Adis Ababa University
Addis Ababa Institute of Technology
School of Electrical and Computer Engineering
Communication Engineering Graduate Program

Quality Assessment for 5G Enhanced Mobile Broadband Service in Addis Ababa

by:

Mubarik Ahmed Beshir

Advisor:
Beneyam Berehanu Haile (PhD.)

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master's Science in Communication Engineering

October, 2024

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
COMMUNICATION ENGINEERING GRADUATE PROGRAM

Quality Assessment for 5G Enhanced Mobile Broadband Service in Addis Ababa

by:

Mubarik Ahmed Beshir

Approval by Board of Examiners	Signature	Date
Chairman, School Graduate Comittee:	____________	____________
Advisor's Name:	____________	____________
Internal Examiner's Name:	____________	____________
External Examiner's Name:	____________	____________

Declaration

I declare that this thesis is entirely my own work and does not include any content from other educational institutions without proper acknowledgment. To the best of my knowledge, it does not contain previously published material by another person without recognition.

Name of the Student	Signature	Date
Mubarik Ahmed	____________	____________

This thesis has been submitted for examination with my approval as a university advisor.

Name of the Advisor	Signature	Date
Beneyam Berehanu (PhD.)	____________	____________

Addia Ababa, Ethiopia

ABSTRACT

The worldwide telecom industry is moving toward 5G network to address high bandwidth, low latency, and massive connectivity requirements. The recent deployment of 5G NR technology in Ethiopia promised to transform the speed and quality of MBB services in majority of the business districts and selected residential areas of Addis Ababa.

To achieve expected outcomes from this new 5G network, its quality and perception of customers should be evaluated in its early stage. This will enable timely and informed measures by subscribers, mobile network operators, mobile device manufacturers, the regulatory authority, ECA, and other stakeholders. In this thesis, spatiotemporal evaluation of QoS metrics-download throughput, upload throughput and latency-is conducted using crowdsourcing application, Ookla SpeedTest, Network performance reporting system, PRS and drive test tool, PHU. A subjective survey is used to assess user experience.

Despite the significant disparity in 5G coverage, result from all four sources indicate that 5G eMBB service performance in AA is very good as compared to average global 5G performance and IMT-2020 minimum technical requirements. Overall average download throughput obtained is 364 Mbps from SpeedTest, 311 Mbps from PRS and 414 Mbps from PHU. And average upload throughput is 58 Mbps from SpeedTest, 20 Mbps from PRS and 89 Mbps from PHU. From subjective survey, MOS on the overall performance of 5G eMBB service in AA is 4.1. The results also show a consistent trend regarding the impact of spatiotemporal and device variations on the performance of 5G network.

Key Words: **5G New Radio, QoS, User Experience, Network Management System, eMBB, Mean Opinion Score, Throughput, Latency**

Acknowledgments

Above all, I thank Allah, the Almighty, for giving me the wisdom and skill to carry out my thesis work.

I would like to express my sincere gratitude to my advisor Beneyam Berehanu (PhD.) for his dedication, guidance, expertise, insightful feedback, and significant contribution to the completion of this thesis. I would also like to thank my evaluators, Yihenew Wondie (PhD.), Murad Ridwan (PhD.) and Yalemzewd Negash (PhD.) for their valuable feedback during the thesis progress presentations.

My special thank goes to my dear wife, Kemeriya Ridwan for her unwavering support, encouragement, and patience throughout my studies. My heartfelt gratitude extends to Yimer Eshetu, Alexander Behailu, and Addisu W. for their collaborative spirit and vital support in providing the necessary resources and data. Their contributions have been instrumental in shaping this work.

To everyone mentioned above and to those whose names may not appear here but have contributed in various ways, thank you. This thesis stands as a collective effort, and I am grateful for each of you.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

ISP	Internet Service Providers
gNB	Next-Generation Node B
ITU	International Telecommunication Union
MNO	Mobile Network Operatorl
KPI	Key Performance Indicators
LTE	Long-Term Evolution
MOS	Mean Opinion Score
MSE	Mean Squared Error
MIMO	Multiple Input, Multiple Output
NMS	Network Management System
QoE	Quality of Experience
QoS	Quality of Service
RMSE	Root Mean Squared Error
MBB	Mobile Broadband
SMS	Short Message Service
SDN	Software Defined Network
UE	User Equipment
4G	Fourth Generation
5G	Fifth Generation
5GC	5G core
eMBB	Enhanced Mobile Broadband
URLLC	Ultra Reliable Low Latency Communication
mMTC	Massive Machine Type Communication
NSA	Non-Standalone
PHU	Probe Handset Unit
PRS	Performance Reporting System
MLR	Multivariate Linear Regression
SVR	Support Vector Regression
MAPE	Mean Absolute Percentage Error
NMS	Network Management System
OFDMA	Orthogonal Frequency Division Multiple Access

OFDMA	Orthogonal Frequency Division Multiple Access
Mbps	Mega bits per second
PDN	Packet Data Network
P-GW	PDN Gateway
PCC	Policy & Charging Control
PCEF	Policy Control Enforcement Function
PCRF	Policy Control and Charging Rules Function
PDU	Protocol Data Unit
AA	Addis Ababa
QCI	QoS Class Identifier
IMT-2020	International Mobile Telecommunications-2020
ms	milliseconds
AF	Application Function
AQoS	Application-level QoS
NQoS	Network-level QoS
SEM	Stractural Equation Model
DT	Drive Test
RF	Radio Frequency
IoT	Internet of Things
VR	Virtual Reality
AR	Augmented Reality
RAN	Radio Access Network
AMF	Access and Mobility Management Function
DT	Data Networks
SMF	Session Management Function
UPF	User Plane Function
AUSF	Authentication Server Function
PCF	Policy Control Function
UDM	Unified Data Management
SA	Standalone
NFV	Network Function Virtualization
MEC	Mobile Edge Computing
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
NG-RAN	Next Generation Radio Access Network

Chapter 1: **Introduction**

1.1 Background

Main drivers for the evolution of mobile networks in the past were mobile voice, messaging, and internet access. The focus was on end consumers equipped with traditional handsets or smartphones.

Consumer demand for mobile broadband services continues to rise with an ever-growing appetite for bandwidth that is needed for 4K and 8K video streaming, augmented reality(AR), virtual reality(VR), and mixed reality(MR) among other use cases [4]. Globally, this growth in mobile data traffic can be attributed to three main drivers:

- Improved device capabilities,
- An increase in data-intensive content, and
- Growth in data consumption due to continued improvements in the performance of deployed networks.

As shown on global mobile data traffic outlook from 2023 to 2029 by Ericsson [5], total global mobile data traffic is expected to grow from 136 EB in 2023 by a factor of around 3.5 and reach 466 EB per month in 2029. 5G's share of mobile data traffic was 25%

at the end of 2023, an increase from 17% at the end of 2022. This share is forecast to grow to around 75% in 2029.

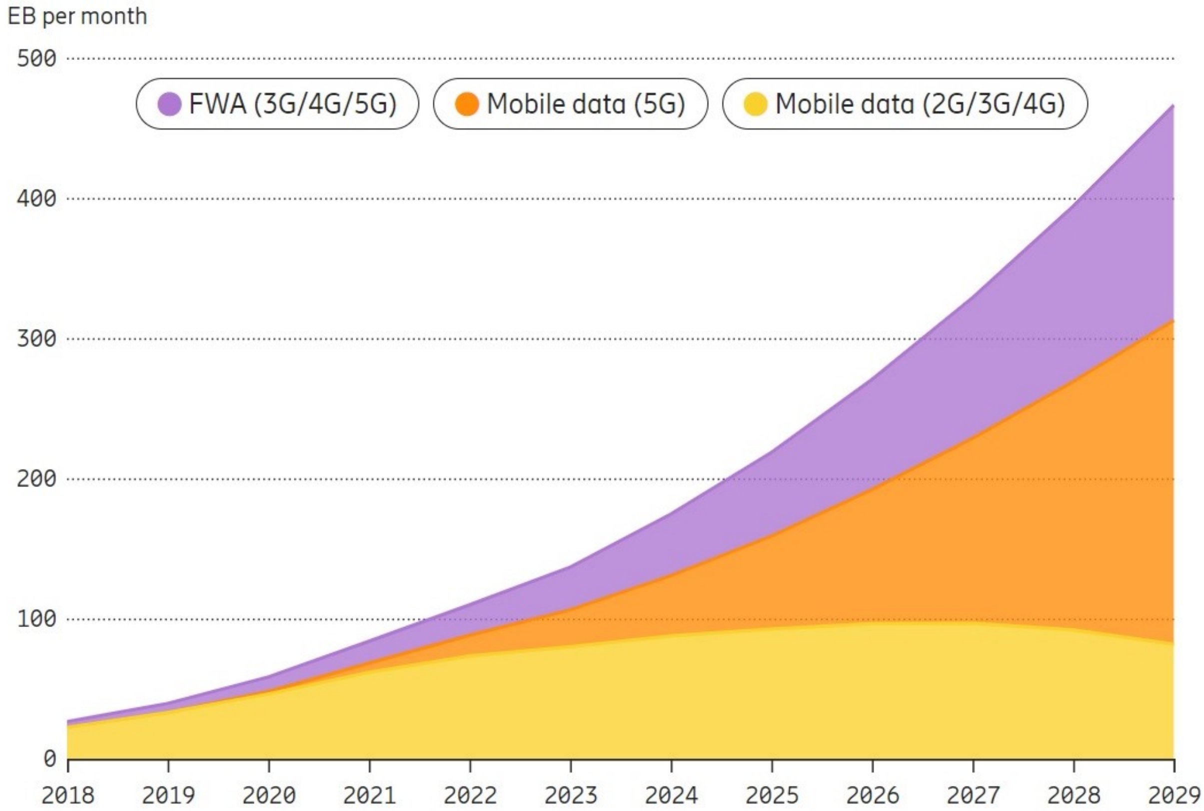

Figure 1.1: Global mobile network data traffic forecast

As indicated in ITU datahub [6], number of MBB subscribers is growing rapidly in Ethiopia as well. Figure 1.2 below summarizes this growth from 2009 to 2023 and shows the rate at which MBB demand is increasing.

The telecom sector in Ethiopia has been under the monopoly of the state-owned operator, Ethio Telecom, since its inception in 1894. In response to the increasing demand for improved service quality and to better meet customer needs, the Ethiopian government initiated the liberalization of the telecom market in 2020. As a result of this policy change, Safaricom Ethiopia commenced its commercial operations in the country in August 2022.

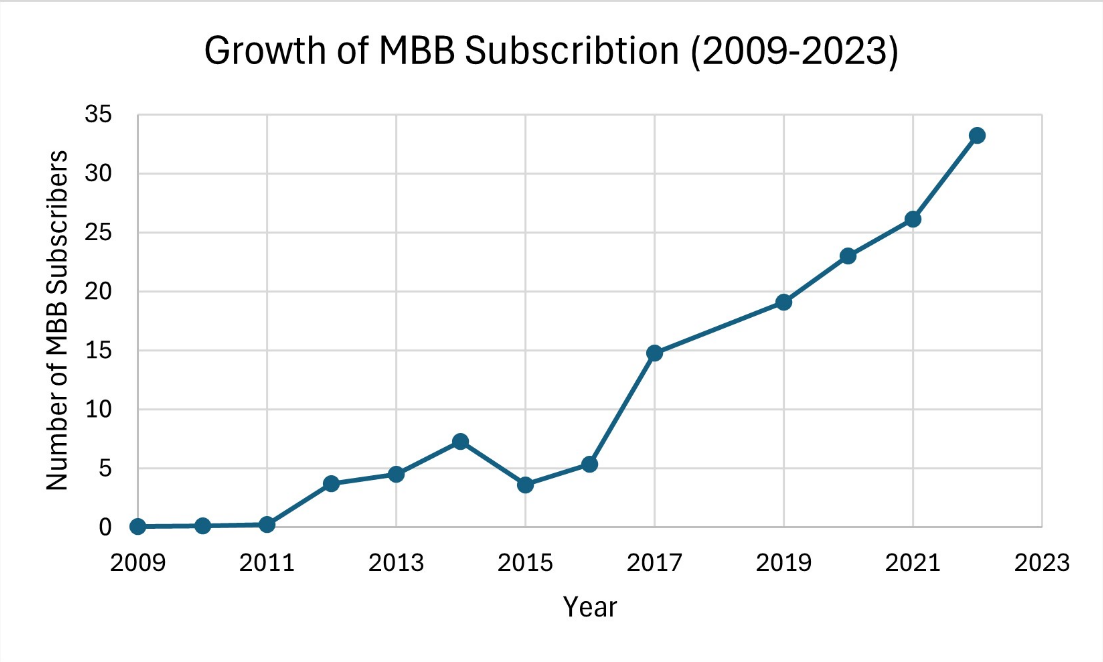

Figure 1.2: Mobile Broadband subscription Growth in Ethiopia

To serve the rapidly growing number of mobile broadband customers in Ethiopia, enhancing coverage and expanding capacity on existing 3G and 4G technologies is insufficient as argued by authors in [7]. Considering this and other factors, Ethio Telecom launched 5G eMBB service in Addis Ababa on September 10, 2023. So far, Safaricom has not launched 5G services in Ethiopia.

1.2 Statement of the Problem

5G network is developed to address high bandwidth, low latency, and massive connectivity requirements. The recent deployment of 5G NR technology in Ethiopia promised to transform the speed and quality of mobile broadband services in majority of the business districts and selected residential areas of Addis Ababa.

Many projects have been deployed to enhance mobile capacity and coverage on 3G and 4G networks all over Ethiopia. However, within a short period of these expansions, data from customer service and other sources shows that customers are not satisfied with the services. Different studies [7, 8], also indicate that user side QoS and QoE on these services were not satisfactory.

It is important to evaluate user side QoS and user experience to determine whether similar situations arise with the recently deployed 5G network in Addis Abeba. This will be very helpful in carrying out timely marketing, network optimization, and other essential tasks. On the other hand, many studies [8–10] have been carried out to evaluate user side QoS measurment techniques and tools for UMTS and LTE services in Addis Abeba, but no such study has been carried out for 5G network.

In this thesis, the first ever user side QoS measurement is carried out on commercial 5G network in Addis Abeba under various environmental conditions, such as open space with clear line of sight, outdoor crowded space with high-rising buildings , mobility or driving and indoor conditions. Additionally, user experience assessment is done to link customer side QoS with user perceptions. With this understanding, this thesis aims to address the following research questions:

1. Does the performance of 5G network in Addis Abeba comply with industry standards?
2. Is there variation of performance in 5G network with change in spatiotemporal conditions?
3. Is there variation of performance in 5G network with change in mobile device?
4. What do users perceive about 5G network in Addis Ababa?

5. What are the major factors affecting 5G user experience?

1.3 Literature review

Studies from domestic as well as global researchers are examined in depth. First, research on QoS and user experience for 3G and 4G services in Ethiopia are discussed. Then, research done on relevance of 5G technology to the Ethiopian telecom market is presented. Finally, studies regarding commercial 5G network QoS and user experience evaluation at the global level are discussed.

Author in [8] evaluates the mobile data QoS measurement tools and factors using download speed, upload speed, and latency performance metrics on 4G LTE mobile network in Addis Ababa. Measurement of the performance metrics using Ookla Speedtest, RTRNetTest, and Nemo Handy-A are analyzed using Mean Absolute Percentage Error (MAPE). It concludes that Nemo does not measure the performance of the LTE data service in real time as the customer experience it. ISP should consider assessing the quality of the measurement technique used.

Video streaming QoE assessment model using machine learning techniques are studied in [10] to estimate user-perceived experience in LTE network. The model predicts perceived QoE in a Mean Opinion Score (MOS), by evaluating Network QoS, Application-level QoS (AQoS) and contextually formulated survey questionnaire. The models take Network QoS metrics such as upload bit rate and download bit, latency and jitter, and packet loss. Content type and resolution also considered from the application level. Contrary to existing models for QoE prediction, the proposed model gives a good estimation of the perceived quality.

On [7], detailed QoS and QoE evaluation for Addis Ababa UMTS data service including both network quality perspectives and user side perception focused on selected enterprise customers are presented. The evaluation is made based on download throughput, upload throughput and latency quality metrics collected from network management system (NMS), indoor walk test, crowdsourcing test using RTR-NetTest tool and contextually formulated survey questionnaire. In general, achieved throughput and latency results show that both QoS and QoE are not good and there is dissatisfaction of customers. The quantitative results are reflected in the perception result of the participants where a Mean Opinion Score value of 2.65 for the satisfaction of downloading files or video/music is achieved.

Paper [11], published in Ethiopia three years before the launch of commercial 5G network in the world, argues that slight changes in mobile users' income and data pricing could pose a threat to mobile capacity by briefly presenting the worldwide and Ethiopian mobile data consumption evolution and a simple empirical study to Addis Abeba mobile data market. A brief explanation of prospective 5G technologies that could increase capacity is also given, along with how they would increase mobile capacity. This study highlights the need for a comprehensive national road-map for capacity-enhancing technology that is based on high-quality studies relevant to the local environment.

There hasn't been any research, as far as the author of this thesis is aware, on user experience and quality of service for 5G users in Ethiopia. However, a lot of researchers looked into user experience and QoS in many different countries such as U.S., Thailand, Italy, Oman and Indonesia.

QoS measurement study is performed on commercial 5G network of three MNOs in three U.S. cities in [12]. Hand off mechanisms in 5G and their impact on network performance is systematically analyzed. It explores the feasibility of using location and possibly other environmental information to predict the network performance. In addition to the measurement findings, the study identifies key research directions on improving 5G users' experience in a cross-layer manner

Author in [13] compares two of the leading mobile network operators in Thailand's telecom market in terms of the service quality of Thailand's 5G networks. Three factors, download speed, upload speed and latency were examined to indicate the quality of internet networks. The researchers employed the test results to determine an average grade of service that was reached by comparing newly collected data to data that had previously been examined utilizing the same format and application in the middle of May 2021.It was established that the results delivered considerably enhanced quality values even though the test region in this study only comprised BTS stations.

In paper [14], large-scale measurement study was performed on commercial 5G Non-Standalone (NSA) deployments in a European country. It leverages the collected dataset, which covers two Mobile Network Operators in Rome, Italy to first, study network deployment and radio coverage aspects, and second, explore the performance of two use cases related to eMBB and URLLC. Results show that 5G NSA can provide higher downlink throughput and slightly lower latency compared to 4G systems. However, performance is influenced by several factors, including propagation conditions, system configurations, and handover events, ultimately highlighting the need for further system optimization.

In paper [15], the performance of the 5G network of two MNO in Thailand at two of the most popular tourist destinations in Bangkok, were evaluated. The results showed that 5G quality of service (QoS) at these two landmarks was significantly lower than the typical performance at BTS Skytrain stations located in the business districts. Additionally, even though these two landmarks are located close to each other, there was a significant difference in 5G QoS between the two.

Authors in [16], provided an overview of MBB networks in terms of deployment environments, performance metrics, and implementation scenarios. They provided measurement-based performance analyses of two existing MNOs Omantel and Ooredoo, in the sultanate of Oman. This performance analysis uses data measurements in various indoor and outdoor environments in five cities. Several performance metrics are considered, such as signal level and quality, throughput, ping rate, and handover. Experimental results demonstrate that the 4G networks were the dominant networks in all measured locations for indoor and outdoor scenarios. Moreover, 5G data measurements are also recorded in the capital city of Oman, Muscat. The results of the 5G measurements show that both MNOs achieved a higher data rate with a lower ping rate.

The study in [17], aimed to discover what factors would influence 5G user experience by using a conceptual framework involving measures of users' predictive judgements of 5G combined with users' measurements of current 4G user experience. The conceptual framework utilized the structural equation model (SEM) approach, based on the primary data of a 254-respondent sample of the Indonesian market. The results imply that the current user's experience of 4G has an effect with a significance value of 0.42 to their later experience when accessing 5G video services. The above literature reviews are summarized on Table 1.2.

