STAGE 4 DELIVERABLE

AND

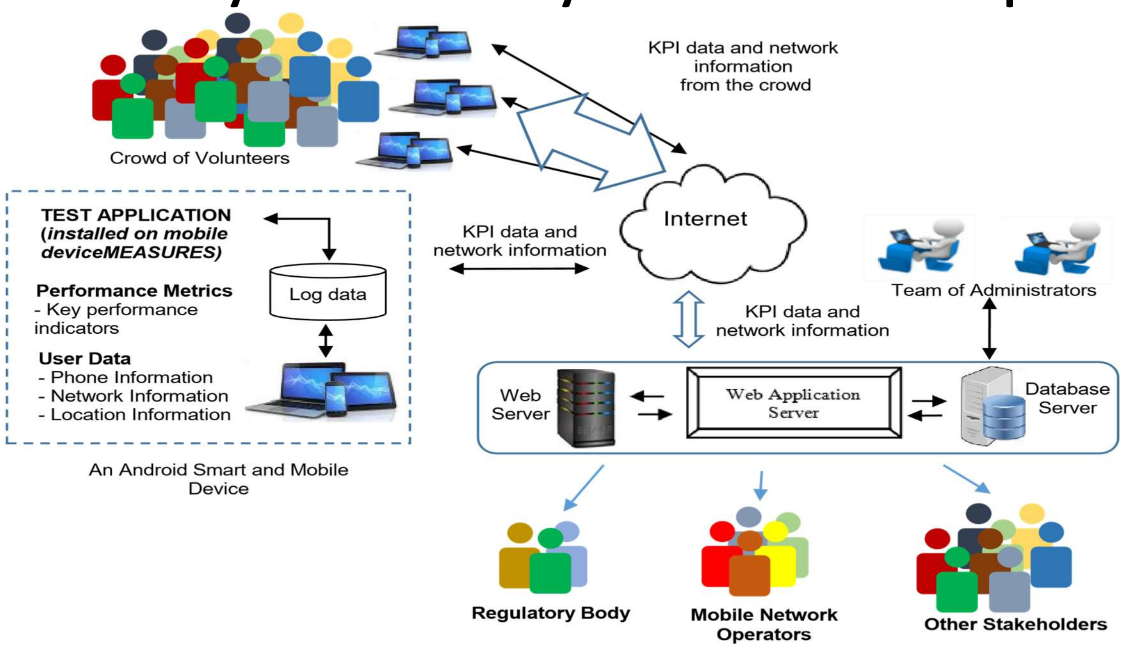
FINAL REPORT

OF

NIGERIAN COMMUNICATIONS COMMISSION RESEARCH GRANT (NCC/R&D/FUTA/010)

Titled

Subscriber Participatory Approach to Data and Voice Services Analysis Provided by Mobile Network Operators



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₦ 12,050,000

EXECUTIVE SUMMARY

Cellular Telecommunications in Nigeria has come a long way. The licensing, rollout, and upgrade of mobile network technologies from the 2G to the ongoing 5G network initiative. The market share among mobile network operators (MNOs) and the total number of subscribers has increased rapidly over the past decade; as of December 2005, there were just 19,519,154 subscribers. By May 2022, there were 204,214,647 subscribers with active mobile (GSM) lines and 301,557,035 connected mobiles (GSM) lines, and four mobile network operators (NCC, 2022). In Nigeria, the cellular network remains the dominant means of accessing the Internet and voice communication for subscribers. Nigerian Communications Commission (NCC) ensures the provision of mobile services comparable to anywhere in the world. Therefore, NCC needs to have first-hand the performance metrics of the services the subscribers provide.

This research presents the subscriber's mobile phone as a tool to measure service performance metrics. The metrics gathered thus are location specific, real-time, authentic, and with a wide coverage area. It aims to address the gap between the reported technical capabilities of the telecom's infrastructure and the quality experienced by the user. Host-based crowdsourcing approach is cost-effective and robust, with significant penetration and extensive data gathering capability.

The quality of service (QoS) analysis is based on location-specific network measurements from volunteers' mobile devices using installed software applications. Location-specific network metrics to be measured for data service includes: download and upload speed, DNS lookup time, video streaming experience, and packet loss. For voice services, metrics to be considered include: Call Set-up Success Rate (CSSR), Radio Signal Quality and Strength (Rx), Dropped Call Rate (DCR), Traffic Channel Congestion (TCH-CONG), Bit Error Rate, and Handover Success Rate (HSR). Other network parameters measured include mobile country codes (MCC), location area code (LAC), and cell ID (CID) (NCC, 2020; Dahunsi & Kolawole, Participatory Analysis of Cellular Network Quality of Service, 2015; ITU, 01).

The developed mobile application is installed on Volunteers' Android Smartphones to measure active mobile performance metrics. The application collects data in the background and sends the results to a web server. Data calculated from each subscriber is collated using a crowdsourcing platform, and network performance analysis is carried out on the data collected. The study obtained can be used by subscribers, regulators, mobile network operators (MNOs), and stakeholders to make an informed decision.

The justification for this research is that with an increase in demand and penetration of mobile services in Nigeria, subscribers are eager to get value for money and benefits comparable to anywhere in the world. A practical, efficient, robust, and relatively cheaper method of measuring the quality of service of voice and data services is of utmost importance. It provides a real-time, location-specific, comprehensive coverage technique for measuring network quality to ensure subscribers can access the best service and experience they expect and pay for. Lastly, the information obtained from the analyzed data can be compared with that provided by the MNOs and used in making informed decisions to ensure Nigeria's communication industry remains a force to be reckoned with worldwide. The amount approved for the research by the NCC is N12, 050 000.00.

A new participatory, mobile phone-based, location-based, and crowdsourcing software system is developed, which ensures a realistic assessment of the quality of voice and data services provided by mobile network operators.

1.0 INTRODUCTION

1. 1 Overview

Cellular Telecommunications in Nigeria has come a long way. The licensing, rollout and upgrade of Mobile network technologies and the race to provide network coverage to reach customers have led to an explosion in the number of subscribers in Nigeria. Coupled with this is the introduction of affordable smart mobile devices with a seamless connection to the internet, responsible for catapulting Nigeria into the top four largest African mobile markets.

Essential services such as making/ receiving voice calls and short messaging services (SMS) are no longer costly. Cellular providers also make Internet connectivity available anywhere and anytime. Allowing instant access to social networks, employment Intranet, academic environments, shopping, Internet browsing, entertainment content, media streaming etc.

From the user's perspective, there must be a utility guarantee concerning their experience regardless of the access platform. However, despite the deep penetration and high technical limits, due to the complexities associated with the cellular networks, it is a frequent case that a user never sees the top performance of the underlying technology. Inability to set up internet connectivity, poor voice quality during calls, dropped calls, lost data packets, or even data network non-accessibility are a few of the frustrations subscribers have to bear with and often pay for; thereby making Quality of Service (QoS) in the provision of services of utmost importance.

Generally, QoS measures the overall level of customer satisfaction with a service. QoS in a cellular network can be defined as a set of specific requirements provided by mobile network operators (MNOs) to users, which are necessary to achieve the required functionality of an application (service). The users specify their performance requirements in QoS parameters such as delay or packet loss, and the network commits its bandwidth using different QoS schemes to satisfy the request. Each service model has its own QoS parameters. The quality of service can be the determining factor in the business market. Its parameters and measures are necessary to indicate how well a service is essential when selecting services offered by different providers. If service features or prices are similar, quality becomes the determining factor for users, as well as; service providers can make use of quality to have an image of a "respected" provider.

It is important to note that QoS is an end-to-end issue, i.e., all entities in the path between the parties are concerned with making the services possible, and all the segments are involved in the process of

QoS guarantee. Also, QoS is specific to the service; QoS requirement for different service quantified by QoS parameters (e.g., jitter, delay, packet loss, call drop rate, handover success rate) is measured via a set of metrics called KPIs that relates to the subscriber's satisfaction in accessing the network service.

Key Performance Indicators (KPIs) help define the performance metrics of a network. They allow mobile operators to maintain their networks so that users remain satisfied. QoS requires understanding the KPIs that impact users' perception of quality. KPIs are unique by service type. Each service type, such as conversational video, voice, and Internet browsing, has unique performance indicators that must be independently measured. Internet applications are typically best-effort services, characterized by variable bit rates, and are tolerant to some loss and latency before the user perceives poor quality. Some KPIs for internet services include transaction latency (including time-to-first-byte and time-to-last-byte of data), transaction per second, concurrent transactions, page hits and object hits, uplink and downlink throughput, re-transmissions, and failed transactions. The KPIs used as standards in the assessment of QoS of voice services are Call Set-Up Success Rate (CSSR), Radio Signal Quality and Strength (Rx), Dropped Call Rate (DCR), Traffic Channel Congestion (TCH-CONG), Stand-Alone Dedicated Control Channel Congestion (SDCCH-CONG) and Handover Success Rate (HSR). Location-specific network metrics for data service include signal strength, download and upload speed, latency, jitter, packet loss, and transactional cost. To fully understand QoS, KPIs must be evaluated over time, at varying load rates and application mixes of different subscribers (IXIA, 2013).

There are many related works worldwide on the performance evaluation of mobile communication network services. Some related works are (Kadioglu, Dalveren, & Kara, 2015; Koutroumpis & Leiponen, 2016; Lasisi & Aderinkola, 2018; Lawal, Ukhurebor, Adekoya, & Aigbe, 2016; Ojih & Okafor, 2019; Ojo, Oyetunji, Popoola, Olasoji, & Adu, 2019; Olayinka, Olukemi, & Chukwuemeka, 2019)

Each KPI has a minimum acceptable value set by the Nigerian Communications Commission (NCC) (NCC, 2020). MNOs carry out measurements of these KPIs, collated and submitted to the NCC every quarter of a year. The established techniques for measuring these KPIs include (Akinlabi & Dahunsi, 2022):

i. Drive testing is a hardware-based technique in which the special equipment is slowly driven through a pre-selected route in an area spanning several kilometres. The equipment steadily measures the critical parameters of the network signal received. This is the most commonly used method.

ii. Special Hardware can also be attached to the equipment used in transmitting radio signals covering an area. This hardware monitors the operations involved in service provision, records logs, and helps calculate KPIs.

iii. Crowdsourcing is a relatively new technique in which the device platform (phones, tablets, modems etc.) used by customers in accessing networking services also serves as a measuring tool for the KPIs, i.e., those experiencing the network should be the source of measurements.

Crowdsourcing is a relatively new concept coined by Jeff Howe, an editor at Wired Magazine, in 2006. It denotes the process of throwing tasks to a large community of connected people, achieving a specified goal (Howe, 2008). These tasks are done conventionally by a delegated person or a set of assigned people, but this time, they are thrown open to like-minded and interested individuals within a large community (Estellés-Arolas, 2012). For information purposes, a pragmatic approach is when journalists and the media usually do the task of news reporting carried out by any interested person who feels there is a piece of information worth sharing for the good of everyone (Starbird, 2012).

A famous example is Wikipedia. Instead of Wikipedia creating an encyclopedia on their own, hiring writers and editors, they gave a crowd the ability to create the information on their own. Other examples are Linux, Yahoo! Answers, YouTube, and Mechanical Turk-based applications. The principle of crowdsourcing is that more heads are better than one. By canvassing a large crowd of people for ideas, skills, or participation, the quality of content and idea generation will be superior.

1.2 Analysis of the Problem

From the user's perspective, it is essential that regardless of the access platform, there is a guarantee of the utility concerning the experience. However, despite the deep penetration and high technical limits set by the NCC, due to the complexities associated with the cellular networks, it is a frequent case that a user never sees the top performance of the underlying technology. Unable to set up calls, poor voice quality during calls, dropped calls, lost data packets, or even data network non-accessibility are some of the frustrations subscribers have to bear with and often pay for.

The NCC sets benchmarks for each KPI to determine how well a particular MNO performs. However, the data used in calculating these parameters are samples, i.e., a representative of the service offered to the user over a given period. The dataset is gathered via drive testing on pre-selected routes or from a few MSCs. These methods result in averages that do not fully reflect actual moment-by-moment QoS as experienced by the user. The research is therefore motivated by the need to: -

i. Measure real-time QoS experience of subscribers
ii. Provide an impartial comparison of KPI between MNOs, since the data is obtained via crowdsourcing
iii. Enhance response time by flagging network problems before users make official complaints and gathering necessary data without requiring drive testing.
iv. Provide day-to-day statistics that MNOs can use in planning, rollout, and upgrading services.

1.3 Project objectives and scope

The scope and objectives of the project in terms of Reference given by the NCC:

i. develop a lightweight, energy-efficient crowdsourcing application that runs as a daemon (unnoticed and in the background) on the mobile phone to measure data to be used to calculate the KPIs for data and voice services and send the performance metrics to the crowd platform,
ii. develop a crowdsourcing cloud platform to archive and analyse the KPIs estimated from (i) using online big data processing techniques and
iii. develop a web interface for the cloud platform to display graphical analysis of the performance metrics and present inferences drawn from the analysis.

In summary, the following research questions answered are:

i. What is the real-time measurement of QoS delivered to the individual customer?
ii. Are the MNOs delivering and meeting the set targets and standards set by the NCC?
iii. Can the developed system (platform) effectively and efficiently measure, log, archive, and analyse customer-centric QoS meeting NCC standards?
iv. What challenges are faced in monitoring mobile voice and broadband QoS using the developed system?
v. What policy recommendations exist for operators, regulators, and policymakers to enhance Africa's mobile broadband and voice QoS offerings?

1.4 Project deliverables

The research deliverables include but are not limited to the following:

i. Development of a participatory, mobile phone-based, location-based, and crowdsourcing technique
ii. Development of a back-end and communication link
iii. Data collection and analysis
iv. Integration and evaluation of the prototype participatory QoS System. Write-up report submission and presentation of research findings to the NCC.

1.5 System Architecture

The Bloom application runs on android smart and mobile devices, using the mobile network-provided services. The application measures relevant network data to determine the quality of data and voice services on cellular networks. The client application runs on users' devices (crowd paradigm), recording and collating the QoS as experienced by each individual, as shown in Figure 1.

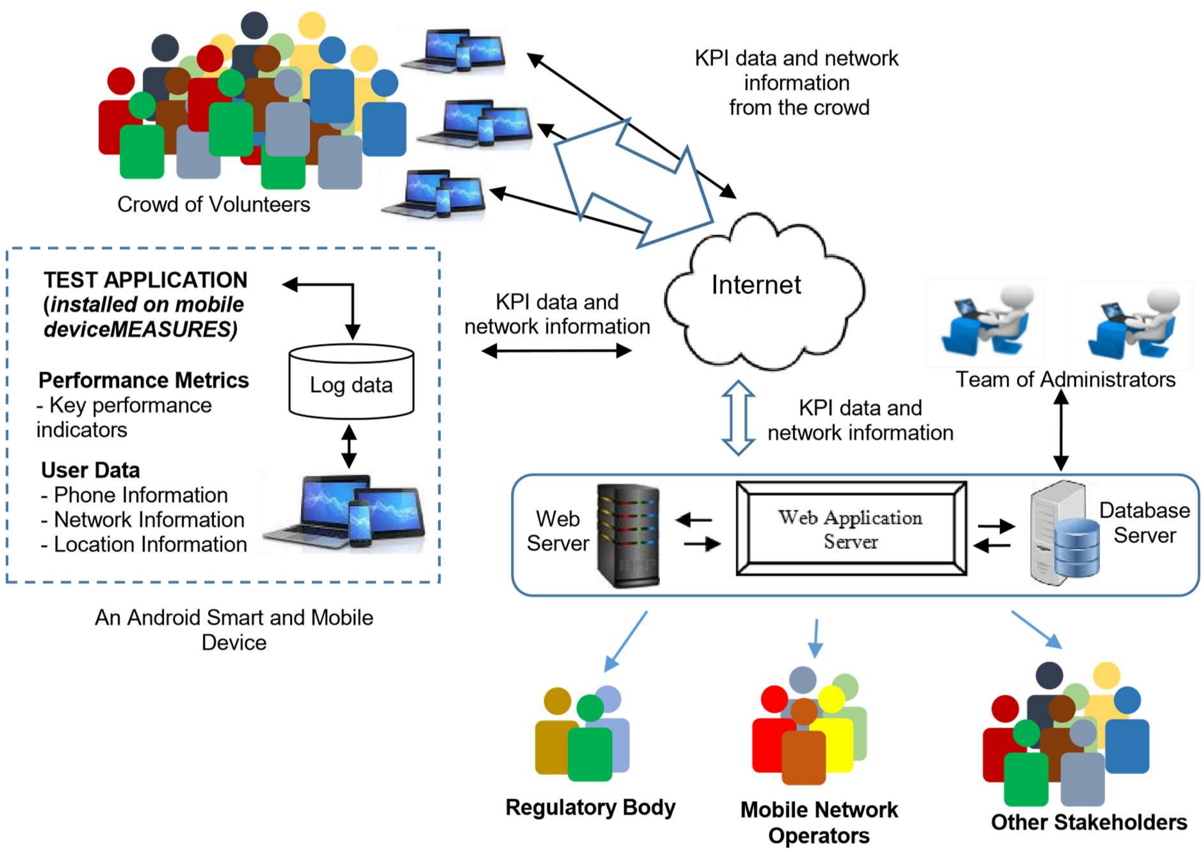


Figure 1: Architecture of the Quality of Service Monitoring System

The app is composed of the User Interface that the individuals interact with. The Task Manager's work behind the interface is getting network parameters, monitoring the QoS of various network services, saving the data to logs, displaying the logs on demand, and uploading encrypted and relevant files (data) to the remote server through the internet. Appropriate data analysis is carried out on volunteers' mobile devices, and crowdsourced network information is downloaded from the server for analysis. Administrators access processed data, and relevant data are sent to various stakeholders. The administrators should work with the Regulatory Commission.

