Drive tests were conducted until out of coverage, or poor coverage was observed under a particular PCI. Depending on the RSRP value, measurements points and drive route were selected until out of coverage or weak coverage were found under a particular PCI. The measurement points determined RSRP, RSRQ, RSSI and SINR values of certain locations. During the drive test, there were several stops due to road traffic signals, changing the measurement route, and taking measurements for other PCIs. During the measurement, only one PCI was kept activated in the network at each phase of the measurement.

Measurements of PCI 50 were taken in two circles. The first circle of PCI 50 was in the direction from Linnanmaa to Ideapark, Ruskonniitty and Pyykösjärvi. The second circle of PCI 50 was in the direction from Ideapark to Pateniemi and Haukipudas. Measurements of PCI 60 were taken in two circles. The first circle of PCI 60 was in the direction from Oulu Public Library to Pikisaari, Hietasaari, Tuira, Isko, Rusko, Haapalehto, Kirkkokangas, Hiironen and Limingantulli. The second circle of PCI 60 was in the direction from Heinäpää to Kirkkokangas, Haapalehto, Kasarminranta and Heinäpää. Measurements of PCI 46 were taken in one circle. The circle of PCI 46 was in the direction from Puolivälinkangas to Koskela, Välivainio, Hietasaari, Haapalehto, Kirkkokangas, Limingantulli and Finnkino Plaza Oulu.

4.6.1 Outdoor Measurement for Qualcomm KDC-5737 dongle

First, the Nemo Outdoor software was opened. Then the LTE full details option was chosen from the workspace. After connecting Qualcomm kDC-5737 to Nemo outdoor via USB cable, it had to go online. With the NB-IoT technology, the frequency band and cell were locked in the Nemo outdoor software during the measurement. From the parameter settings of Nemo outdoor software, RSRP, RSRQ, RSSI and SINR were selected. The whole approximate measurements directions were sketched on a printed google map based on PCI location. The measurements were started from near to PCI location and continued until weak coverage or no coverage regions were found based on RSRP values. Several stops were made while conducting this measurement. The measurement route had to be changed when the out of coverage regions was found. One GPS receiver was connected to the Nemo outdoor software via USB cable to measure the current location during this measurement. When measurement recording was done, then the recording file can be exported to different formats for post-processing requirements. The flowchart of the measurement procedure is shown in Figure 9.

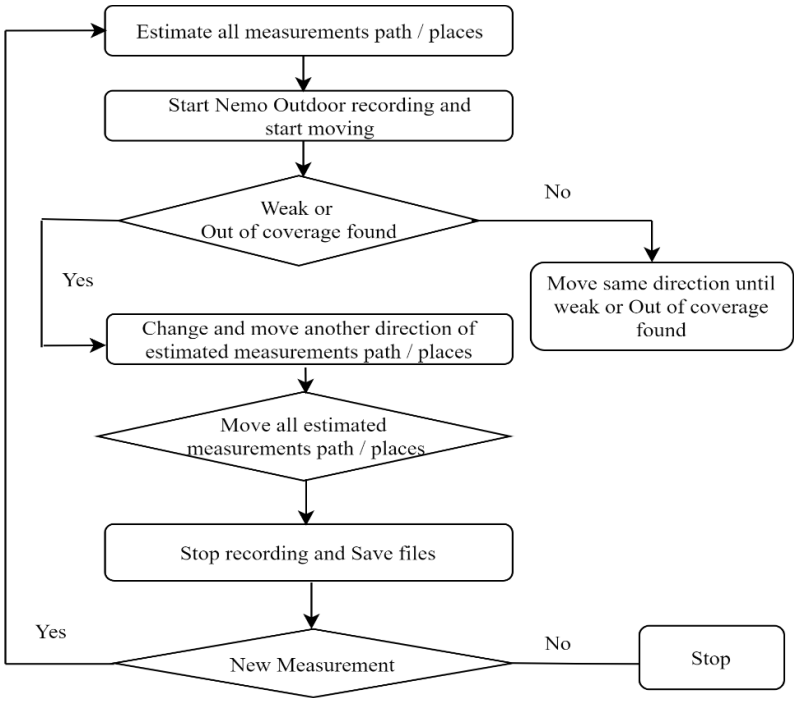

Figure 9. Flowchart of outdoor measurement for Qualcomm kDC-5737.

4.6.2 Outdoor measurement for Quectel BG96 module

Quectel BG96 module was connected to QNavigator software which was operated on the laptop. The test points were selected based on RSRP values until the weak or out of coverage was found in PCI. A total of 43 test points were selected in the coverage measurement of PCI 46, 44 test points were selected in the coverage measurement of PCI 50, and 41 test points were taken in the coverage measurement of PCI 60. The signal strength parameters RSSI, RSRP, SINR and RSRQ, were extracted using the 'QCSQ' AT command. The GPS of google map was crossed the test point, the QCSQ AT command was used in the QNavigator interface to find the signal strength of the test point. The flowchart of the measurement procedure is shown in Figure 10.

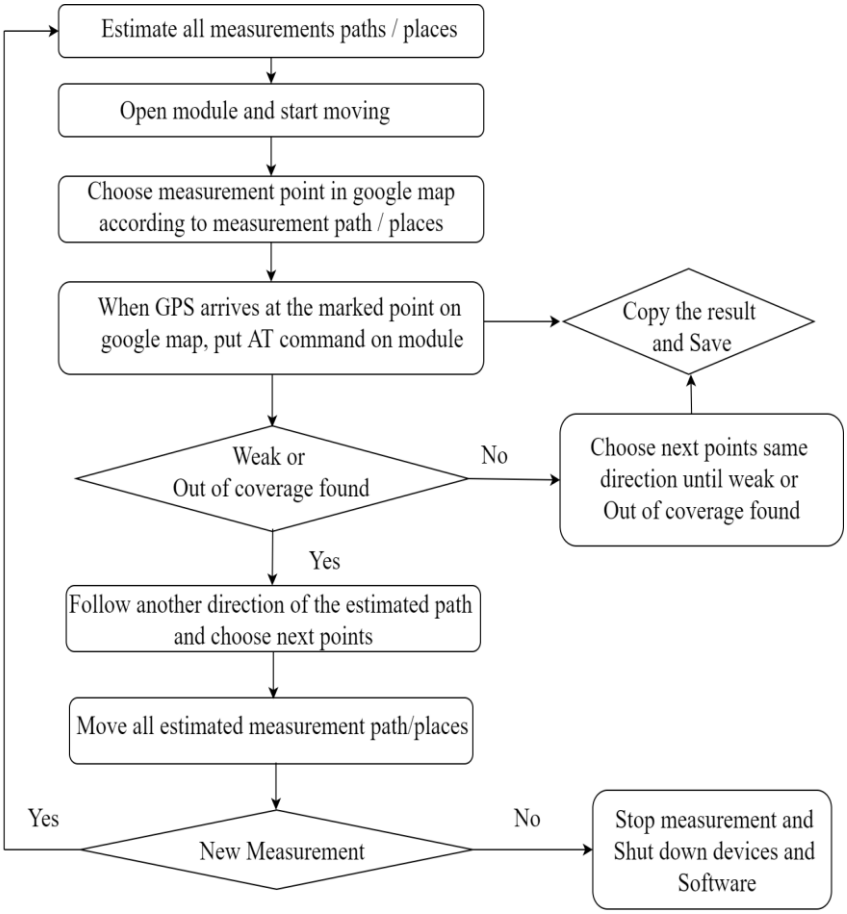

Figure 10. Flowchart of outdoor measurement for Quectel BG96 module.

5 PERFORMANCE EVALUATION

This chapter includes all the measurement results with analysis. The networks coverage performance of three PCIs based on RSRP, RSRQ, RSSI and SINR have been presented. Some of the figures have been obtained by using Nemo analyzer software. The values of the measured KPIs have been further used to attribute the measurement point to one of the six levels specified in Table 6.

Table 6. KPIs values for NB-IoT [43]

Performance Level	**RSRP (dBm)**	**RSRQ (dB)**	**RSSI (dBm)**	**SINR (dB)**
Excellent	> = - 80	> = - 5 dB	> = - 85	> = 20
Good	> = - 90 to < - 80	< - 5 to > = - 10	< - 85 to > - 95	> = 10 to < 20
Fair	> = -100 to < - 90	< - 10 to > = -15		> = -5 to < 10
Poor	> = -110 to < - 100	< - 15 to > = - 20	< - 95	> = -20 to < -5
Very poor	> = - 130 to < - 110	< - 20		< - 20
No signal	< - 130			

Excellent signal strength is the prerequisite for reaching the maximum data speeds and experiencing the minimum latency, and UE stays in the CE level 0. So, the performance of the application layer is the best. Moreover, *good* signal strength can enable good data speed with low latency, and UE stays in the CE level 0. The *fair* signal strength offers fair data speeds with fair latency, and UE stays in the CE level 1. If *poor* signal level, then data speeds are poor with high latency, and UE stays in the CE level 2. The *very poor* signal strength usually results in very low data speed and very high latency, and UE survives in CE level 2. As a result, the application layer performance will drop drastically. Getting to *no signal* will typically result in the disconnection of the device from the network [2], [22], [44].

5.1 Results Under PCI 46

The RSRP is the measurement of all the resource elements that carry the reference signal. While the power of the reference signal increases, the RSRP value also increases. The quality of the radio channel can be determined by the level of the RSRP values [2], [33]. Signal strength degrades if the signal is blocked or obstructed by the building blocks and trees [27], [29]. The RSRP represents the signal strength in the network coverage area. If the RSRP value is high, the radio channel quality is good, and the user's communication performance will likely be good. The values of RSRP depend on the distance between the UE and the eNB. While the UE distance increases from the eNB, RSRP values decrease because the power of the reference signal is attenuated due to propagation losses in the radio channel [2], [33].

The measured RSRP values under the network coverage region of PCI 46 using the kDC-5737 dongle have been presented in Figure 11. The colour legend in the right corner indicates the intensity of the RSRP values throughout the test location area. The PCI 46 has a transmit power level of 39 dBm, a beamwidth of 65° directed towards the South with an electrical down tilting of 2° and mechanical tilting of 0°, which is true for all the figures presented in Section 5.1.

After analysing the drive test result of the kDC-5737 dongle, 88 per cent of all the RSRP values observed were equal to or greater than -80 dBm. *Excellent* RSRP values can be observed in the case of PCI 46 while using the kDC-5737 dongle. It is visible in Figure 11, when the distance of the kDC-5737 dongle increases from the PCI 46, RSRP values do not decrease in the span of several kilometres. Although, the RSRP values degrade at some points in the marked region. Three out of all test points have *fair* signal strength. The average RSRP value drops to between -90 dBm and -100 dBm in these points. One location point has *good* level of signal strength. The red marked test point indicates *very poor* level of signal quality as the RSRP value drops significantly from -100 dBm to -130 dBm range.

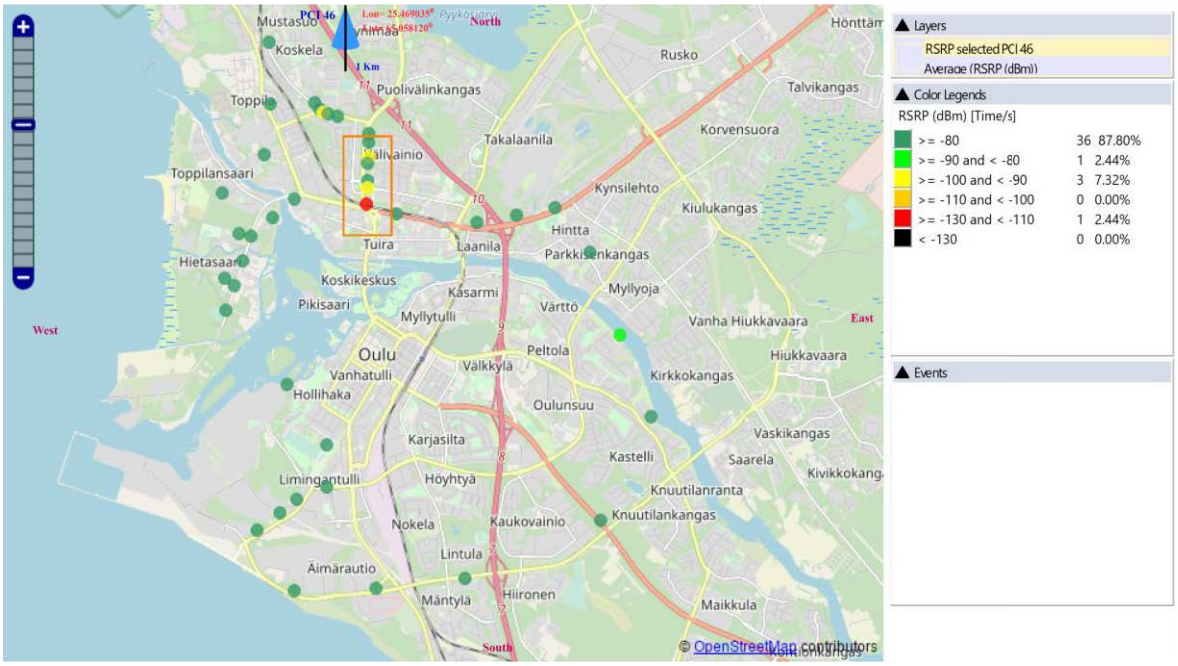

Figure 11. RSRP values of PCI 46 using kDC-5737 dongle.