Reference	Objective	Methodology	Result
[10], 2021	To evaluate 4G LTE user-side QoS measurement techniques & tools in the case of AA.	Metrics: throughput and latency Tools: Nemo Handy-A forDT, and RTR-NetTest and Ookla Speedtest for CS measurement.	Measurement error of the Nemo Handy-A is less than other tools in all parameters. But it costs time, money and unfair representation of measurement area.
[2], 2018	To study & compare user side QoE measurement techniques for AA LTE data service	Metrics: throughput and latency. Tools: Nemo handy, Opensignal and speedtest and Survey for QoE. Analysis done using actix, Matlab and excel.	Latency: SpeedTest and Nemo Handy have minimum difference. DL throughput: OpenSignal & Nemo Handy have minimum difference.
[7], 2020	To evaluate performance of two ML algorithms (MLR & SVR) in predicting video streaming quality	Metrics: throughput, latency, jitter and packet loss. Tools: nPerf, Survey & Python software	SVR is recommended for quantifying the user's perceived quality. It shows a high correlation and low MSE between the measured and the predicted QoE.
[4], 2017	To argue mobile capacity could face a challenge in near future and give insight on potential capacity enhancing 5G technologies.	A simple empirical argumentative analysis using straightforward excel-based calculation to compare network data capacity with forecasted data demand results.	Mobile capacity will face a challenge in near future with small changes in user's income and data price.
[3], 2020	To study performance of commercial 5G network in 3 US cities: Minneapolis, Chicago and Atlanta.	Metrics: DL/UL throughput and latency. Tools: Two smartphones & iPerf. Intensive measurement conducted on three MNOs: VZ, T-Mobile and Sprint.	All cloud servers exhibit low throughput compared to the iPerf throughput. The average throughput ranges from 119 to 730 Mbps with a median of 222 Mbps across all servers.

Table 1.1: Summary of Literature Review

1.4 Objective

1.4.1 General Objective

General objective of this thesis is spatiotemporal evaluation of QoS and user experience for 5G eMBB service in Addis Ababa.

1.4.2 Specific Objectives

Specific objectives of the thesis include:

- To analyze 5G user side QoS measurement tools and select the best one.
- To perform measurements using identified tools on selected spatiotemporal conditions.
- To evaluate 5G network performance variations with change in spatiotemporal conditions.
- To assess experience and perception of 5G users with questioner.
- To analyze correlation of QoS data with subjective user experience result.
- To enable subscribers, mobile network operators, mobile device manufacturers, the regulatory authority, ECA, and other stakeholders to take timely and informed measures on 5G network in AA.

1.5 Methodology

The methodology employed in this thesis includes the selection of 5G QoS measurement metrics, the selection of mobile devices and measurement tools, as well as the execution of a field measurement campaign and a survey utilizing a questionnaire. This research primarily focuses on the most pertinent QoS measurement metrics, specifically download throughput, upload throughput, and latency. Two distinct smartphone models have been chosen for this study: Samsung Galaxy A53 5G and iPhone 12 Pro Max. User side QoS and QoE data are collected from four different sources:

1. Field measurement campaign using Oakla SpeedTest
2. Performance reporting system (PRS)
3. Drive test data using probe handset unit (PHU) and
4. Subjective survey with questionnaire

The field measurement campaign and system side data collection is performed by considering different spatial and temporal conditions. The spatial scenarios considered are:

- Outdoor open space with clear LoS between UE and RF pane.
- Outdoor crowded space with high surrounding building and obstructions between UE and RF panel.
- Mobility or driving condition on vehicle with speed between 20 to 50 km/h and
- Indoor condition with non-LoS between UE and RF panel.

Two temporal scenarios are considered to incorporate low and high traffic hours of the day. To see performance of 5G in low traffic hour, morning time from 9:00 AM to 12:00 is considered and afternoon from 2:00 to 5:00 is considered to observe the performance in high traffic hour.

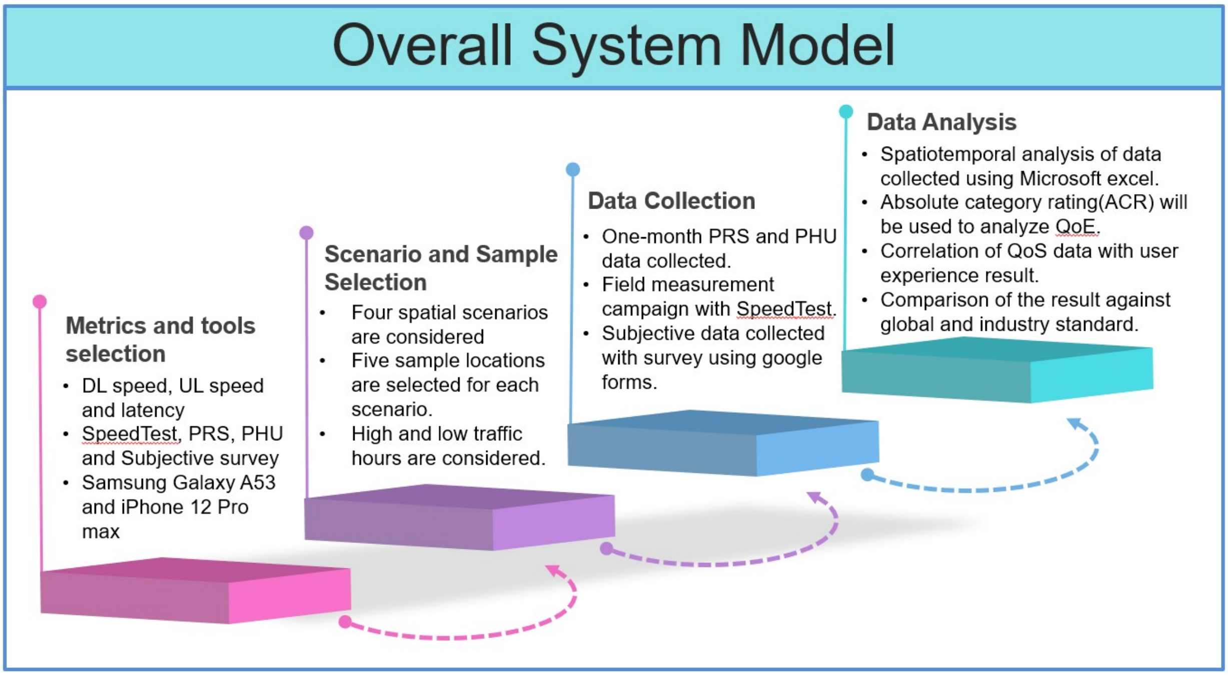

Figure 1.3: Overall System Model

A subjective survey questionnaire has been employed to evaluate the perceptions of 5G users in AA. The methodology and key actions to be undertaken are outlined in the figure below:

1.6 Scope

The scope of this thesis is to evaluate user side quality of service and user experience for 5G eMBB service in Addis Ababa. Since Safaricom has not launched 5G service in Ethiopia, only the Ethio Telecom 5G network is considered in this thesis.

1.7 Thesis Contribution

As far as the knowledge of the author of this thesis is concerned, most of stakeholders including mobile network operators, Ethiopian Communication Authority, mobile device manufacturers, etc. have no end-to-end user side QoS and user experience data of newly deployed 5G network in Addis Ababa. This thesis contributes to all stakeholders by:

- Investigating the trend and gaps on measuring user side QoS and user experience for 5G network and giving insight about areas which need improvement.

- Studying performance of 5G network in Addis Ababa using QoS measurement and user experience assessment to shed light on 5G network performance on the ground for further marketing, optimization, and other necessary actions.

- Analyzing 5G performance variation due to mobility, blockage and change in mobile device.

- Providing early-stage benchmark data for further 5G QoS and QoE related studies in Ethiopia.

Chapter 2: **Overview of 5G Network**

2.1 Introduction to 5G Network

As opposed to previous generations of mobile networks that targeted only mobile phones and one type of user, the 5G network needs to serve a diverse set of devices and applications from super secured and expensive phones for security forces to cheap and dumb IoT devices. Furthermore, the same device may host or relay very different applications ranging from resilient voice services to simple IoT services [18]. Consumer needs for more bandwidth continue to increase, with virtual and augmented reality leading the way toward connections with ultra-high bandwidths and very low latency. The challenge for the network operator is to deploy a network with these characteristics at reasonable costs. The most challenging part is to provide it cheaper than previous generation of networks [4].

In addition to enhancing the experience for the several billion people who are already connected, it is imperative to link the unconnected people and things and, in certain situations, provide 5G in place of fixed access. 5G is beneficial to have a system that enables providing essential functions at minimal complexity and costs [4]

According to M.2083, 5G IMT-2020 applications fall into the following three broad usage scenarios as illustrated in Figure 2.1 below [19]:

- Enhanced Mobile Broadband (eMBB)
- Ultra Reliable Low-Latency Communications (URLLC)
- Massive Machine Type Communications (mMTC)

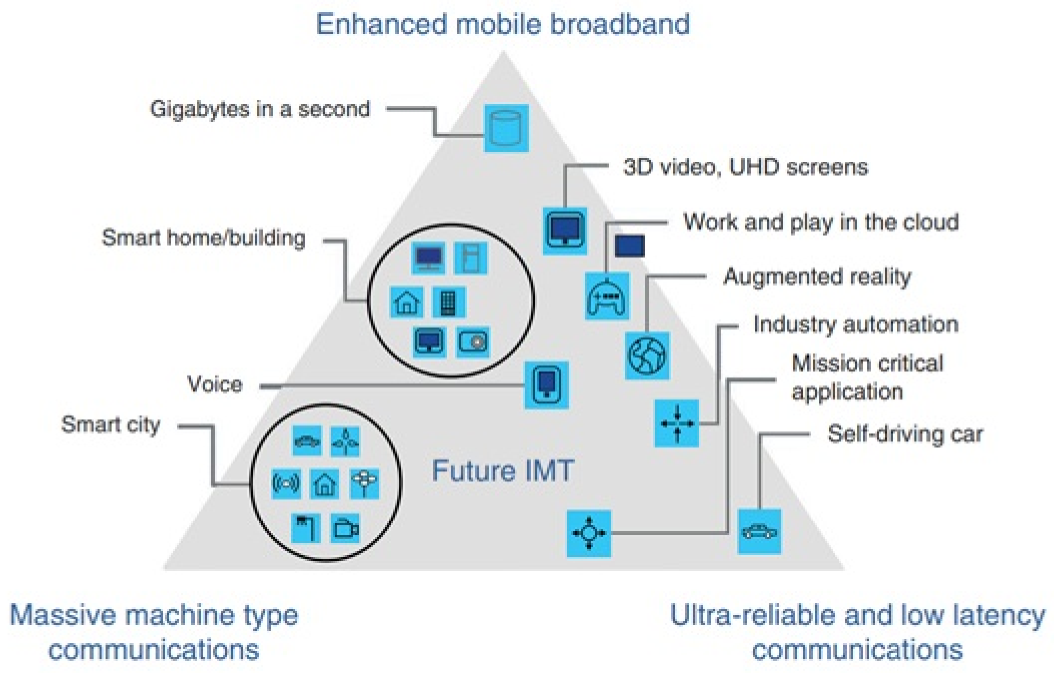

Figure 2.1: Broad Usage Scenarios of 5G

A short summary of 5G technical performance requirements, shown in Table 2.1., can be used to illustrate how 5G differ from 4G [19]

	IMT-Advanced (4G)	**IMT-2020 (5G)**
Minimum peak bitrate	DL: 1Gbps UL: 0.05Gbps	DL: 20Gbps UL: 10Gbps
Mobility	350km/h	500km/h
User plane latency	10ms.	1ms.
Connection density	100K devices per km2	1M devices per km2
Traffic capacity	0.1Mbit/s/m2	10Mbit/s/m2 in hot spots
Frequency bandwidth	Up to 20MHz/carrier	Up to 1GHz

Table 2.1: QoS comparison between 4G and 5G

2.2 5G Network Architecture

The 5G system architecture is built around network functions that are the smallest set of functionalities deployable in a multi-vendor environment. Internal interfaces, structures and contexts within a network function are not subject to standardization. Figure 2.2. below shows the non-roaming architecture model.

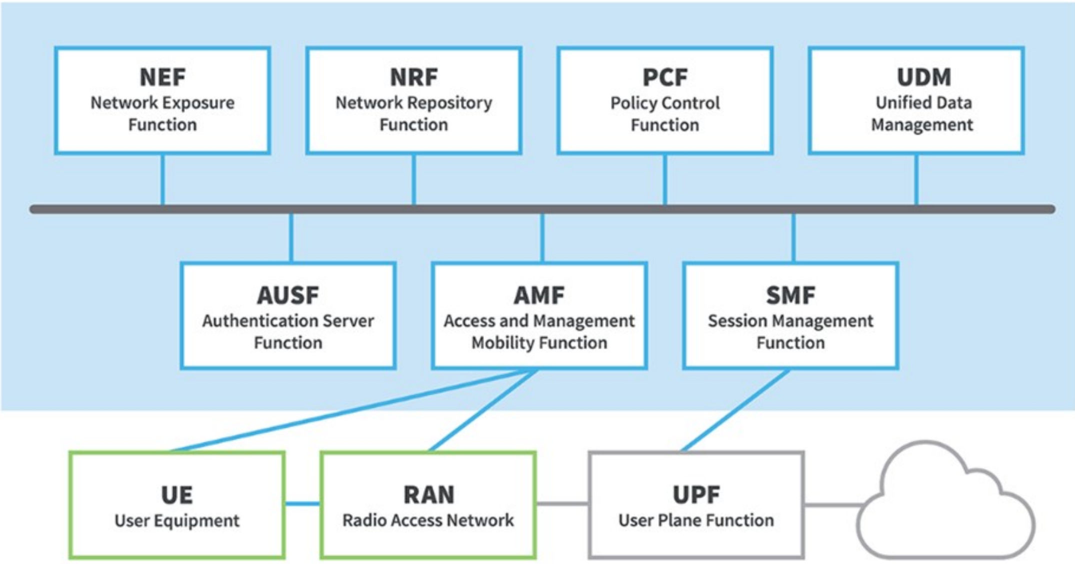

Figure 2.2: 5G network architecture [1]

Working principles and functions of each block are described as follows [1]:

- User Equipment (UE) connect over the 5G New Radio Access Network to the 5G core and further to Data Networks (DN), like the Internet.
- The Access and Mobility Management Function (AMF) acts as a single-entry point for the UE connection.
- Based on the service requested by the UE, the AMF selects the respective Session Management Function (SMF) for managing the user session.

- The User Plane Function (UPF) transports the IP data traffic (user plane) between the User Equipment (UE) and the external networks.

- The Authentication Server Function (AUSF) allows the AMF to authenticate the UE and access services of the 5G core.

Other functions like the Session Management Function (SMF), the Policy Control Function (PCF), the Application Function (AF) and the Unified Data Management (UDM) function provide the policy control framework, applying policy decisions and accessing subscription information, to govern the network behavior.

2.3 5G Network Deployment Scenarios

There are two types of deployment modes for 5G technology. These are standalone and non-standalone deployments [2]. The 5G non-standalone standard was finalized in late 2017 and utilizes existing LTE RAN and core networks as an anchor, with the addition of a 5G component carrier. 5G deployment from the ground up with the new core architecture and full deployment of all 5G hardware, features, and functionality is known as standalone deployment [2].

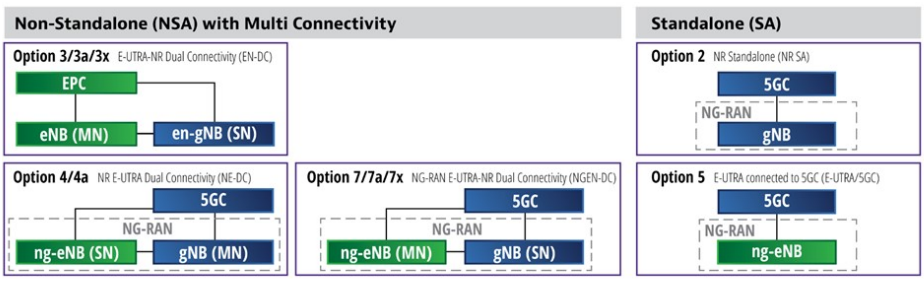

Figure 2.3: 5G deployment scenarios [2]

2.4 Key 5G Technologies

2.4.1 Network Function Virtualization (NFV)

With NFV, network operators can deploy various network functions, such as firewalls or encryption, on virtual machines (VMs). Whenever a user requests a new network function, the network operator will deploy a VM for the requested function automatically. NFV enables network slicing, a virtual network architecture that allows multiple virtual networks to be created atop a shared physical infrastructure [20].

2.4.2 Software Defined Network (SDN)

SDN moves the control plane away from network hardware and enable external control of the data plane through a logical software entity called a controller. SDN is a new architecture that allows dynamic reconfiguration of the network. In a traditional network device such as a router, switches contain both the control and data plane. SDN separates the control and data plane in network entities enabling centralization management of a cellular network [20].

2.4.3 New Radio Frequencies

5G uses extremely high frequencies in the 30 GHz to 300 GHz range. One of the most important advantages of using higher frequencies is that they support a huge capacity for fast data. Further, they are also highly directional causing no or less interference to nearby users [21]. The air interface defined by 3GPP for 5G is known as New Radio (NR), and the frequency bands for 5G networks come in two sets:

- Frequency range 1 is from 450 MHz to 6 GHz. and
- Frequency range 2 is from 24.25 GHz to 52.6 GHz.

2.4.4 Massive MIMO and Beamforming

MIMO, (multiple-input, multiple-output) is a radio antenna technology which deploys multiple antennas at both the transmitter and receiver to increase the quality, throughput, and capacity of the radio link. MIMO uses techniques known as spatial diversity and spatial multiplexing to transmit independent and separately encoded data signals, known as "streams", reusing the same time period and frequency resource [22]. The large number of antennae in a Massive MIMO system enables 3D beamforming, which creates both horizontal and vertical beams toward users instead of sending out information in omni-direction. This increases data rates and capacity for all users, particularly useful in urban areas with high-rise buildings.

2.4.5 MEC (Mobile Edge Computing)

Mobile edge computing or Multi-access Edge Computing (MEC), is a form of network architecture that enables cloud computing to be done at the edge of a mobile network or Base Station.

Without edge computing, 5G will not be able to meet the performance goals of very low latency and massive broadband, simply because it takes time for data to travel over the fiber networks connecting the radios on the towers to the network core [20].

2.4.6 NOMA (Non-Orthogonal Multiple Access)

NOMA is a prominent multiple access technique proposed for 5G. In NOMA, for multiple accesses, different power levels are used to serve different users, while sharing the same time, frequency, and spreading-code resources between the multiple users. Also, the entire bandwidth can be exploited by each user for the entire communication time to achieve low latency and high data rates. Compared to previous orthogonal multiple access techniques, NOMA offers lots of benefits like high spectrum efficiency, low latency with high reliability and high speed massive connectivity [3].

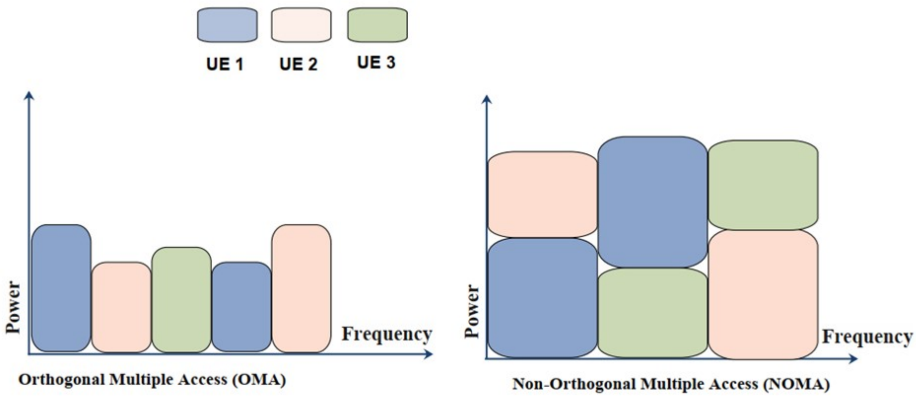

Figure 2.4: Comparison between OMA and NOMA [3]

2.5 QoS in 5G Networks

The QoS in 5G network is based on the QoS flows model as described in Figure 2.5 below. There are small differences from the model in the 4G network [23].