2.0 GENERAL ACHIEVEMENTS

Table 1: Detailed project implementation so far against the background of the stipulated activities in the Work plan.

Objectives	**Stages**	**Activity**	**Activity Description**	**Expected Outcomes**	**Status of Implementation**	**Percentage Completion**	**Remark**
Objective 1	Stage One	Activity One	develop a lightweight, energy-efficient crowdsourcing application that runs as a daemon (unnoticed and in the background) on the mobile phone to measure data to be used to calculate the KPIs for data and voice services and send the performance metrics to the crowd-platform	Development of participatory mobile phone-based, location-based crowdsourcing technique	Participatory mobile phone-based, location-based crowdsourcing technique	100%	Deployed and data collection has commenced
Objective 2	Stage Two	Activity Two	Develop a crowdsourcing cloud platform to archive and analyse the KPIs estimated from (i) using online big data processing techniques	Development of the back-end and communication link	Website, back-end, and communication link	100%	Deployed and hosted.
Objective 3	Stage Three	Activity Three	Develop a web interface for the cloud platform to display graphical analysis of the performance metrics and present inferences drawn from the analysis.	Development of Web app with big data mining and visualisation capabilities	Web app with big data mining and visualisation capabilities	100%	Developed and deployed
Objective 3	Stage Four	Activity Four	Integration and evaluation of the prototype participatory QoS System	Robust prototype participatory QoS System	Robust prototype participatory QoS System	100%	Robust prototype participatory QoS System
Objective 3	Stage Four	Activity Five	Volunteer Recruitment, Data Collection, and Analysis	Volunteer Recruitment, Data Collection, and Analysis	The app was launched, data collection and analysis	100%	Data collection and analysis in progress
Objectives 1, 2 and 3	Stage Four	Activity Six	Write-up, report submission, and presentation of research findings to the Commission	All stage reports and research findings submitted	Submission, of research findings to the Commission	100%	All stage reports submitted.

The overall percentage completion of the project is 100%.

3. DELIVERABLE ONE

DEVELOPMENT OF A PARTICIPATORY, MOBILE PHONE-BASED, LOCATION-BASED, AND CROWDSOURCING TECHNIQUE

3.1 Development of the mobile application

The first step in the application development was defining the intended use and audience, followed by the main goals and objectives of the mobile application. Highlighting various user needs helps clearly define the features that should be implemented in the application. The intended use is to measure the Quality of Broadband service offered by Nigeria MNOs, aggregate all the data estimated from the measured metrics, and store them for analysis. The intended audience is, first, Subscribers to Mobile Network Operators (MNOs) in Nigeria; secondly, researchers in mobile communication QoS and related fields; thirdly, the Mobile communication regulatory bodies and the mobile network operators in Nigeria.

The main goal of the mobile application is to gather as much accurate and reliable data as possible while ensuring optimal usage of the device resources. This resource includes device battery, device memory, and device data usage.

The user needs to be met include:

i. Subscribers to various MNOs in the country need to make decisions as regards mobile communication services with the backup of reliable data.
ii. Regulatory bodies need to access the services offered by MNOs in the country independently.
iii. Researchers in this field need readily available results/data rather than duplicating similar systems when such resources are needed.
iv. Subscribers need quick and reliable information about their current active mobile network quality.

3.2 App Story/Workflow

The various screen and features of the mobile application are outlined in this section.

3.2.1 Home Screen

a. The home screen displays the currently active network name and network type of the device at the top.
b. The information at (a) above is two circular clickable buttons aligned vertically. The first button, when clicked, takes the user to the Voice Test screen, while the second button takes the user to the Broadband Test screen.

3.2.2 Reporting Screen

a. The Reporting screen has two tabs. The left tab shows the history of all Voice test results carried out by the user, while the right tab shows all Broadband test results.
b. The voice tests history shows a list of cards that display the data measured from Voice tests. The information displayed is the time, and date the test occurs, the network type at the time of taking the test, the type of test (Automatic or manual), the Cell ID, and all the Voice KPIs measured during the tests (Call Drop Rate, Call Setup Success Rate, Bit Error Rate, Congestion Rate, Handover Success Rate)
c. The Broadband tests history shows a list of cards that display the data measured from Broadband tests. The information displayed is The time and date the test was taken, the network name and type at the time of taking the test, the type of test (Automatic or manual), and all the Broadband KPIs measured during the tests (DNS Lookup Time, Download Speed, Upload Speed, Video Streaming Experience).
d. There are extra features on this screen that allows user to filter the number of test results that can be displayed at once and visualize these results graphically.

3.2.3 Network Info Screen

This screen shows information about the device's active or inactive network. The information displayed are; Signal level, Signal Strength, TAC, PCI, RSRP, RSRQ, RSSNR, Distance to Cell, MCC, and MNC.

3.2.4 Data Usage Screen

It is an analysis section that shows the application's daily, monthly, and Total data usage.

3.2.5 Others

a. ***Settings Screen***

This screen contains features that help the user personalize the application. These features include functionality that allows the user to switch the application theme to either Dark or Light mode. An option to select the type of KPI parameters that would be measured during a manual test. In addition, functionality to change the phone number to receive rewards.

b. ***Contact Us Screen***

Gives details on how to contact the developers and managers of the Bloom Mobile Application

3.3 General Data Collection

i. ***Device ID:*** The device first IMEI is used to recognise a device uniquely.

ii. ***Device IMEIs:*** This is retrieved from the Android Subscription Manager class. The Subscription Manager was used in place of the popular Telephony Manager due to privacy changes in Android.

iii. ***Device IP Address:*** This is retrieved by accessing the Inet Addresses of the available network interfaces.

iv. ***Device Location:*** This is retrieved using the Fused Location Provider, which provides a simple API to access the device's last known location.

v. ***Test Type:*** This can be either manual or automatic. The test type is identified as manual if the user initiated a test directly from the home screen of the mobile application, while it is automatic if the test is scheduled and run in the background without explicit initiation by the user; data is collected by listening to voice service call in the background through android Job.

vi. ***Network Type:*** A Telephony Manager class method returns the currently active network type (2G, 3G, or 4G).

vii. ***Operator Name:*** In Android 7 and above, it is returned by the Subscription Manager class, while in Android 6 & below, the Telephony manager returns the name.

3.4 KPI Data Collection

The QoS app was built as a crowdsourced voice and broadband aggregation mobile app on the Android operating system. Based on reviews, the app collects selected voice and broadband key performance indicators (KPIs). The measurement and collation of the key performance indicators are in two sections in the mobile app: the voice and the collation.

The KPIs collated for the voice section are: call setup success rate, call drop rate, channel congestion, signals strength, and bit error rate. The KPIs collated for the broadband section are DNS lookup time, upload speed, download speed, and video experience. Other network parameters measured include mobile country codes (MCC), location area code (LAC), and cell ID (CID).

(Dahunsi & Kolawole, Participatory Analysis of Cellular Network Quality of Service, 2015) selected CSSR, Rx, DCR, TCH-CONG, SDCCH-CONG, and HSR as Voice KPIs for determining the Quality of Service of MNOs in Nigeria. (Kadioglu, Dalveren, & Kara, 2015) CSSR, Call setup time (CST), DCR, Speech quality (PESQ), and Rx as their Quality of Service KPIs for Voice in Turkey. Voice KPI measured by (Popoola, Atayero, Faruk, & Badejo, 2018)were CSSR, DCR, SDCCH congestion, and TCH congestion. According to (Kuboye, B, & Fajuyigbe, 2009), congestion in the GSM network emanates from the Common Control Channels (CCCH) Congestion, Traffic channels congestion (TCHC), Dedicated Control Channel Congestion (DCHC), and Pulse Code Modulation Congestion (PCMC) and finally, in the measured KPIs section of the Nigeria Communication Commission (NCC) website (NCC, 2020) the measured Voice KPIs (GSM) for various MNOs are CSSR, DCR, SDCCH-CONG, and TCH-CONG. (Dahunsi & Akinlabi, 2019) worked on broadband data and analysed download speed, upload speed, dns lookup and latency KPIs.

3.4.1 Measuring Voice KPI on Mobile Phone Using Android OS

To understand how to compute the various KPIs, it is important to first look at the android operating system telephony architecture presented in Figure 2. The GSM modem performs wireless communication on the android operating system. The modem exposes serial ports for communication to the android operating system to interact with through AT command sets. Since the android operating system is an open-source software meant for anyone to be able to peruse and modify, the android team implemented a general software that would allow smartphone manufacturers to communicate with the GSM modem without writing the entire system from the ground up. This software is called the Radio Interface Layer (RIL).

The Radio Interface Layer is a software layer in the android operating system which provides an interface to the hardware's radio and modem. It consists of two interface components: the RIL Daemon and the Vendor RIL. The RIL Daemon talks to the telephony services and dispatches solicited commands to the Vendor RIL. The Vendor RIL is specific to a particular radio implementation and dispatches unsolicited commands up to the RIL Daemon. For consumer applications to talk to the modem through the RIL, the Android exposes some java APIs called android telephony APIs. This set of APIs is the only intersection available to communicate with the GSM modem. Although it is possible to interact with the modem through the RIL by sending specific AT commands, this requires maximum superuser privileges. Communication to the Android modem is only possible through the Java APIs provided by the implementers on the android operating system, and these sets of APIs are well protected, i.e., there are limited APIs exposed to the application developer.

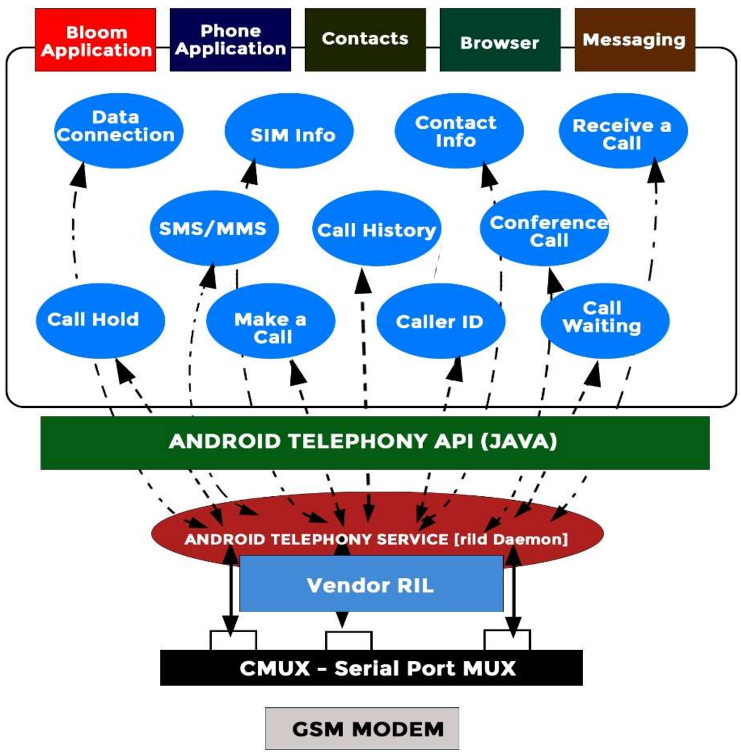


Figure 2: Structure of the Android Telephony Stack

(Adopted from http://androidqueries.com/documentation-radio-interface-layer-function-ril-androids-telephony-system-architecture-2636.html)

a. Call Setup Success Rate

Call Setup Success Rate is the measure of a successfully connected call that occurs when a call attempt invokes a call setup procedure. Call Setup is the total number of successful calls to the total number of calls. A successful call occurs when the signal is exchanged between the parties involved. In the app, a call is successful if the duration of the call exceeds zero and the call is not dropped.

Sometimes, it is impossible to know the main reason why the call was not completed. Such cases include where the other user didn't pick up the call, or the user was busy on another call. During phone calls, the current state could be monitored using the API provided by the Android framework. The change of states during phone calls was used to determine the CSSR.

b. Radio Signal Quality and Strength (Rx)

The Android framework provides a method to compute this method.

c. Drop Call Rate (DCR)

During Phone Calls, the reason for termination of the call is mainly determined by monitoring the signal strengths and the handover procedure. A low signal would likely cause a phone call to be terminated, and a failed handover would cause a call to be dropped. DCR is the percentage of calls dropped after a call connection has been established by two or more MS. A call is dropped if the call ends when the signal quality is incapable of maintaining the call, i.e., poor signal coverage. A dropped call is also recorded if a handover request fails. For rooted devices, the DCR can be extracted from the system logs.

https://android.googlesource.com/platform/frameworks/base/+/master/telephony/java/android/telephony/DisconnectCause.java API

d. Traffic Channel Congestion (TCH-CONG)

TCH-CONG measures the failure of a device to connect to a GSM or related technology service needed by the user after an SDCCH has been assigned. It is the rate of blocked calls due to resource unavailability. Congestion on TCH makes it impossible for a call to be completed and makes handover from another cell impossible to perform. It can be expressed as the percentage congestion of the TCH measured during the busy hour. It is calculated as presented in Equation 1.

$$TCCH - CONG = (number\ of\ calls\ blocked\ due\ to\ unavailable\ resources / Total\ number\ of\ requests) \times 100\% \quad (1)$$

The recommended threshold for this KPI is 10%. A class in the android framework could detect Congestion in outgoing Calls. After calls, this API is queried to detect whether the call was terminated due to Congestion.

e. Bit Error Rate (BER)

Bit error rate (BER) is the end-to-end number of bit errors per unit time. The bit error ratio (also BER) is the number of bit errors divided by the total number of transferred bits during a studied time interval. The bit error ratio is a unitless performance measure, often expressed as a percentage. BER shows the reliability and throughput of the MNO network involved. For a 2G network, the function getBitErrorRate() is provided by the android framework to obtain the RXQUAL, and the result is mapped to obtain the BER. For 3G and 4G networks, the Android framework did not provide a convenient function, so there was a need to improvise. For 4G networks, BER is computed by calculating the signal-to-noise ratio as a percentage (Mkheimer & Jamoos, 2012). For 3G networks, the computation was derived from the network's signal strength, i.e., a signal good signal strength indicates a low bit error rate, as shown in Figure 3.

```
when (cellSignalStrength.level) {
    0 -> {
        ber = 20.0
    }
    1 -> {
        ber = 3.2
    }
    2 -> {
        ber = 1.6
    }
    3 -> {
        ber = 0.4
    }
}
```

Figure 3: Code listing for computing BER for 3G networks

f. Handover Success Rate

Unsuccessful handover may be caused by Interference over the air interface, hardware faults (such as BTS transceiver), location area code (LAC) boundaries that are wrongly planned, and Coverage limitations. The recommended threshold for this KPI is 90%. The formula for HSR is given in equation 2.

$$HSR = (number\ of\ intracell\ and\ intercell\ handover\ attempts / Total\ number\ of\ handover\ requests) \times 100\% \quad (2)$$

During a call between two mobile subscribers, either subscriber moves from one location to another. The MS (Mobile station/phone) receiver usually changes cell tower connection from a cell with lower signal strength to another with higher signal strength. This is referred to as Hand Over. To compute this metric, during a call, set up a background task to listen for cell tower location changes as provided by this – https://developer.android.com/reference/android/telephony/PhoneStateListener#onCellLocationChanged(Android.telephony.CellLocation) API in the android framework. When the cell change and the call continue, a successful handover is recorded, but if the call stops and the signal strength decreases, a call handover failure and a call dropped is recorded.

3.4.2 Measuring Broadband KPI on Mobile Phone Using Android OS

a. Upload Speed

The upload speed is the amount of information in megabytes that can be transferred from a device to an internet server per second. On installation of the mobile application, a 2.49MB video file is included in the application's assets. The application uses the UploadTask class from the firebase API to upload this file to the test server. A time limit of 10 sec is set to ensure that the whole upload task doesn't exceed 10secs in a case where the device network is very slow. There are two cases to be handled; (Case 1) if the upload completes before the time limit is exceeded. (Case 2) if the time limit is reached and the upload task has not been completed. In Case 1 above, the upload speed is calculated as the file size in megabytes divided by the total time required to upload the file entirely to the server. While in Case 2, the upload speed is calculated as file size in megabytes that have been uploaded so far divided by the set time limit.

b. Download Speed

This is the amount of information in megabytes a device receives per second from an internet server. The application uses the Task class from the firebase API to download a 2MB zip file from the test server. A time limit of 10sec is set to ensure that the whole download task doesn't exceed 10secs in a case where the device network is very slow. There are two cases to be handled: (Case 1) if the download task completes before the time limit is exceeded. (Case 2) if the time limit is reached and the download task is not complete. In Case 1, the download speed is calculated as the total megabytes transferred divided by the time taken for the transfer to complete.

c. Video Streaming Experience

Research has proven that the Quality of Service measurement is insufficient to account for the overall user satisfaction, unlike other Key Performance Indicators. Also, according to the ITU recommendation P.911 (ITU, 01), measurement of Audiovisual material, e.g., Video quality, must be carried out subjectively. One good approach to measure the video streaming experience on the Android framework is: (1) Measuring the network QoS such as latency, throughput, packet loss, e.t.c. (2) Converting the network QoS metrics into application performance metrics employing protocols' modelling. (3) Mapping the application QoS onto the end user's QoE in the Mean Opinion Score (MOS). In the Bloom application, there was no need to measure the network QoS, as the application was able to get the application QoS directly from the inbuilt android Medial player library API. Thus, the application QoS was mapped directly to the end user's QoE using the model described in the code block below. The MOS has a scale of 0-5, where 0-1 is equivalent to a very poor experience, 1-2 is equivalent to a Poor experience, 2-3 is equivalent to a Fair experience, 3-4 is equivalent to a Good experience, and 4-5 is equivalent to a very good experience.