Figure 12 demonstrates all the test points with corresponding RSRP values for the BG96 module. The RSRP ranged from -101 dBm to -137 dBm for all the test points. For a better explanation of the measured data, three random points have been taken at three different distances from the PCI 46 shown in Figure 12. Point A is the closest point from the base station, which is exactly 2 km away from PCI 46. The RSRP value of this point is -104 dBm. The remaining two points, B and C, are 5 km and 4 km away, respectively. Whereas the measured RSRP values of points B and C are -125 dBm and -130 dBm, respectively. At point B, the BG96 module features higher RSRP value than point C even though the distance to point B is longer than point C from the PCI 46. It is noteworthy that point B is located within the beamwidth of PCI 46 directed towards the South direction. The Figure 12 shows that the RSRP value decreases due to propagation loss with increasing distance between the BG96 module and the PCI 46. As a result, Figure 12 depicts lower RSRP values for the BG96 compared to the kDC-5737 dongle. It also shows two out of network coverage test points in the South direction even though the horizontal beamwidth of PCI 46 directed towards the South direction.

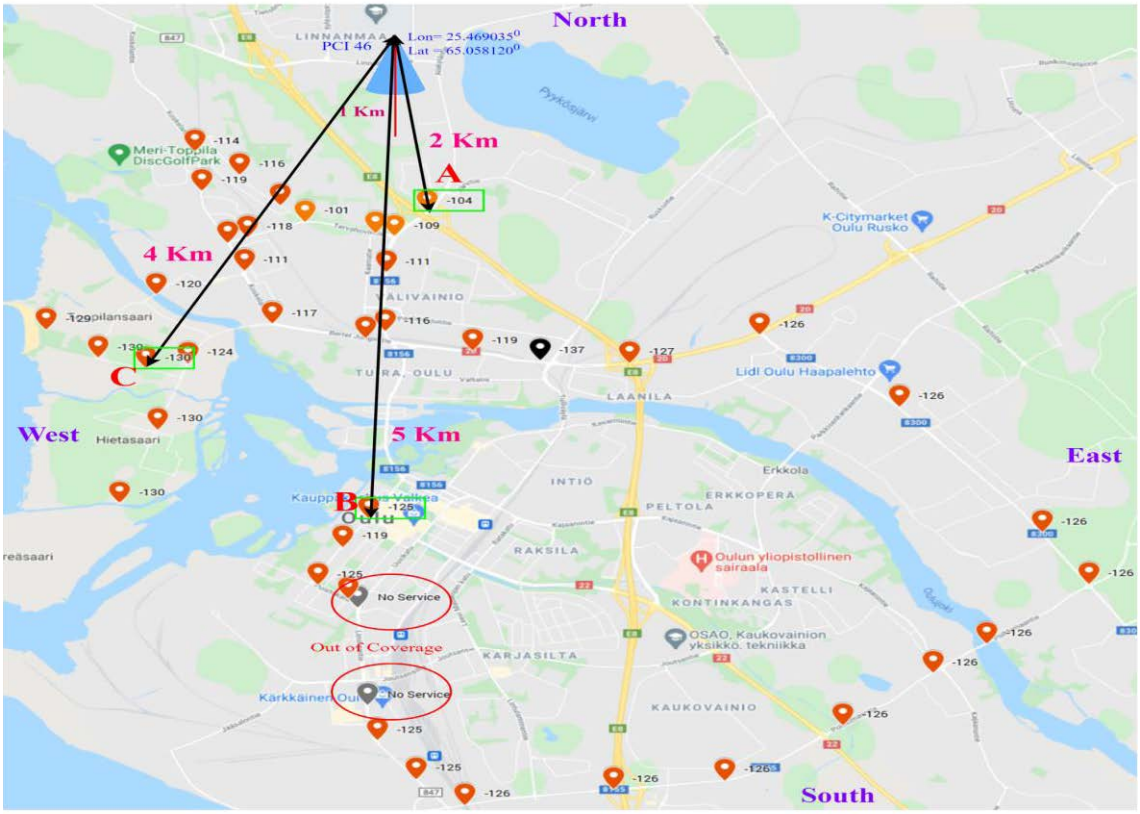

Figure 12. RSRP values of PCI 46 using BG96 module.

The analysed RSSI values of the drive test result for the kDC-5737 dongle is presented in Figure 13. In this case, 97 per cent of all test points featured the RSSI values observed to be equal to or greater than -85 dBm. It is also visible in Figure 13 that when the distance of the kDC-5737 dongle increases from the PCI 46, RSSI values do not attenuate in the span of several kilometres from PCI 46. As a result, most of the test points featured an *excellent* level of RSSI. Just one test point out of all shows *very poor* RSSI.

The measurement results of the BG96 module are reported in the Figure 14. The result of the RSSI of this device ranged from -94 dBm to -114 dBm. If the distance between the PCI 46 and the BG96 module increases, the RSSI values decreases. As a result, the Figure 14 shows poor RSSI in test location while using the BG96 module. Likewise, in Figure 12, three test points have also been taken to compare the effect of the RSSI in the coverage area. The highest RSSI has been observed for the test point closest to PCI 46 amongst the three points. The RSSI values measured in two other points, B and C, are -109 dBm and -110 dBm. These points are located within the range of between 2 to 5 km from the PCI 46.

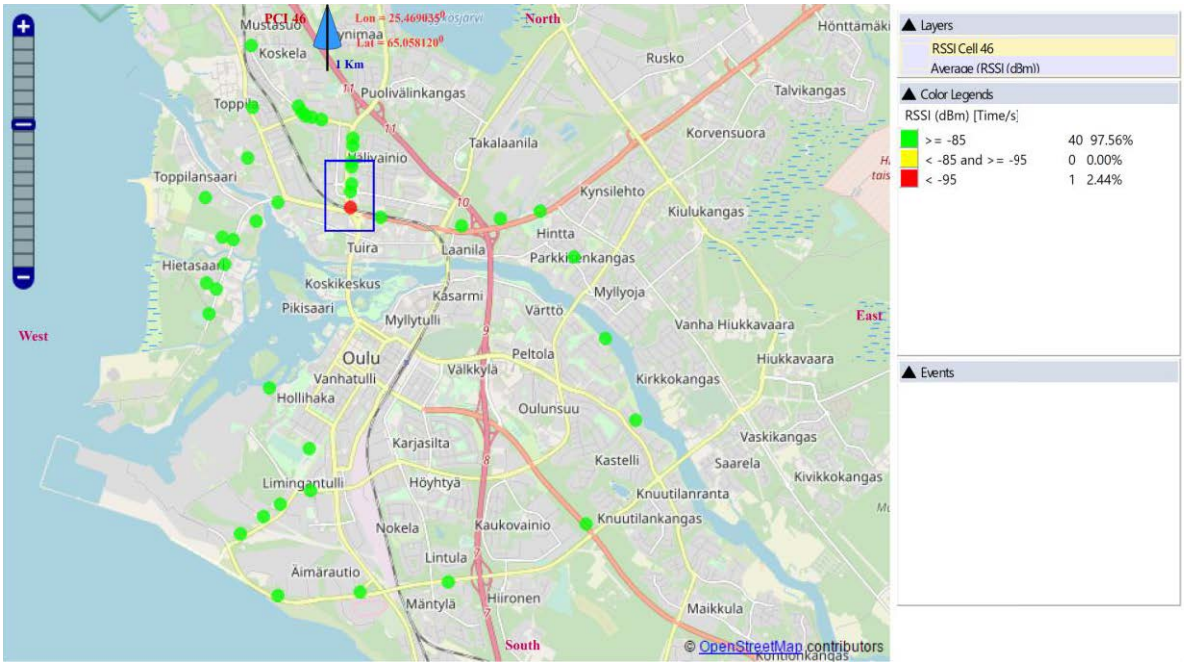

Figure 13. RSSI values of PCI 46 using kDC-5737 dongle.

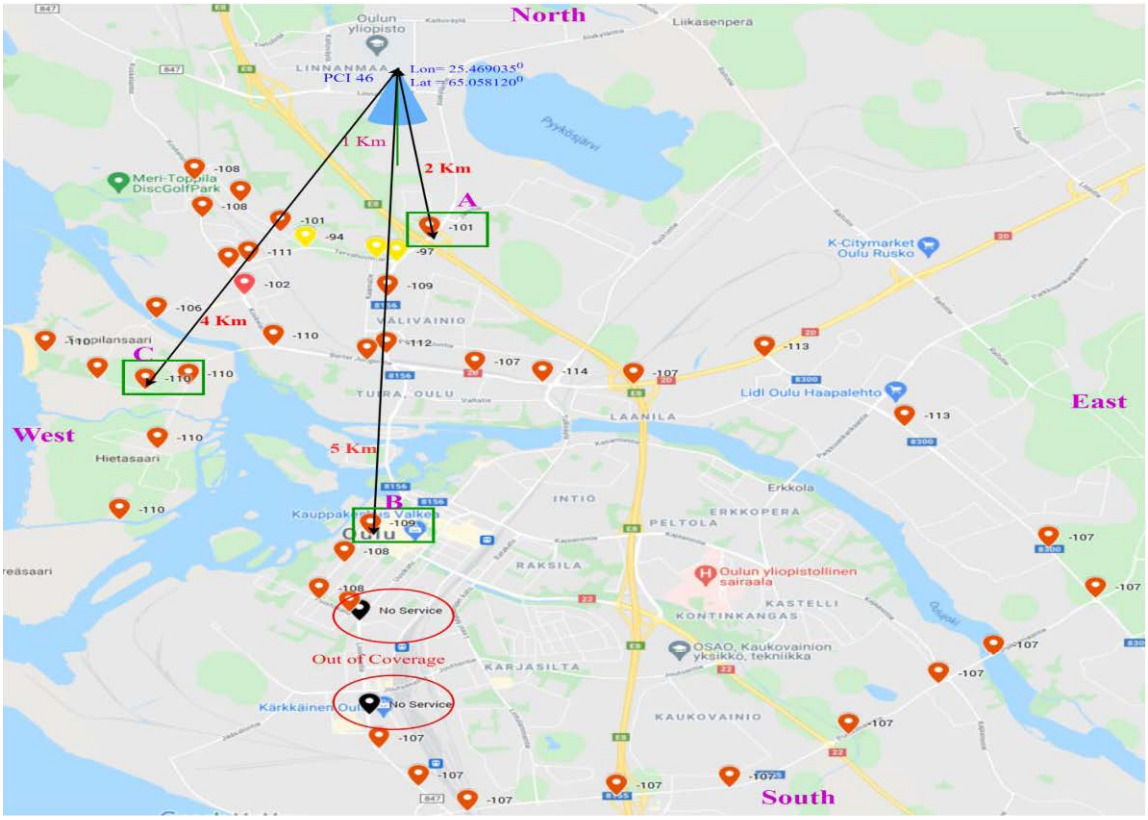

Figure 14. RSSI values of PCI 46 using BG96 module.

The SINR effect measured by both devices has been demonstrated in Figures 15 and 16, respectively. After analysing the drive test result of the kDC-5737 dongle, almost 12 per cent of SINR values were observed to be equal to or greater than 20 dB, which corresponds to the

excellent level according to KPIs values for NB-IoT presented in Table 6. In addition, nearly 88 per cent of SINR values recorded are equal to or greater than -5 dB and less than 10 dB, which is considered to be *fair* signal strength.