When the PDU session is established, different QoS flows are created that carry similar traffic in terms of Class Indicators set in the QoS template. Therefore, all traffic

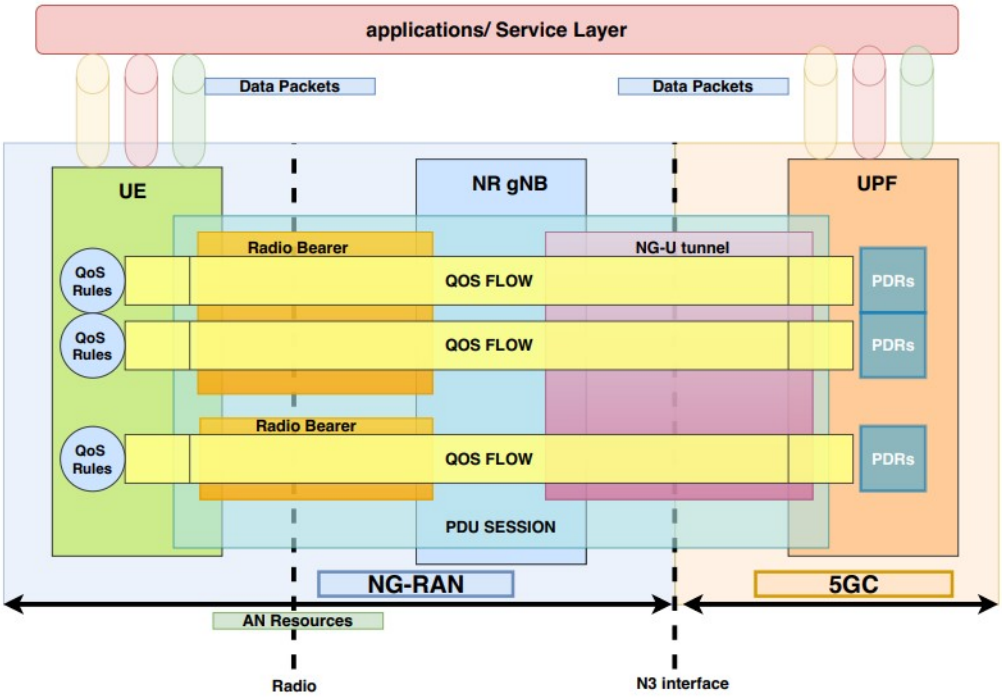

Figure 2.5: QoS in 5G network

mapped with the same QoS flow will receive the same treatment in terms of scheduling policy, queue management, prioritization, and rate allocation, and so on.

In NG-RAN, it is established that for each UE at least one data bearer (default bearer) and other additional bearers depending on the QoS flows. To transport the information over the air NG-RAN associating UL and DL QoS flows with data bearers and to differentiate them from other UE that are connected, the QoS flows of each UE are mapped with their corresponding PDU session. 5G also supports guaranteed flow bit rates and QoS with non-GBR as in the previous generation. However, as a new feature "reflective QoS" has been introduced which means that UE uses the same UL QoS parameters as those obtained through DL flow since one of the most significant improvements in 5G is the increase in uplink performance, so similar QoS rules can be used due to this symmetry [23].

2.6 5G Network Coverage in Addis Ababa

Ethio Telecom has launched the rollout of 5G technology in specific areas of Addis Ababa to enhance its competitive position and elevate customer satisfaction. This service was implemented in a non-standalone configuration, by layering 5G service on existing sites that previously provided 2G, 3G, and 4G services. In this initial phase, the operator strategically focused on locations characterized by a high density of 5G-capable devices, higher education institutions, proximity to major highways, hotels, and real estates. The geographic coverage of the 5G network in Addis Ababa is depicted on Figure 2.6 below:

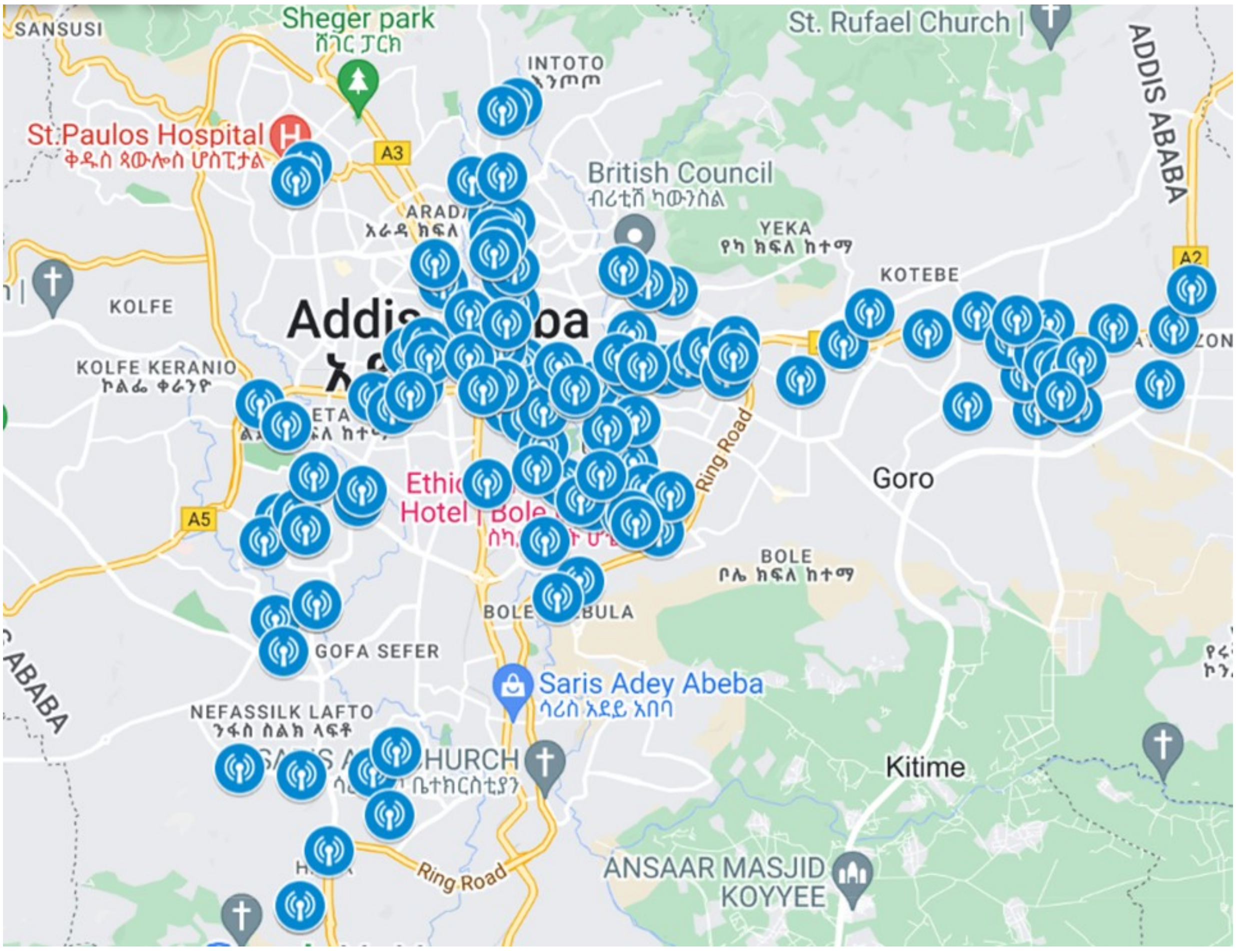

Figure 2.6: 5G network coverage in Addis Ababa

Chapter 3: **QoS and QoE Measurement Methods and Tools**

3.1 Overview of QoS and QoE

ITU defines QoS as totality of characteristics of a telecommunications service that bear on its ability to satisfy stated and implied needs of the user of the service. On the other hand, the ITU definition for QoE is the degree of delight or annoyance of the user of an application or service. Parameters in QoS such as throughput, latency, packet loss, loss rate, network delay, etc. did not fully represent the level of customer satisfaction because in the assessment of eMBB service quality, there is a satisfaction value represented in QoE. So even though the QoS parameter is still considered vital, it is not enough to describe the level of user satisfaction [23].

QoE depends on QoS and network performance. If there is congestion in the network and consequently network performance is lower, the result will be poor quality experienced by the end-user. In this thesis both QoS parameters such as download speed, upload speed and latency and QoE are assessed.

3.2 Spatial and Temporal Scenarios Considered

Spatial and temporal variations of wireless traffic are much more complicated than before. The spatial distributions of the wireless traffic are very different between different geographic locations. For example, the traffic in business areas with high-rising buildings could be much heavier during the daytime than that during midnight, and it is reversed in the residential areas [24]. On the other hand, interference and multi-path fading in crowded, indoor and mobility conditions is much higher than that in open space with clear line of sight between UE and RF antenna. This difference will have a direct impact on performance of 5G network.

To fully understand the performance of 5G network, considering all these spatial and temporal variations is crucial. The following four spatial scenarios are selected as they represent almost all environmental conditions faced by customers:

- Outdoor open space with clear LoS between UE and RF panel
- Outdoor crowded space with high surrounding building and obstructions between UE and RF panel,
- Mobility or driving condition on a vehicle with speed between 20 to 50 km/h
- Indoor condition with no LoS between the phone and RF panel.

As clearly shown in Figure 3.1 below, 5G traffic in AA varies with time of the day keeping other parameters constant. The traffic during late night or early morning is lighter than that during the afternoon or early evening.

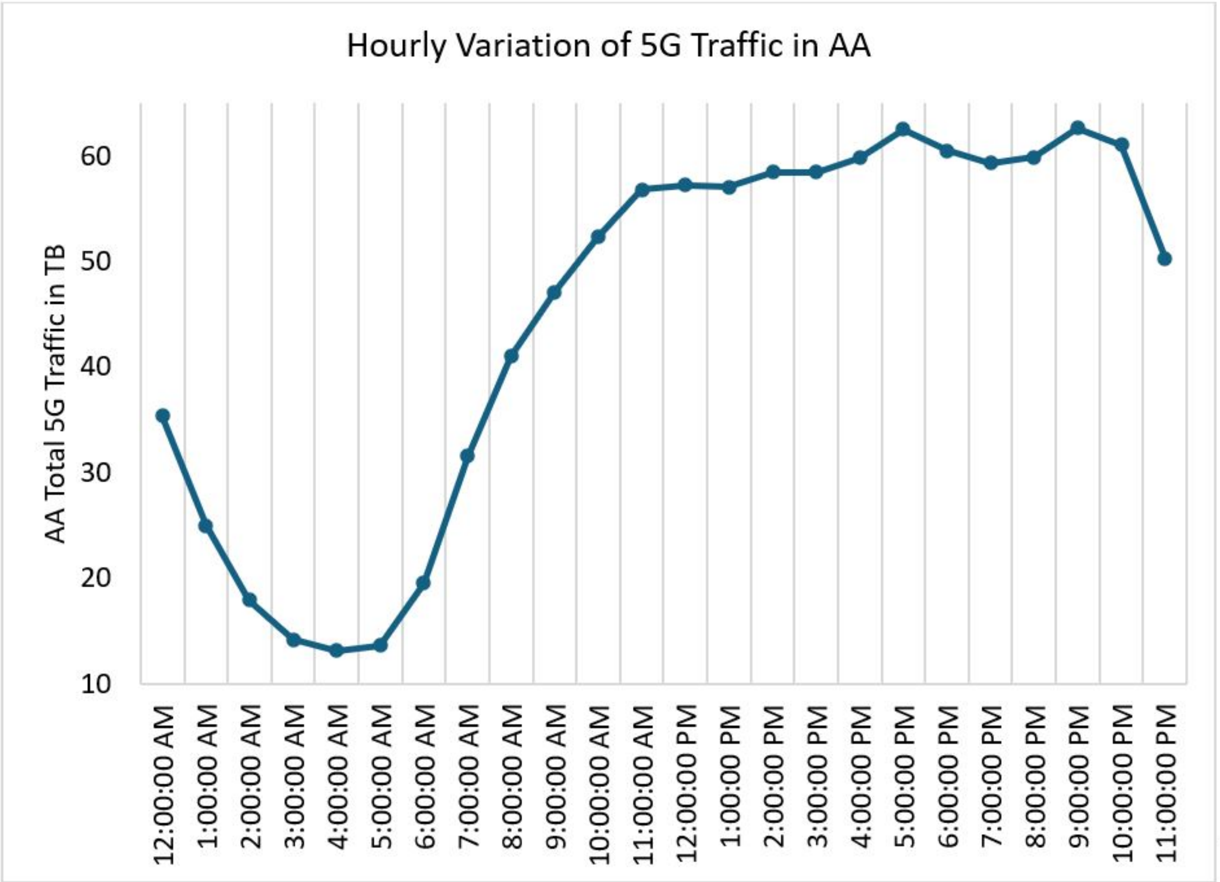

Figure 3.1: Hourly Variation of 5G Traffic in AA

To accommodate this hourly variations in our study, two temporal conditions are considered. The first one is in the morning from 9:30 AM to 12:00 AM which represents low traffic hours and the second is in the afternoon from 2:00 PM to 5:00 PM representing relatively high traffic hours.

3.3 Sampling Method and Sample Selection

3.3.1 Sampling Method

Since 5G network covers only some areas of Addis Ababa city, selecting a probabilistic sampling method would not give us the required data as most of the city has no 5G coverage. Hence, we used non-probabilistic sampling called purposive sampling. Purposive sampling is a technique used in qualitative research to select a specific group of samples for analysis. In purposive sampling, the researcher has a specific purpose or objective when selecting the sample. Therefore, the sample is selected based on the characteristics or attributes the researcher is interested in studying [25]. It allows the researcher to focus on specific areas of interest, in our case areas with 5G coverage and 5G users, and gather in-depth data on those topics.

Out of many categories of purposive sampling, a maximum variation purposive sampling is selected. We selected this technique since we are looking to examine a diverse range of scenarios such as open space with a clear line of sight, crowded spaces with high-rising buildings, indoor and driving conditions that are all relevant to our research. In addition to these spatial scenarios, we will consider two temporal conditions which allows us to gain as much insight from as many scenarios as possible.

3.3.2 Sample Selection

To take the measurements by considering the scenarios considered, we have selected areas for each scenario across Addis Ababa city.

Figure 3.2: Giorgis, Menilik Sqare

Figure 3.3: Churchil road around Eliana Hotel

For outdoor open space with clear LoS between UE and RF panel, locations such as Meskel Square, Friendship Park, Millennium Hall, Giorgis Menelik Square and Ethio-Cuba Friendship Park, are considered.

For outdoor crowded space with high surrounding buildings, areas such as Mexico around Zemen Band HQ, Megenagna around Zefmesh Grand Mall, Bole around Edna mall square, Kasanchis around Elile Hotel and Piasa around Eliana Hotel are selected. For indoor condition with non-LoS, buildings such as Megenagna Betelhem Plaza, Golagol Tower, Friendship Business Center, AAiT main building, and 6-Kilo ethio telecom building are selected. For mobility or driving scenarios, five routes with 5G coverage are selected.

The locations, routes and buildings selected for measurement are described on the table 3.1 below:

Measurement Scenarios	**Locations Selected for Measurement**
Outdoor open space with clear LoS	Giorgis, Menilik Square
	Friendship Park
	Bole Millennium Hall
	Meskel Square
	Ethio-Cuba Friendship Park
Outdoor crowded space with high buildings	Kasanchis around Elile Hotel
	Megenagna around Zefmesh Grand Mall
	Piasa around Eliana Hotel
	Mexico, around Zemen Bank HQ
	Bole, around Edna Mall Square
Indoor condition with non LoS	Megenagna, Betelhem Plaza
	Golagol Tower
	Friendship Buisness Center
	AAiT Main Building
	6-Kilo Ethio telecom Building
Mobility or driving condition	6 kilo to 4 kilo road
	Kebena to Megenagna road
	Urael to Megenagna road
	Gurdshoal to CMC
	Bole alem cinema to 22 road

Table 3.1: Sample locations, buildings and routes selected for measurement

3.4 UE and QoS Measurement Metrics

3.4.1 5G User Equipment Selected

We used two types of 5G capable smartphones: Samsung Galaxy A53 5G and iPhone 12 Pro Max, from now on referred to as SG53 and iP12 respectively. To ensure that our measurements are not affected by the device, We confirm that, despite 5Gs high throughput, the device side processing is not a bottleneck as both devices selected are high-end smartphones with big processing capacity:

- SG53 5G has Octa-core (2x2.4 GHz Cortex-A78 and 6x2.0 GHz Cortex-A55) chip set, and
- iP12 has Hexa-core (2x3.1 GHz Firestorm + 4x1.8 GHz Icestorm)

3.4.2 5G QoS Measurement Metrics

Some of typical 5G QoS parameters include upload throughput, download throughput, latency, jitter, packet loss, and packet error. In this thesis, three QoS measurement metrics are used to evaluate eMBB service in Addis Ababa. These parameters are:

- Download throughput or data rate,
- Upload throughput or data rate, and
- Latency or ping

3.5 5G QoS Measurement Tools

5G QoS testing tools are categorized as hardware and software-based. Hardware-based tools completely replace the end user's equipment in the absence of the users or share the Internet access with normal traffic, while software-based tools can be web-based or dedicated software clients. There are different network measurement methods and tools as listed in Table 3.2. below:

Measurement Methods	Some Measurement Tools
Network Management System	CEM, OMC, EMS, PRS
Minimization Drive Test	Nastar, Omstar, TEOCO
Drive/Walk Test	TEMS, Nemo Handy-A and PHU
Crowdsourcing	Ookla Speedtest, RTR-NetTest and OpenSignal

Table 3.2: 5G QoS measurement tools

3.5.1 Network Management System (NMS)

A network management system is used to control the system and its resources by controlling its usage, access monitoring, and reporting its current and historical status. This helps in judgment, forecasting, decision-making, analyzing data, and making positive efforts to maintain the quality of service [9]. Some of these tools include CEM, OMC, EMS, and PRS. In this thesis, we used Huawei iMaster PRS due to its convenience in extracting the required download and upload throughput per user in different spatial and temporal scenarios.

Performance Reporting System (PRS)

PRS is an integrated solution for managing the performance reports of wireless networks. This system enables multiple users to manage the performance reports of multiple systems, vendors, and versions, thus providing a basic supporting platform for monitoring and analyzing the wireless network performance [26].

We can query the performance KPIs at time or object dimensions, which improves the query efficiency. The time dimensions are Raw, hour, day, week, month, and busy-hour data. The object dimensions are TRX, Cell, City, Cluster, Cell Group, BSC, Region, and entire network. The PRS provides internal KPI reports on key NEs and supports user-defined KPIs and reports. This helps us to focus on the key information [27]. PRS is located in a distributed client/server network and is connected element management system of multiple vendors and OSS. The following figure shows the position of PRS in the network.