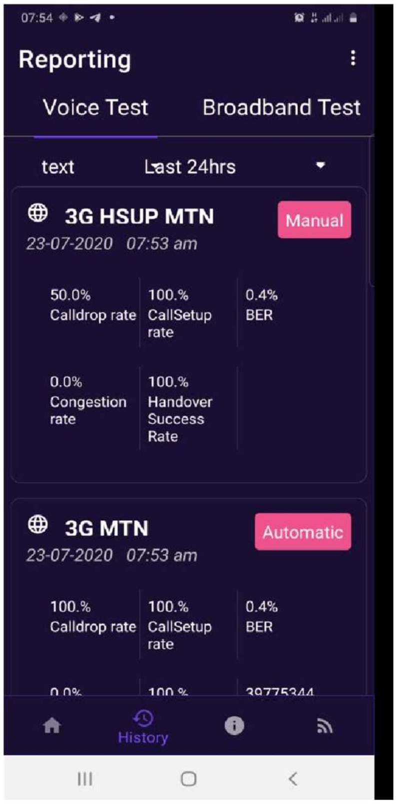
d. DNS Lookup Time

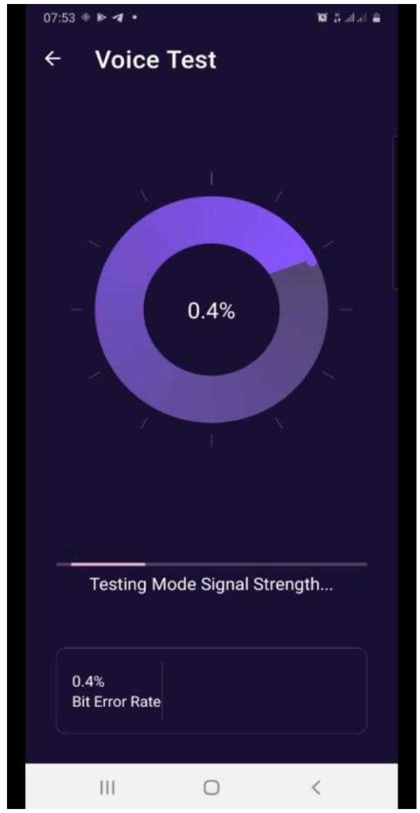
This is the time it takes to resolve the hostname into its corresponding IP address. This is measured by recording the current time in milliseconds just before the use of the inetAddress class to resolve a particular hostname to its corresponding IP address. If the hostname is resolved successfully, the current time is measured and subtracted from the start time. This difference in time is recorded as the DNS Look-up time. A list of different hostnames was provided where any can be randomly picked as a host.

Appendix A1 and A2 present the algorithms for estimating Voice KPIs.

3.5 Installing the Application

The app can be downloaded and installed on an Android Mobile Phone via a link on the Bloom Website https://bloomperf.ng/. Figure 4 shows the Bloom mobile application's reporting interface, voice test interface, and broadband test interface. More interfaces are presented in Appendix B. The "how to use video" can be downloaded from https://bitly/howtouse_bloom





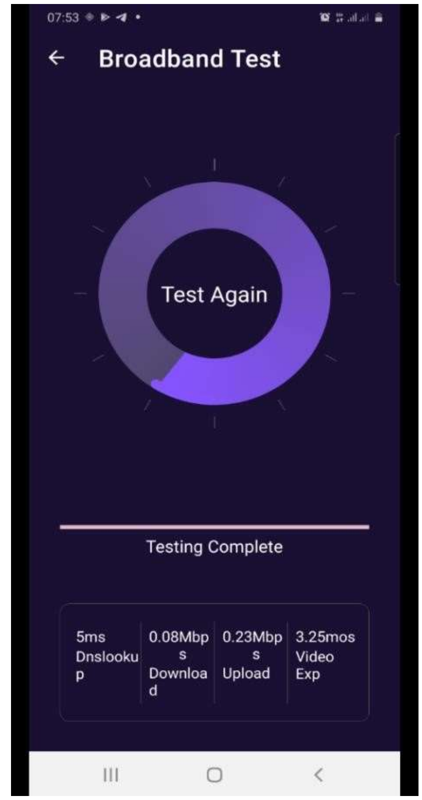


Figure 4a: Reporting interface Figure 4b: Voice test interface Figure 4c: Broadband Test Interface

4. DELIVERABLE TWO

DEVELOPMENT OF A BACK-END AND COMMUNICATION LINK

4.1 System Architecture

The Bloom mobile application is programmed to request network and quality of service information from the GSM architecture subsystem. Figure 5 presents the system's network architecture. Arrows 1 and 3 in Figure 1 represent the bloom application request for information from the base transceiver station (BTS) and network switching subsystem (NSS). Conversely, the arrows pointing to the opposite side, numbered 2 and 4, depict the receipt of the data request. The data received from the base transceiver station (BTS) are the base station information such as the location of the base transceiver station, number of cells, the distance between cells, signal strength, Peripheral Component Interconnect (PCI), distance to cell, Mobile Country Code (MCC), Mobile Network Code (MNC) etc.

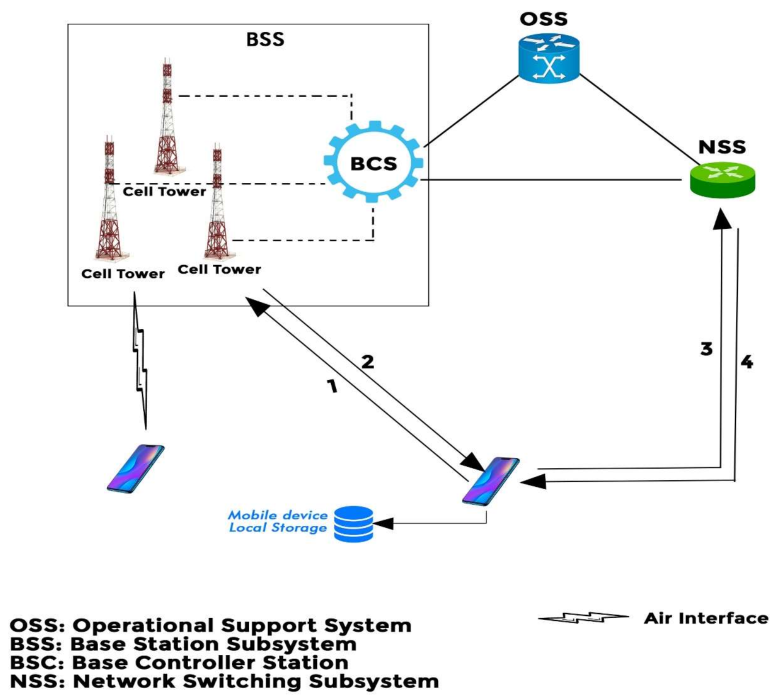


Figure 5: System's network architecture

Data such as the handover information, state of the call receiver (active or inactive), and general call information (call drop, call success, and all other call authentication) are retrieved from the mobile services switching center, which resides in the network switching subsystem. Also, the authentication center in the network switching subsystem is where the user's information is stored. The Bloom mobile application collects relevant user information from this source.

After data is retrieved from the radio layer via different subsystems in the network architecture, it is stored in the phone's local storage. The data is transferred via the internet from the mobile phone to the Firestore database. Appendix A presents a sample of data stored in the Firestore database. The data architecture is presented in Figure 6.

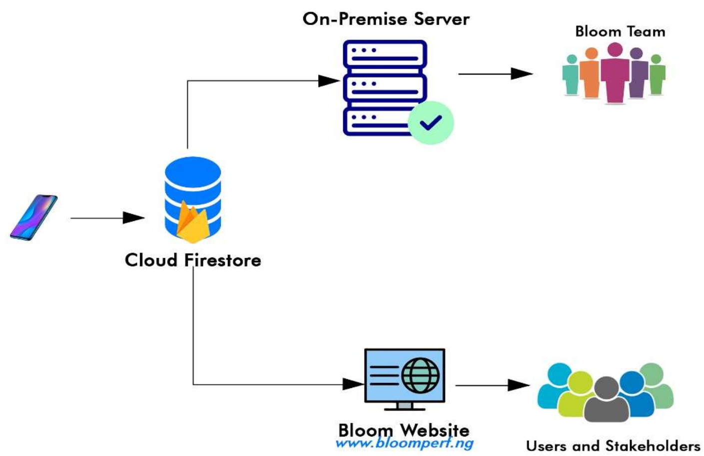


Figure 6: Data flow architecture of the system

There are two major consumers of the information on the database: the Website and an on-premise server. For the Website, a RESTful API calls the data, which is analysed and presented to volunteers and stakeholders. The data saved in the Cloud Firestore is additionally backed up on the on-premise server for analysis and other applications. Figure 7 shows a block diagram of the basic components of the host-based system and their interaction with each other. The entry point, main activity, and testing server are all on the mobile phone. The mobile phone activities are connected to the Cloud Firestore. The Cloud Firestore feeds the Local Server and Web Application with data collected through the application programming interface (API). The APIs define how the different software parts communicate with each other using requests and responses.

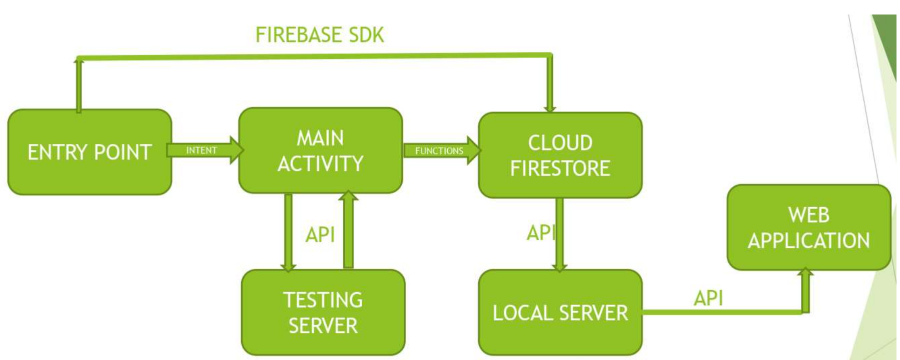


Figure 7: Communication with parts of the software application through API

Appendix C shows a sample of the data saved to the Cloud Firestore

4.2 Back-end System Architecture

Figure 8 presents the back-end system architecture showing the interfaces between mobile and web applications. The mobile application measures and collects the KPIs and saves the data in the local file. The data in the local file is uploaded to the cloud. A background job queue ensures that both are synchronized. Data is stored in the firebase. The web application API is developed to ensure a seamless interface between the firebase and the web application.

The Firestore cloud functions for mobile applications were utilized to store and present the KPIs. Firestore is a NoSQL document database built for automatic scaling, high performance, and ease of application development. While the Firestore interface has many features similar to traditional databases, a NoSQL database differs from them. It describes relationships between data objects and has a mobile library that can be used for data storage on the Android operating system.

This library stores the collected data using JSON format on Firestore. Firestore stores the data locally and pushes it to the cloud when connected to the internet. This ensures that data is not lost and is readily available when local users request it.

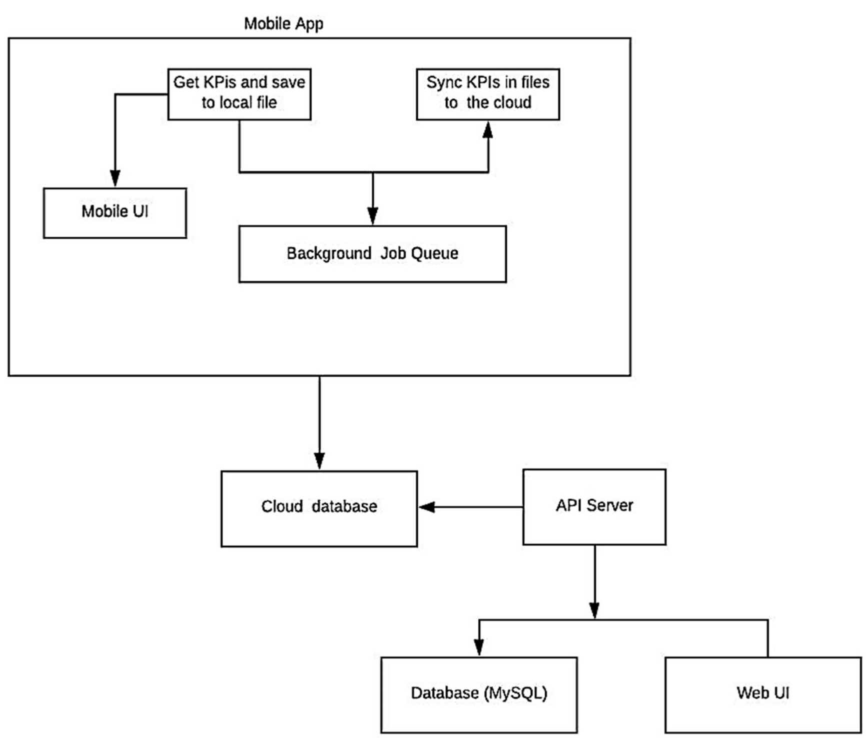


Figure 8: Back-end System Architecture

4.3 Cloud-hosted database

A cloud-hosted database eases synchronization configuration procedures with the mobile client because the database models have easy-to-configure cloud services. Cloud-hosted databases also solve issues regarding data distribution during scale-up operations (which are handled by the cloud host) and data availability, both of which are essential features. Cloud Firestore, for instance, is a Backend-as-a-Service (BaaS) deployment option under the larger Google Cloud Platform, providing server-side services for mobile and web clients. The database designed and implemented is non-relational, and the DBMS service selected for cloud storage is Cloud Firestore. The tipping points for choosing are as follows:

1. Cloud Firestore does not have native presence support for instant data synchronization, but it can leverage Firebase Real-time Database's support for presence by syncing Cloud Firestore and Real-time Database using Cloud Functions if the need arises.
2. The scalability of Cloud Firestore is more robust compared to Firebase's Realtime Database.
3. MongoDB has been filtered out due to not having robust support for mobile clients, but both Firebase Real-time Database and Cloud Firestore have.
4. Cloud Firestore is comparably cheaper than Firebase's Real-time Database.
5. Firebase Real-Time Databases are limited to zonal availability in a single region, and Cloud Firestore ensures data is shared across multiple data centers at once, providing robust data consistency at any instant.

4.4 The Web Application API

The JSON RESTFUL API is consumed for data analysis and presentation on the web application. JSON or JavaScript Object Notation is an encoding scheme designed to eliminate the need for an ad-hoc code for each application to communicate with servers that communicate in a defined way. The JSON API module exposes an implementation for data stores and structures, such as entity types, bundles, and fields.

The API for the application was developed with the python programming language and the Flask Web application framework built on Python. The API server works by fetching the data stored by the mobile app on Firestore and saving it in an SQLite-powered database so it can be represented in JSON format to the web application. A background job runner cloaked with a cache was implemented as part of the

API to retrieve the data from Firestore. This enables web application users to get real-time data collated from the mobile application. The server is written in the python programing language and powered by SQLite.

4.5 The Web Application

The web application gives access to general information about the research and is the platform on which preliminary results are presented. The intended audiences are subscribers to MNOs, researchers in mobile communication QoS and related fields, and mobile communication regulatory bodies in Nigeria. The platform is to provide information about the research on mobile communication QoS and access to insights from data gathered from volunteers' devices. Users and stakeholders access data from the Cloud Firestore via the Bloom website and researcher via an on-premise server. Figure 9 presents the web application development infrastructure.

The web application software was developed using React rather than pure HTML, CSS, and Vanilla JavaScript. React is well suited for a web application with a single-page feature instead of the traditional Website resulting from the latter. Furthermore, React was chosen over other single-page web application JavaScript libraries like Vue or Angular.