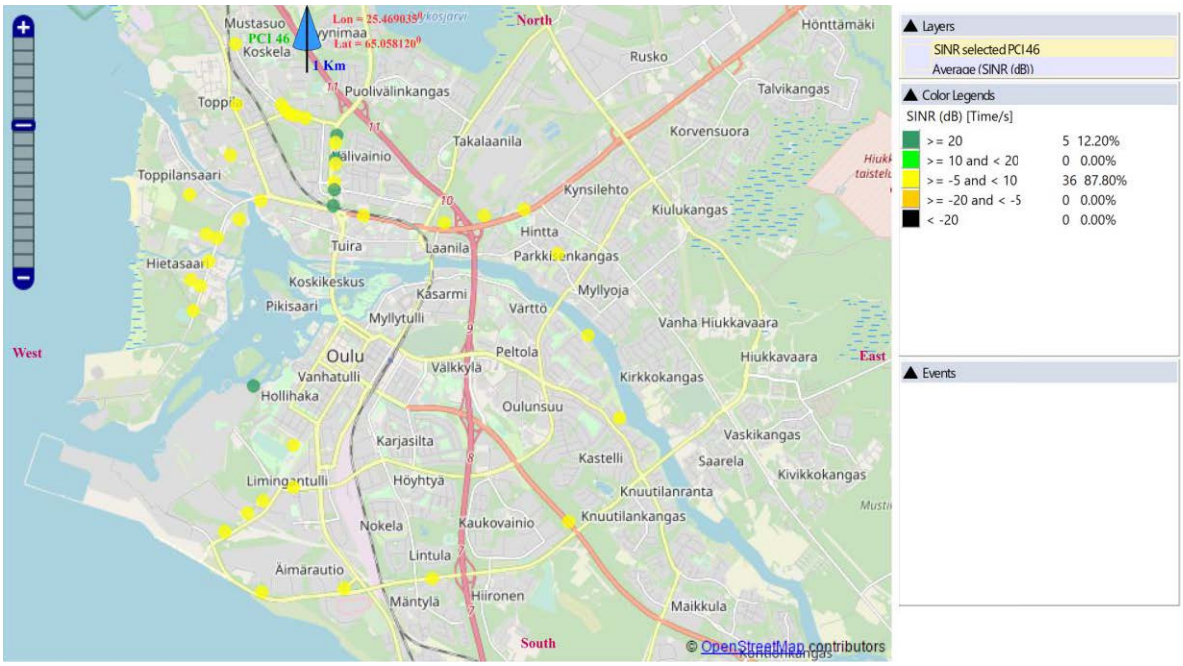

Figure 15. SINR values of PCI 46 using kDC-5737 dongle.

SINR quantifies the strength of the received signal compared to unwanted noise and interference. It describes the radio conditions and throughput of the network. If SINR is high, then the throughput is high, which means more useful bits are transmitted. If SINR is low, then signal quality is poor because the number of useful bits is attenuated due to pathloss [2], [33].

The range of SINR values has been measured using the BG96 module in the range of 0 to 250. The range 0 to 250 are the logarithmic value of SINR expressed in one-fifth of a dB, translated in dB ranging from -20 dB to +30 dB. For all the test points, the SINR ranged from 21 dB to -9 dB for the case of the BG96 module shown in the Figure 16. It can be seen from the following figure that closest points from the base station show *good* SINR values while *poor* SINR in the far points.

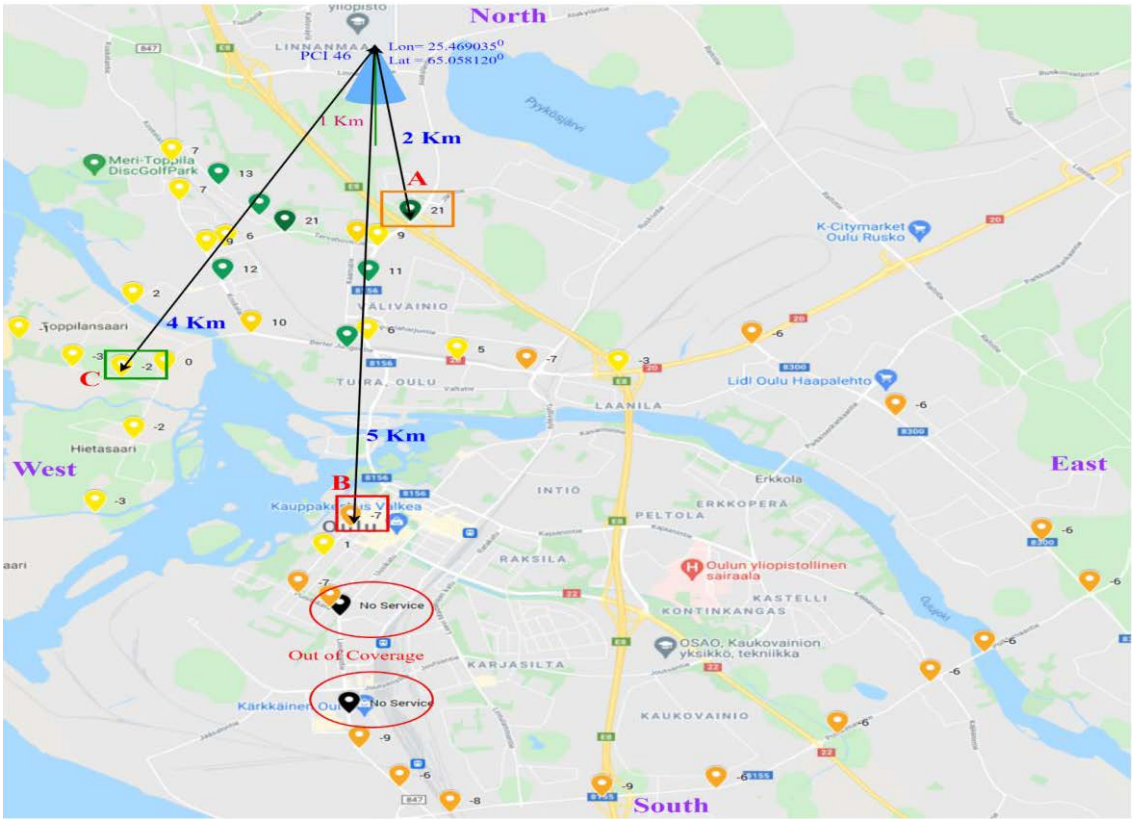

Figure 16. SINR values of PCI 46 using BG96 module.

Figures 17 and 18 illustrate the RSRQ values in different locations for the two measurement devices. After analysing, the measured data of the kDC-5737 dongle has been presented in Figure 17. From Figure 17, it can be observed that around 60 per cent of RSRQ values are equal to or greater than -5 dB. However, 33 per cent values are less than -5 dB and equal to or greater than -10 dB. The RSRQ ranged from -3 dB to -18 dB using the BG96 module shown in Figure 18.

RSRQ is the ratio of two power KPIs: RSRP and RSSI. RSRP measures the average power of the reference signal to UE from eNB. On the other hand, RSSI is the total received power, including downlink power, interference, and thermal noise [2], [33], [45].

For the kDC-5737 dongle, *excellent* RSRP and RSSI have been shown in Figures 11 and 13, respectively. So, both the RSRP and the RSSI are *excellent*, so there is a low deviation of both the RSRP and the RSSI, which means that low noise and interference does not affect the received signal significantly. As a result, Figure 17 shows the *excellent* RSRQ values for the kDC-5737 dongle. If noise and interference are high, then the value of the RSSI is much higher than that of the RSRP.

Since three points have been taken which are the same distance for the Figures 12, 14 and 16. In point A, the measured RSRP, RSSI and SINR values are -104 dBm, -101 dBm and 21 dB. The SINR is in *excellent* level according to KPIs values for NB-IoT presented in Table 6. On the other hand, The RSRP and the RSSI are at *poor* level. As a result, despite of *poor* RSRP and RSSI *good* level of RSRQ is observed in point A shown in Figure 18, because of *excellent* SINR. The *good* RSRQ values have been observed for all test points closest to PCI 46. Both devices show different behaviour at PCI 46.

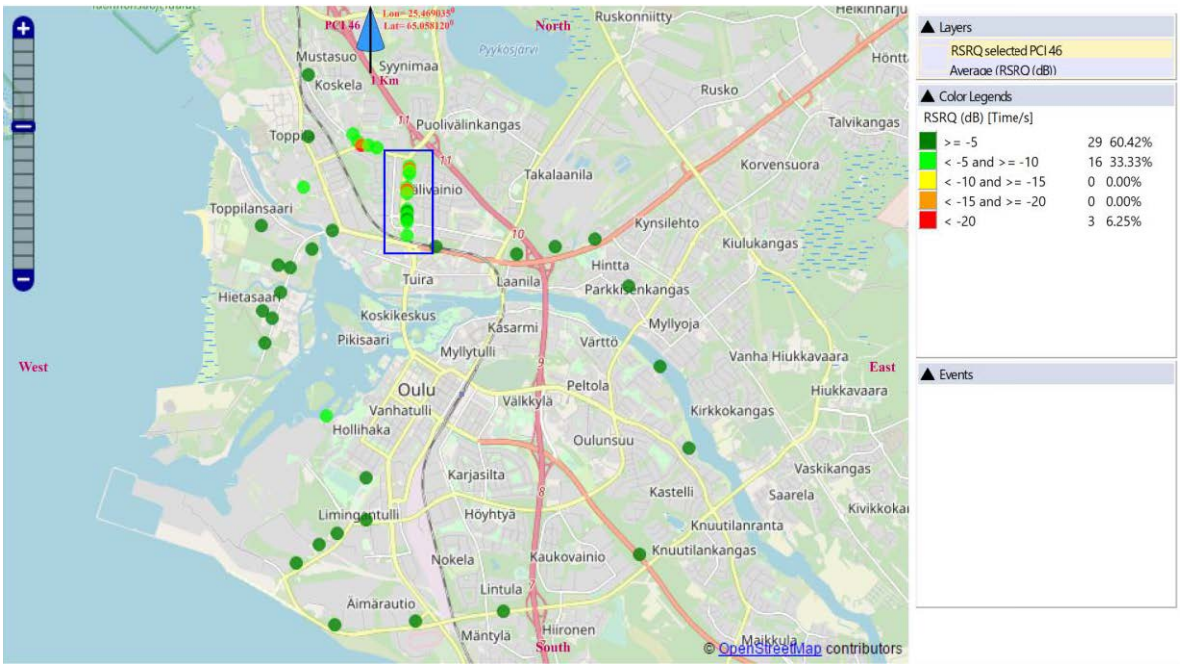

Figure 17. RSRQ values of PCI 46 using kDC-5737 dongle.

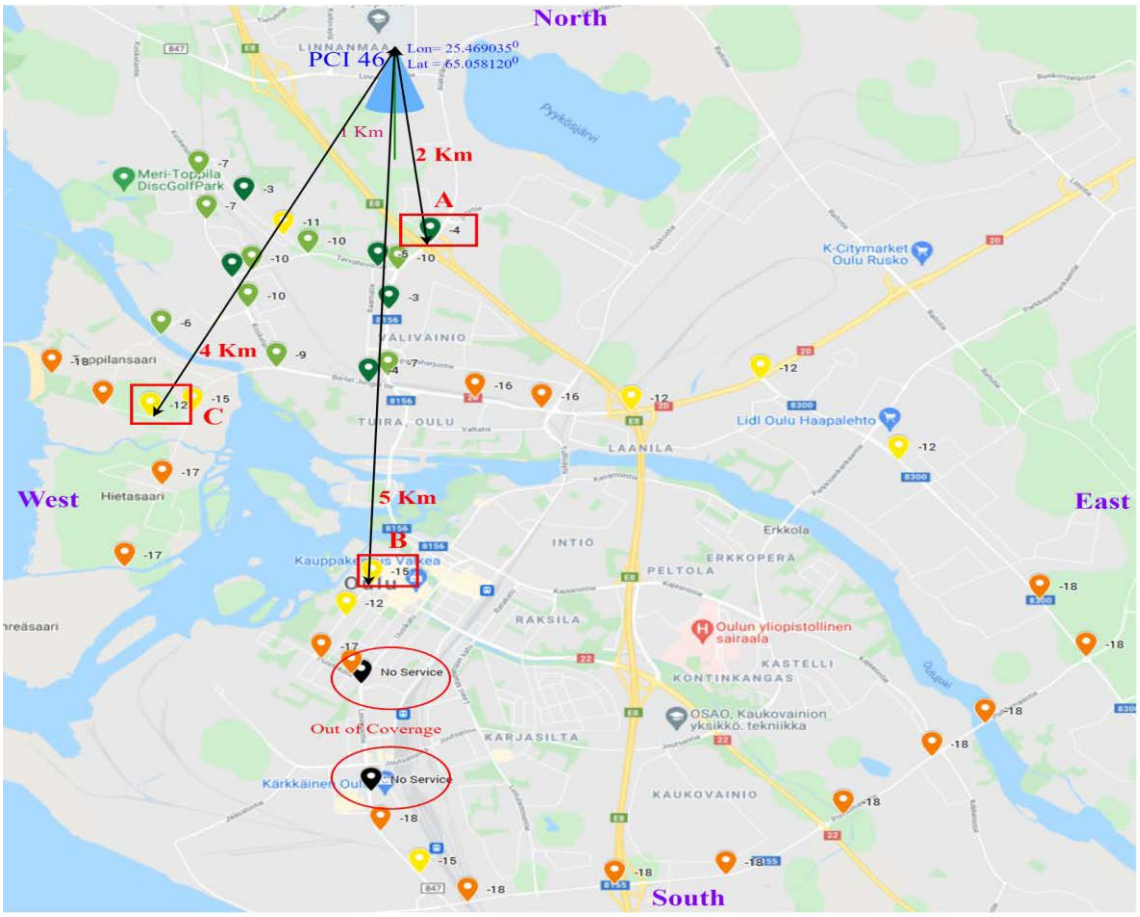

Figure 18. RSRQ values of PCI 46 using BG96 module.