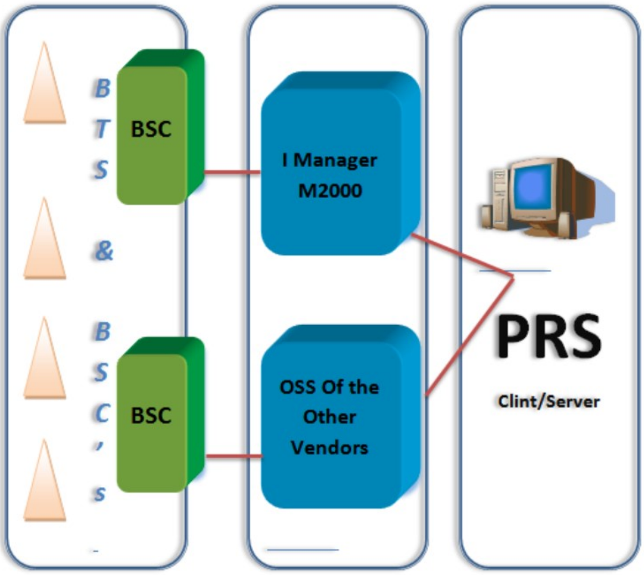

Figure 3.4: Position of PRS in the network

3.5.2 Drive Test (DT)

Drive testing is a method of measuring and assessing the coverage, capacity, and quality of a network. The drive test method records a wide variety of physical and virtual metrics on the mobile network service in a given geographical area. Even though drive testing only covers areas with roads, it still requires a lot of time and resources. Instead, only a few tests are always taken in a given location and specific roadways which are not re-tested frequently. Additionally, drive testing cannot measure how connectivity changes throughout the day. Test vehicles drive through an area at a specific time, but not all areas at all times of the day. This method is used mainly for network bench-marking, optimization, troubleshooting, and service quality monitoring. Some of the tools are Nemo Outdoor, Nemo Handy-A, Test Mobile System (TEMS) and GENEX Probe [9]. Although we couldn't access 5G drive test tool due to license and system ownership issue, we have incorporated data generated by 5G DT tool called probe handset unit (PHU).

Probe Handset Unit (PHU)

PHU is an air-interface testing software developed by Huawei. It can display the wireless parameter data in real time, and record the test data. It is used to perform wireless network tests and record test data at any time anywhere. The test data can be imported to an analysis tool and a detailed analysis report can be generated. In the report, it is possible to locate the problem and develop an optimization solution based on the analysis data of multiple tests. It support for Voice, FTP UL, FTP DL, SMS, and PDP tests [28].

3.5.3 Crowdsourcing Tools

In the field of telecommunications, crowdsourcing makes a viable addition to state-of-the-art bench-marking methods for mobile networks, when combined with mobile sensing approaches to employ smartphones as end nodes. The two issues in conventional mobile testing and measurement are:

- Higher test costs due to the diversity of mobile devices and platforms. and
- Difficulty in conducting large-scale user-oriented performance and usability testing.

Crowdsourcing provides a promising way to address these challenges and issues. Crowdsourcing test tools are free tools downloaded from Google Play or Apple Store. Some of these available tools include RTR-NetTest, G-Net Track, Speedtest by Ookla, OpenSignal and nPerf.

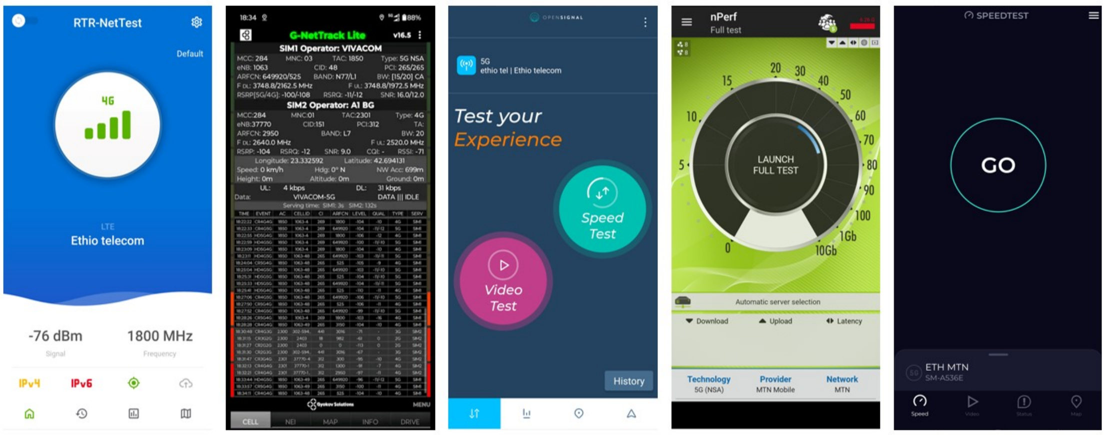

Figure 3.5: Crowdsourcing Tools Studied

To select the best crwodsourcing tools for this thesis, the above five crowdsourcing tools are studied in detail by considering the following points:

1. Supporting 5G technology

2. Providing accurate measurement
3. Measurement speed and
4. Convenience for accessing measurement data

RTR-NetTest was convenient to access measurement data but it doesn't display 5G technology. The speed test result indicates that it detects 5G network but it displays as if it is 4G network. This will confuse readers, examiner, advisor etc. On the other hand, G-NetTrack support 5G technology but accessing measurement data is not convenient.

The rest three tools Speedtest by Ookla, OpenSignal and nPerf support 5G technology, provide relatively accurate measurement and are more convenient for accessing measurement data. With repeated test comparison, we found that Speedtest by Ookla is very fast and provides test results in excel format unlike nPerf and OpenSignal. Hence, we will use Speedtest by Ookla crowdsourcing application in this thesis.

SpeedTest by Ookla

Ookla, the company behind Speedtest by Ookla, is based in Seattle, US. It's the global leader in fixed broadband and mobile network testing applications, data and analysis. As a result of the test volume across all Speedtest platforms, Ookla has the most comprehensive analytics on worldwide internet performance and accessibility [29]. Speedtest by Ookla is the definitive way to test the speed and performance of internet connection. Every day, over 18 million unique tests are actively initiated by users in different parts of the world. Since its founding in 2006, more than 50 billion tests have been taken with Speedtest by Ookla. Some the its features include [30]:

- Discover download, upload, and jitter,
- Measure ping at 3 stages: idle, download, and upload,
- Real-time graphs show connection consistency,
- Track past tests with detailed reporting, and
- Easily access and share measurement results,

Speedtest operates mainly over TCP testing with a HTTP fallback for maximum compatibility. It has flexibility of server selection and the default policy of server selection from Speedtest is to choose a server located near to the UE. Since there were no SpeedTest servers in Ethiopia during the field test period, we used Somtel International server which is located at Hargesa, Somaliland.

SpeedTest measures ping (latency), download speed, and upload speed. To measure download throughput, upload throughput and latency, SpeedTest follow the following procedures [30].

Download Throughput:

- The client establishes multiple connections with the server over port: 8080. The client requests the server to send an initial chunk of data.
- The client calculates the real-time speed of the transfers, then adjusts the chunk size and buffer size based on this calculation to maximize usage of the network connection
- As the chunks are received by the client, the client will request more chunks throughout the duration of the test. During the first half of the test, the client will establish extra

connections to the server if it determines additional threads are required to measure the download speed more accurately.

- The test ends once the configured amount of time has been reached.

Upload Throughput:

- The client establishes multiple connections with the server over the defined port and sends an initial chunk of data.
- The client calculates the real-time speed of the transfers and adjusts the chunk size and buffer size based on it to maximize usage of the network connection, and request more data.
- As the chunks are received by the server, the client will send more chunks throughout the duration of the test.
- During the first half of the test, the client will establish extra connections to the server if it determines additional threads are required to measure the upload speed more accurately.
- The test ends once the configured amount of time has been reached.

Latency/Delay:

- This test is performed by measuring the time it takes for the server to reply to a request from the user's client.
- The client sends a message to the server, and upon receiving that message, the server sends a reply back.

- The round-trip time is measured is measured in ms (milliseconds).
- This test is repeated multiple times with the lowest value determining the final result.

3.6 QoE Measurement Methods

The evaluation of QoE is performed using a subjective test called Mean Opinion Score [MOS]. The MOS is used in telecom services since this is a subjective measure given by the opinion of the user who is consuming the service or content. ITU-T describes Absolute Category Rating (ACR) as the most commonly used scale for converting subjective questions to numerical values [31]. Table 3.3 shows responses of subjective questions with their respective scales.

Subjective Response of Subscribers	**ACR Converted Scale**
Excellent	5
Good	4
Fair	3
Poor	2
Bad	1

Table 3.3: 5 point absolute category rating(ACR)

Mean opinion score (MOS) is calculated as the arithmetic mean over single ratings performed by human subjects for a given stimulus in a subjective quality evaluation test and is given by [32]:

$$MOS = \frac{\sum_{n=1}^{N} R_n}{\text{N}}$$

Where R are the individual ratings for a given stimulus by N subjects.

3.7 Analysis Methodology and Tools

Measurement results of the three QoS metrics for each of the four measurement scenarios are analyzed using Microsoft excel. One month upload throughput, download throughput and latency measurements are taken and the result for each of the spatiotemporal scenarios are evaluated against minimum technical performance requirements of 5G network. This will show the real QoS of 5G network in Addis Ababa and used to identify performance gaps observed for further corrective action.

Furthermore, QoS measurement results are also evaluated against minimum required throughput for commonly used eMBB services such as UHD video streaming, VR and online gaming applications. This will help us to correlate the QoS measurement results with customer experience result obtained with questioner. The analysis also identifies the variation of performance with change in mobility, blockage, device and measurement hours.

3.8 The Gap Observed in 5G QoS and QoE Assessment

Although, the operator implemented new customer experience management(CEM) system and has clear and matured process for handling customer complaints, it has no license for 5G drive test tools to check and act on 5G related customer complaints and did not evaluated user side experience of 5G eMBB service. This brought challenges to measure user side QoS and have clear user experience data on the services and take timely marketing, optimization and further planning actions.

Chapter 4: **Data Collection Mechanism**

To have clear insight into QoS and user experience of 5G eMBB service, it's important to collect both objective and subjective data from different systems and 5G users across Addis Ababa city. As discussed in section 3.5, we have used data from the following four sources :

- SpeedTest by Ookla
- iMaster PRS
- Probe Handset Unit(PHU)
- QoE Assessment Using Survey

4.1 QoS Data Collection

4.1.1 SpeedTest by Ookla

A total of 1,214 field measurements were taken for one month from March 08 to April 08, 2024, using the two smartphones SG53 and iP12.

Measurement locations, number, and time of measurements done using each of the smartphones are shown in Table 4.1 below.

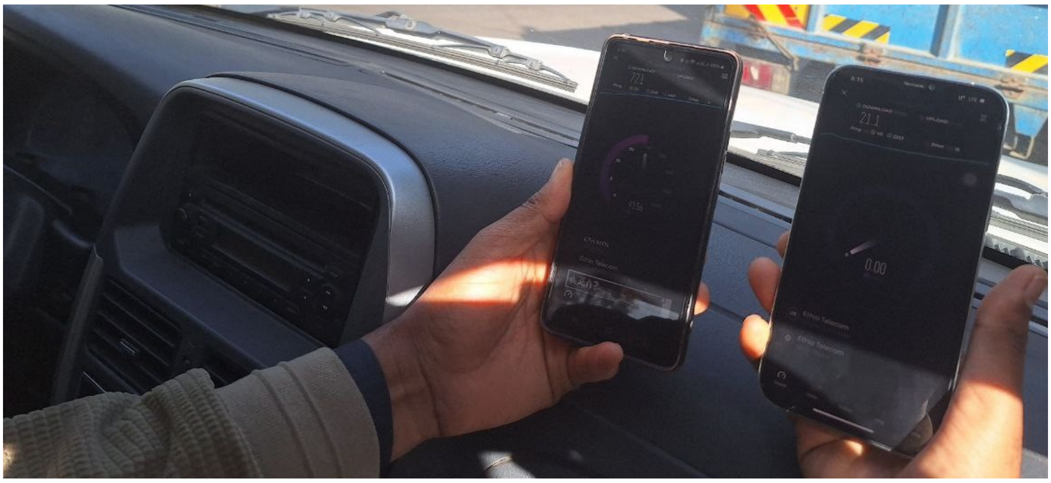

Figure 4.1: Sample Picture During Drive Test Field Measurement

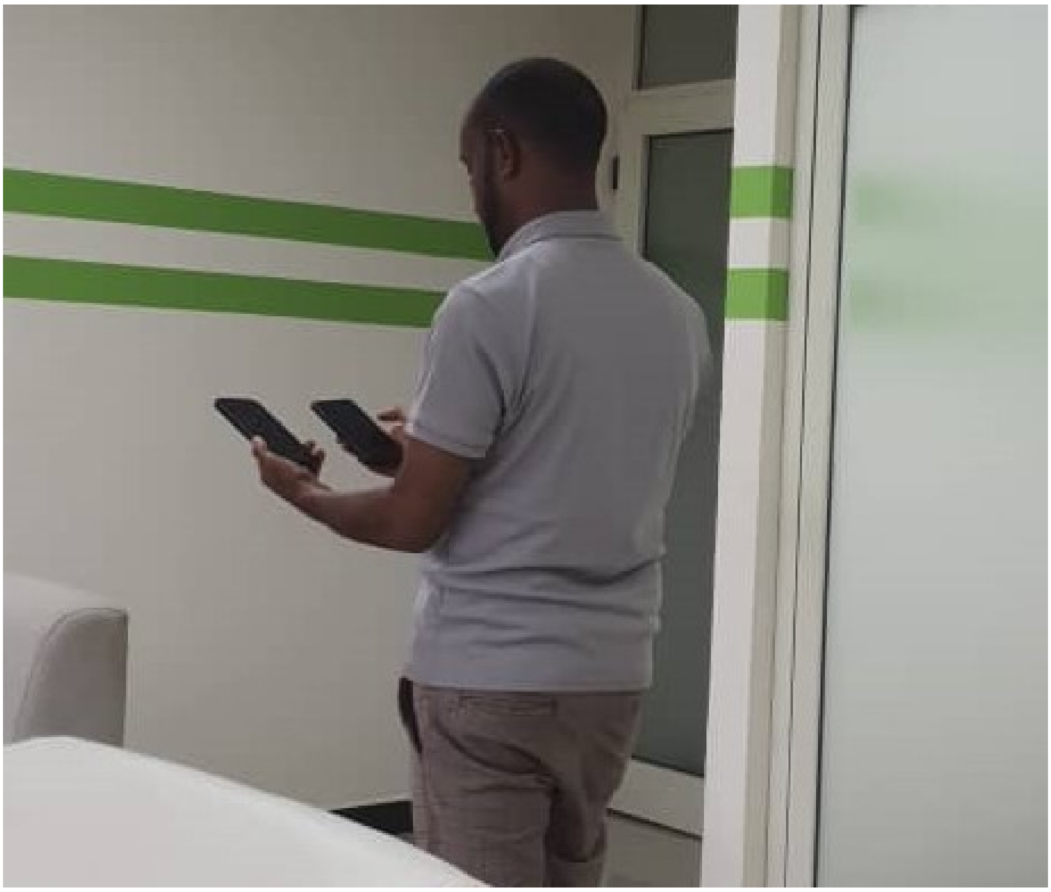

Figure 4.2: Sample Picture During Indoor Measurement

The variation in the number of measurements across different locations and device models is due to two main reasons. First, there is a variation in 5G coverage and the ability

Measurement Scenarios	Measurement Location	Location Code	Number of Field Measurements				
			Morning		Afternoon		Total
			iP12	SG53	iP12	SG53	
Outdoor open space with clear LoS	Giorgis Menelik square	O1	11	12	14	13	325
	Friendship park	O2	25	13	16	26	
	Bole Millinium Hall	O3	32	21	19	13	
	Meskel Square	O4	15	11	18	8	
	Ethio Cuba friendship	O5	10	10	22	16	
Outdoor crowded space with high-rising buildings	Around Elile Hotel	C1	11	9	14	8	271
	Around Zefmesh	C2	23	14	13	17	
	Around Eliana Hotel	C3	13	11	15	11	
	Zemen Bank HQ	C4	13	13	21	13	
	Around Edna Mall	C5	11	7	21	13	
Mobility or driving condition	6 kilo to 4 kilo road	D1	18	11	38	18	311
	Kebena to Megenagna	D2	29	13	9	17	
	Urael to Megenagna	D3	14	14	16	6	
	Gurdshoal to CMC	D4	16	8	23	16	
	Bole to 22 road	D5	9	13	14	9	
Indoor condition with non LoS	6 kilo ethio telecom	B1	17	12	21	14	307
	Friendship Tower	B2	12	11	19	9	
	AAiT Main Building	B3	27	24	18	11	
	Betelhem Plaza	B4	13	10	27	15	
	Golagol Building	B5	11	13	16	7	
Grand Total number of field measurements							**1214**

Table 4.1: Details of Ookla SpeedTest Measurement

of devices to pick up 5G signals at different times and locations. For example, an iPhone might detect a 5G signal at a specific location and time, while a Samsung device might not, and vice versa. Second, the measurement speed varies between devices, leading to different numbers of measurements.

To address these differences, we included all measurements but averaged the observations per location, time, and device. This approach increases the number of measurements and avoids bias from selecting one measurement result over another.

4.1.2 iMaster Performance Reporting System (PRS)

One-month 5G network performance report from March 08 to April 08, 2024, is generated from PRS. These dates were selected to align with the dates we conducted our field measurement using SpeedTest by Ookla application. This data includes many attributes specifying the time, serving cell and 5G network performance-related KPIs on hourly basis such as: 5G total traffic, DL/UL traffic volume, user DL/UL average throughput, average user number, cell downlink/uplink average throughput, etc.

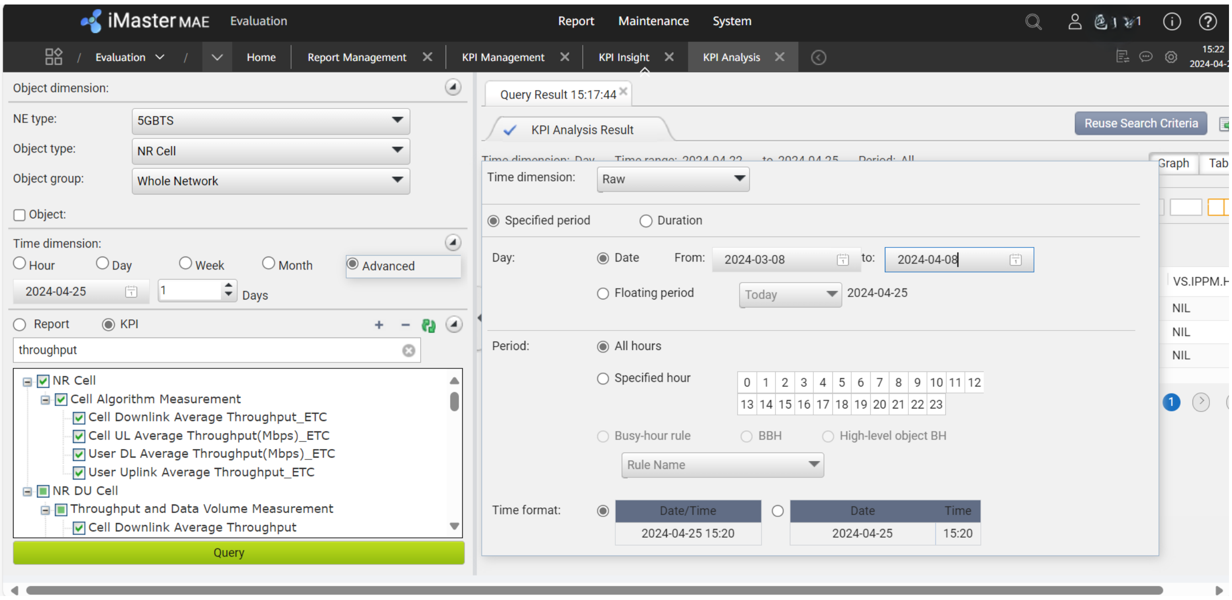

Figure 4.3: Screenshot of PRS

Out of these parameters, we have selected user DL and UL average throughput. We could not obtain latency per user data for 5G from iMaster PRS. Since PRS data is generated in cell level, obtaining serving cells for each of the 20 sample locations is important. An Android application called Network Cell Info Lite is used to identify serving cells for each scenario and sample locations. As shown in Figure 4.4 below, this application gives network type, serving site and cell ID information for a particular location.