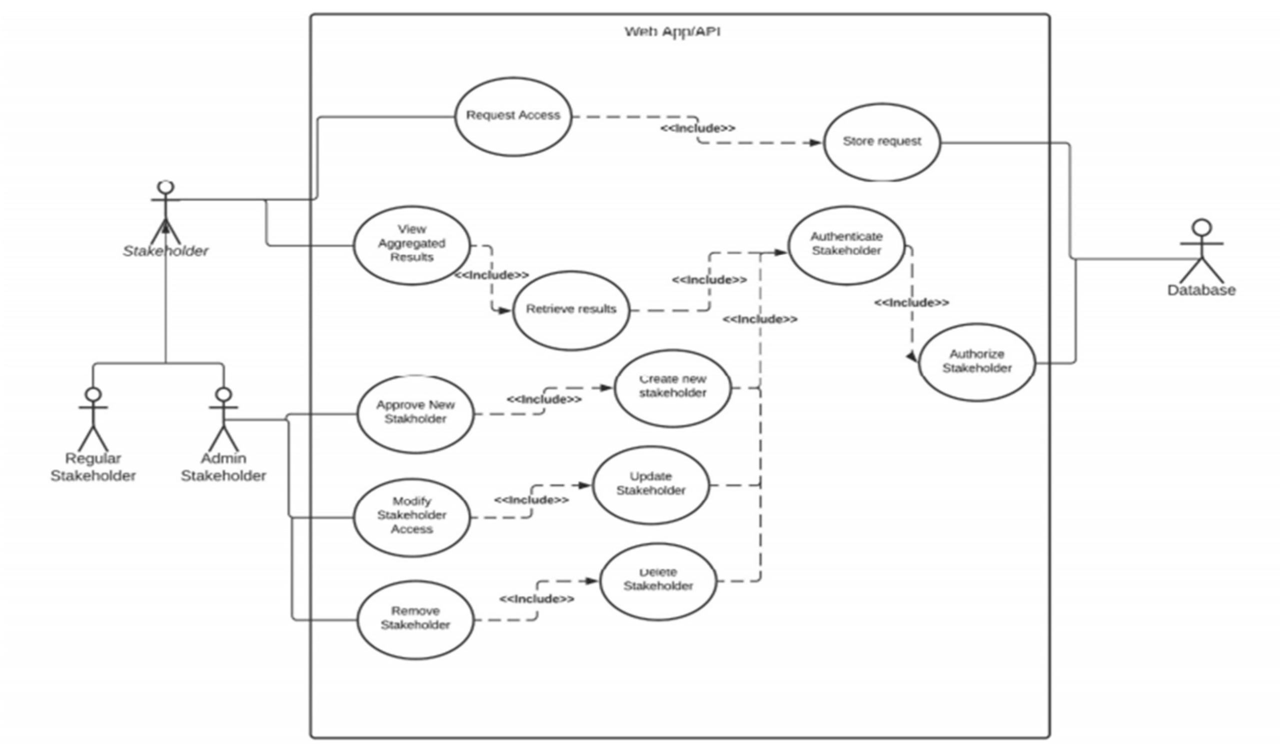


Figure 9: Web Application Development Architecture

4.5.1 Web App Features

The pages specified under the application flow sub-section of the design were implemented accordingly; by using React leverage was on robust packages and optimisation techniques to meet the software requirements, some of which are:

a. **React Router:** This optimizes routing between pages without reloading the entire web application, making it a single-page web application.

b. **Code-splitting:** This optimization procedure reduced the average load time of each page from about 10.25 seconds to less than 2 seconds (with a network speed of about 214 Kbps). It also allowed a light-sized placeholder gif to be displayed while a new page loads rather than a blank page.

c. **Recharts and Nivo:** These packages provided the various charts used. Specifically, Recharts was used to implement the line, bar, and pie charts in the KPI scores and analytics pages, while Nivo was used to implement the doughnut charts in the analytics pages.

d. **Axios:** Axios was used to configure and create requests sent to the API endpoints instead of using JavaScript's default fetch function.

e. **React-Query and React-Query-Devtools:** While Axios handles sending requests to the API endpoints, better optimisation was implemented using these packages. They provide hooks functions that update the user interface when requests are made to the API and when error or success responses are received. React-Query also provided caching options to reduce the frequency at which requests were sent. At the same time, react-query-devtools were used only in the development environment to debug API-related issues that arose during development. The API endpoints were accessed via their respective universal resource identifiers structured in JavaScript objects.

f. **Open Street Maps and Leaflet:** These packages provided the map (leaflet) and the map data (open street maps) used in the general statistics and interactive maps pages. They are free and open-source alternatives to the more popular google maps (OpenStreetMap, 2021).

g. **Extraction of Geographic Boundary Data:** An Open street maps API called Nominatim provides polygon data for a location through the request endpoint (OpenStreetMap, 2021). Requests for multiple locations simultaneously are not allowed, and successive requests within a one-minute window are limited to eleven. These bottlenecks were handled using a web automation script using Selenium WebDriver written in Python to automate the process of sending requests for the polygon of all the thirty-six states and the federal capital territory and saving the result in a JSON object in a JSON file. This JSON file was used to dynamically update the map without sending requests to open street map API. The required credit acknowledgment was added, keeping in line with Open street map's copyright policy.

4.5.2 Web App Story/Workflow

The various screen and features of the mobile application are outlined in this section.

a. **Home Screen:** this page provides basic information about the quality of service research and has interactive elements (links) which can be used to navigate to other parts of the web application.

b. **Stakeholder Landing Page:** this page is the stakeholder is directed upon successful authentication. It has a menu list that links to other pages.

c. **Coverage Map Page:** two maps are provided on separate tabs on this page. The tabs can be switched by clicking on the tab icon. The first map shows the states in which tests were made. Each highlighted state can be clicked to navigate to another page that presents aggregated and peak scores for voice and data broadband services metrics per month or quarter views for that state

d. **Data KPI Scores Page:** this page provides aggregated and peak scores for data broadband services metrics per month or quarter view nationwide. The measurement period can be switched using the "Monthly" or "Quarterly" tabs. There is an additional filter layer for a specific month or quarter.

e. **Voice Analytics Page:** this page provides results from preliminary analysis for voice services metrics per week. There is an additional filter layer to view each MNO separately. Also, each MNO's total test count and share in the total count and by network type are available. The horizontal bar below each chart is an interactive brush that can be dragged from the right or left to reduce the number of weeks shown.

Figures 10 and 11 present the default homepage and the stakeholder's platform. Other pages are presented in Appendix E.

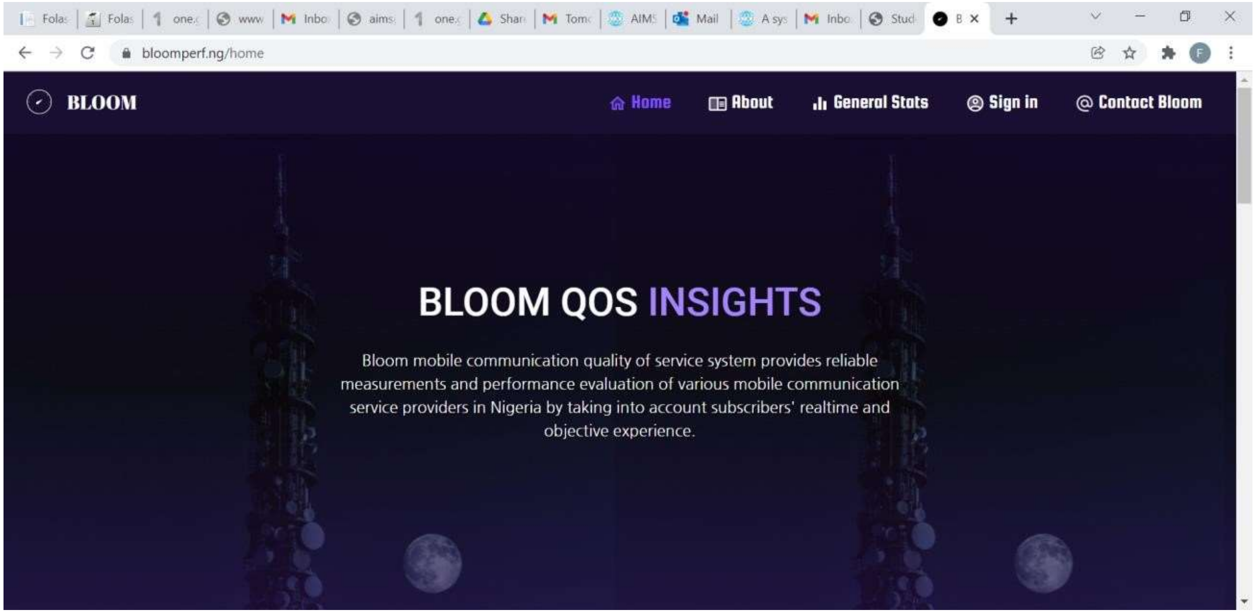


Figure 10: Default homepage

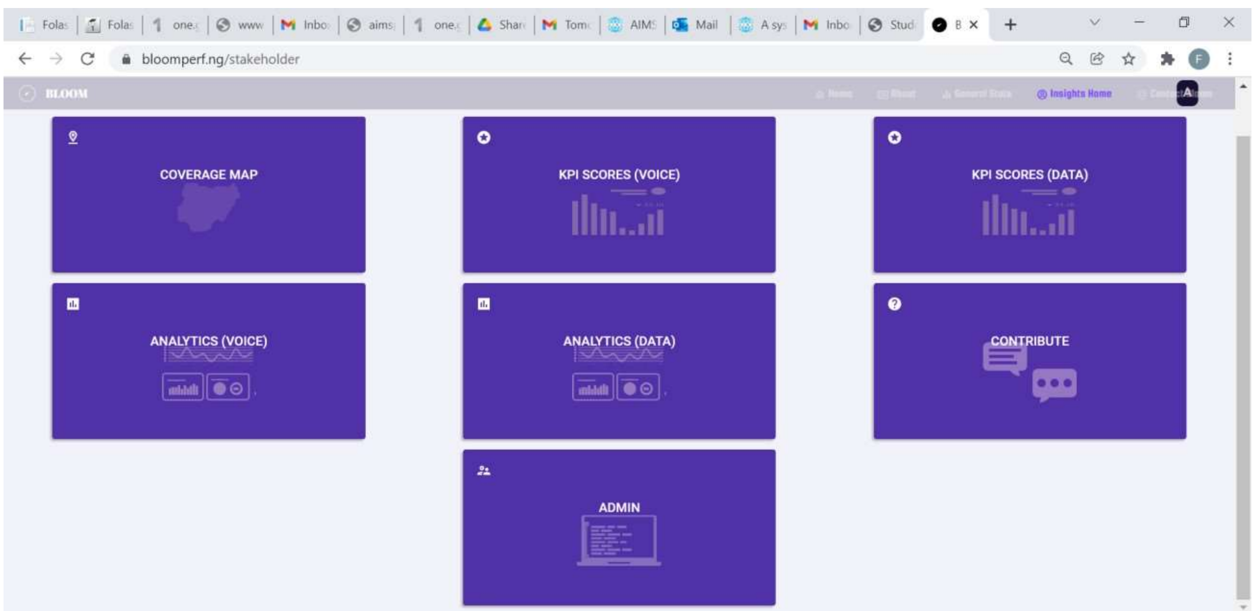


Figure 11: Stakeholder's homepage

4.6 Data Migration to a Local Server

This operation involves creating a JavaScript Node application that queries the cloud database intermittently and downloads all the available data created after the last recorded data-dump time. This operation is carried out twice, with the second iteration serving as an optimization the first time. The first migration test is carried out using a csv file.

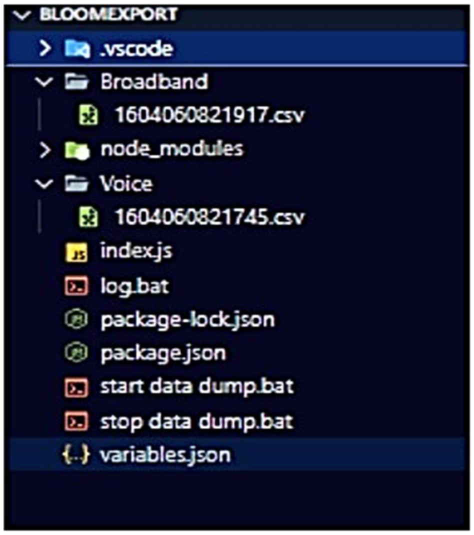
Packages used for this operation include:

a. **PM2:** this package ensured that the application could automatically restart in case of any interruption or crash.
b. **JSON2CSV:** this package transformed the data exported from Cloud Firestore in JSON format to a csv format.
c. **Firebase Admin:** this package creates the authorization configuration to connect the application with Cloud Firestore and write query operations executed for pulling data from Cloud Firestore.
d. **Node-Cron:** this package schedules the intermittent data-dump tasks.

Data security, availability, and reusability are integral to a local data access platform that allows authorised users to access data just as it is available on the cloud database. Data security is considered to protect data from loss and unauthorised access. Data availability and reusability cover the need for migrated data to be available to researchers whenever it is needed in a user-preferred format, unlike just csv format in the first migration. Also, to ensure that the migrated data can be helpful for various implementations based on specific metrics, periods etc.

The second migration operation optimises the first with the following features:

a. **Improved data pipeline:** The structure was improved with clearly defined functions and generally adhered to better coding practices like project file-structure organisation, which is presented in the file layout in Figure 12.
b. **Local Database:** This migration did not store the migrated data as a csv file but in a local instance of a MongoDB database. The database schema for the cloud database was replicated on the local database by mapping correlating datatypes and data structures. Another contributing factor to the success of the cloud database in local database migration is that both database management systems were documented. The local database added here serves the following purposes:
    i. data source for a local data access platform for researchers.
    ii. storage of logged information for the data migration process.
    iii. user database to be used for authentication.



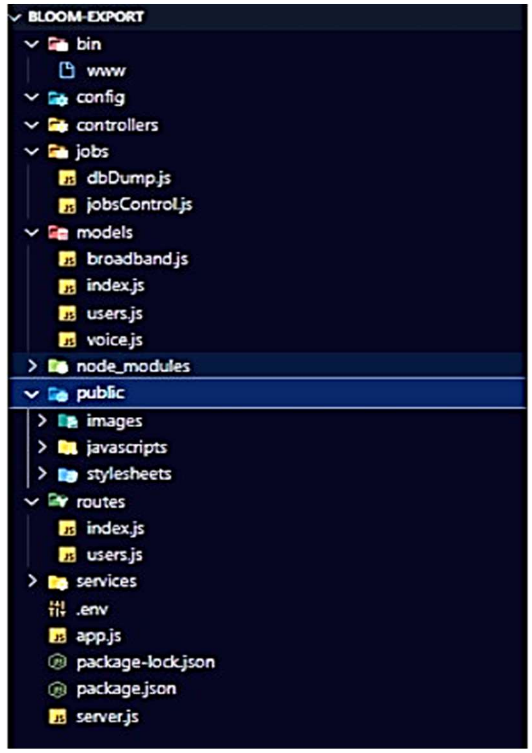


Figure 12: Project File Structure for the first migration(left) and second migration (right)

5. DELIVERABLE THREE

DATA COLLECTION AND ANALYSIS

5.1 Overview

Data is downloaded and saved on the laboratory server for archiving and further analysis. Some analysis that has been carried out on the data using Python is presented in this section.

5.2 Voice KPI analysis

NumPy and Pandas were the data cleaning and preparation software used to handle outliers and null values. The individual columns that contained the KPI values were inspected for outliers and null values. It was noticed that null values and outliers were less than 2% of the total data point in the columns that mattered most. Therefore because of the peculiarity of telecommunication data, the rows with at least one missing value were dropped, reducing the data point by about 2%.

From inspection, there were 101 unique IMEIS, indicating data was gathered from 97 different mobile devices. Data were collected from 21 different states, with 18 in Nigeria and two outside Africa. The states in Nigeria are Adamawa, Ondo, Nasarawa, FCT, Lagos, Niger, Rivers, Ogun, Oyo, Osun, Ekiti, Bauchi, Delta, Kogi, Plateau, Edo, Kaduna, Gombe, and the states outside the country are England (United Kingdom), California (United States of America), and in a state in Turkey (The state is unknown because it appears in Arabic). For Nigeria, data was collected from the four major mobile network operators in Nigeria (MTN, Airtel, Glo, 9mobile). There were two other mobile network operators outside the country: Three (United Kingdom), T-mobile (United States of America), and Turk Tecom in Turkey.

From the diagram in Figure 13, the majority of the data was obtained from Ondo state, followed by Lagos state. Ondo State because the Team was able to motivate her students to install the application and keep it on. The least data collected were from Kaduna and Gombe states. In Lagos state, 4000 data points were obtained, while in Ondo state, there were slightly above 6000 data points. From Figure 14, most subscribers use MTN mobile operators, followed by AIRTEL, the GLO, and 9MOBILE in Nigeria. Figure 14 shows data collection skyrocketed in January 2022 with more than 6000 data points.