5.2 Results Under PCI 50

The PCI 50 has an electric tilt of 16° with a beamwidth directed towards the North, where the transmit power and mechanical tilt are the same as the PCI 46, as discussed in section 5.1. The measured RSRP values have been demonstrated in Figures 19 and 20 for two devices. Nearly 70 per cent of RSRP values observed were in between -130 dBm to -110 dBm, which corresponds *very poor* signal strength. Yellow marked points indicate the *fair* signal strength closest to the base station, while black marked points denote the out of network coverage.

All RSRP results using the BG96 module ranged from -91 dBm to -133 dBm. Points A, B and C have been taken for better explaining the results. These points are within 2 to 4 kilometres away from the base station. The RSRP value of points A and B are -97 dBm and -127 dBm, respectively, whereas the distance to both points is the same but in different directions from PCI 50. Highest transmit power is transmitted towards the North direction where point A is located. RSRP values of point C is -110 dBm which is 4 km away from PCI 50. Figure 20 shows the effect of propagation losses in RSRP values with respect to increasing the distance of the test point location. It also illustrates four out of network coverage points in both South and North direction. Both figures represent the low RSRP values for both devices.

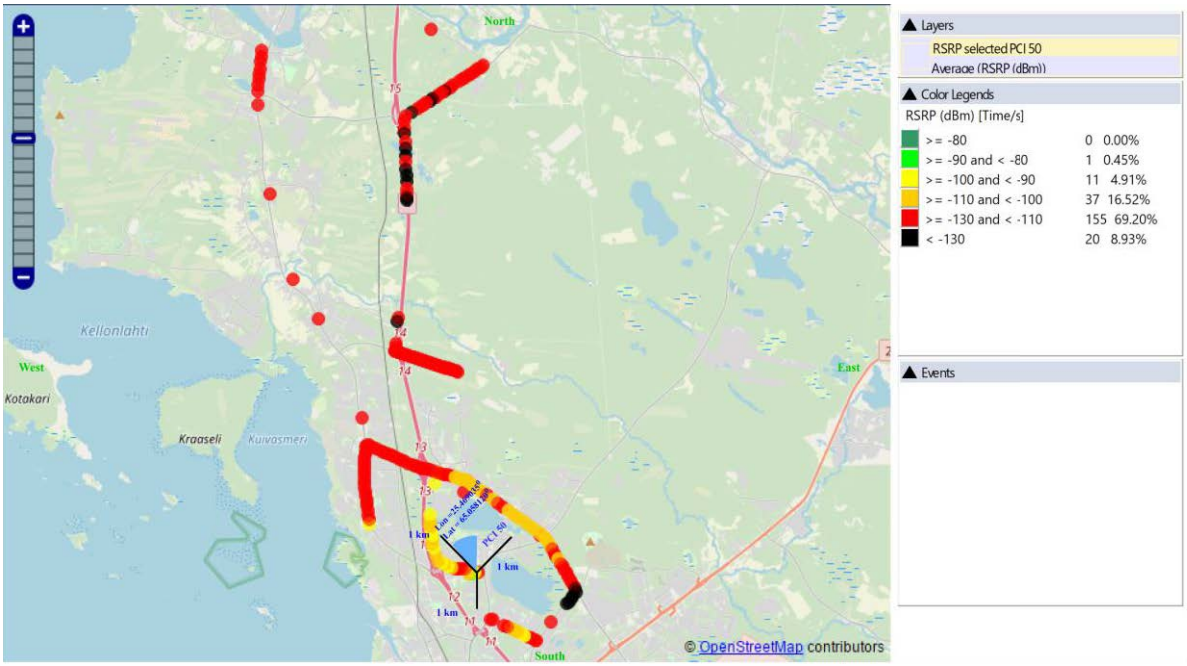

Figure 19. RSRP values of PCI 50 using kDC-5737 dongle.

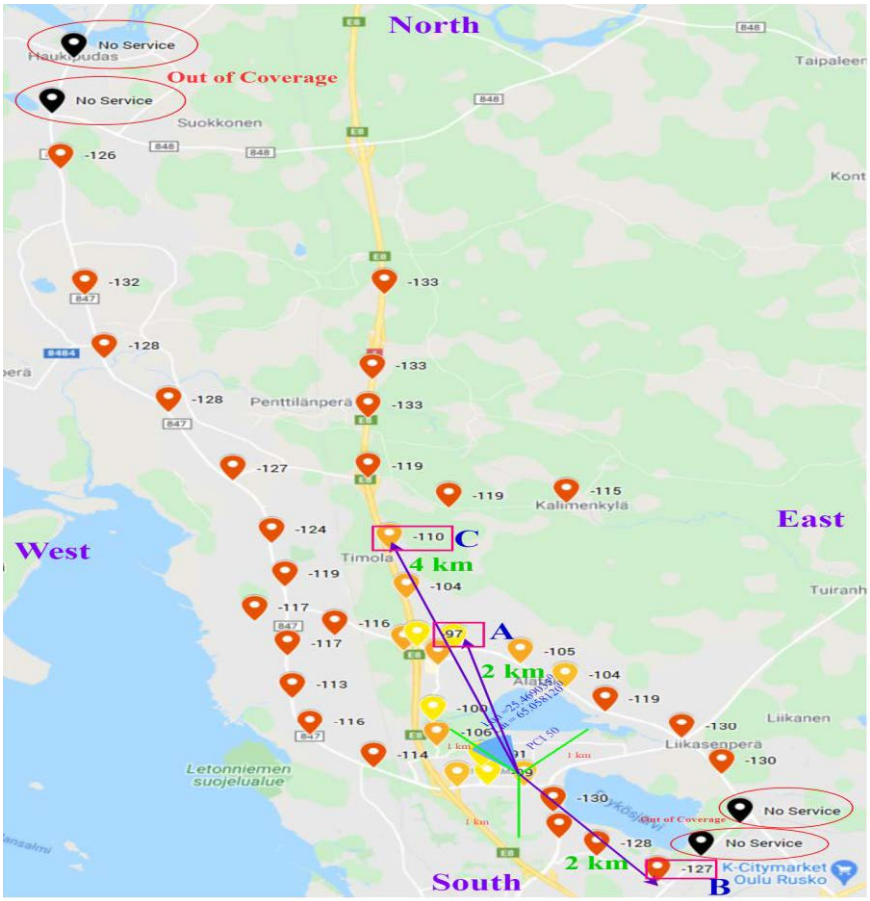

Figure 20. RSRP values of PCI 50 using BG96 module.

The results of the RSSI for both devices are presented in Figures 21 and 22. Two out of all test points have excellent RSSI closest to the base station for the kDC-5737 dongle. Almost 91 per cent of RSSI values observed were greater than -95 dBm, indicating the *poor* RSSI level.

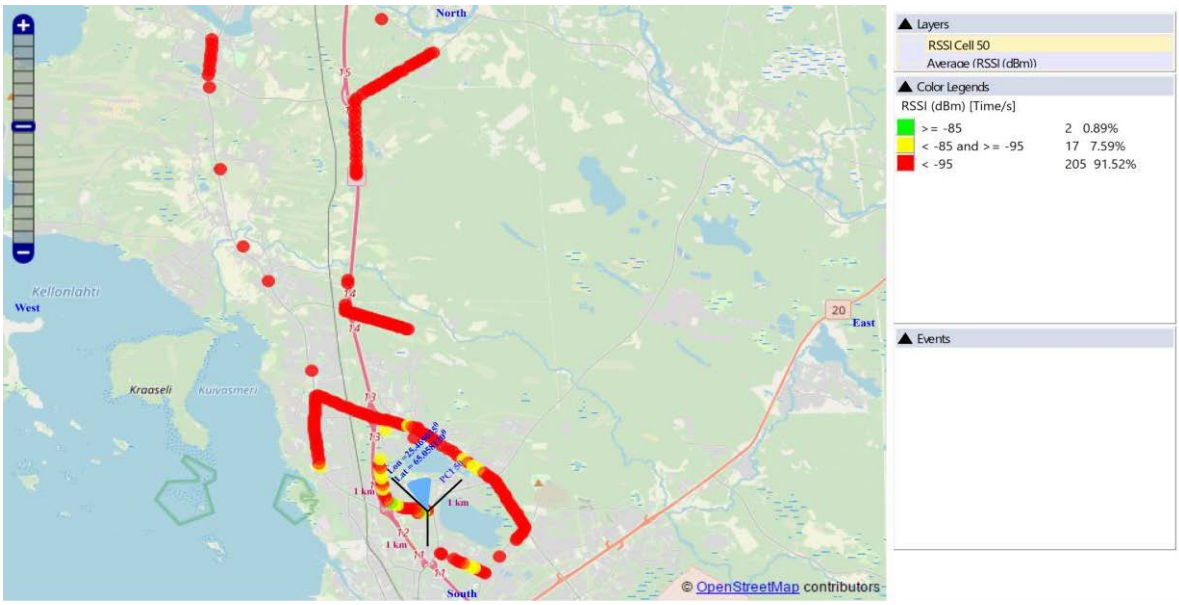

Figure 21. RSSI values of PCI 50 using kDC-5737 dongle.

The RSSI of the BG96 module ranged from -91 dBm to -114 dBm using the BG96 module shown in Figure 22. Both A and B are 2 km away from the base station. The RSSI values observed in these two points, A and B are -90 dBm and -112 dBm. The RSSI value at point C is -105 dBm which is 4 km from PCI 50. Figure 22 demonstrates the effect of the communication distance between test points location and the base station on the RSSI.

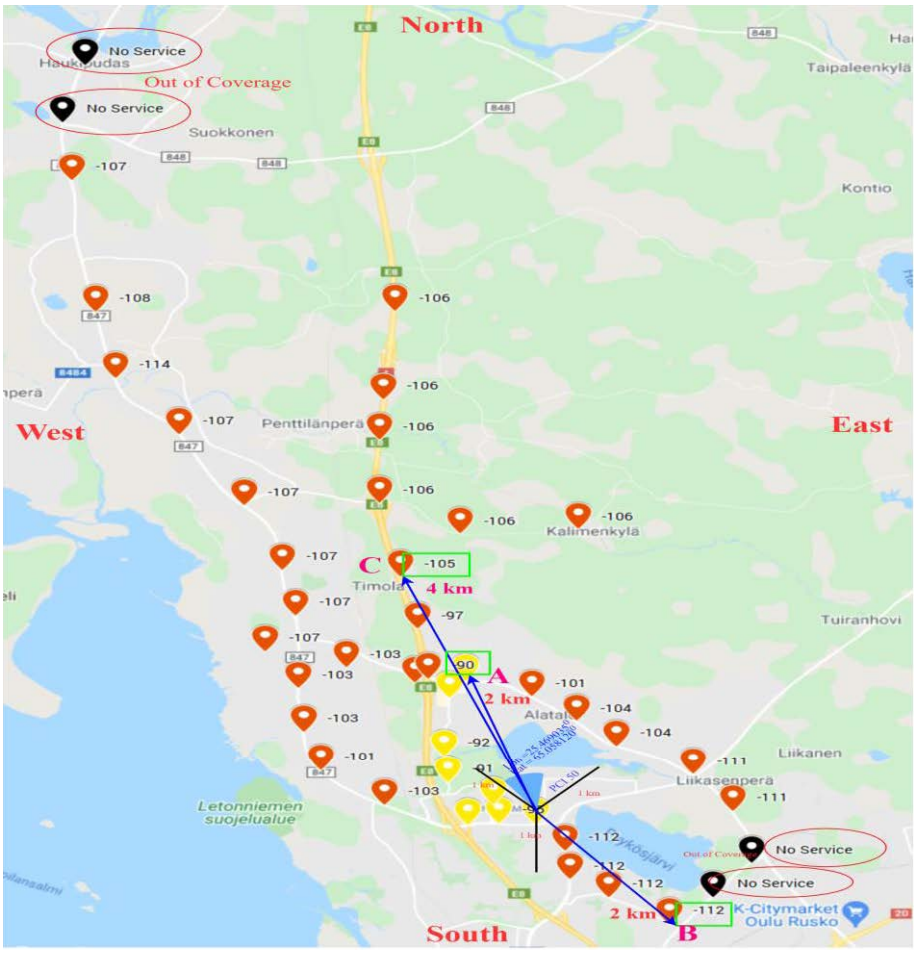

Figure 22. RSSI values of PCI 50 using BG96 module.