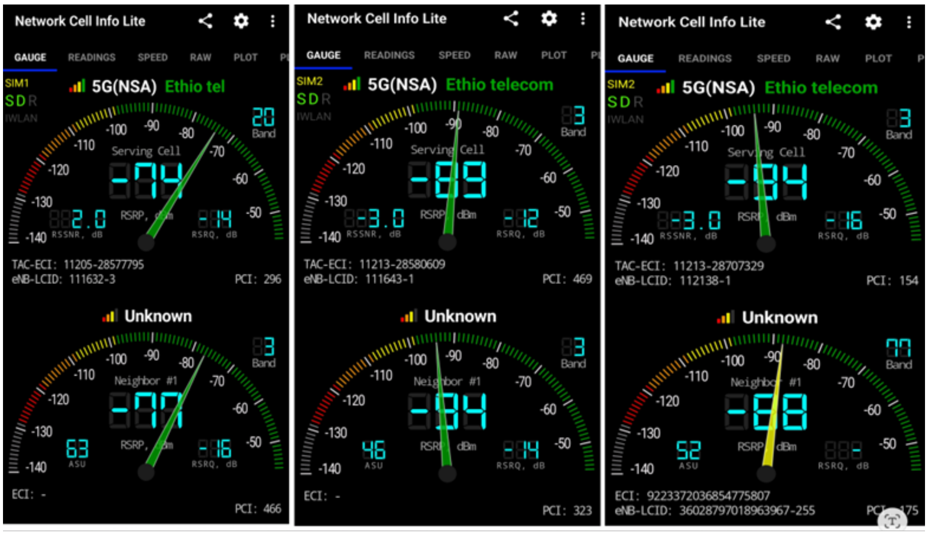

Figure 4.4: Screenshot of Network Cell Info App

To determine download and upload throughput of a specific sample location, we selected serving cell of the location, date, and hour which matches with the date and hour in which field measurement is conducted for that particular location. This way the data obtained by the field measurement using Ookla SpeedTest and data generated from PRS will indicate performance of 5G network at the same location and time.

4.1.3 Probe Handset Unit (PHU)

Currently, the operator, Ethio Telecom, has no drive-test tool or license for 5G network and it has become difficult to obtain drive-test tool and perform drive-test on those selected 20 locations to get data that aligns in test date, time and location with that of crowdsourcing SpeedTest application and PRS results.

But the vendor, Huawei, regularly performs drive-test across Addis Ababa to check 5G QoS using drive-test application called Probe Handset Unit (PHU) installed on Huawei P40 Pro smartphone. Their latest test was performed from March 12 to 26, 2024, just two weeks before our measurement time. Thanks to the cooperative Huawei team, we have got the raw data of this latest drive test which covers all the 20 sample locations.

Although this data doesn't provide enough information to assess impact of temporal variation and change in user equipment, it will add one additional perspective to overall performance and impact of spatial variation on 5G performance.

4.2 QoE Data Collection

To evaluate the perception of the users, an online questionnaire which consists of 14 subjective questions are prepared. Out of these 14 questions, 3 questions are about demography of the participants, 3 questions are about phone model, frequently used service type, and issues faced while using 5G, 7 questions are about quality of 5G service, and 1 question for receiving any additional comment or experience about 5G network.

Question No.	Question
1	Age range
2	Gender
3	Educational background
4	Mobile phone model
5	Services usually used by the customer
6	Overall satisfaction on 5G service
7	Satisfaction on download speed in different hours of the day
8	Satisfaction on upload speed in different hours of the day
9	Satisfaction on delay or latency in different hours of the day
10	Satisfaction on download speed under different spatial conditions
11	Satisfaction on upload speed under different spatial conditions
12	Satisfaction on delay or latency under different spatial conditions
13	Issues or challenges faced while using 5G network.
14	Any additional feedback or experience

Table 4.2: Subjective questions to assess user experience

Chapter 5: **Results and Discussions**

5.1 Ookla SpeedTest Result

5.1.1 Overall SpeedTest Result

Overall average download throughput, upload throughput, and latency obtained from 1,214 SpeedTest measurements are 364 Mbps, 58 Mbps, and 50 milliseconds respectively. A summary of the three measurement metrics results under the four measurement scenarios is depicted in Table 5.1 below:

Measurement Scenarios	**Average DL Throughput in Mbps**	**Average UL Throughput in Mbps**	**Average Latency in msec**
Outdoor open space with clear LoS	497	81	46
Outdoor crowded space with high-rising buildings	330	61	47
Mobility or driving condition	319	62	50
Indoor condition with non LoS	311	28	57
Overall Average Performance	**364**	**58**	**50**

Table 5.1: Summary of SpeedTest Result

Figure 5.1 below shows summarized overall performance of 5G network in AA in four different scenarios: outdoor open space with clear line of sight, outdoor crowded space with high-rising buildings, mobility or driving and indoor conditions.

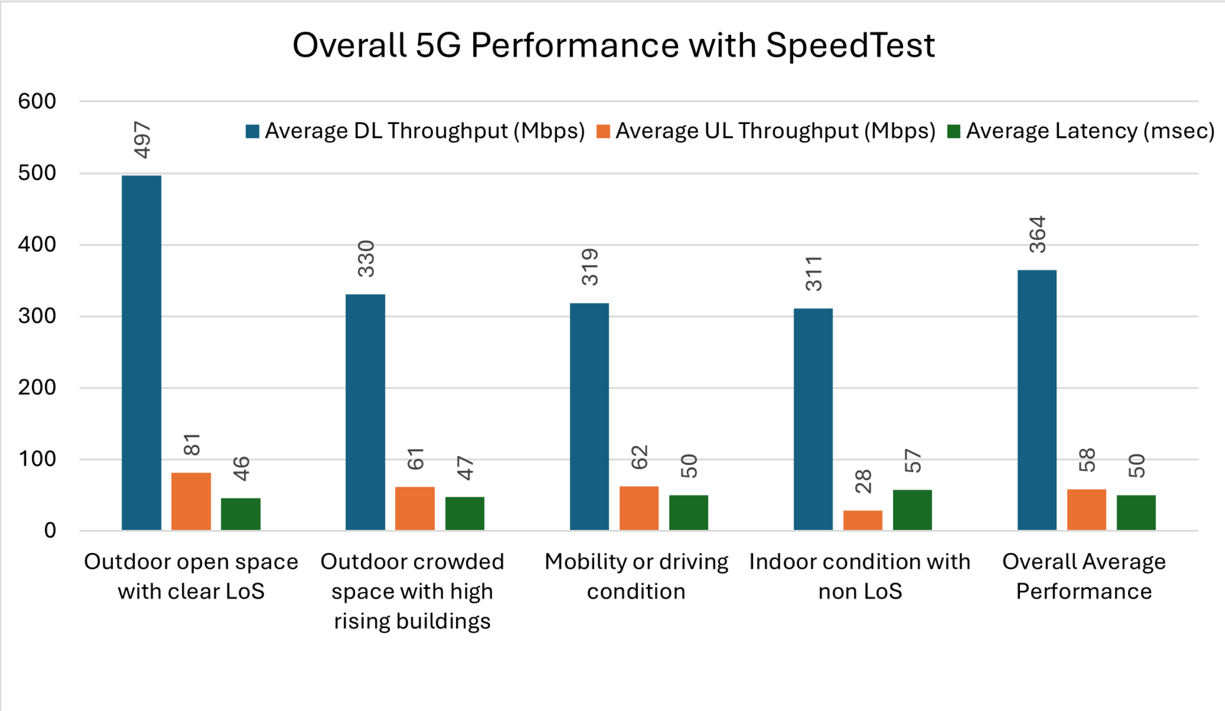

Figure 5.1: Overall test result of SpeedTest by Ookla

5.1.2 Distribution of SpeedTest Measurement Data

To gain a clear understanding of the measurement results, it is essential to examine not only the average values but also the overall data distribution, including the median, standard deviation, maximum and minimum values, as well as any outliers.

Among the 1,243 measurements, the maximum recorded download throughput was 946 Mbps, achieved with the iP12 at location O2 in an outdoor open space with a clear LoS scenario. Conversely, the minimum DL throughput was 63 Mbps, recorded with the same iP12 at location B4 in an indoor condition with non-LoS between the UE and RF antenna.

For upload throughput, the maximum recorded was 156 Mbps with the SG53 device at location O4 in an outdoor open space with clear LoS. The minimum UL throughput, on the other hand, was 0.3 Mbps, also recorded with the SG53 device at location B2 in an indoor condition with non-LoS.

The minimum latency was measured at 12 milliseconds with the iP12 at location O1 in an outdoor open space with clear LoS, while the maximum latency reached 148 seconds, also using the iP12 at location B5 in indoor conditions with non-LoS.

As illustrated in the cumulative distribution function of DL throughput in Figure 5.2 below, 15% of the measurement results fall below 200 Mbps, while another 15% exceed 530 Mbps. The majority, 70% of the measurements, fall within the range of 200 Mbps to 530 Mbps, which corresponds to +/- one standard deviation from the mean.

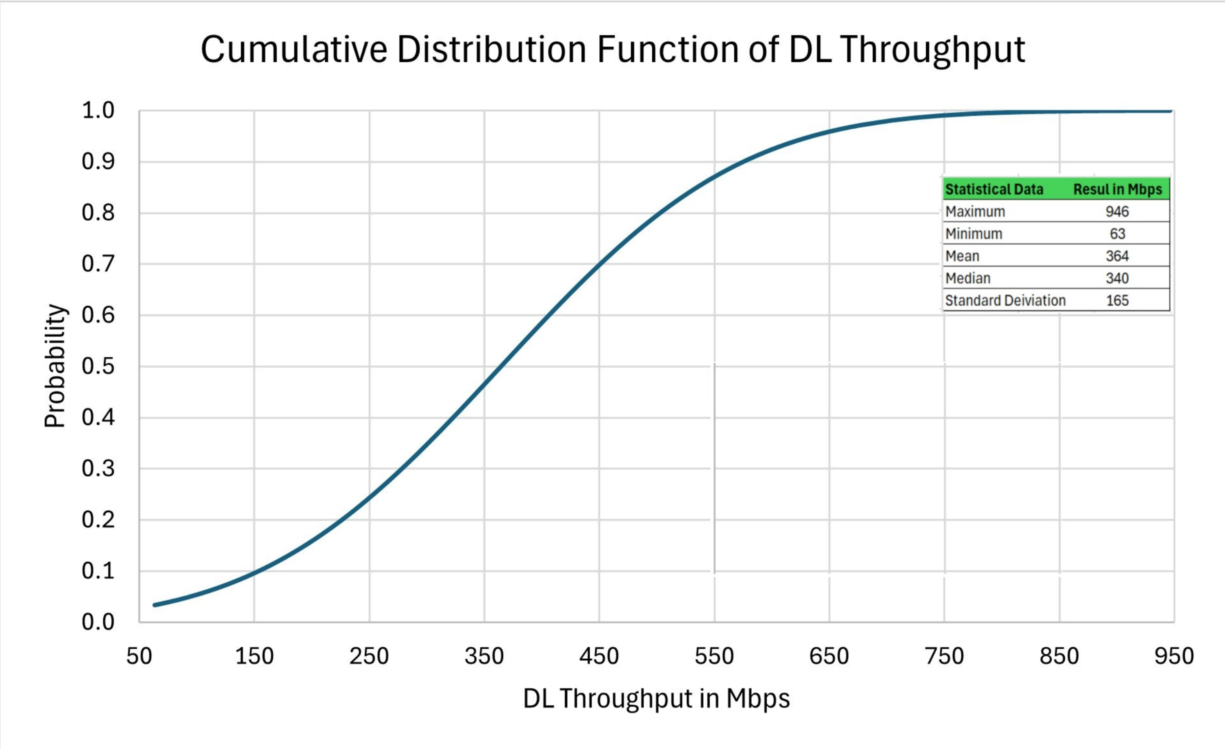

Figure 5.2: CDF graph of DL throughput data

In the same fashion, cumulative distribution functions of UL throughput and latency depicted in Figures 5.3 and 5.4 shows that 70% of the measurement results are +/- one standard deviation from the mean.

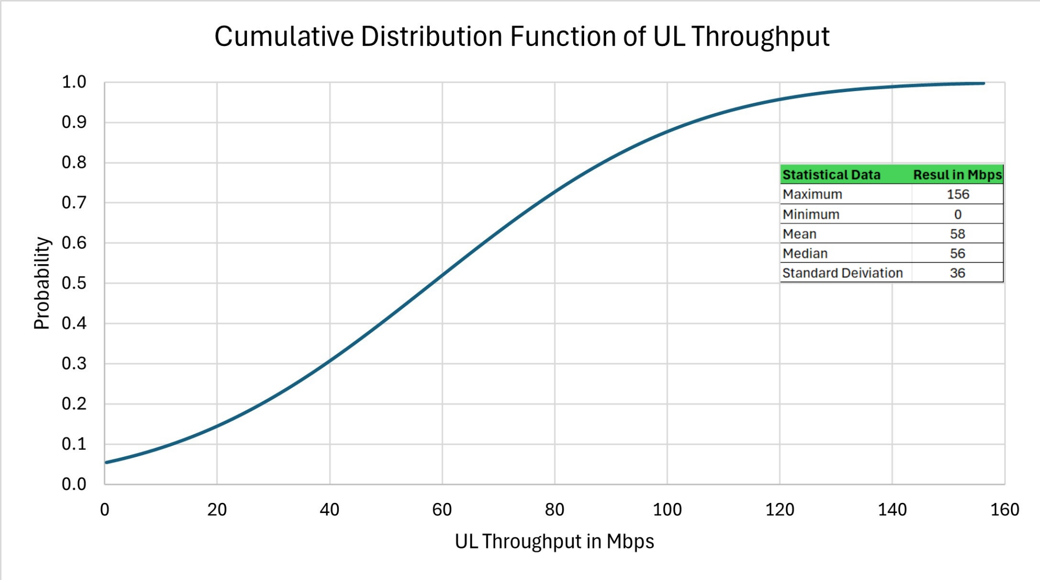

Figure 5.3: CDF graph of UL throughput data

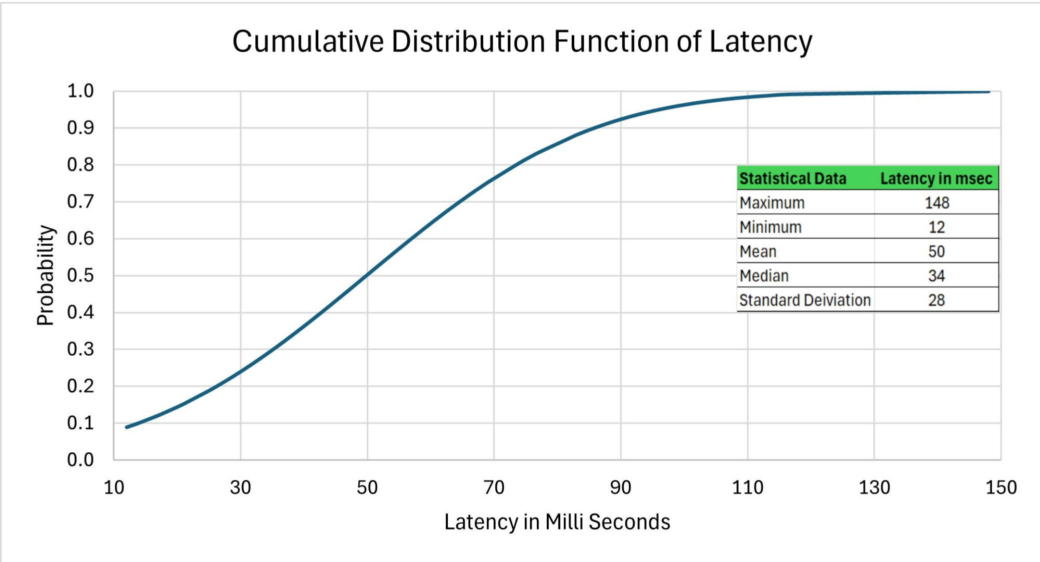

Figure 5.4: CDF graph of latency data

This suggests that the measurement results for all three metrics are uniformly distributed, with no outlier results significantly deviating from the majority. This indicates that the maximum variation purposive sampling method employed to select our samples effectively incorporated a diverse range of scenarios without bias.

5.1.3 Impact of Spatial Variation on 5G SpeedTest Results

As clearly shown in Table 5.2 and Figure 5.5 below, performance of 5G is highly affected by spatial changes in locations. The best performance is achieved in outdoor open space with a clear line of sight in all three measurement metrics with an average DL throughput of 497 Mbps, average UL throughput of 81 Mbps, and average latency of 46 msec. The worst performance is in indoor condition with a non-LoS scenario with average DL throughput of 311 Mbps, average UL throughput of 28 Mbps, and average latency of 57 m seconds.

Measurement Scenarios	Measurement Location	DL Throughput in Mbps	UL Throughput in Mbps	Latency in msec
Outdoor open space with clear LoS	O1	536	67	41
	O2	500	87	58
	O3	500	97	43
	O4	489	64	44
	O5	460	91	51
Crowded space with high-rising buildings	C1	436	65	63
	C2	348	68	44
	C3	335	55	42
	C4	305	68	48
	C5	229	50	33
Mobility or driving condition	D1	383	66	52
	D2	334	63	45
	D3	341	72	42
	D4	264	54	49
	D5	272	54	60
Indoor condition with non LoS	B1	400	35	62
	B2	344	24	50
	B3	335	31	67
	B4	239	31	53
	B5	238	19	53

Table 5.2: Variation of SpeedTest 5G performance with change in location

Taking outdoor open space with clear LoS as a reference DL throughput decreases by 40% in outdoor crowded space; by 44% in mobility or driving condition and by 46% in indoor conditions with non-LOS scenarios. Similarly, UL throughput decreases by around 27% in outdoor crowded spaces and mobility conditions and by 97% in indoor condition. The latency also increases as we traverse from outdoor open space to indoor conditions.

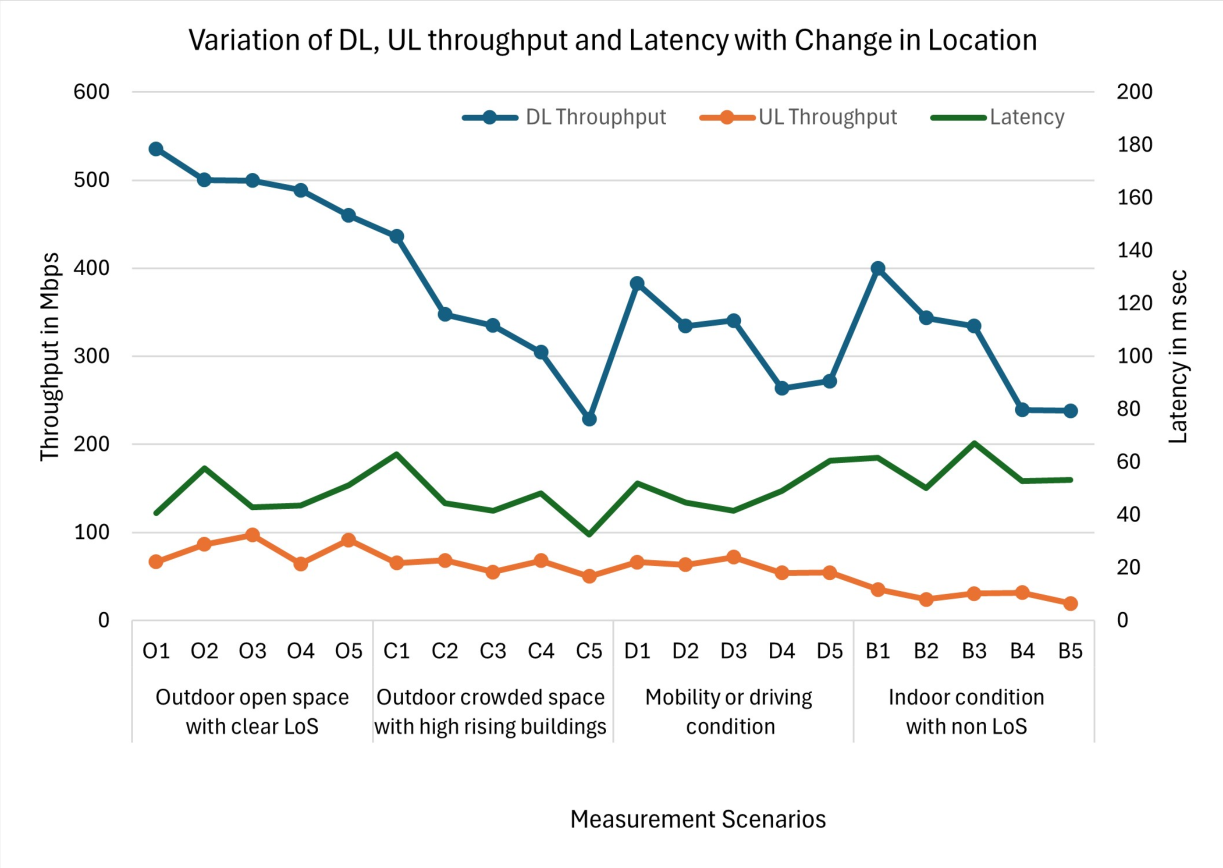

Figure 5.5: Impact of spatial variation on performance of 5G network

This result shows that performance of 5G is highly affected by factors like signal blockage, multi-path fading and interference. The best performance is achieved when all these factors are minimum in the case of outdoor open space with clear LoS between the mobile device and RF antenna. On the hand, 5G performance become worst, when there is signal blockage and multi-path fading in the case of indoor scenario with non-LoS.