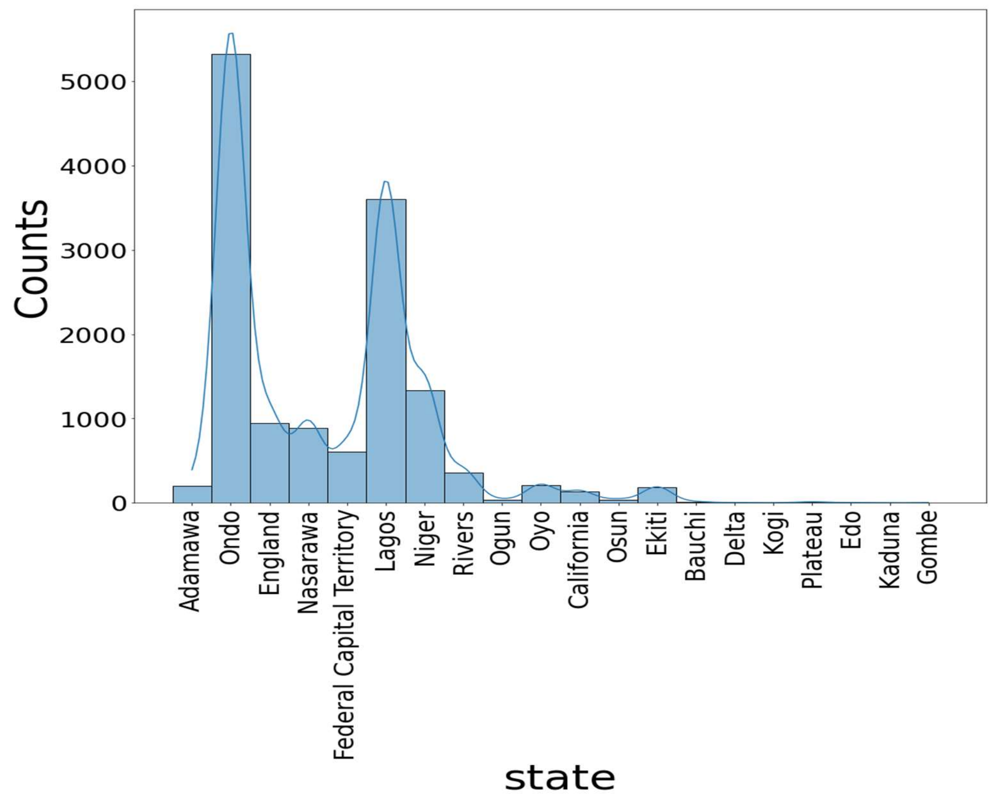


Figure 13: States where QoS Host-based data was collected

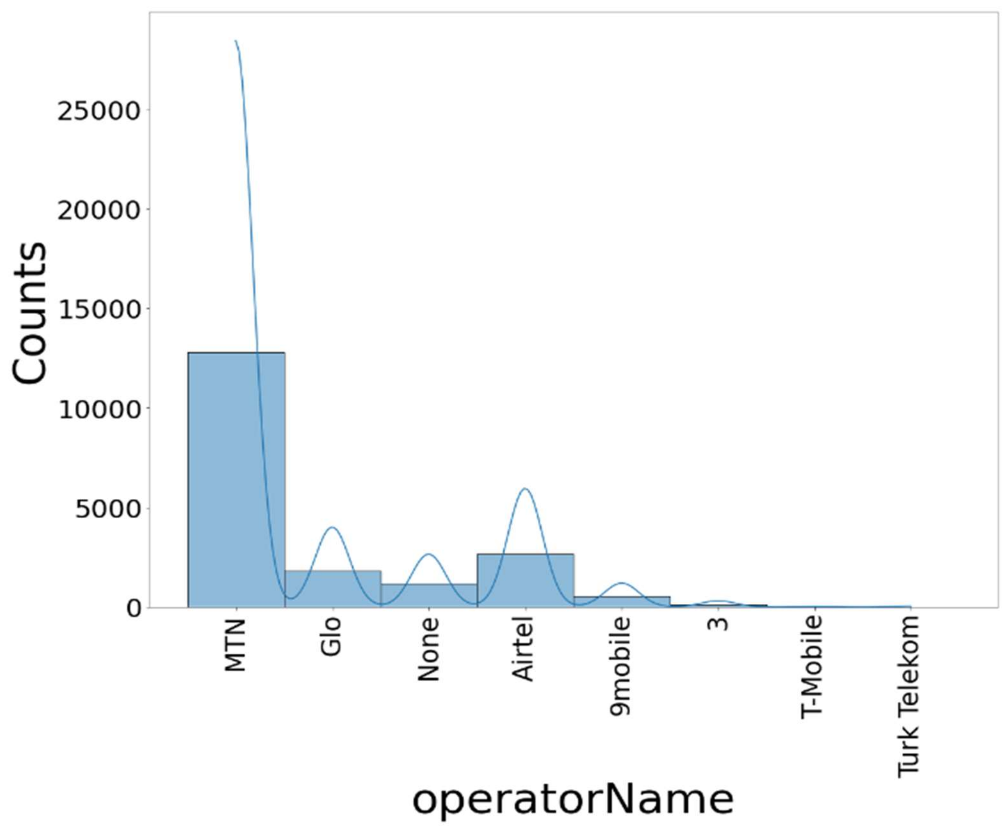


Figure 14: Mobile operators Bloom data collection distribution

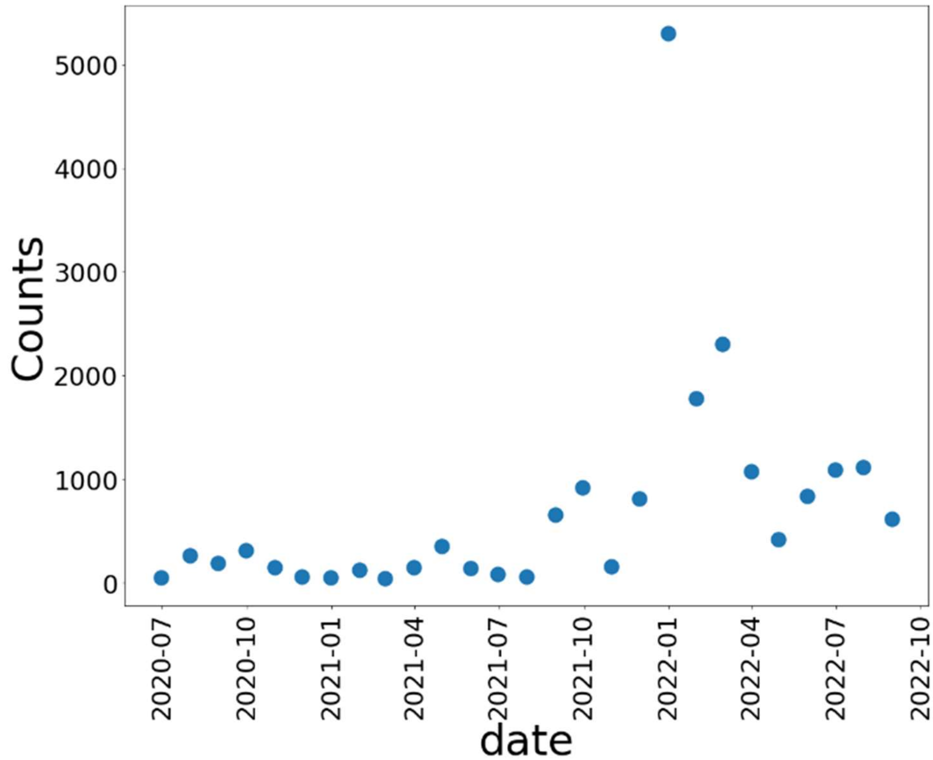


Figure 15: Dates with Bloom data collection distribution

From table 2, the four major mobile network operators in Nigeria performed below the thresholds for the various key performance indicators. For the call setup success rate, the NCC threshold is 98%, and only Glo and Airtel exceeded it a little. Likewise, for the Handover success rate, the 90% threshold set by NCC was exceeded by only Etisalat. For the dropped call rate, all mobile network operators didn't meet the standard; for the congestion rate, only 9mobile exceeded the 2% threshold.

Compared with the Three network in the United Kingdom, the mobile network outperforms all mobile networks in Nigeria with an excellent rating in Hand over and Congestion. This implies that enough base stations are near each other. Furthermore, the Three network was the best call drop rate as it had the lowest call drop. But all Nigerian mobile network operators did better in Call setup success rate.

Table 2 proves to be consistent with reality as an increase in handover failure resulting from inactive or no base stations will lead to Congestion in available base station as long as the mobile network is available and a low call dropped rate.

Etisalat had the lowest call drop rate based on the various locations the data was collected.

Table 2: Estimated KPIs for each of the Mobile Network Operators

KPIs	Etisalat	MTN	Glo	Airtel	Three (UK)
Call setup success rate (%)	95.53	97.4	98.23	98.29	75.8
Call drop rate (%)	15.21	21	19.62	22.09	5.79
Congestion rate (%)	0.93	8.8	12.36	22.65	0.0
Handover success rate (%)	97.11	70.4	71.31	55.62	100

Each of the columns that contains information about the needed KPIs has a Boolean value that is TRUE or FALSE, SUCCESS, or FAILURE. Since all the KPIs have rates, equation (3) was used to calculate the KPI scores.

$$\text{KPI Scores} = \frac{Total\ data\ points - True\ or\ Success}{Total\ Data\ points} \times 100\% \quad (3)$$

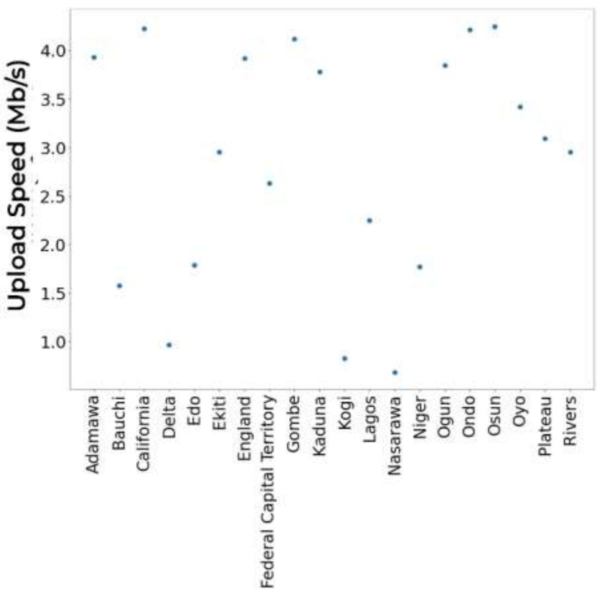
5.3 Broadband KPI analysis

Broadband KPIs were averaged throughout data collection. The KPIs are DNS lookup time, Upload Speed, Download Speed, and Video Streaming Experience. After the broadband analysis was carried out, the best video streaming experience was found in Osun state. The best download and upload speed was in Adamawa state, and the best DNS lookup was in Gombe state. However, all the nations represented (Nigeria, USA, and England) were compared the download and upload speed in England was better than all the other networks, as seen in Figures 16, and 17. With a download and upload speed almost twice other counterparts with 0.65Mb/s download speed and 0.51Mb/s for upload speed.

Figure 16 -19 shows scatter plots of the change in KPIs with locations. Download speed, Upload Spe ed, DNS lookup time, and video streaming experience, respectively.

Table 3: The average KPI values per mobile network operator.

Operator Name	Video Streaming Experience	Download Speed	DNS Lookup Time	Upload Speed
3	3.918095	0.655188	179.4873	0.509505
9mobile	3.782208	0.27 5712	22.68293	0.063618
Airtel	2.717226	0.175142	1114.831	0.221559
Glo	2.081861	0.33987	2382.614	0.226819
MTN	3.13154	0.467812	970.1715	0.302332
T-Mobile	4.224772	0.441291	237.709	0.321317



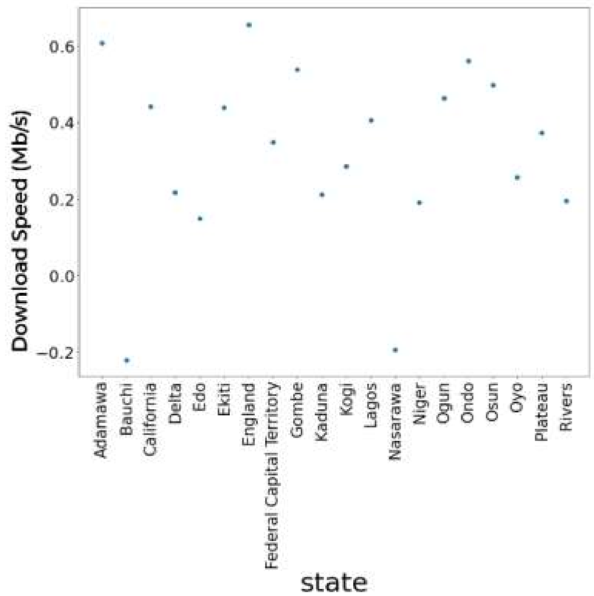
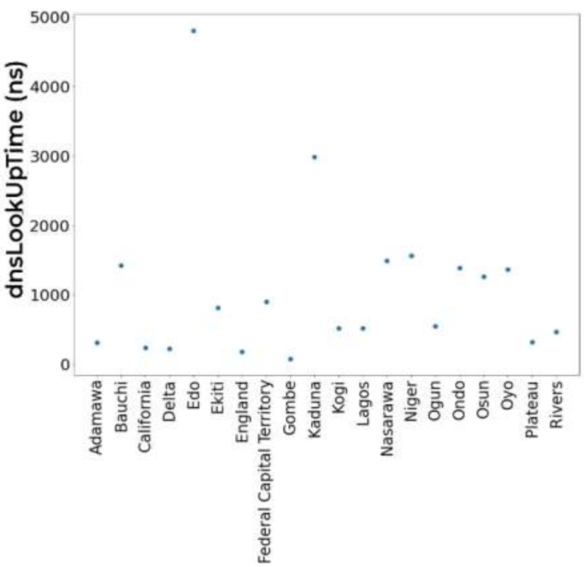


Figure 16: The upload speed for each state

Figure 17: The upload speed for each state



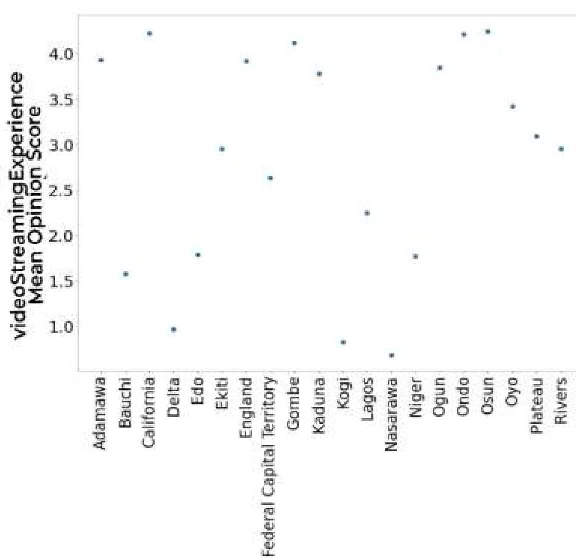


Figure 18: The DNS lookup for states

Figure 19: Video streaming experience states

From Tables 3 and 4, as already established, the Three networks in England have the best download and upload speed and the second-best video streaming experience. T-mobile, California, has the best video streaming experience averaging 4.22. Locally, the MTN network performed best with Nigeria's second highest video streaming experience (3.13), the best upload and download speed, and the second lowest DNS lookup time. The three networks in England have the best download and upload speed and the second-best video streaming experience. T-mobile, which is California has the best video streaming experience averaging 4.22. Locally, the MTN network performed best with Nigeria's second to highest video streaming experience, the best upload and download speed, and the second lowest DNS lookup time.

Table 4: The average broadband KPI values per state.

State	Video Streaming Experience	Download Speed	DNS Lookup Time	Upload Speed
Adamawa	3.931193	0.60712	310.7549	0.37408
Bauchi	1.576244	-0.22037	1425.917	0.140774
California	4.224772	0.441291	237.709	0.321317
Delta	0.966212	0.218131	224.6667	0.172494
Edo	1.789952	0.148655	4808	0.256301
Ekiti	2.954762	0.437857	816.6222	0.284125
England	3.919128	0.655876	179.3477	0.509265
Federal Capital Territory	2.630948	0.348138	899.4752	0.24632
Gombe	4.1187	0.538141	77.33333	0.185361
Kaduna	3.779414	0.212597	2983	0.025
Kogi	0.830095	0.285608	519	0.30989
Lagos	2.24669	0.405821	516.9172	0.276811
Nasarawa	0.684939	-0.19304	1491.102	0.060838
Niger	1.769971	0.191873	1567.45	0.219434
Ogun	3.843977	0.462372	548.0303	0.235524
Ondo	4.210299	0.56068	1391.311	0.332877
Osun	4.246905	0.497368	1260.526	0.212783
Oyo	3.419868	0.256627	1366.791	0.234973
Plateau	3.090244	0.373518	317.7273	0.234282
Rivers	2.953957	0.19514	469.8061	0.272573

5.3 Access to KPI analysis

Customers and volunteers can access individual KPI analysis through the app installed on their mobile phones. The web App provides stakeholders access to the KPI analysis, not the raw data. NCC personnel can access the data analytics platform through the stakeholder's username and password below. Given below is temporary access until there is a request to have one created.

User name – fmdahunsi@futa.edu.ng

Password - 3j0kASgkUE

The KPI data on the server in the laboratory can be accessed through a request by interested researchers and stakeholders after filling the required forms and signing the data management documentations.

6. DELIVERABLE FOUR

INTEGRATION AND EVALUATION OF THE PROTOTYPE PARTICIPATORY QOS SYSTEM. WRITE-UPS REPORT SUBMISSION AND PRESENTATION OF RESEARCH FINDINGS TO THE NCC

6.1 Integration and Evaluation of the Prototype Participatory QoS System

The developed system has three major parts: the mobile application, the back-end, and the web application. These were designed to ensure that solutions and methodologies are interoperable and can work seamlessly together. Being designed and developed from the ground-up together. The data from the mobile application was analyzed to confirm the quality of data collection and accuracy via comparative analysis.

The developed system was tested and evaluated with the world-accepted quality of service evaluation: the drive test technique. Benchmarking was carried out several times using several methodologies. Professionals in drive tests with verified tools and software were employed to carry out the benchmarking exercise. The Hilux jeep belonging to the School of Engineering and Engineering Technology, the Federal University of Technology, was used for one of the test drives. Figure 20 shows one of the many benchmarking and evaluation exercises.

Figure 20a,b: Benchmarking exercise of Bloom QoS App with TEMS Investigation drive test

For performance evaluation to be carried out under the same condition, benchmarking between multiple network operators was carried out using the drive test approach. For Table 2 evaluation, TEMS Investigation software, the international standard, was used alongside the developed system. Key performance indicators, namely Call drop rate, Handover success rate, Call set up success rate, and Congestion rate for the four major operators in Nigeria (MTN, Glo, Airtel, 9Mobile), were analysed to evaluate the relationship between the two (2) data collection equipment.