Figures 23 and 24 represent the effect of SINR values which have been measured during the drive test under PCI 50. Nearly 77 per cent of SINR values observed were between -5 dB to 10 dB which are at the *fair* level. Green marked test points imply the *excellent* level of the SINR. The SINR values observed between 21 dB to -15 dB using the BG96 module are shown in Figure 24. Far points from PCI 50 show *poor* SINR, while the closest points show *excellent* and *good* SINR values. Both devices demonstrated almost identical behaviour in respect of SINR.

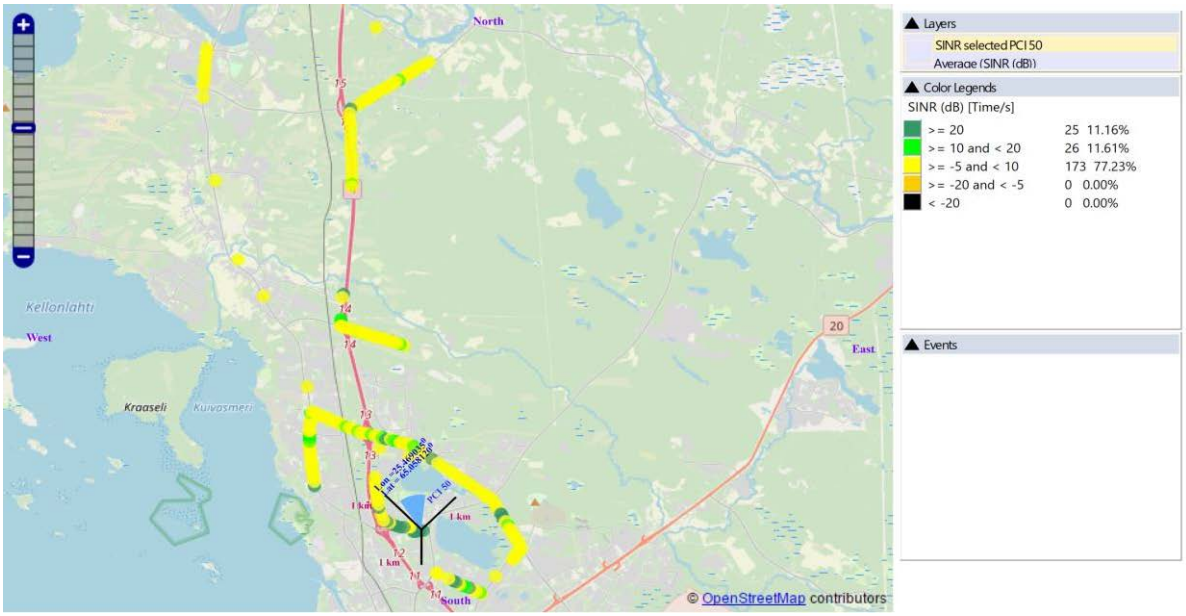

Figure 23. SINR values of PCI 50 using kDC-5737 dongle.

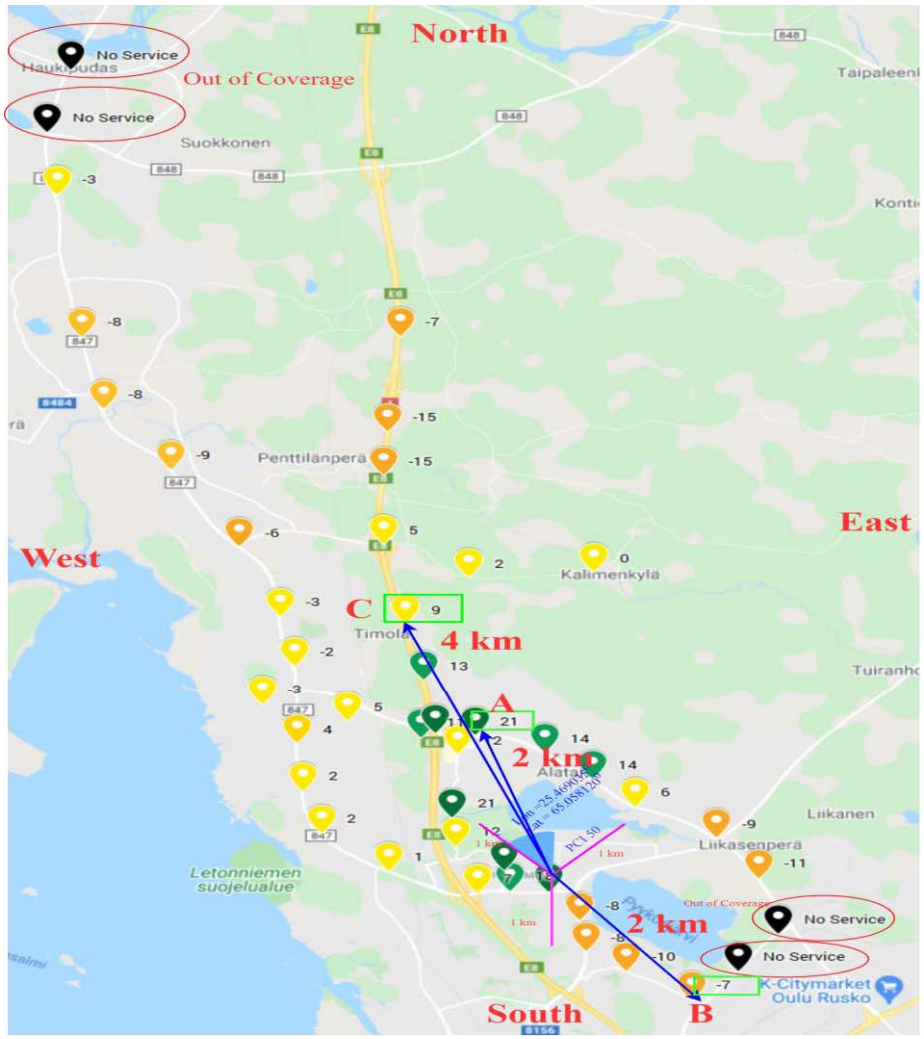

Figure 24. SINR values of PCI 50 using BG96 module.

The RSRQ values of both devices are demonstrated in Figures 25 and 26. Around 41 per cent of RSRQ values observed were less than -5 dB and equal to or greater than -10 dB, which are in *good* signal quality. Green marked test points indicate *excellent* signal quality closest to the base station. The signal quality level is *fair* throughout the coverage area of PCI 50.

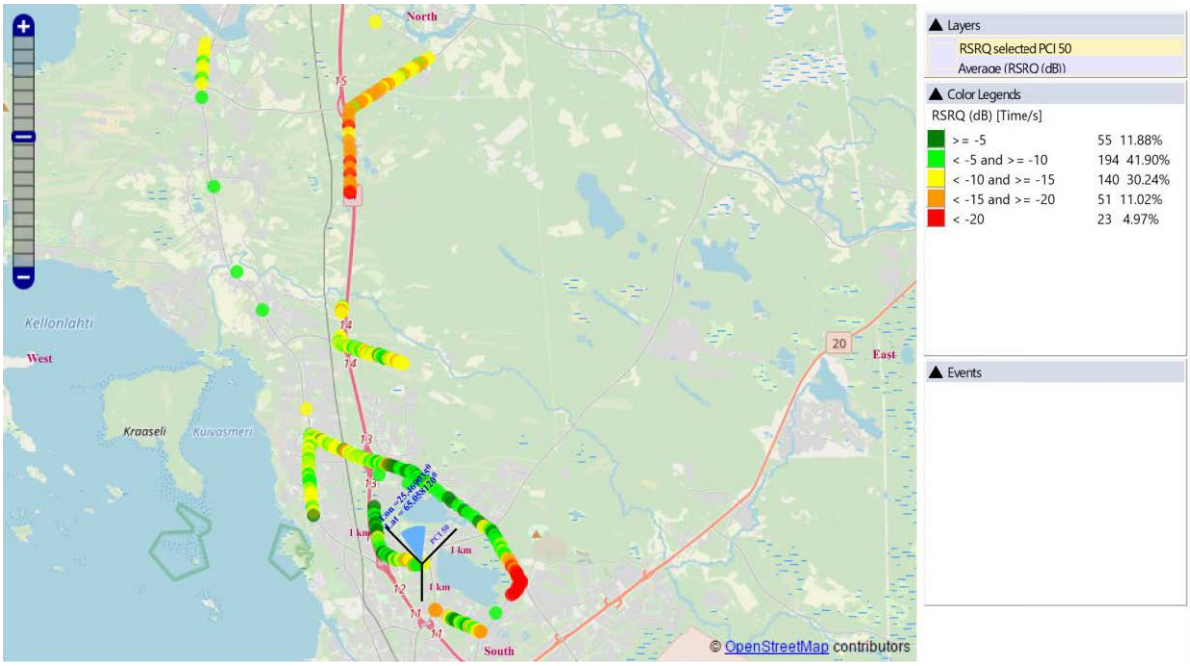

Figure 25. RSRQ values of PCI 50 using kDC 5737 dongle.

Three points have been taken for the BG96 module shown in Figure 26 since those three points are the same distance for Figures 20, 22 and 24. Measured RSRP and RSSI in point C are -110 dBm and -105 dBm which indicate *poor* signal levels. The SINR value is 9 dB at the same point C, which is at *good* level. As a result, RSRQ value at point C is 12 dB, which indicate *fair* signal quality because of the *good* SINR level observed at the C point. The closest points to PCI 50 show *good* RSRQ values. Both devices show almost the same identical behaviour.

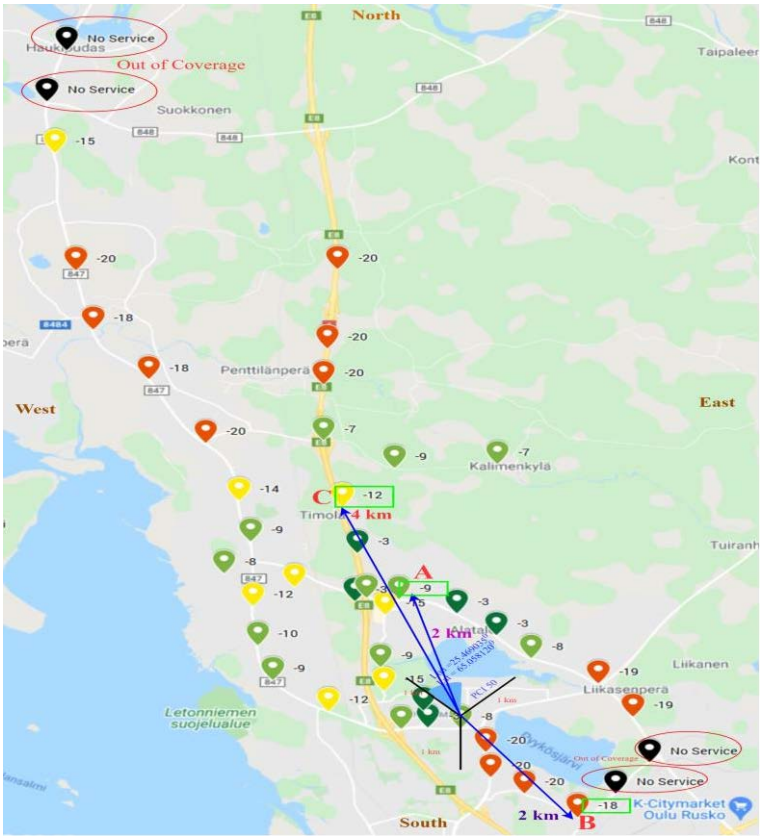

Figure 26. RSRQ values of PCI 50 using BG96 module.