5.1.4 Impact of Temporal Variation on 5G SpeedTest Results

To show the impact of temporal variation in 5G performance, the measurement result of DL throughput, UL throughput and latency at two different times of the day, morning and afternoon is depicted in Figure 5.6 below. In all three measurement metrics, 5G performance in the afternoon or high-traffic hours is better than in the morning or low-traffic hours. Although the variation is not the same for all scenarios and measurement metrics, overall average DL throughput increases by 12%, UL throughput increases by 5%, and latency decreases by 46% in the afternoon compared to morning performance.

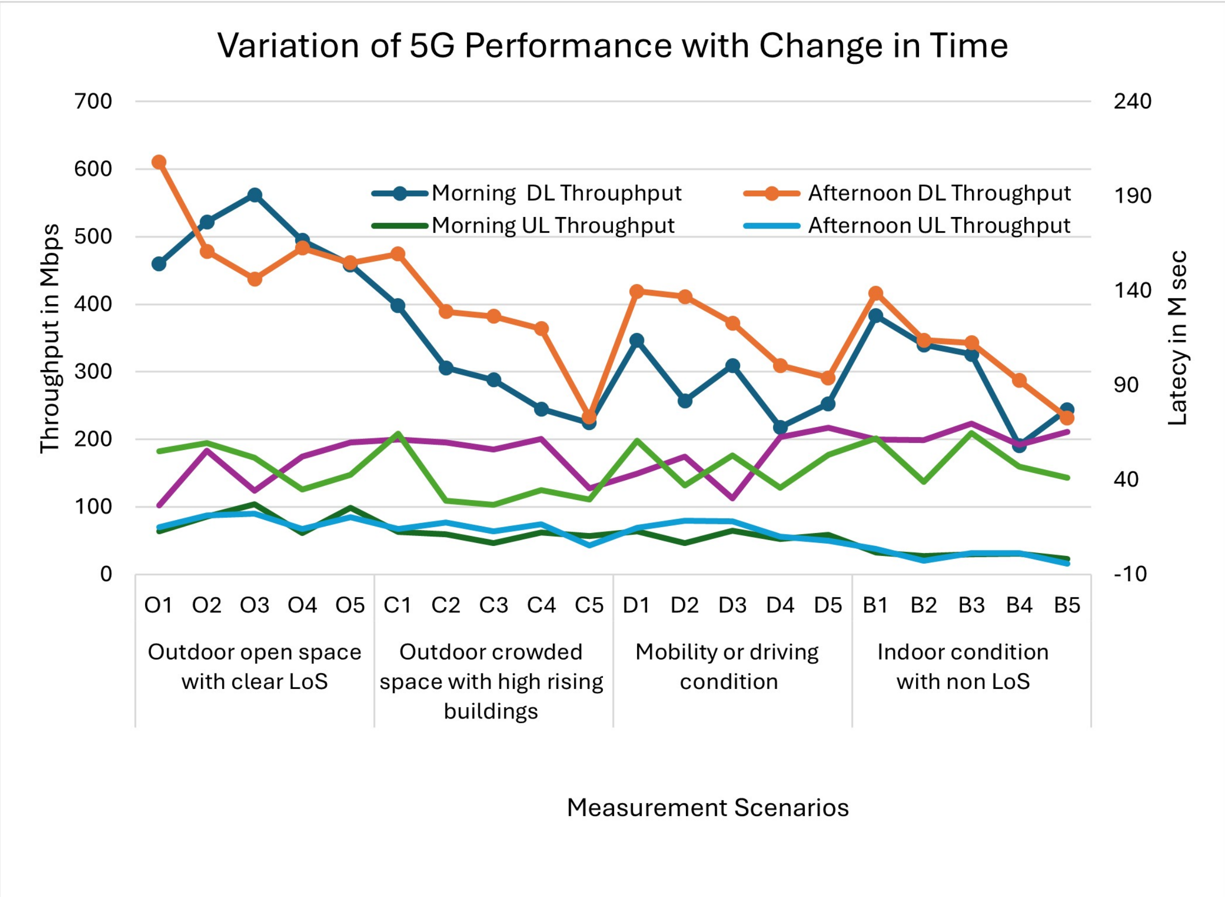

Figure 5.6: Impact of temporal variation on performance of 5G network

5.1.5 Impact of UE model on SpeedTest 5G Performance

The impact of UE model on 5G performance is analyzed using two different model smartphones: SG53 and iP12. Their performance at different times and locations is analyzed in detail. The download throughput of iP12 is 12% higher than SG53 in open space with a clear line of sight but in indoor condition download throughput of SG53 is higher than iP12 by 8%. The difference in DL throughput between the two phones is minimal in driving and indoor conditions. On average, the DL throughput of iP12 is higher than SG53 by around 4% considering all four scenarios. Latency of iP12 is lower than SG53 in all four scenarios and on average latency of iP12 is lower than SG52 by about 28%. On the other hand, upload throughput of SG53 is higher than iP12 in all four scenarios. On average, UL throughput of SG53 exceeds that of iP12 by 22%.

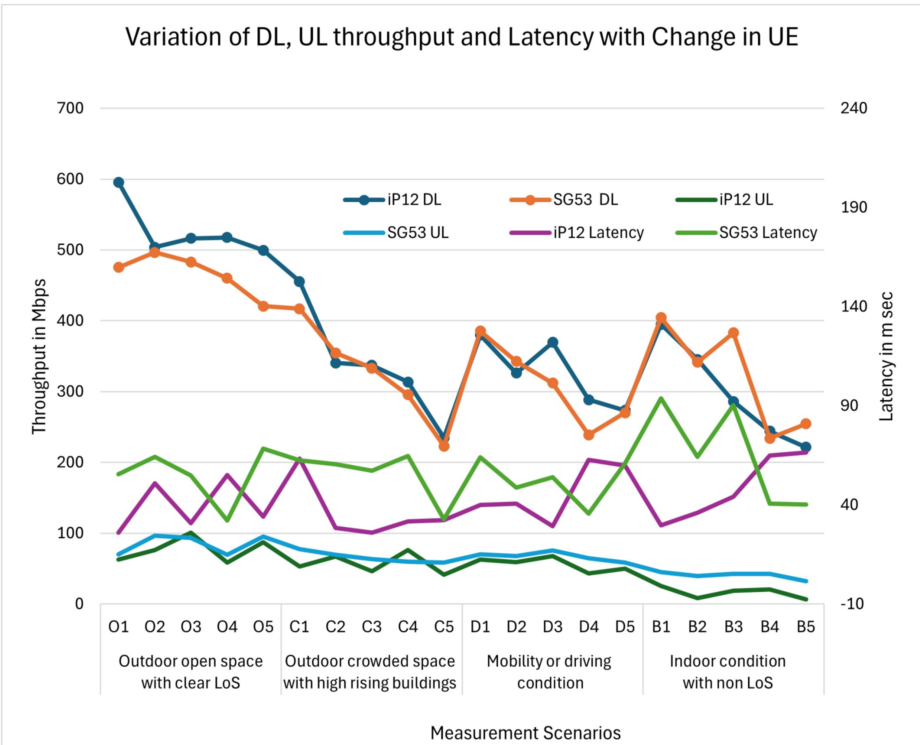

Figure 5.7: Impact of change in UE on performance of 5G network

5.1.6 Comparison of SpeedTest Result with Global 5G Performance

As indicated in the state of 5G 2024 report by GSMA Intelligence [33], global average 5G download speed, upload speed and latency at the end of 2023 were 223 Mbps, 24 Mbps and 40 msec respectively. GSMA Intelligence considered 5G connection in 39 countries and used data provided by Ookla SpeedTest Intelligence. On the other hand, a report by Ookla on the state of worldwide connectivity in 2023 [34], global 5G median download speed, upload speed and latency at the end of 2023 Q3 were 203 Mbps, 19 Mbps and 44 msec respectively. The median download speed, upload speed and latency obtained in our test are 340 Mbps, 56 Mbps and 34 msec respectively. Although the measurement time slightly differs, this performance would have positioned Ethiopia among the top 10 countries in terms of 5G performance as shown in Figure 5.8 below:

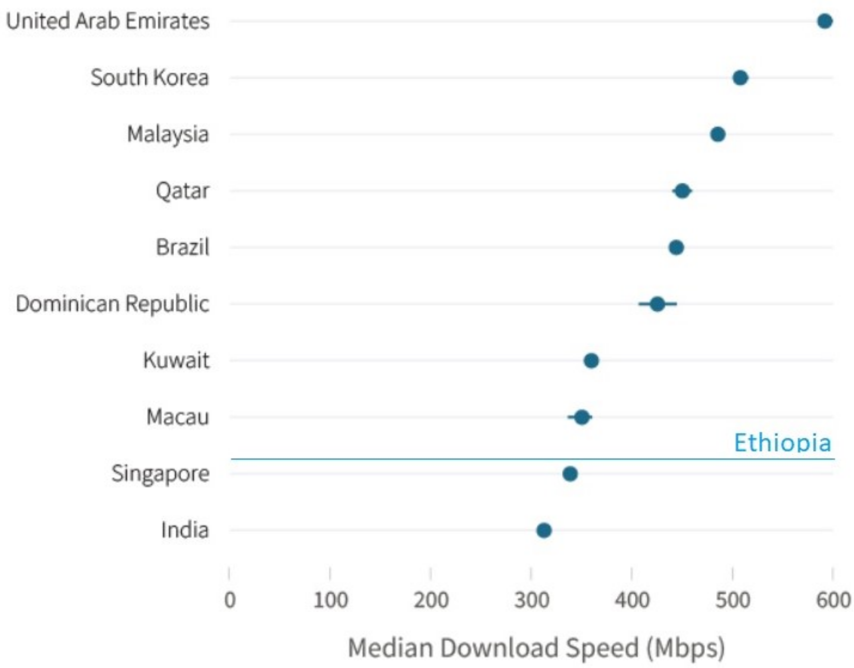

Figure 5.8: Fastest countries for median download speed in 2023

5.2 iMaster PRS Result

5.2.1 Overall PRS Result

The data generated from PRS is analyzed to align with field measurement using SpeedTest in scenario, location, date and time. Overall average download and upload throughput obtained by considering the four scenarios and 20 sample locations are 311 Mbps and 20 Mbps respectively. A summary of download and upload throughput results under the four scenarios are shown in Table 5.3 and Figure 5.9 below:

Measurement Scenarios	**Average DL Speed in Mbps**	**Average UL Speed in Mbps**
Outdoor open space with clear LoS	468	38
Outdoor crowded space with high rising buildings	304	17
Mobility or driving condition	220	10
Indoor condition with non LoS	250	15
Overall Average Performance	**311**	**20**

Table 5.3: Summary of iMaster PRS result

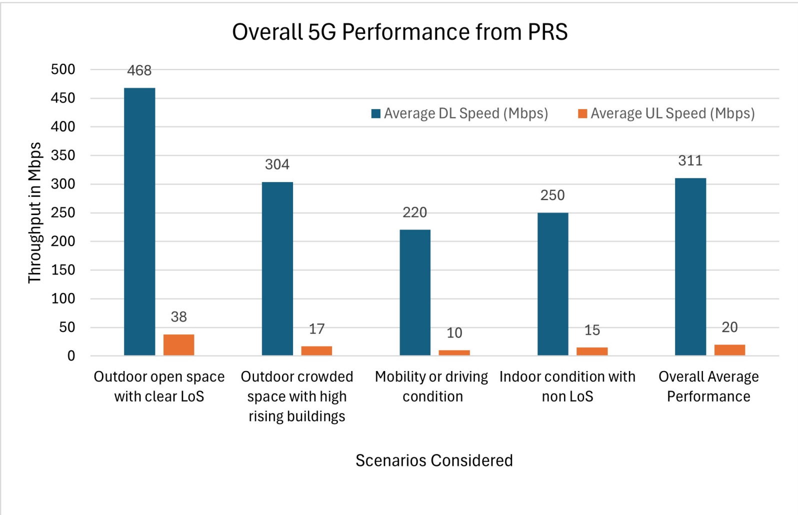

Figure 5.9: Overall 5G performance from PRS data

5.2.2 Distribution of PRS Data

Maximum DL and UL throughput obtained from PRS data are 650 Mbps and 76 Mbps respectively. On the other hand, minimum DL and UL throughput results are 132 Mbps and 1 Mbps. As shown on cumulative distribution function of DL and UL throughput on Figures 5.10 and 5.11, around 70% of the measurement results are within one standard deviation from the mean. This indicates that the data is uniformly distributed.

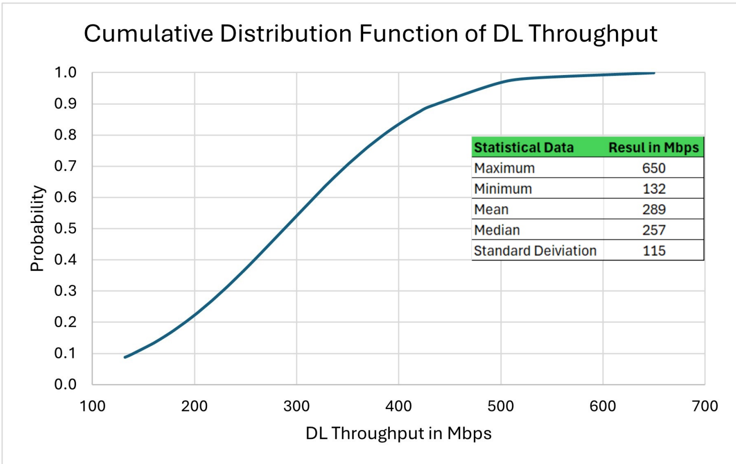

Figure 5.10: CDF of PRS download throughput data

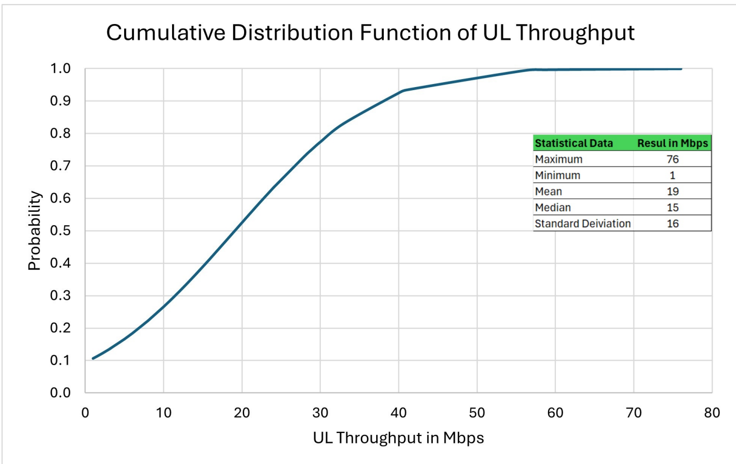

Figure 5.11: CDF of PRS upload throughput data

5.2.3 Impact of Spatial Variation on 5G PRS Results

Table 5.4 and Figure 5.12 below make it quite evident that spatial variations in location have a significant impact on 5G performance.

Measurement Scenarios	Measurement Location	Average DL Speed in Mbps	Average UL Speed in Mbps
Outdoor open space with clear LoS	O1	551	47
	O2	540	24
	O3	397	22
	O4	394	32
	O5	459	68
Outdoor crowded space with high-rising buildings	C1	350	25
	C2	294	29
	C3	312	9
	C4	310	19
	C5	253	3
Mobility or driving condition	D1	273	13
	D2	189	9
	D3	180	11
	D4	246	10
	D5	216	8
Indoor condition with non LoS	B1	380	16
	B2	204	20
	B3	285	4
	B4	218	23
	B5	165	13

Table 5.4: Impact of spatial variation on 5G PRS Performance

The best performance is attained in outdoor open space with a clear LoS condition for both download and upload throughput with an average of result of 468 Mbps and 38 Mbps respectively. From this best performance, the download speed drops by 42% to 304 Mbps in crowded space with high-rising buildings by 72% to 220 Mbps in mobility or driving condition and by 60% to 250 Mbps in indoor condition. Upload speed also drop by 76% to 17 Mbps by 116% to 10 Mbps and by 86% to 15 Mbps.

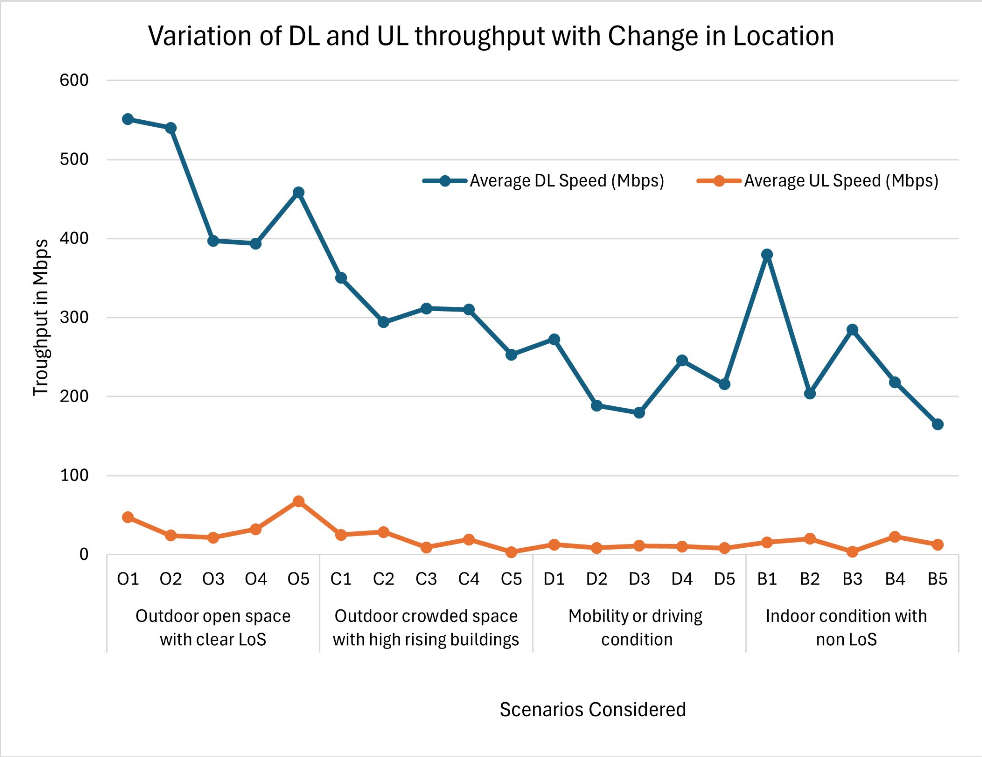

Figure 5.12: Impact of spatial variation on PRS 5G performance

5.2.4 Impact of Temporal Variation on 5G PRS Result

Separate PRS data is generated for two different durations of the day, morning or low traffic hours from 9:00 AM to 12:00 PM and afternoon or low traffic hours from 2:00 PM to 5:00 PM for each of the four measurement scenarios and sample locations.