Table 5: Benchmarking the Host-Based with Drive Test Methods

MNO	Voice KPIs	Drive Test	Host-based Approach
ETISALAT	Call set up success rate	84.73	99.3
	Call drop rate	7.24	2.7
	Call completion rate	94.5	97.3
	Handover success rate	99.5	96.6
	Call block rate	15.27	0.6
	Congestion rate	2.12	1.6
MTN	Call set up success rate	94.09	99.1
	Call drop rate	6.8	9
	Call completion rate	93.2	91
	Handover success rate	97.04	68
	Call block rate	5.91	0.3
	Congestion rate	7.3	6.3
GLO	Call set up success rate	94.67	96.3
	Call drop rate	2.2	2.8
	Call completion rate	97.8	91
	Handover success rate	96	91
	Call block rate	5.32	3.7
	Congestion rate	15.38	16.9
AIRTEL	Call set up success rate	100	100
	Call drop rate	2.2	4.1
	Call completion rate	97.8	95.9
	Handover success rate	83.4	78.4
	Call block rate	0	0
	Congestion rate	5.59	6.9

The collected data for the KPIs were correlated using Equation 4. The correlation coefficient estimated is 0.985284, which indicates a strong correlation between the bloom application and the TEMs Investigation. The result of the correlation is shown in Figure 21.

Rank correlation coefficient formula (r) = $\frac{\sum(x_i - \bar{x})\,(y_i - \bar{y})}{\sqrt{\sum(x_i - \bar{x})^2 \,\sum(y_i - \bar{y})^2}}$ (4)

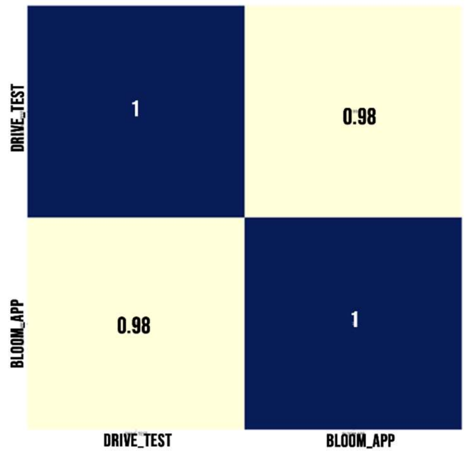


Figure 21: Correlation analysis of host-based and drive test approach

6.2 Summary of Previous Reports Submitted

Presently, three reports have been submitted: the Research Kick-off, First Phase, and Second Phase Report.

a. Project kick-off report

The research kicked-off meeting took place at the Computer Science Departmental Office, Digital Resource Centre, The Federal University of Technology, Akure, on March 20 2020. The objective of the meeting was to establish the project in more detail and ensure that all team members were on the same page in ensuring the timely and proper completion of the research. The meeting also discussed the project structure, concept, and steps necessary for its successful implementation. Duties, roles, and responsibilities were discussed, and meeting times, research space, research materials, and financial details were brainstormed. In summary, the Team arrived at a common understanding of tasks, defined roles, responsibilities, and concrete next steps.

The research actively kicked off when the first tranche of funds was released to the research team by the University Management on August 12 2020.

b. Summary of First Report

A Project Charter, Risk Management Register, and the Work Breakdown Structure were developed at the research's commencement to ensure a smooth running of the research and timely completion. The work breakdown structure is presented in Figures 22 and 23. The task was divided into work packages to ensure that each task was manageable and could be accomplished within the specified time. Project management ensures proper expectations around what should be delivered, by when, for how much, and within specified standards. Project management provides the ability to establish a hierarchy of tasks for effective and efficient completion and indicates which steps are sequential and which tasks are dependent on one another.

The methodology for the implementation of the research was presented, and methods to build the mobile, web, and cloud storage. The QoS app is designed as a crowdsourced voice and broadband aggregation mobile app on the Android operating system. The app collects some voice and broadband key performance indicators (KPIs) selected based on reviews. The measurement and collation of the key performance indicators are in two sections in the mobile app: the voice and the collation.

The key performance indicators (KPIs) presented for the voice were computed for all mobile cellular networks irrespective of the network type, i.e., 2G, 3G, and 4G. The computed KPIs apply only to the mobile network and not the fixed network.

The thresholds for the voice QoS measurements were from the NCC website (https://ncc.gov.ng/technical-regulation/standards/qos#measured-kpisfor-operators).

Android OS was considered for this project because it is currently one of the most stable and deployed in most mobile devices. It is open-source and has a great user base. This research scope limits vulnerability related to security and malicious attacks on the Android operating system. Though data gathered and transferred to the server are encrypted to ensure optimal security, the Android framework provides inbuilt APIs to collect signal strength and quality.

It can be found at https://developer.android.com/reference/android/telephony/SignalStrength.
This is what is used by the mobile phone to ensure connection to the base station of the best signal Strength. The speech quality wasn't computed, but an alternative KPI describes the speech quality, the bit error rate. The bit error rate (BER) is the number of bit errors per unit time, so a high bit error rate implies low speech quality during calls and vice versa.

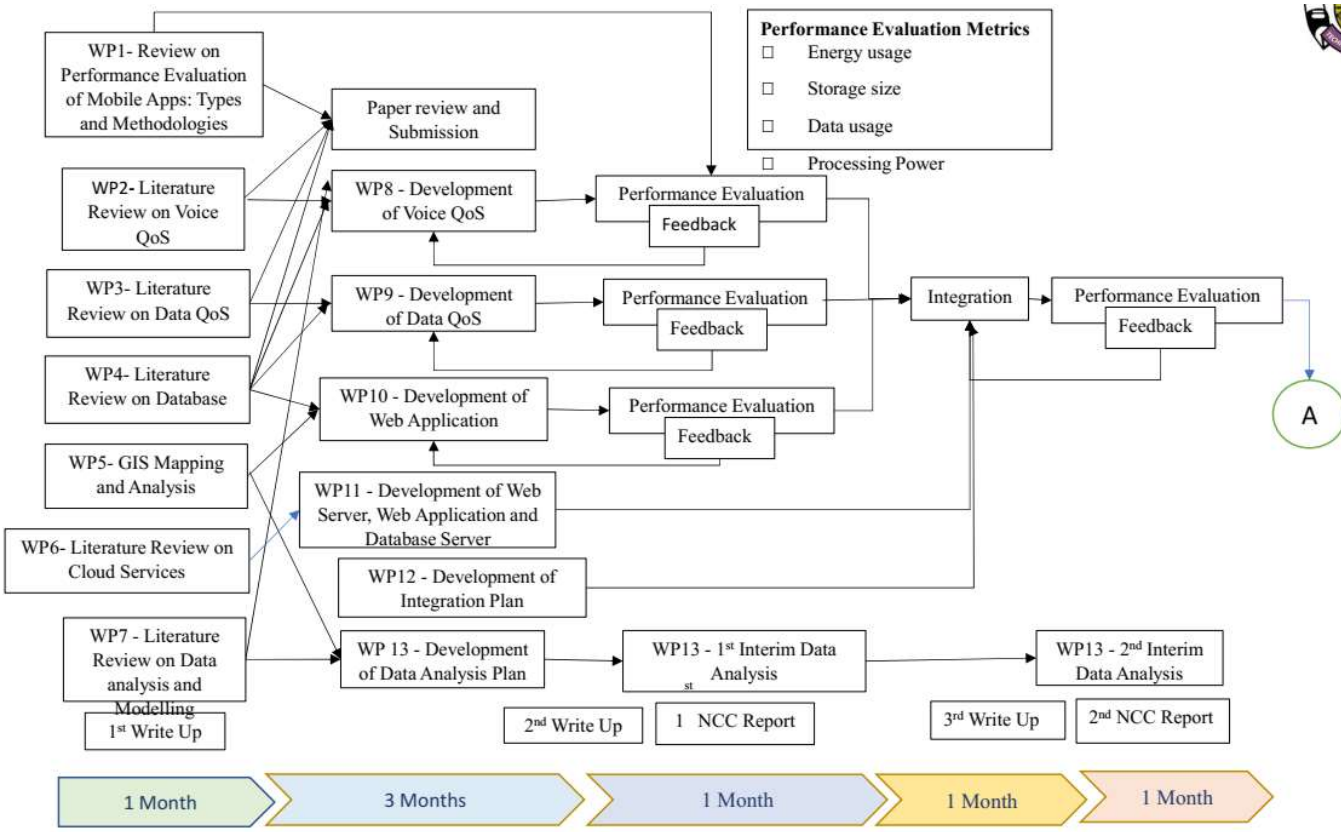


Figure 22: Work Breakdown Structure Part One

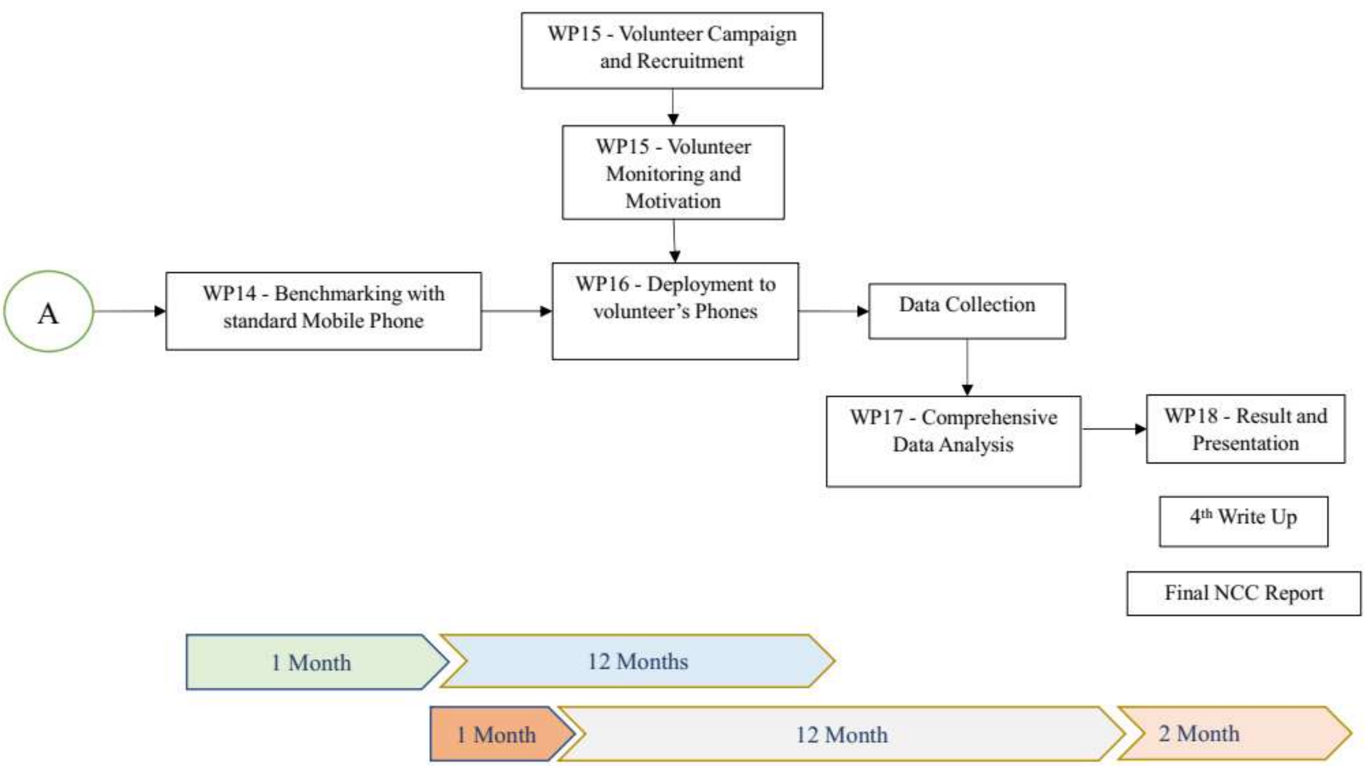


Figure 23: Work Breakdown Structure Part Two

6.3 Stage 2 and 3 Deliverable and Second Interim Report

The completion of the developed apps, integration, and system testing are implemented in this phase. The report starts with a general introduction to the research and specifies the general achievement of the research. The preliminary impact of the research grant and the research constraints and limitations. The targets were evaluated vis-a-viz the work done to ensure that every part of the specified research work was covered. This phase also includes several volunteer campaigns and data collection.

6.4 Stage 4 Deliverable and Final Report

This report presents the research holistically and systematically. Data collected in the previous phases were analysed and presented. The final report includes research conclusions, recommendations, and future collaboration plans.

The presentation of research findings to the Nigerian Communications Commission concludes the research. The Research Team is eagerly awaiting this great opportunity.

7. IMPACT OF RESEARCH GRANT

7. Introduction

The impact of the project will be discussed succinctly in this section

7.1 Establishment of a Mobile Communication Research Laboratory

A mobile communication research laboratory was established with the grant money provided by NCC. The laboratory is a work in progress and will serve and meet three pivotal research laboratory needs for mobile communication research:

a. software development
b. data analytics and artificial intelligence
c. high-speed computational research

7.2 Development of Software Applications

Software applications were developed for the virtual cloud, web, mobile, and back-end platforms. Git from GitHub is the version control tool for properly tracking changes to source code alongside a safe and secure source code backup in a remote location. The name of the mobile and web applications is "Bloom." To ensure proper correlation amongst both applications and settings and configurations carried out.

7.3 Papers Written and Submitted for Publication

Some papers as research output while carrying out the research.

a. Published papers

1. Dahunsi F. M., Idogun J. and Olawumi A. (2021). "Commercial Cloud Services for a Robust Mobile Application Backend Data Storage" *Indonesian Journal of Computing, Engineering, and Design (IJoCED)*, 3(1), pp. 31-45. https://doi.org/10.35806/ijoced.v3i1.139
2. Dahunsi F. M., Joseph A. J., Sarumi, O. A., Obe O. O. (2021). "Database Management System for Mobile Crowdsourcing Applications" *Nigerian Journal of Technology (NIJOTECH).* 4(4), pp. 713 -727. https://www.ajol.info/index.php/njt/article/view/216646
3. Audu J. A., Dahunsi F. M., Obe O. O., Sarumi O.A. (2021) "Android Architectures for a Robust Mobile Application Development." *Nigerian Research Journal of Engineering and Environmental Sciences, 6(2), 607-617. https://doi.org/10.5281/zenodo.5805197*

b. Submitted paper for publication

1. Dahunsi F. M., Abisoye O. B., Obe O. O., Sarumi O.A. and Mebawondu O. J. (2021) "Performance Evaluation of Mobile Voice Quality of Service Techniques: A Systematic Review" *Nigerian Journal of Technological Development.*

c. Manuscripts in progress

1. Performance Evaluation of Mobile Service Delivery in Nigeria: Methods and Issues.
2. Predicting the Quality of Service of Mobile Services using Host-Based Data Approach
3. Modeling and Analysis of Mobile Networks Operator's Key Performance Indicators Using Host-Based and Drive Test Approach

7.4 Human Capacity Development

There are presently two graduate students and four undergraduates (now serving) trained in various research areas. The research team profoundly believes in building up the younger generation and sustainability of research ideas and methods through generations. Other researchers and students can access the data collected and analyze them further. The equipment purchased and the laboratory is a research enclave for students and staff. Therefore the human capacity development of this research is far-reaching and robust.

8. ANSWERS TO RESEARCH QUESTIONS

a. **Research Question 1:** What is the real-time measurement of QoS delivered to the individual customer?

The real-time measurements of QoS delivered to the individual customer were achieved using the developed host-based approach developed by the research. Individual customers can access the quality of service in real-time by doing a manual test. They also have access to daily, weekly, and monthly measurements with automatic background tests.

b. **Research Question 2:** Are the MNOs delivering and meeting the set targets and standards set by the NCC?

From the host-based data and drive test data collection carried out during the research, the MNOs are meeting a large percentage of the set target of the regulator based on their resources. There are a few targets they need to work on to meet the regulator's set standard. MNOs can achieve this by investing more in infrastructure and in-country personnel.

c. **Research Question 3:** Can the developed system (platform) effectively and efficiently measure, log, archive, and analyse customer-centric QoS meeting NCC standards?

The system developed can effectively and efficiently measure, log, archive, and analyse customer-centric QoS meeting NCC standards

d. **Research Question 4:** What challenges are faced in monitoring mobile voice and broadband QoS using the developed system?

   i. Recruiting and maintaining volunteers on the developed system because of the privacy concerns of revealing their location, call details, and others
   ii. Volunteers are concerned about the amount of data consumed when the application is up.
   iii. Volunteers are reluctant to know the quality of service offered; some are indifferent about it, and at the end of the day, it does not matter. They can't prosecute the MNOs, and the network is in the same condition. They need to use the network provided and manage the quality offered.

e. **Research Question 5:** What policy recommendations exist for operators, regulators, and policymakers to enhance Africa's mobile broadband and voice QoS offerings?

The Nigerian regulatory body, the Nigerian Communications Commission (NCC), teams up in collaboration with regulatory bodies all over the world, such as the International Telecommunication Union (ITU), African Telecommunications Union (ATU-UAT), Commonwealth Telecommunications Organisation (CTO). In collaboration with these other regulatory bodies, NCC develops world-class sustainable policies to ensure optimal QoS delivery to customers.