5.3 Results Under PCI 60

The analysed RSRP values of the drive test result for the kDC-5737 dongle are demonstrated in Figure 27. The colour legend in the right corner indicates the intensity of the RSRP values throughout the test location area. The PCI 60 has a transmit power level of 46 dBm, a beamwidth of 65° directed towards the South with an electrical down tilting of 2° and mechanical tilting of 0°, which is true for all the figures presented in Section 5.3.

After analysing the drive test result of the kDC-5737 dongle, almost 65 per cent RSRP values observed were equal to or greater than -130 dBm and less than -110 dBm, and almost 15 per cent RSRP values observed were equal to or greater than -110 dBm and less than -100 dBm as shown in Figure 27. *Poor* RSRP values can be observed in the case of PCI 60 while using the kDC-5737 dongle. It is visible in Figure 27, when the distance of the kDC-5737 dongle increases, RSRP values decrease in the span of several kilometres. Although, the RSRP values do not degrade in some points in the marked region closest to the base station. Three out of all test points have *excellent* signal strength. Twenty of all test points have *good* signal strength between -80 dBm and -90 dBm. The red marked test point indicates *very poor* level of signal quality as the RSRP value drops significantly from -100 dBm to -130 dBm range. Black marked test point indicates an out of coverage region while RSRP value drops below 130 dBm. The signal quality is *very poor* around these out of coverage test points.

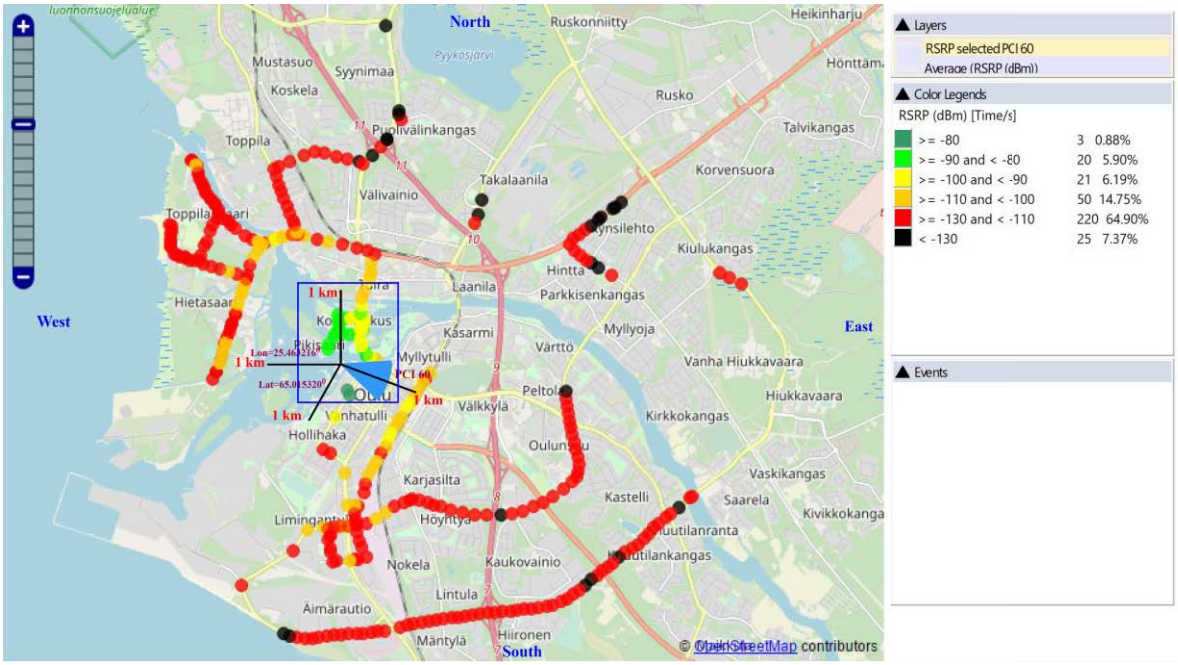

Figure 27. RSRP values of PCI 60 using kDC-5737 dongle.

The Figure 28 shows all the test points with corresponding RSRP values for BG96 module. The RSRP ranged from -82 dBm to -132 dBm for all the test points. For better explanation of the measured data, three random points have been taken at three different directions from the PCI 60 shown in Figure 28. The distance of point A is exactly 1.5 km which is the closest marked point from PCI 60. The RSRP value of this point is -101 dBm. The remaining two points, B and C, are 3 km in different direction from PCI 60. Whereas the measured RSRP values of points B and C are -118 dBm and -129 dBm, respectively. At point B, the BG96 module features higher RSRP value than point C even though the distance to point B is the same as point C from the PCI 60. It is noteworthy that point B is located within the beamwidth of PCI 60 directed towards the Southeast direction. The Figure 28 shows that the RSRP value decreases due to propagation loss with increasing distance between the BG96 module and the PCI 60. As a result, Figure 28 depicts low RSRP values for the BG96 which are almost the same for the kDC-5737 dongle. So, both devices demonstrated identical behaviour in respect of RSRP. It also shows three out of network coverage test points in the Northeast direction.

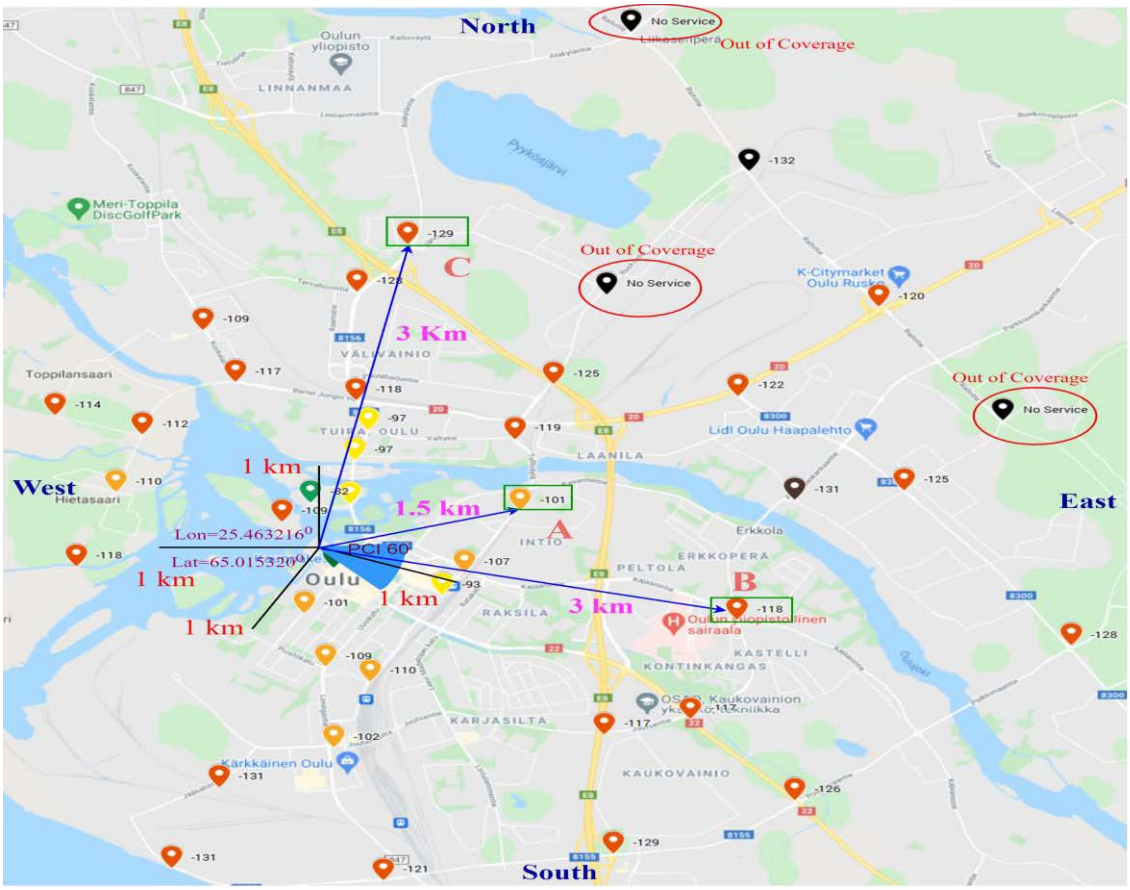

Figure 28. RSRP values of PCI 60 using BG96 module.

The measured RSSI values under the network coverage region of PCI 60 have been presented in Figure 29. After analysing the drive test result of the kDC-5737 dongle, almost 85 per cent of RSSI values were observed to be less than -95 dBm, shown in Figure 29. This figure shows that when the distance of the kDC-5737 dongle increases from the PCI 60, RSSI values attenuate in the span of several kilometres from PCI 60. Although, The RSSI values do not degrade in some points in the marked region closest to the base station. Nineteen out of all test points have *excellent* RSSI in the marked area. The red marked test point indicates *very poor* RRSI level as the RSSI value drops below 95 dBm. As a result, most of the test points feature *poor* level of RSSI.

The measurement results of the BG96 module are reported in the Figure 30. The RSSI ranged from -81 dBm to -113 dBm using the BG96 module for all the test points. When the distance of the BG96 increases from PCI 60, then the RSSI value decreases. As a result, the Figure 30 shows *poor* RSSI in the test coverage area. Similarly, in Figure 28 three test points have also been taken to compare the effect of RSSI in the coverage area with respect to distance. Closest point to PCI 60 features the highest RSSI amongst the three points. The RSSI values observed in two other points, B and C, are -109 dBm and -113 dBm. These points are located within the range of between 1.5 to 3 km from the PCI 60.

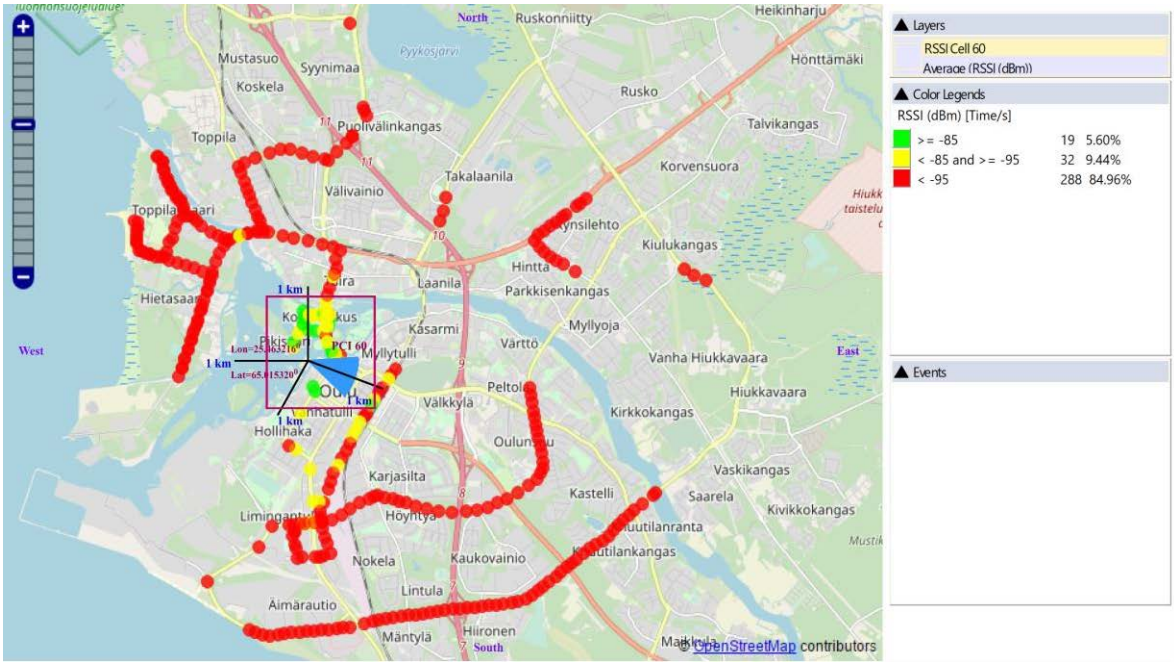

Figure 29. RSSI values of PCI 60 using kDC-5737 dongle.