As indicated in Table 5.5, there is variation in both download and upload throughput with a change in measurement time. Average download throughput in the morning is higher than that in the afternoon by 7% for outdoor open space with clear LoS condition. But overall average download throughput in the afternoon is higher than that of the morning result by around 7% considering all four scenarios. On the other hand, the overall average upload throughput in the morning is higher than that of the afternoon result by 21%.

Measurement Scenarios	Measurement Location	Morning DL Speed	Afternoon DL Speed	Morning UL Speed	Afternoon UL Speed
Outdoor open space with clear LoS	O1	530	571	38	6
	O2	650	431	40	7
	O3	405	389	30	13
	O4	415	372	41	23
	O5	421	496	59	76
Crowded space with high-rising buildings	C1	352	348	22	28
	C2	249	339	24	33
	C3	257	366	8	10
	C4	149	471	24	14
	C5	276	229	3	3
Mobility or driving condition	D1	218	327	10	15
	D2	204	173	12	5
	D3	192	167	12	10
	D4	259	232	15	5
	D5	201	230	8	8
Indoor condition with non LoS	B1	331	429	11	20
	B2	192	216	20	20
	B3	335	234	6	1
	B4	180	256	16	29
	B5	166	164	19	6

Table 5.5: Impact of temporal variation on PRS 5G performance

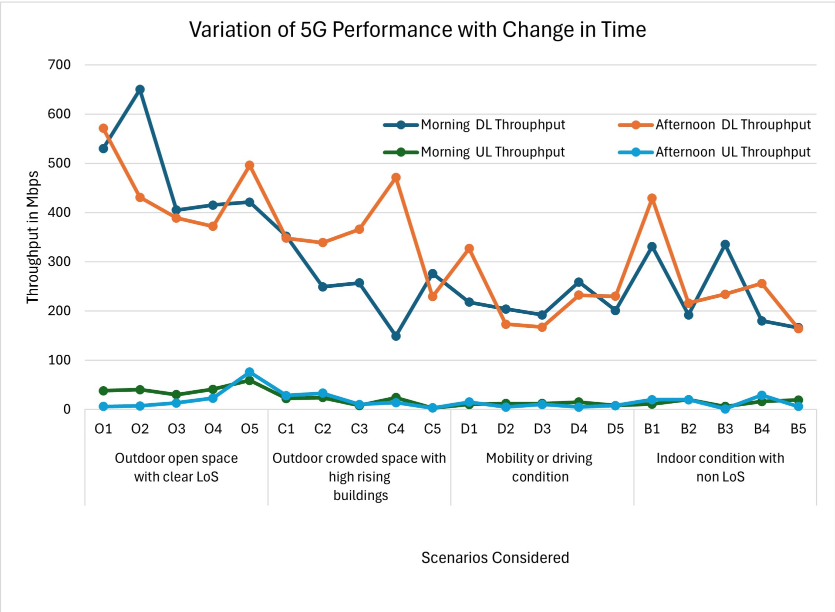

Figure 5.13: Impact of temporal variation on PRS 5G performance

5.3 Probe Handset Unit (PHU) Result

5.3.1 Overall PHU Result

The PHU data consists of download and upload throughput for all 20 sample locations categorized under four environmental scenarios. As shown in Table 5.6 below, the overall average download and upload throughput obtained with PHU are 414 Mbps and 89 Mbps respectively by considering all four environmental scenarios.

Measurement Scenarios	**Average DL Speed in Mbps**	**Average UL Speed in Mbps**
Outdoor open space with clear LoS	526	123
Crowded space with high rising buildings	422	101
Mobility or driving condition	355	76
Indoor condition with non LoS	354	57
Overall Average Performance	**414**	**89**

Table 5.6: Summary of PHU result

5.3.2 Impact of Spatial Variation on 5G PHU Results

PHU result also revealed that the best average download and upload throughput attained are 526 Mbps and 123 Mbps respectively and both are registered in outdoor open space with clear LoS condition. Download throughput dropped by 22% to 422 Mbps in crowded space with high-rising buildings, by around 38% in mobility and driving and indoor conditions. Average upload throughput also drop by 19% to 101 Mbps in crowded space with high-rising buildings, by 47% to 76 Mbps in mobility or driving condition, and by 73% to 57 Mbps in indoor condition.

Measurement Scenarios	Measurement Location	Average DL Speed in Mbps	Average UL Speed in Mbps
Outdoor open space with clear LoS	O1	574	90
	O2	531	150
	O3	371	114
	O4	623	134
	O5	531	128
Crowded space with high-rising buildings	C1	382	84
	C2	495	107
	C3	496	93
	C4	356	120
	C5	383	103
Mobility or driving condition	D1	393	60
	D2	376	86
	D3	323	95
	D4	375	46
	D5	308	93
Indoor condition with non LoS	B1	401	71
	B2	364	79
	B3	369	41
	B4	348	39
	B5	287	55

Table 5.7: Impact of spatial variation on PHU 5G performance

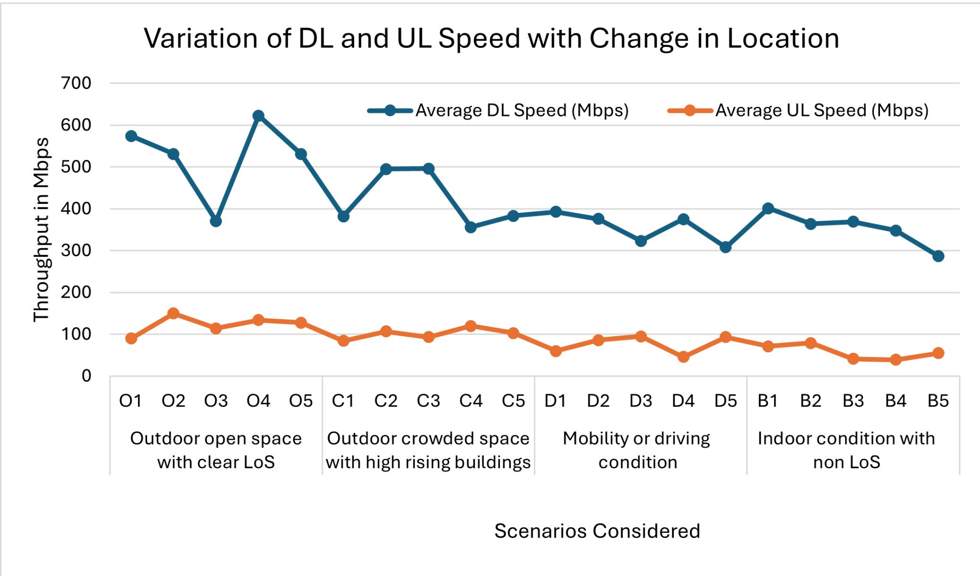

Figure 5.14: Impact of spatial variation on PHU 5G performance

The upload and download throughput distribution of PHU data across AA city is shown on Figures 5.15 and 5.16 below. Average download throughput in most of the areas with 5G coverage is from 200 Mbps to 400 Mbps and shown in yellow color in Figure 5.15. On the other hand, average UL throughput in most of the areas is above 75 Mbps and shown in green color in Figure 5.16.

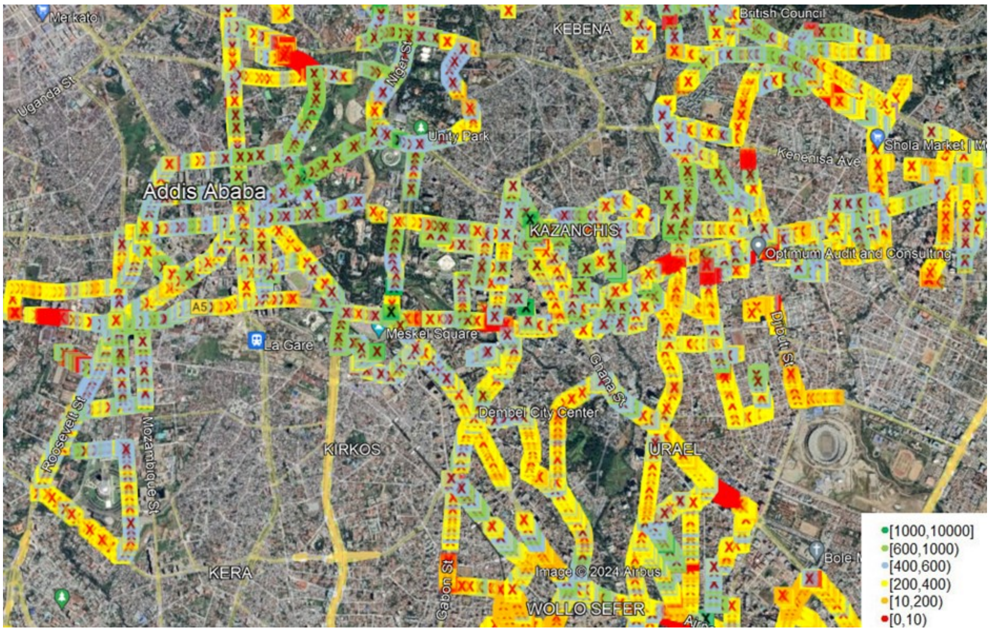

Figure 5.15: Download speed performance of 5G across AA from PHU

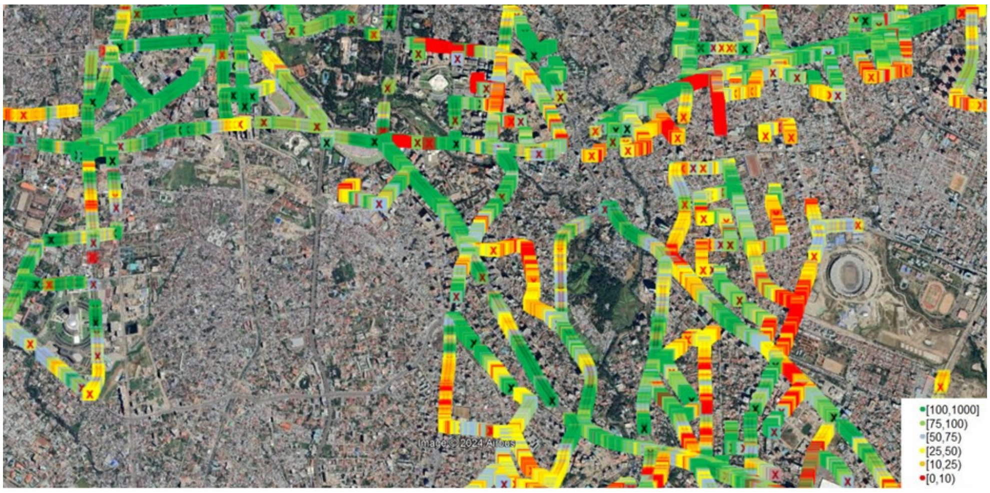

Figure 5.16: Upload speed performance of 5G across AA from PHU

5.4 User Experience Assessment Result

Questionnaire was prepared on Google forms and distributed to 5G users in AA through email, social media platforms, text, etc. Although it became difficult to get 5G users easily, a total of 93 users responded to the questionnaire from April 10 to May 01, 2024.

5.4.1 Demography of Participants

Most of the participants are male constituting 76% of total participants. Participants with age range from 35 to 54 and educational background of master's degree and above constitute 52% and 48% respectively. And 69% participants use Samsung phones. The demography of participants and their phone model is shown in Table 5.8 and Figure 5.17 below:

Question	Category	No of Participants	Percentage
Gender	Female	22	24%
	Male	71	76%
Age Range	19 to 24	9	10%
	25 to 34	34	37%
	35 to 54	48	52%
	Above 55	2	2%
Educational Background	Bachelor's degree	38	41%
	Diploma or certificate	2	2%
	Grade 10 and below	1	1%
	Master's degree and above	45	48%
	University or college student	7	8%
Phone Model	Samsung Galaxy	64	69%
	iPhone	20	22%
	Other	9	10%

Table 5.8: Demography of participants and their phone model

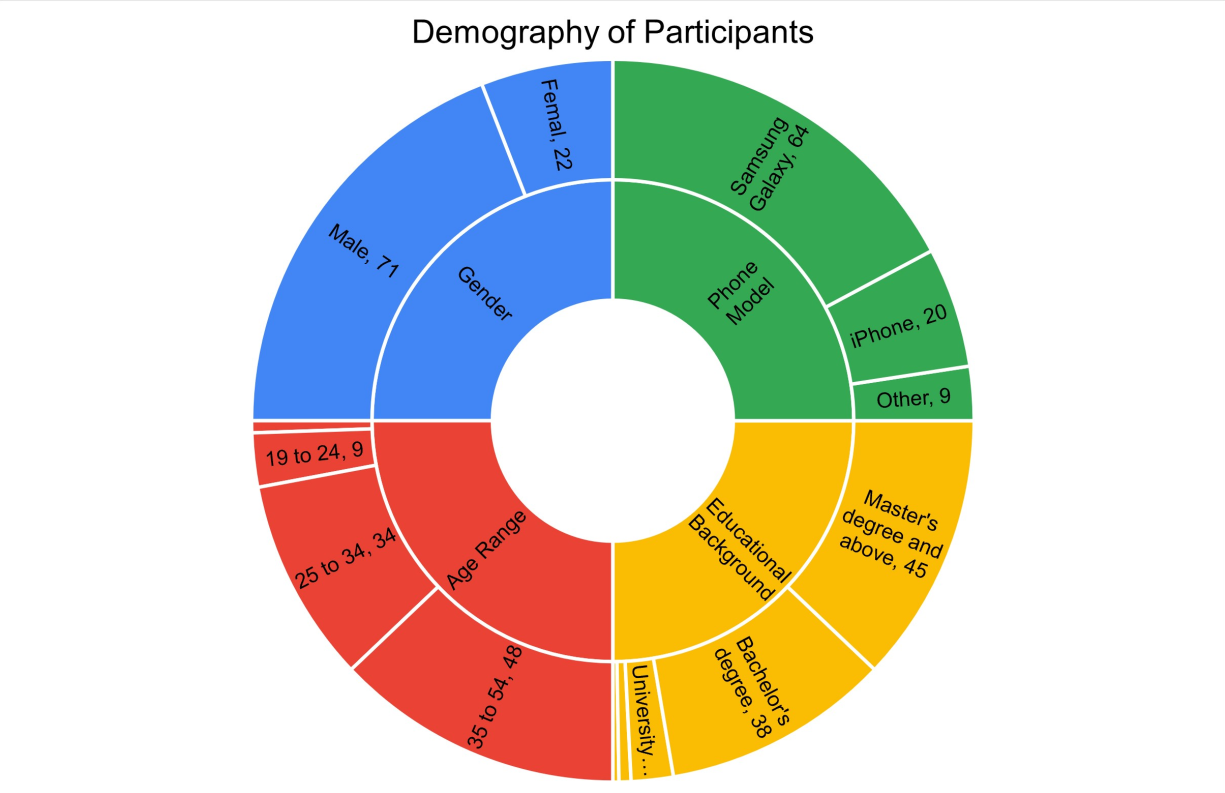

Figure 5.17: Demography of participants

5.4.2 Overall 5G User Experience Result

According to the survey results, 56% of participants expressed satisfaction with 5G service in AA, while an additional 29% reported being very satisfied. This indicates that approximately 85% of respondents are either satisfied or very satisfied with the service. Conversely, only 3% of participants indicated dissatisfaction, and a mere 1% reported being very dissatisfied with the 5G service in AA.

The overall MOS derived from all survey participants is 4.1. A detailed analysis of satisfaction levels by individual user equipment models reveals that users of iPhone devices report a higher satisfaction level, with a MOS of 4.5. In contrast, users of Samsung devices have a MOS of 3.95, while users of other device models achieve a MOS of 4. This data suggests that the performance of iPhone devices on the AA 5G network significantly surpasses that of other device models.

Customer satisfaction on overall performance of 5G service in AA is very good as [35] indicates, services with mean opinion score of 4 and above have good customer satisfaction. Figure 5.18 below shows overall satisfaction of participants.

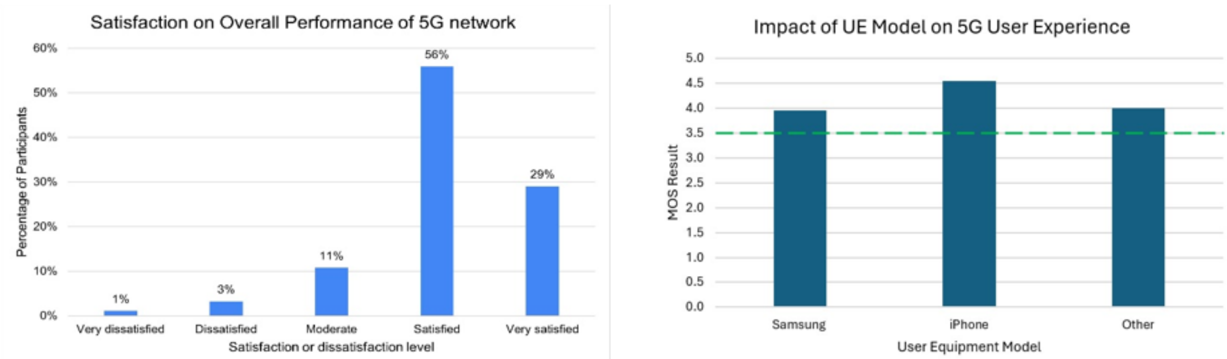

Figure 5.18: Overall 5G user experience result

5.4.3 Impact of Spatial Variation on User Experience

The survey questions were designed to assess the impact of spatial variation on customer experience across four distinct environmental conditions: open spaces with clear LoS, crowded space with high-rise buildings, mobility or driving and indoor conditions. The data were collected using a 5-point likert scale. The MOS for the three metrics: download throughput, upload throughput, and latency were calculated for each spatial scenario. As illustrated in Figure 5.19, the optimal user experience was recorded in the open space with a clear line of sight, yielding an average MOS of 3.7. In contrast, this score decreased to 3.1 in indoor conditions.

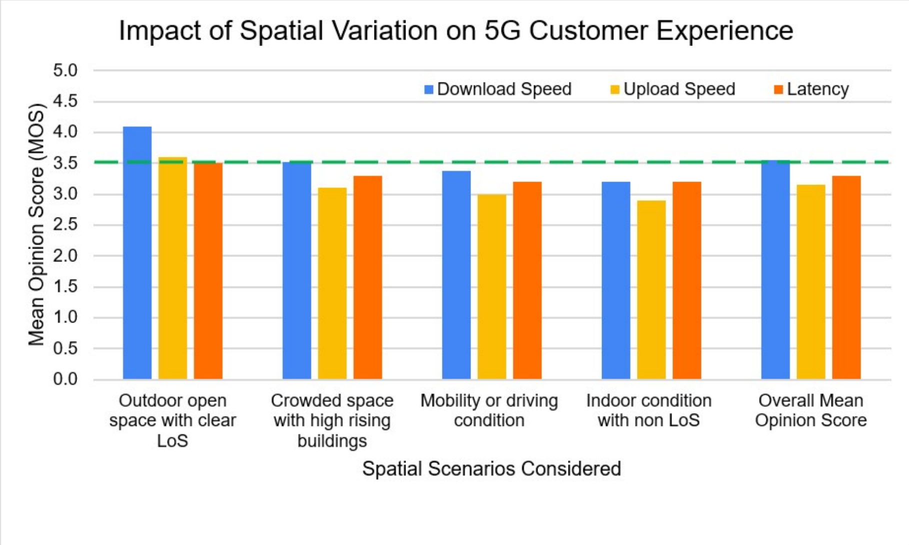

Figure 5.19: Impact of spatial variation on 5G user experience

5.4.4 Impact of Temporal Variation on User Experience

According to the mean opinion score results, customer satisfaction on download and upload throughput is marginally higher in the afternoon compared to the morning. However, there is no observed variation in latency with respect to the time of measurement. Figure 5.20 below illustrates the fluctuations MOS in download throughput, upload throughput, and latency as a function of measurement time.