9. CONCLUSION AND RECOMMENDATION

9.1 Conclusion

Obtaining an actual KPIs dataset for the moment-by-moment QoS of the internet and voice service as experienced by the user is a significant factor in evaluating the QoS of a network. This research focuses on obtaining the actual KPI dataset for the four major network operators currently in Nigeria, and the result obtained from the analysis of these datasets is a handy tool for both the users and the operators. Data collected are archived and can be used for further research purposes. Human capacity was built on the performance evaluation methodology of mobile communication systems, which can be applied to other communication sectors. However, volunteer recruitment is challenging because of the many permissions to be given to the host-based mobile application by the mobile phone for performance evaluation purposes.

It has been established that the developed system can measure, log, archive, and analyse customer-centric QoS meeting NCC standards. Data analysis for proof of concept is established with a correlation of 99% with the world acclaimed TEMS Drive Test performance evaluations method.

The assumptions made are that:

1. The users can correctly operate the mobile devices and the required services.
2. The desired services are not barred.
3. Mobile devices are in standard working conditions (this can be checked as any faulty device will show an anomaly in its own data compared with others of the same/similar location). This covers modified or faulty mobile devices
4. The phone's global positioning system (GPS) sensor is on for precise location estimation.

9.2 Recommendation and Future work

The recommendations and proposed future work are presented in this section.

1. Researchers have developed a prototype and have established the proof of concept. Based on the new well-celebrated research-to-product innovation and creation by the Nigerian Communications Commission. The Commission (NCC) should link researchers with established software industries to work with them in transforming the research into a commercial product.
    a. Individuals can purchase the product and install them on their mobile phones.

b. Host-based data collected and archived can be commercialized and available to researchers, mobile network operators, and other stakeholders.

2. Nigerian Communications Commission should integrate the application with their performance evaluation system. It is seamless and presents the performance analytics of the MNOs in a single, easy-to-use interface.
3. The NCC should build and establish a Mobile Communication Laboratory at the Federal University of Technology, Akure. An established research hub where researchers all over the country and the world can come together and have required resources on the mobile communication network. It will ensure the development of the required skill set in this field and move the country forward from being an importer to an exporter of mobile communication technology. This is fundamental because one of the primary mandates of the Nigerian Communications Commission is to regulate the MNOs to ensure they maintain and deliver the set quality of service provision. Also, mobile communication is the primary modern technology available to all Nigerians at affordable rates. It is essential to maintain the quality and deliver good service to all. The Federal University of Technology has been involved in mobile communication and performance evaluation and has built human resources in this area. Establishing a Mobile Communication Laboratory at the Federal University of Technology, Akure is a step in the right direction.
4. The NCC should establish a mobile Communication Research Chair at the Federal University of Technology, Akure, to assist with all the resources required to continue innovative research to change the face of Communication Research in the country.
5. Scholarships for undergraduate and postgraduate students of the Federal University of Technology, Akure to work on mobile communication-related challenges and issues. Furthermore, they can work on innovative research and products.
6. The Nigerian Communications Commission should broker linkages between the industry and researchers to ensure there are internship opportunities for both cross-collaboration and visitations.

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APPENDIX A1

Voice KPI Data Collection Algorithm

Firstly, listen to a change in state on the TELEPHONY MANGER
(There are four (4) primary states on the Android system **TELEPHONY MANAGER,** which are idle state, ringing state, and, in call state, off the hook (call about to be started))

If the present state of the app is **"off the hook"** and the previous state is **"idle"**
Call type is set to **outgoing call**
If the present state of the app is **"off the hook"** and the previous state is **"ringing."**
Call type is set to the **incoming call**

When the call is started
Check for **location** by checking if GPS is enabled or location is turned on the device
Check for **Permissions**

If permissions are not granted access,
RETURN permission not yet granted for this operation
Check if GPS is enables
If GPS is disabled
RETURN bloom mobile can't take the test while the location is off
Check on what sim a call is being made by checking the call subscription id and subscription name by using **an android service called TELEPHONY SUBSCRIPTION SERVICE**
Check the state of calls every one second during the call
If the call state has changed to **"Idle"** after its previous state was **"in call"**
Check call logs
Check if the phone has multiple sims
If the phone has multiple sims
On the call log, check the last call id that matches the subscription ID of any of the device's sim cards.
If the phone is a single sim
Continue
Get the location from the Android location manager

Map signal strength to these corresponding values
if 0 if signal strength = -101
if 1 if signal strength = -90
if 2 if signal strength = -70
if 3 if signal strength = -67
if 4 if signal strength = -30
Map BER to these corresponding values (Mkheimer and Jamoos 2012)
0 to 0.2
1 to 0.4
2 to 0.8
3 to 1.6
4 to 3.2
5 to 6.4
6 to 12.8

7 to 20.0

Initialize variables for (These parameters are assigned values by several logs listed below)

Bit Error Rate
Network Information
Handover Attempt,
Received Signal Level, (Array of all signal strength during the call)
Is Call Dropped, (Boolean)
Congested, (Boolean)
Call,
Call Setup, (success failure, neutral)
Voice KPIs

Handover Logic

If our new cell and previous cell are in a different location
If the location of the cell is different from the location of the cell after 1 second

From **PHONE LISTENER** on the android system,

Get;
Call state,
Cell info,
Cell location,
Signal strengths,
service state
Get all call signals and append them to a list

(Recall we are checking for a change of phone state above, and we are still considering if the phone state is ***"idle"*** *after its previous state was* ***"in call")***

If call type is **"Outgoing Call"**

Call setup success is **True**

If the cell signal strength is at the barest minimum which is -101 and if the signal strength is completely off

Call setup success is **True**
Call dropped is **True** ***(https://electronics.howstuffworks.com/4-reasons-phone-keeps-dropping-calls.htm*)**

If the service state is changed to **"Out of service"**

Call drop is set to **True** ***(https://electronics.howstuffworks.com/4-reasons-phone-keeps-dropping-calls.htm)***

When the device is a rooted device

Run ***"su -c logcat -b radio -t 100"*** to get the last 100 radio information
Check if the result contains information about the cause of disconnection

If the response is busy, then call success should be true
If CDMA drop, lost signal, error unspecified, out of network is true, then call dropped will be true
If the cause is Congestion: then Congestion is true
If outgoing failure from the android system, the call is dropped, and call setup is false

If there is power off during a call attempt call set returns neutral (this occurs when the phone is on airplane mode)

Specify network parameters and network type

Specify network parameters

Check for carrier name (if carrier name doesn't exist), **return false**

Initialize connectivity manager and check cellular transport.

Check if android systems via **CELLULAR TRANSPORT** report congested

If yes, congested is set to **True**

Check for a change in location

If current time – handover request time <= 5 seconds (i.e, handover request is sent and takes more than 5 seconds for handover to happen)

Congestion is set to **True**

Handover Success is set to **False**

Else:

Handover Success is set to **True (**then the current cell id, previous cell ID, and time are being initialized and stored in a variable)

If the user ends the call when handover is just completed,

Call drop is set to **True**

Check for **NETWORK TYPE** from the android system

BER for 2G

Put all the bit error rates gotten during the call into an array

BER = the maximum value in the array

If the android system doesn't get the BER, it results in a large number

BER for 4G

get the signal-to-noise ratio per time

calculate the Bit Error Rate with the formula below

BER = $\frac{15}{rceived\ signal\ to\ nise\ ratio\ (snr)\ \times 0.01 \times 100}$

Append all calculated BER during the call to an array

Select the maximum value as the BER

If BER is 0

BER for 3G

Get signal strength from the Android system

If signal strength = 0

BER = 20.0

If signal strength = 1

BER = 3.2

If signal strength = 2

BER = 1.6

If signal strength = 3

BER = 0.04

(These values were tested by an emulator)

Telephony manager is the radio layer on Android; the only way to talk to it is through the phone listener without root access

APPENDIX A2

Broadband KPI Data Collection Algorithm

DNS Lookup Algorithm

1. Declare a list hostnames as a variable (in this case, www.google.com , www.twitter.com, www.facebook.com, www.wkikpedia.com, www.microsoft.com, www.youtube.com
2. Declare a variable for the time before the hostname resolution starts in milliseconds
3. Start hostname resolution
4. Subtract the stored variable of the time in which the DNS lookup started from the current time in milliseconds

Mathematically

DNS Look-up = time before hostname resolution (in milliseconds) - Time after domain resolution (in milliseconds)

Download Speed Algorithm

1. Declare a variable for the download link (firebase helped to perform the download operation)
2. Declare a variable for the time before download starts in milliseconds
3. Trigger a task for firebase to download the file from the link declared in step 1
4. If the download doesn't start, return a value of –1
5. At the end of the download, subtract the value declared in step 2 from the current time in milliseconds
6. Convert the time to seconds by dividing by 1000 (since the unit of download speed is in Mbyte/Sec) and assign it to a variable
7. Convert the size of the downloaded file to Megabyte by dividing by 2^20 (1024 * 1024) and assign it to a variable
8. Divide the assigned variable in step 7 by the assigned variable in step 6 i.e. divide the file size in MB by the time difference in seconds.

Mathematically

$$\text{Download Speed} = \frac{size\ of\ the\ download\ file\ in\ megabytes}{time\ diference\ in\ seconds}$$

Upload Speed Algorithm

1. Declare a variable for the file to be uploaded (firebase helped to perform the upload operation)
2. Declare a variable for the time before upload starts in milliseconds
3. Declare a variable for time limit (in case of terrible network connection)
4. Trigger a task for firebase to upload the file declared in step 1,
5. If the upload doesn't start, return a value of –1
6. At the end of the upload, subtract the value declared in step 2 from the current time in milliseconds
7. Convert the time to seconds by dividing by 1000 (since the unit of download speed is in Mbyte/Sec) and assign it to a variable
8. Convert the size of the uploaded file to Megabyte by dividing by 2^20 (1024 * 1024) and assign it to a variable
9. Divide the assigned variable in step 7 by the assigned variable in step 6 i.e. divide the size of the file in MB by the time difference in seconds
10. If the file doesn't complete the upload task within the time limit set in 3
11. Assign a variable for the size that has been uploaded at that time
12. Repeat steps 7 –9

a. Convert the time limit to seconds by dividing by 1000 (since the unit of download speed is in Mbyte/Sec) and assign it to a variable
b. Convert the size of the uploaded file to Megabyte by dividing by 2^20 (1024 * 1024) and assign it to a variable
c. Divide the assigned variable in step b by the assigned variable in step a i.e. divide the size of the file in MB by the time difference in seconds

Mathematically

Upload Speed = $\frac{size\ of\ the\ upload\ file\ in\ megabytes}{time\ diference\ in\ \sec on}$

Video Streaming Experience Algorithm

1. Declare a variable for the streaming link
2. Declare a variable for initial buffering time
3. Declare a variable for mean rebuffering time
4. Declare a variable for rebuffering frequency
5. Declare a list for buffer percentage
6. Declare a list for initial buffer times
7. Declare a function for mean opinion score (the methodology for calculating Video streaming experience