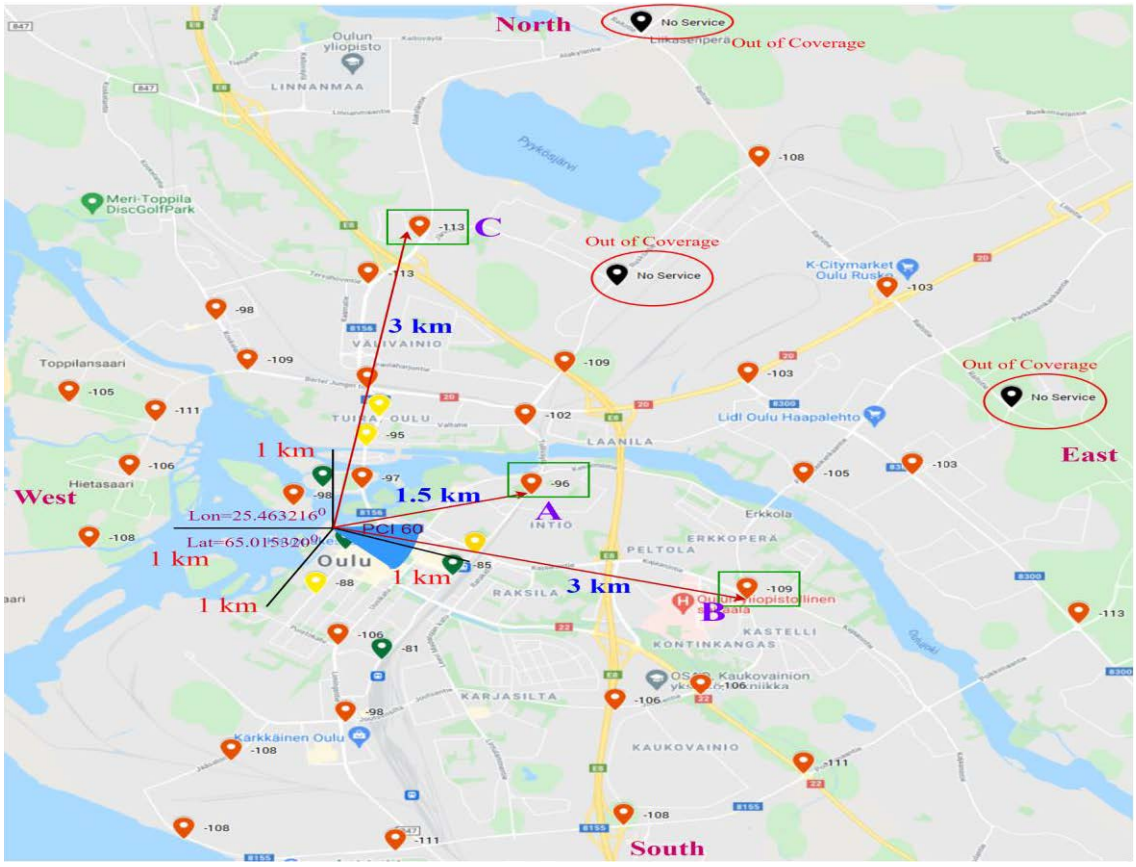

Figure 30. RSSI values of PCI 60 using BG96 module.

Figures 31 and 32 demonstrate the SINR values which have been measured during drive test under PCI 60. After analysing the drive test result of the kDC-5737 dongle, almost 8 per cent

of SINR values observed were equal to or greater than 20 dB, which corresponds to the *excellent* level. And almost 83 per cent SINR values observed to be equal to or greater than -5 dB and less than 10 dB which resembles to *fair* level according to KPIs values for NB-IoT presented in Table 6. The yellow marked test point indicates *fair* level of signal and interference in the coverage area. Green marked test point implies the *excellent* level of the SINR.

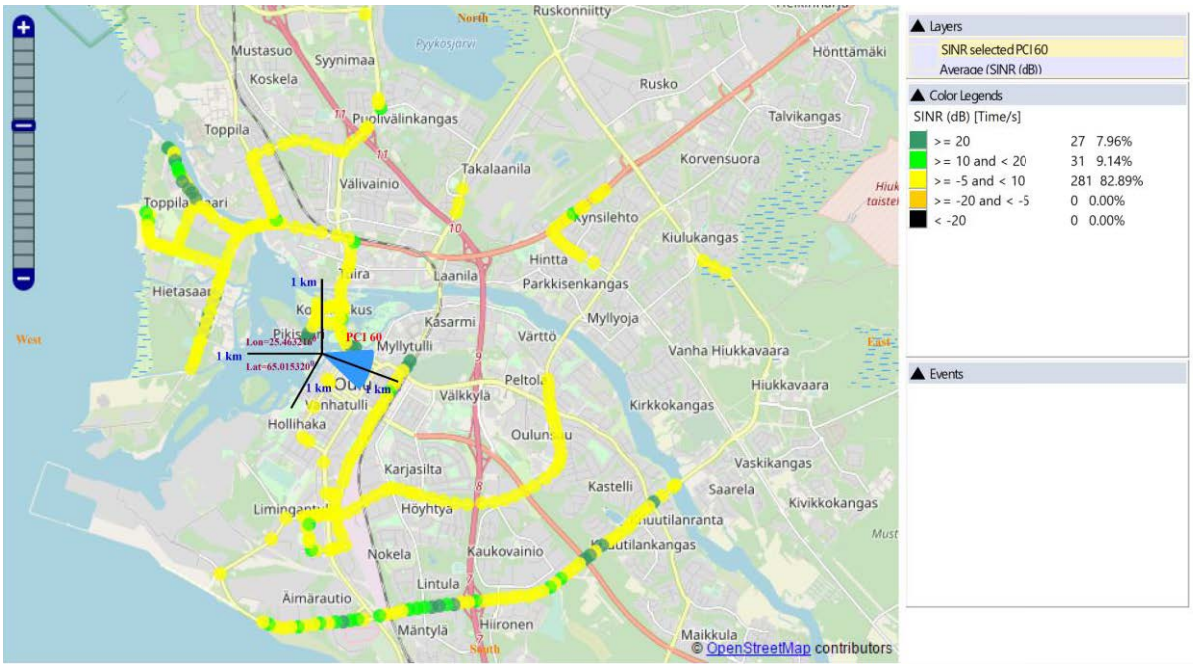

Figure 31. SINR values of PCI 60 using kDC-5737 dongle.

The SINR ranged from 21 dB to -16 dB using BG96 module shown in the Figure 32. It can be observed from following figure that closest points from PCI 60 show *excellent* and *good* SINR values while *poor* SINR in the far points. Both devices demonstrated almost identical behaviour in respect of SINR. With the increase in the communication distance from PCI 60, the SINR degrade for both devices.

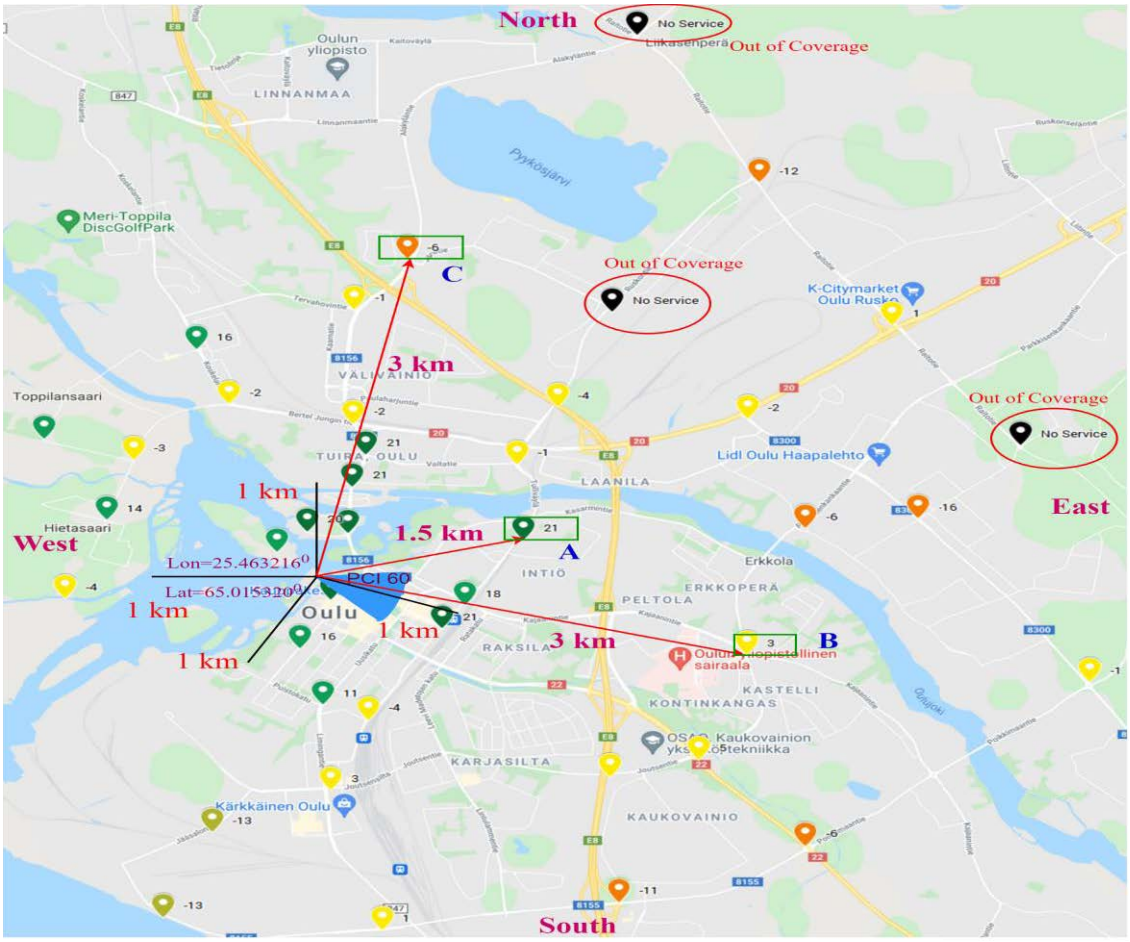

Figure 32. SINR values of PCI 60 using BG96 module.

The RSRQ values of both devices are demonstrated in Figures 33 and 34. After analysing the drive test result of kDC-5737 dongle, almost 20 per cent RSRQ values were observed to be equal to or greater than -5 dB, almost 26 per cent RSRQ values were observed to be less than -5 dB and equal to or greater than -10 dB, almost 32 per cent RSRQ values observed to be less than -10 dB and equal to or greater than -15 and almost 17 per cent RSRQ values observed to be less than -15 dB and equal to or greater than -20 shown in Figure 33. The RSRQ ranged from 4 dB to -20 dB using the BG96 module.

For the kDC-5737 dongle, *Poor* RSRP and RSSI have been observed in Figures 27 and 29, respectively. Since both the RSRP and the RSSI are *poor*, hence the SINR values significantly affect the received signal level. Almost *fair* SINR has been featured in Figure 31 throughout the test coverage area. As a result, almost *excellent* level of RSRQ is observed in the marked area from PCI 60 shown in Figure 33.

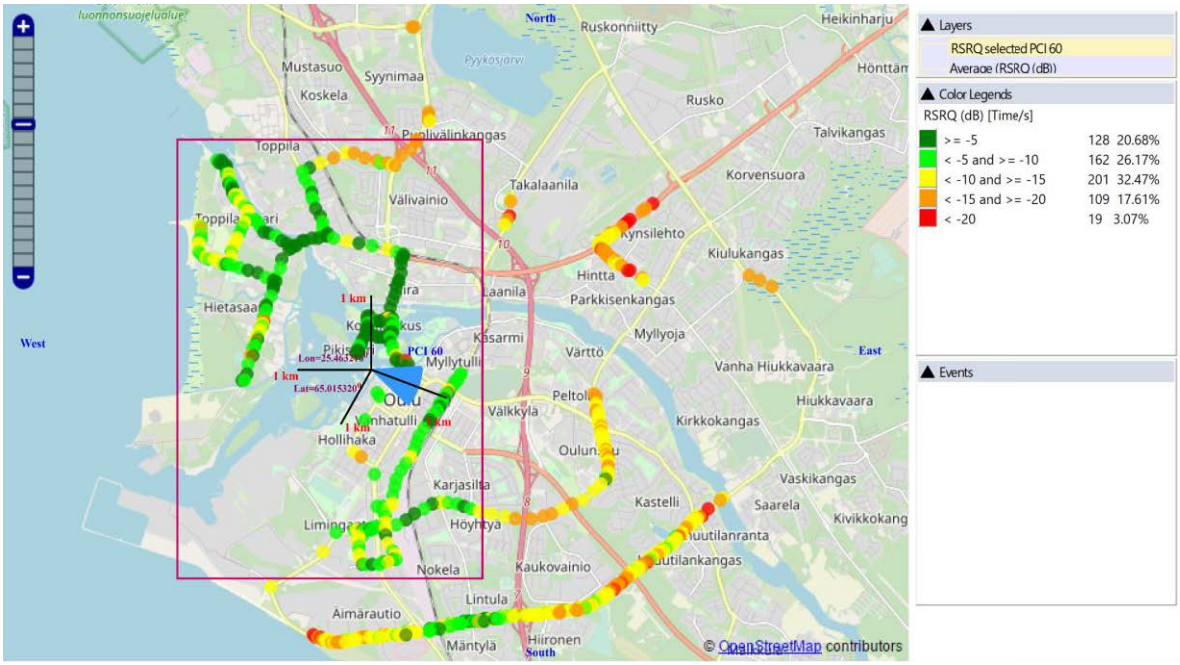

Figure 33. RSRQ values of PCI 60 using kDC-5737 dongle.