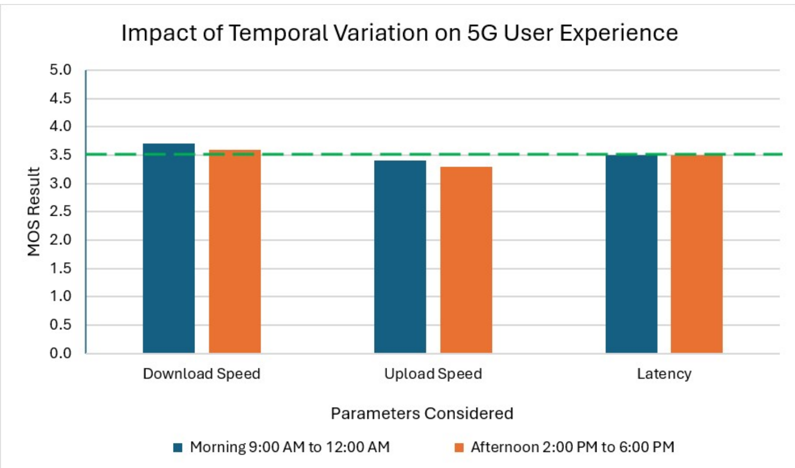

Figure 5.20: Impact of temporal variation on 5G user experience

5.4.5 Other Results and Feedback from Users

In addition to service quality related questions, two questions were added to collect most frequently used services and challenges faced while using 5G connection. 33% of participants use 5G connection for web site and social media browsing, 23% use it for online meeting and video conferencing, 21% use it for video streaming services. Only 3% of participants use 5G for high speed demanding applications like online gaming and VR/AR services. This indicates that although 5G connection with good speed is available in AA, most customers are using it for normal services which work fine with earlier generation technologies such as 4G LTE. A summary of frequently used service types are shown in Table 5.9 below:

S. No.	Frequently Used Service Type	No. of Participants	Percentage
1	Web site and social media browsing	68	33%
3	Online meeting and video conference (Skype, MS Teams, Zoom, etc...)	46	23%
2	Live and on-demand HD video streaming (Netflix, Apple TV, YouTube, etc.)	42	21%
4	Large file download and upload (Software, video clip, movie, music, etc.)	39	19%
5	Virtual reality and augmented reality	5	2%
6	Online gaming (Call of duty, GTA, Destiny, PUBG, etc...)	3	1%

Table 5.9: Frequently used service types with 5G connection

On the other hand, issues faced by 5G users in AA are summarized in Table 5.10 below. 50% of participants raised absence of continuous and stable 5G coverage across AA as a challenge. This 5G coverage issue is also raised by 50% of participants who put their feedback at the end of the questionnaire. Other challenges raised include, faster battery drainage and device overheating, lack of compelling use cases and high service charge and absence of attractive 5G package.

S. No.	Issues Encountered Frequently while Using 5G Connection	No. of Participants	Percentage
1	Absence of continuous and stable 5G coverage	76	50%
2	Faster battery drain and device overheating	29	19%
3	Lack of compelling use cases or services	23	15%
4	High service charge and absence of attractive 5G package	21	14%
5	I didn't encounter any issue	4	3%

Table 5.10: Frequent issues faced by 5G users in AA

Finally, it is worth mentioning that few participants, five to be exact, expressed their dissatisfaction in the comment section by stating that quality of 5G network is not better than 4G. They reported difficulties in accessing web pages while using a 5G connection and recommended that the service provider focus on optimizing earlier generation technologies, such as 3G and 4G, prior to fully implementing 5G services.

5.5 Correlation of QoS and QoE Results

By evaluating all four spatial scenarios, we found that the average DL and UL throughputs from Ookla SpeedTest were 364 Mbps and 58 Mbps, respectively. In comparison, using PRS yielded averages of 311 Mbps for DL and 20 Mbps for UL. The performance with PHU was even better, recording 414 Mbps for DL and 89 Mbps for UL.

Notably, the results obtained from PHU surpass those of both Ookla SpeedTest and PRS, while remaining relatively close to the Ookla SpeedTest figures. Conversely, PRS delivered the lowest throughput among the three tools.

The impact of spatial variation on 5G performance, as assessed by all three tools, indicates that both DL and UL throughputs are highest in open spaces with clear line of sight, followed by crowded space with high-rising buildings. The lowest results were observed in mobility or driving scenarios, as well as in indoor condition with non-LoS, with results being similar across all three tools.

Furthermore, the subjective quality of experience aligns with the QoS results. The Mean Opinion Score for outdoor open spaces with clear LoS is the highest at 3.7, which decreases to 3.1 for indoor conditions with non-LoS.

5.6 Limitations of the Results

Some of the limitations of the results include:

- While we have successfully collected all three QoS metrics data from SpeedTest and upload and download throughput from PRS and PHU, obtaining latency per user from PRS and PHU become challenging. We exhaustively explored the PRS, PHU and CEM. Regrettably, none of these sources yielded a clear and direct result for latency.

- Although high caution is taken during PRS data analysis in selecting serving cells for sample locations, we cannot fully guarantee that the locations are served by only these selected cells as some corners of the location might be served by cells other than the cell selected and even on serving cells might change due to handover.

- The data obtained from PRS may not accurately reflect indoor and mobility conditions, as it is generated at the cell level and aligned with the specific spatial parameters taken into account. To address this limitation, we have tried to enhance the accuracy of our data collection by utilizing SpeedTest and PHU.

Chapter 6: **Conclusion and Future Work**

6.1 Conclusion

The aim of this thesis was to evaluate QoS and user experience of 5G eMBB service in AA using three QoS measurement metrics download throughput, upload throughput and latency under different spatiotemporal conditions.

Overall average download throughput obtained is 364 Mbps from SpeedTest, 311 Mbps from PRS and 414 Mbps from PHU. As stated in [36–38], to enjoy services like UHD video streaming, online gaming, virtual reality and augmented reality seamlessly without disruption, a download speed required is around 30 Mbps. The minimum requirement for user experienced data rate is also 100 Mbs [39]. The result obtained from all the three sources is higher than both requirements above. This good result is reflected in subjective user experience result as well since MOS result obtained from users for download speed is 3.6. As stated in [35], average MOS result greater than 3.5 indicates better customer satisfaction.

Average upload throughput is 58 Mbps from SpeedTest, 20 Mbps from PRS and 89 Mbps from PHU. As described in minimum technical performance requirements for IMT-2020 radio interface report [39], uplink user experienced data rate should be greater than

50 Mbps. Although the results obtained from SpeedTesta and PHU are above this value, the result obtained from PRS is below half of this requirement. The average mean opinion score (MOS) obtained from users for upload speed is also 3.2 and it is below 3.5 in all temporal and spatial scenarios except for open space with clear line of sight condition in which case it is 3.6.

Due to system side limitations, latency or delay per user is obtained only from SpeedTest and the average result is 50 milliseconds. As stated in [39], the minimum requirement for user plane latency is 4 milliseconds for eMBB service. The result obtained from SpeedTest is more than 10 times higher than the minimum requirement. This low result in latency is also reflected in user experience as the average MOS result for latency is 3.3 which is below moderate or satisfactory level.

The MOS derived from subjective survey assessing the overall performance of 5G eMBB services in AA is 4.1, suggesting a favorable level of customer satisfaction. This result may be attributed to the robust download throughput observed across various spatiotemporal conditions, as approximately 77% of respondents reported utilizing 5G connections for applications which need good download speed over upload speed and latency.

The objective QoS results obtained from SpeedTest, PRS, and PHU, alongside the subjective QoE results derived from the survey, exhibit a consistent trend regarding the impact of spatial variations on the performance of 5G networks. Maximum QoS results are recorded across all three data sources in outdoor open space with clear LoS conditions. However, these results demonstrate a progressive decline as the scenario transitions from outdoor open spaces to crowded outdoor environment, with further deterioration observed under mobility and indoor conditions. The lowest results are recorded in indoor environments with non-LoS, as indicated by SpeedTest and PHU data, and in mobility scenarios as reported by PRS. Similarly, the subjective survey results reveal that the highest average MOS of 3.7 is achieved in open spaces with clear LoS, with a continuous decrease in scores as the location shifts from outdoor open areas to crowded outdoor spaces, further declining in mobility conditions, and reaching the lowest average MOS of 3.1 in indoor conditions.

Finally, the impact of variations in UE on 5G performance has been assessed utilizing QoS result from SpeedTest and QoE result derived from subjective survey, employing two distinct smartphone models. The SpeedTest results indicate that, on average, the download throughput and latency metrics for the iP12 outperform those of the SG53 when measured under similar time and location. Conversely, the upload throughput for the SG53 consistently exceeds that of the iP12 across all four measurement scenarios. The mean opinion score results from the subjective survey, which evaluated the overall performance of 5G services for each device model independently, yielded scores of 4.6 for the iP12 and 3.9 for the SG53. This disparity in user experience underscores the differences in download throughput and latency between the two devices, suggesting that users of the iP12 perceive the 5G performance more positively than those utilizing the SG53.

6.2 Future Work

The following areas are good research areas related to this topic and they are recommended for future work:

- To further generalize evaluation of QoS and user experience for 5G services, devising framework or standard using real time data from different systems and machine learning techniques.

- The same methodology can be followed for other parameters like packet loss, jitter, radio state transitions, and radio power consumption under diverse scenarios with detailed comparisons to 4G/LTE network.

- Systematic analysis of hand off mechanisms in 5G and their impact on network performance can also by studied.

- Further study can be performed which provides insights into how upper-layer applications should best utilize 5G by balancing the critical trade off between performance and energy consumption, as well as by taking into account the availability of both network and computation resources.

Bibliography

[1] H. Remmert. (2021) What is 5g network architecture? [Online]. Available: https://www.digi.com/blog/post/5g-network-architecture

[2] V. Solutions. (2024) What is 5g architecture? [Online]. Available: https://www.viavisolutions.com/en-uk/what-5g-architecture

[3] R. Dangi and et al, "Study and investigation on 5g technology: A systematic review," *Sensors 2021; Vol. 22 no. 1 article no. 26*, 2022.

[4] D. Chandramouli, *5G for the Connected World,*. John Wiley and Sons Ltd., 2019.

[5] Ericsson. (2023) Mobile data traffic outlook. [Online]. Available: https://www.ericsson.com/en/reports-and-papers/mobility-report/dataforecasts/mobile-traffic-forecast

[6] ITU-datahub. (2024) Ethiopian active mobile-broadband subscriptions. [Online]. Available: https://datahub.itu.int/data/?e=ETH&i=11632

[7] A. R. Bisrat, "Quality of experience evaluation for addis ababa umts enterprise data customers," Msc. thesis, SECE, Addis Ababa University, Addis Ababa, 2018.

[8] B. Alemayehu, "Evaluation of user side quality of service measurement techniques for addis ababa lte data service," Msc. thesis, SECE, Addis Ababa University, Addis Ababa, 2018.

[9] B. A. M. Misgun, "Evaluation of 4g lte user side data qos measurement tools: The case of addis ababa, ethiopia," Msc. thesis, SECE, Addis Ababa University, Addis Ababa, 2021.

[10] A. S. Fite, "Qoe assessment model for addis ababa lte video streaming service using machine learning techniques," Msc. thesis, SECE, Addis Ababa University, Addis Ababa, 2020.

[11] B. Berehanu and et al, "On the relevance of capacity enhancing 5g technologies for ethiopia," in the 10th Ethiopian ICT Annual Conference (EICTC-2017), Addis Ababa, 2017.

[12] A. Narayanan and et al, "A first look at commercial 5g performance on smartphones," in WWW '20: The Web Conference 2020, Taipei, Taiwan, 2020.

[13] T. Daengsi and et al, "5g quality of service in bangkok and metropolitan areas: Revisiting bts skytrain station areas," *Bulletin of Electrical Engineering and Informatics Vol 13(No 4)*, 2023.

[14] K. Kousias and et al, "Coverage and performance analysis of 5g non-standalone deployments," in WiNTECH '22: Proceedings of the 16th ACM Workshop on Wireless Network Testbeds, Experimental evaluation and CHaracterization, Sydney, NSW, Australia, 2022.

[15] T. Daengsi and et al, “Exploring 5g data rates around thailand iconic landmarks,” in International Conference on Digital Applications, Transformation and Economy (ICDATE) 2023, Miri Malaysia, 2023.

[16] A. A. El-Saleh and et al, “Measurements and analyses of 4g/5g mobile broadband networks: An overview and a case study,” *Wireless Communications and Mobile Computing, vol. 2023, p. e6205689*, Apr. 2023.

[17] R. D. Mardian and et al, “User experience of 5g video services in indonesia: Predictions based on a structural equation model,” *Information, Vol. 13, no. 3*, 2022.

[18] GeeksforGeeks. (2022) 5g network architecture. [Online]. Available: https://www.geeksforgeeks.org/5g-network-architecture/

[19] S. Sirotkin, *5G Radio Access Network Architecture,.* John Wiley and Sons Ltd., 2021.

[20] V. Singh and et al. (2023) What is 5g technology – requirements, initiatives, and enabling technologies. [Online]. Available: https://www.greyb.com/blog/5g-technology/

[21] GSMA. (2024) 5g spectrum guide – everything you need to know. [Online]. Available: https://www.gsma.com/spectrum/5g-spectrum-guide/

[22] A. ABACUS. (2024) Understanding massive mimo technology. [Online]. Available: https://my.avnet.com/abacus/solutions/markets/communications/5g-solutions/understanding-massive-mimo-technology

[23] P. A. P.-C. Alcaraz, “Study on quality of service in 4g and 5g networks,” Bsc. thesis, School of Information and Communications Technology, Turku University of Applied Science, Turku, 2020.

[24] Y. Zhong and et al, “Effect of spatial and temporal traffic statistics on the performance of wireless networks,” *ResearchGate, doi: 10.48550/arXiv.1804.06754*, 2018.

[25] K. Nikolopoulou. (2022) What is purposive sampling? definition and examples. [Online]. Available: https://www.scribbr.com/methodology/purposive-sampling/

[26] *Introduction to Huawei iManager PRS*, Huawei Technologies Co., Ltd., 2009.

[27] *iManager Performance Report System*, Huawei Technologies Co., Ltd., 2010.

[28] *GENEX Probe Wireless Air Interface Testing Software*, Huawei Technologies Co., Ltd., 2009.

[29] Ookla. (2024) Speedtest. [Online]. Available: https://www.speedtest.net/about

[30] B. Mishra. (2023) Flowchart that outlines the process of ookla measuring throughput. [Online]. Available: https://www.linkedin.com/pulse/flowchart-outlines-process-ookla-measuring-throughput-badal-mishra/

[31] *Mean opinion score interpretation and reporting*, International Telecommunication Union, ITU-T-P.800.2, 2009.

[32] Arimas. (2023) M.o.s. mean opinion score. [Online]. Available: https://arimas.com/2017/08/01/mos-mean-opinion-score/

[33] F. Amaya and K. Bahia, “The state of 5g 2024,” GSMA, GSMA Intelligence, Tech. Rep., 2024.

[34] S. Kechiche, “The state of worldwide connectivity in 2023,” Ookla, Tech. Rep., 2023.

[35] C. Pedro and S. Raimund, “Quality of experience in cloud services: Survey and measurements,” *ScienceDirect*, vol. 68, 2014.

[36] D. Howdle. (2024) Broadband speeds required for streaming services. [Online]. Available: https://www.cable.co.uk/broadband/guides/broadband-streaming/

[37] V. Media. (2023) What is a good internet speed for gaming? [Online]. Available: https://www.virginmedia.com/blog/gaming/internet-speed-for-gaming

[38] P. Christiansen and K. Parrish. (2023) What is a good internet speed for gaming? [Online]. Available: https://www.highspeedinternet.com/resources/how-much-speed-do-i-need-for-online-gaming

[39] E. Mohyeldin, “Minimum technical performance requirements for imt-2020 radio interface(s),” in ITU-R Workshop on IMT-2020 terrestrial radio interfaces , Geneva, 2019.

Appendix A

User Experience Assessment for 5G Network in AA

The survey aims to evaluate quality of service and user experience for 5G services in AA. By analyzing the data collected through this survey and other sources, the research aims to provide insights into the current state of 5G network in AA and identify potential areas for improvement.

* Indicates required question

1. Your age range: *

O Under 18

O 19 to 24

O 25 to 34

O 35 to 54

O Above 55

2. Your gender: *

O Male

O Female

3. Your educational background: *

O Master's degree and above

O Bachelor's degree

O University or college student

O Diploma or certificate

O Grade 12-1 1

O Grade 10 and below

4. Your mobile phone model: *

- ○ Samsung Galaxy
- ○ iPhone
- ○ Other

5. Choose services you usually use with 5G connection. (You can choose one or more options) *

- ☐ Live and on-demand HD video streaming (Netflix, Apple TV, YouTube, etc.)
- ☐ Large file download and upload (Software, video clip, movie, music, etc.)
- ☐ Online meeting and video conference (Skype, MS Teams, Zoom, etc.)
- ☐ Web site and social media browsing.
- ☐ Online or cloud gaming (Call of duty, GTA, Destiny, PUBG, etc.)
- ☐ Virtual reality and augmented reality
- ☐ Other

6. How satisfied or dissatisfied are you with overall performance of 5G services in *

O Very satisfied

O Satisfied

O Neutral

O Dissatisfied

O Very dissatisfied

7. How satisfied or dissatisfied are you with download speed of 5G network during the following hours of the day? *

	Very dissatisfied	Dissatisfied	Moderate	Satisfied	Very Satisfied
Morning 9:00 AM to 12 PM	○	○	○	○	○
Afternoon 2:00 PM to 6:00 PM	○	○	○	○	○

8. How satisfied or dissatisfied are you with upload speed of 5G network during the following hours of the day? *

	Very dissatisfied	Dissatisfied	Moderate	Satisfied	Very Satisfied
Morning 9:00 AM to 12 PM	○	○	○	○	○
Afternoon 2:00 PM to 6:00 PM	○	○	○	○	○

9. How satisfied or dissatisfied are you with delay or time it takes to load web pages or videos using 5G network during the following hours of the day? *

	Very dissatisfied	Dissatisfied	Moderate	Satisfied	Very Satisfied
Morning 9:00 AM to 12 PM	○	○	○	○	○
Afternoon 2:00 PM to 6:00 PM	○	○	○	○	○

10. How do you rate the download speed of 5G network when you use it under the * following scenarios?

	Very low speed	Low speed	Moderate speed	High speed	Very high speed
Outdoor open space	○	○	○	○	○
Crowded space with high rising buildings	○	○	○	○	○
Indoor condition	○	○	○	○	○
While driving or using transport	○	○	○	○	○

11. How do you rate the upload speed of 5G network when you use it under the following scenarios? *

	Very low speed	Low speed	Moderate speed	High speed	Very high speed
Outdoor open space	O	O	O	O	O
Crowded space with high rising buildings	O	O	O	O	O
Indoor condition	O	O	O	O	O
While driving or using transport	O	O	O	O	O

12. How do you rate the delay or time it takes to load web pages or videos on 5G connection when you use it under the following scenarios? *

	Very low speed	Low speed	Moderate speed	High speed	Very high speed
Outdoor open space	O	O	O	O	O
Crowded space with high rising buildings	O	O	O	O	O
Indoor condition	O	O	O	O	O
While driving or using transport	O	O	O	O	O

13. Which of the following issues did you encounter most while using 5G service in AA? (You can choose one or more options) *

- [ ] Absence of continuous and stable 5G coverage
- [ ] High service charge and absence of attractive 5G package
- [ ] Lack of compelling use cases or services
- [ ] Faster battery drain and device overheating
- [ ] I didn't encounter any issue

14. Any other comment or experience? (Optional)

Submit Your answer:
____
____
____