For better understanding the effect of RSRQ, three points have been taken shown in Figure 34. Since those three points are the same distance for the Figures 28, 30 and 32. In point, A the measured RSRP, RSSI and SINR values are -101 dBm, -96 dBm and 21 dB. The RSRP and the RSSI are at *poor* level, while the SINR is in *excellent* level according to KPIs values for NB-IoT presented in Table 6. As a result, despite of *poor* RSRP and RSSI *good* level of RSRQ is observed in point A shown in Figure 34, because of *excellent* SINR.

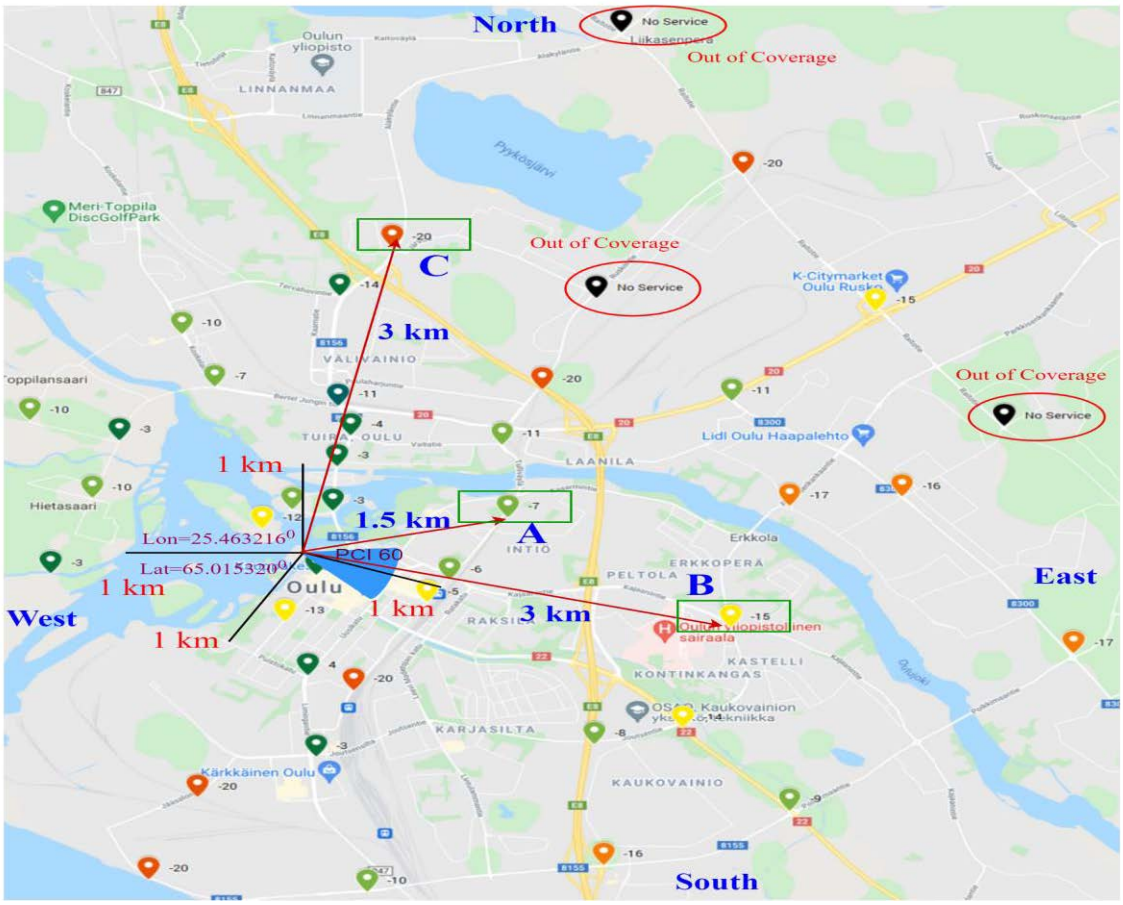

Figure 34. RSRQ values of PCI 60 using BG96 module.

6 DISCUSSION

The measurement results are presented in the previous section for each PCI in order of RSRP->RSSI->SINR->RSRQ. These four KPIs have been measured using the Quectel BG96 module and Qualcomm kDC-5737. These measurement results provide the values of the RSRP, RSRQ, RSSI and SINR of different locations for three PCIs. These four results illustrate network coverage performance, signal strength, signal and radio channel quality, and user's communication performance of NB-IoT technology in different places. The key focus of this work was to find out the signal quality of three PCIs implementing NB-IoT technology.

A suitable measurement setup was proposed for the Quectel BG96 including the Quectel BG96 module, one laptop with installed QNavigator software, one 4G supported sim card and USB cables for connection. A SIM card, one laptop with installed Nemo outdoor tool, one GPS receiver, USB cables and NB-IoT data terminal were used for the measurement setup of the Qualcomm kDC-5737 dongle.

There were some challenges while taking measurements. The device setup and the antenna connection of the Quectel BG96 module should be made very carefully. Displacement or inaccuracy of antenna position might affect the received signal strength at the receiver end. So, after a while, the antenna connection of the Quectel BG96 module should be checked, and one should make sure that the antenna is in the right place away from the body to avoid body interference. The Qualcomm kDC-5737 dongle should be placed and operated with a minimum distance of at least 20 cm from the body. During the measurement, the GNSS of the BG96 module was not working, so that measurements were taken using Google Maps GPS coordinates to measure the latitude and longitude of certain places. So, the slight variation of position accuracy might have happened. There was no antenna attached to the outside of the moving car during the drive test. So that, some variation may have in the measured signal strength parameters.

The kDC-5737 dongle experienced high non-line of sight (NLOS) propagation effects in three red marked points than all green points in Figure 17. No outage coverage points have been seen in the PCI 46 using the kDC-5737 dongle. On the other hand, two out of coverage points have been observed using the BG96 module in the South. It is noticeable that the horizontal beamwidth of this following PCI directed towards the South. High rise buildings exist between the PCI 46 and the two outage coverage points shown in Figure 18. The BG96 module experienced maximum NLOS propagation effects near these two outage coverage points. As a result, the nearest points of marked outage points feature *poor* RSRQ levels shown in Figure 18. So, PCI 46 needs coverage optimization in the South direction.

The kDC-5737 dongle experienced high NLOS propagation effects in the red marked points in Figure 25 for PCI 50. So, the red marked points indicate *poor* RSRQ, while the green marked points feature *good* RSRQ levels. Twenty outage coverage points were observed using the kDC-5737 dongle from the base station in the North and South direction. It is remarkable that the horizontal beamwidth of PCI 50 directed towards the North. Four out of coverage points have been observed both in the South and North direction using the BG96 module. So, PCI 50 requires coverage optimization in the North and South directions.

Wide and high buildings exist between the PCI 60 and all the test points of the Southeast direction. On the other hand, detached and semi-detached houses exist beside the river in the West direction of PCI 60. So, the kDC-5737 dongle experienced less NLOS propagation effects in the West direction than the Southeast direction from the base station. As a result, most of the test points feature *good* level of RSRQ in the marked area of the West direction from PCI 60 shown in Figure 33. The signal quality indicator is widely used to interpret the interference over

the communication between the NB-IoT device and the base station. Twenty-five outage coverage points were observed using the kDC-5737 dongle in the North, East, and South directions from the base station. Using the BG96 module, three outage coverage points have been observed in the North and East directions from the base station. So, PCI 60 needs coverage optimization in the North, East, and South directions even though the horizontal beamwidth of PCI 60 directed towards the Southeast direction.

For the case of PCI 46, 50 and 60 closest points featured *excellent* RSRP for both devices. In the case of the BG96 module, the closest points from the base station showed *excellent* SINR, while the rest of the test points featured *fair* to *poor* SINR throughout the coverage area under three PCIs. All test points featured *fair* SINR throughout the coverage area for the kDC-5737 dongle under three PCIs. Almost all the RSSI test points featured *poor* levels for the kDC-5737 dongle throughout the coverage region of PCI 50 and 60, while under PCI 46, RSSI test points was *excellent*.

In the case of PCI 46, the results of the BG96 module were not consistent with the results of the kDC-5737 dongle. The kDC-5737 experienced *excellent* signal strength compared to the BG96 module throughout the test location area of PCI 46. On the other hand, both devices consistently achieved almost the same results during the measurement under PCI 50 and 60.

The measurements results estimate the key NB-IoT performance metrics radio channel quality, signal strength, and communication performance of NB-IoT technology. Due to the limited number of measurements, all aspects of the different behaviour of the signal strength and quality for both devices could not be captured. Improvement of the accuracy is possible by taking more extensive measurement campaigns. Another perspective direction for improving different KPIs is the optimization of the network planning and configuration.

7 SUMMARY

The thesis work studied coverage measurement of NB-IoT technology in 5GTN. Several measurements have been taken through two devices with different parameter configurations under three different PCIs. Network KPIs have been analysed to estimate the NB-IoT signal strength and network coverage range. Several key performance indicators such as RSRP, RSRQ, SINR and RSSI have been measured and analysed through drive test. All the measurements have been conducted at different locations in Oulu, Finland.

The signal strength and network coverage of NB-IoT technology have been measured at different places under the three 5GTN base stations in Oulu, Finland. Drive tests have been conducted to measure the signal strength, quality, and network coverage performance of NB-IoT technology using the Quectel BG96 module, Qualcomm KDC-5737 dongle, and Keysight Nemo Outdoor software. Overall network coverage performance has been checked by finding the values of RSRP, RSRQ, RSSI, and SINR at different locations within several kilometres of the 5GTN base stations. The signal quality and the network coverage of different PCIs show the performance for outdoor scenarios of the 5GTN base stations in NB-IoT technology.

Almost *excellent* RSRP, RSRQ, and *fair* SINR have been observed in PCI 46 using the kDC-5737 dongle. Using the BG96 module, overall *Poor* levels of RSRP, RSRQ and SINR have been observed in the following PCI 46 throughout the test location area. So, using the kDC-5737 dongle, overall network coverage of the following PCI 46 meets the desired goal of at least *good* signal strength and quality.

In the case of PCI 50 and 60, *poor* RSRP and RSSI, *fair* SINR and RSRQ have been observed using both devices. So, both devices show almost the same identical behaviour for PCI 50 and 60. The overall network coverage of PCI 50 and 60 do not meet the desired goal of at least *good* signal strength and quality throughout the coverage area.

Any device without a network connection is considered out of coverage. The importance of network coverage is immense in ensuring network connectivity. Minimum RSRP is required to ensure network connectivity. The network coverage performance of a particular PCI can be determined by considering RSRP values. If the RSRP is at *good* level, then good signal quality can be obtained. Although the higher value of RSRP does not necessarily indicate better signal quality. Good signal quality can be obtained depending on the values of SINR, even though for *poor* RSRP values. A *good* level of SINR indicates less amount of noise and interference in the received signal. In the case of different PCIs of 5GTN base stations, the network signal strength and quality have not been observed according to desired levels after several kilometres from the base station. So proper network planning and optimization can enhance signal strength, radio channel quality, and user's communication performance.

The 5GTN offers several RAN technologies, including LTE-M, 5G NR and NB-IoT. 5GTN based NB-IoT networks have the capability to serve various innovative IoT applications. 5GTN based NB-IoT network addresses the 5G use cases of massive machine type communication (mMTC). This network is designed to support the analysis and development of upcoming wireless communication technologies, widely used for the research and development activities carried out by the University of Oulu. The 5GTN will be extended by bringing more applications and adding new connectivity solutions into it. Future work will include collecting and analysing further measurements data in both outdoor locations and indoor environments aiming for the extension of this work.

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