Appendix B: Sample of data collected from the mobile app and stored in Firestore


```
{
   "createdAt":1625825839687,
   "keyPerformanceIndicators":{
      "cell":{
         "cellGSM":{
            "cellCID":84998406,
            "cellLAC":50566
         },
         "cellCDMA":null,
         "cdma":false,
         "gsm":true
      },
      "setUpSuccessful":"SUCCESS",
      "handoverSuccessRate":0.0,
      "ber":7.5,
      "congestionRate":0.0,
      "callDropped":true,
      "receivedSignals":[
         -70,
         -107
      ],
      "congested":false,
      "handoverAttempts":[
         {
            "time":1625825837579,
            "successful":true,
            "prevCell":null,
            "cell":{
               "cdma":false,
               "cellGSM":{
                  "cellLAC":50566,
                  "cellCID":84998406
               },
               "cellCDMA":null,
               "gsm":true
            }
         }
      ]
      "outgoingCallDuration":9,
      "dropRate":0.0,
      "successRate":0.0
   },
   "device":{
      "imeis":[
         ""
      ],
      "macAddress":"E2:03:0D:25:86:D7",
      "id":"dce4h0YGQre53OTS3rRa-E",
      "ipAddress":"192.168.0.100"
   },
   "location":"7.3023454 5.1390167",
   "manual":false,
   "networkInfo":{
      "operatorName":"MTN Nigeria Communications",
      "networkType":"4G LTE"
   }
},
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APPENDIX C

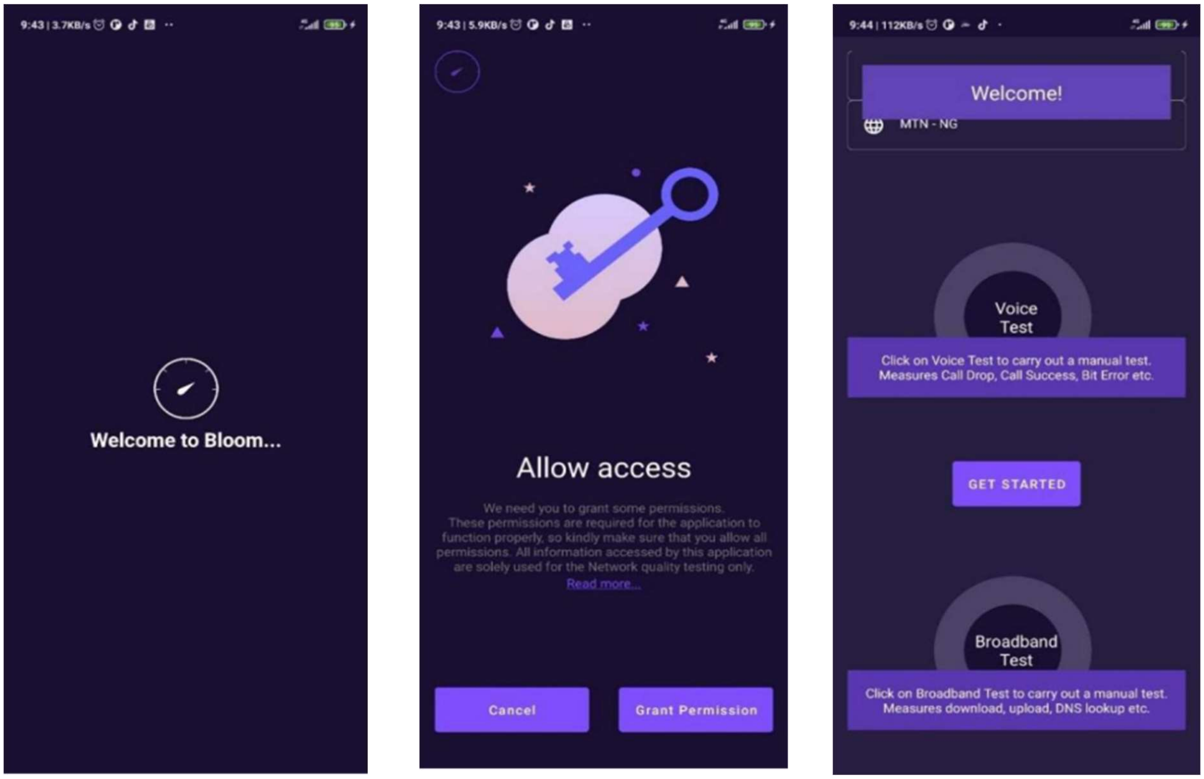

Figure C1. Welcome and Access request pages

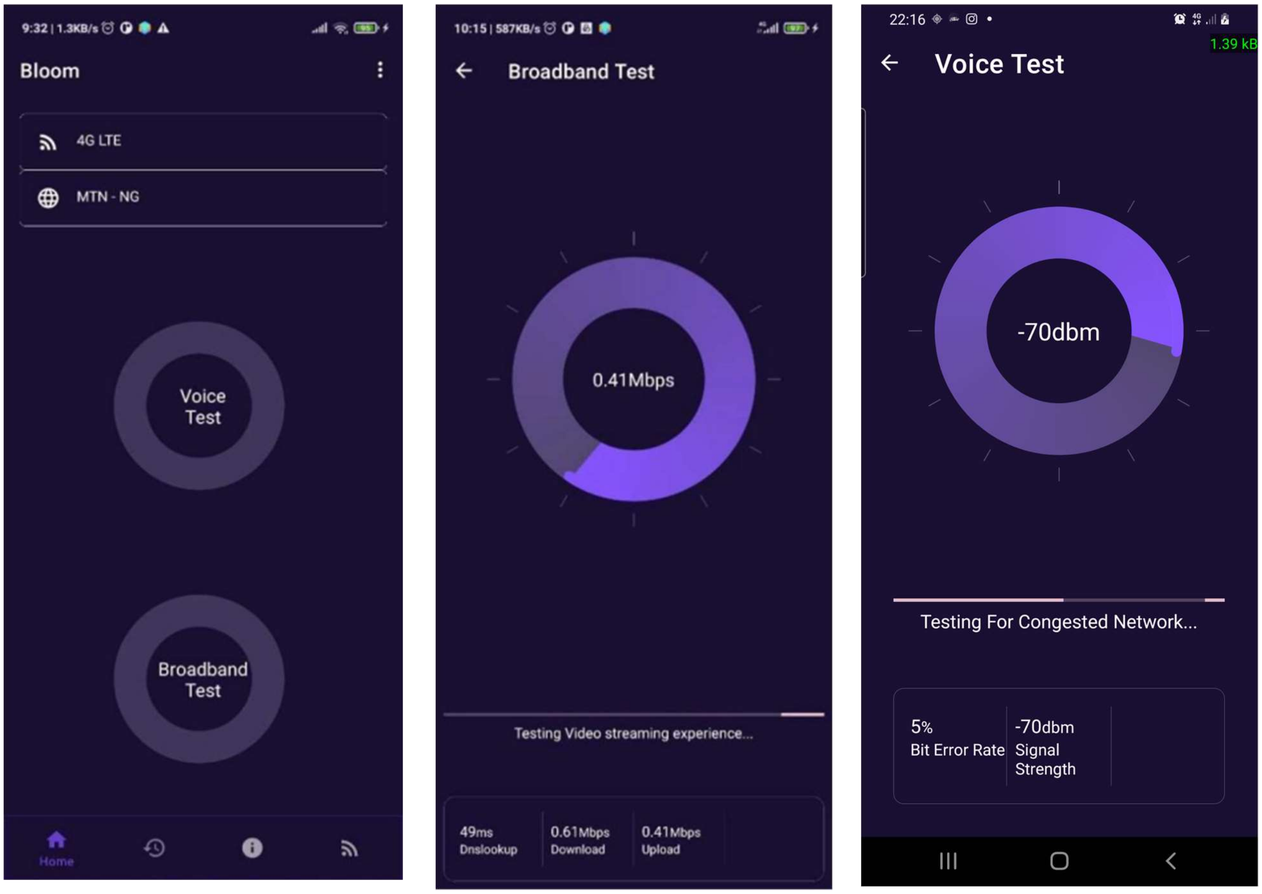

Figure C2: Test History Screens

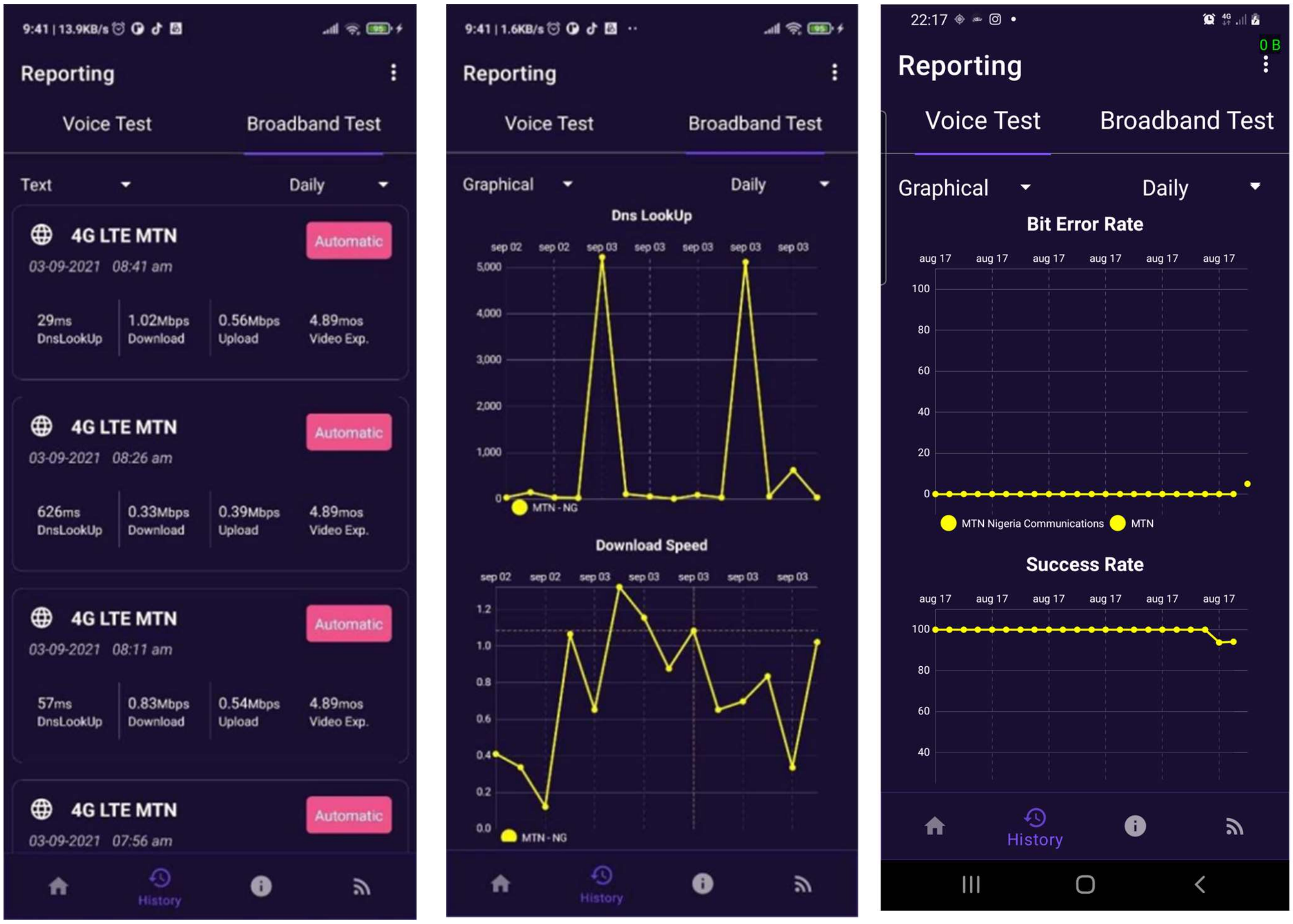

Figure C3: Reporting Screens

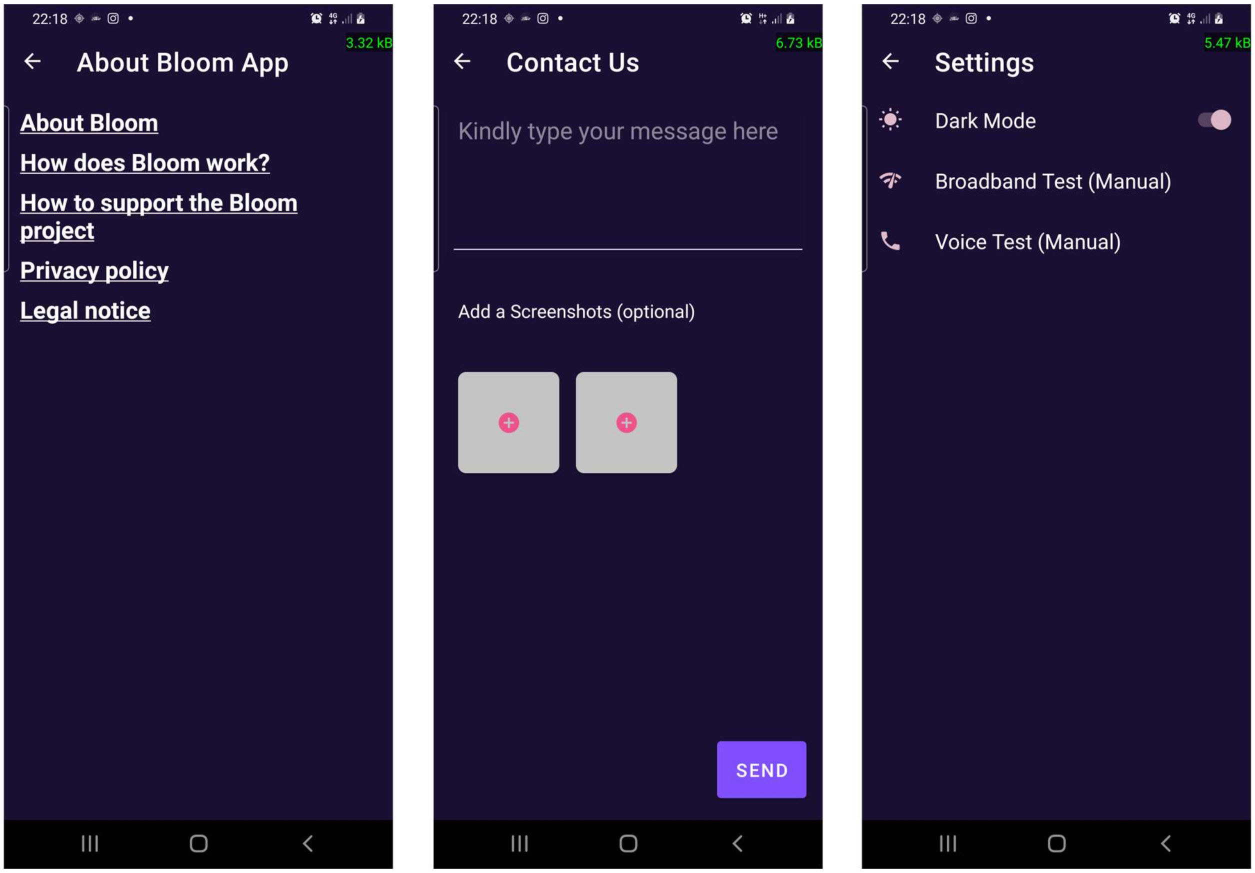

Figure C4: About Us page, Contact Us page, and Settings page

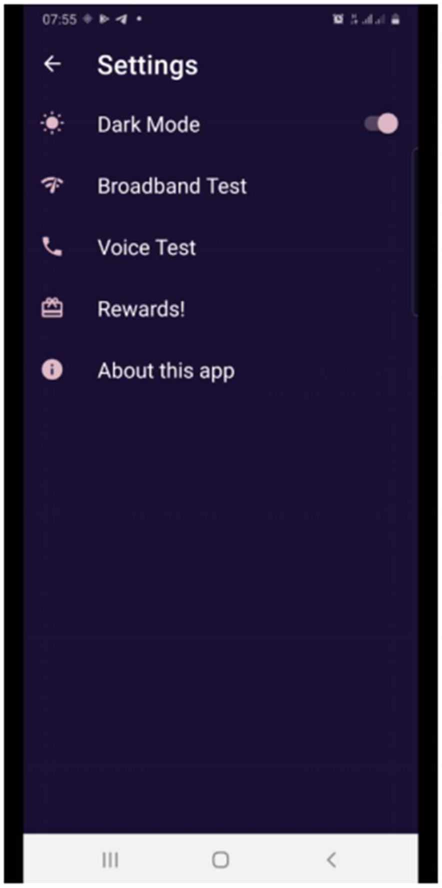

Figure C5a: Dark Mode

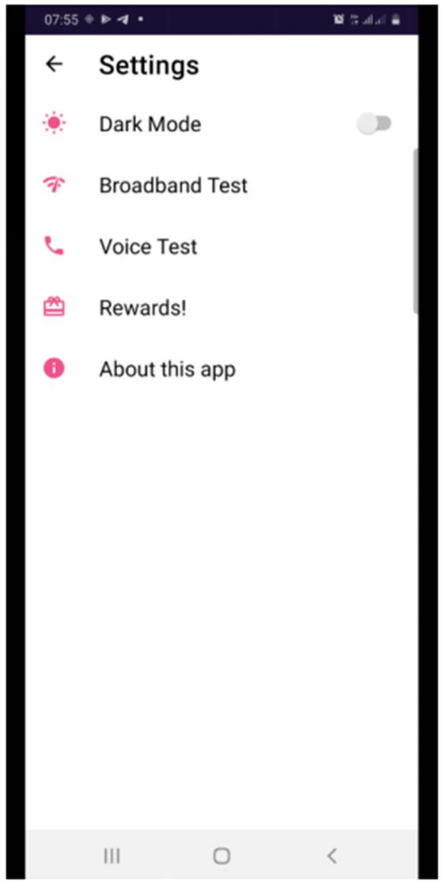

Figure C5b: Light Mode

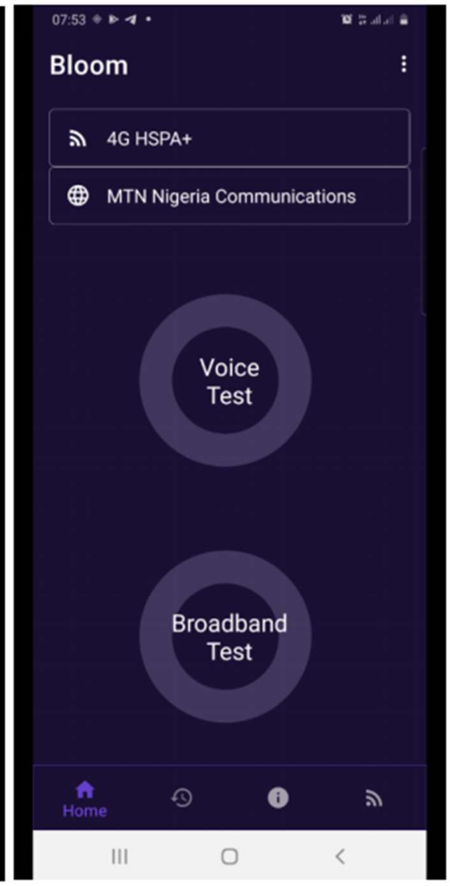

Figure C5c: Test Interface

APPENDIX D

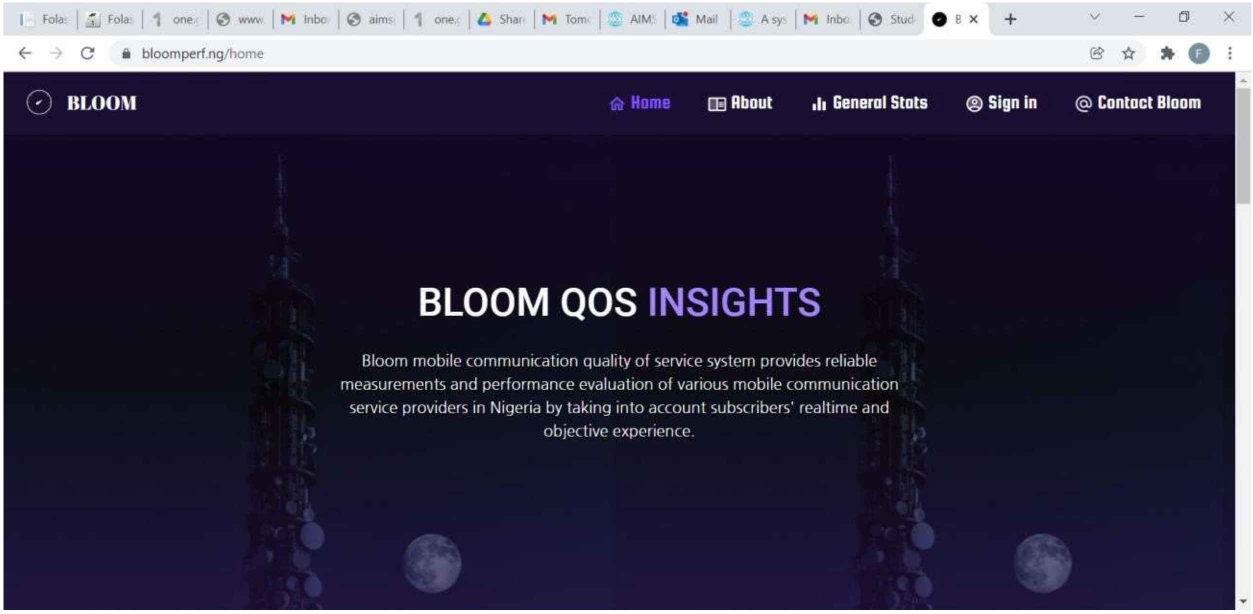

Figure D8: Default homepage

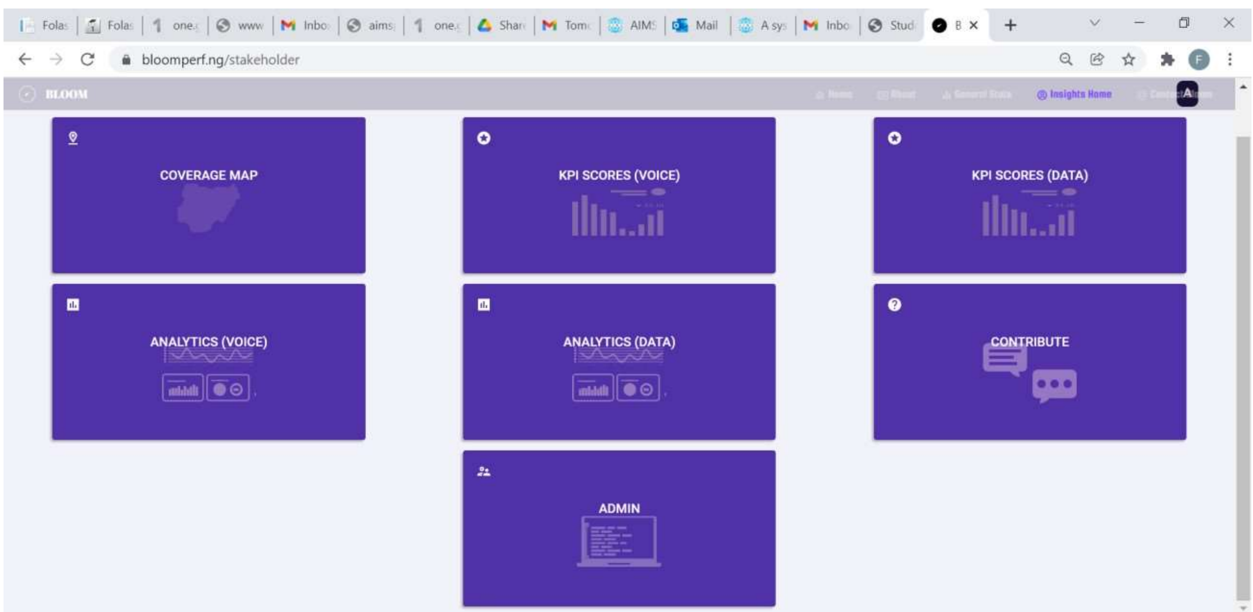

Figure D9: Stakeholder's homepage

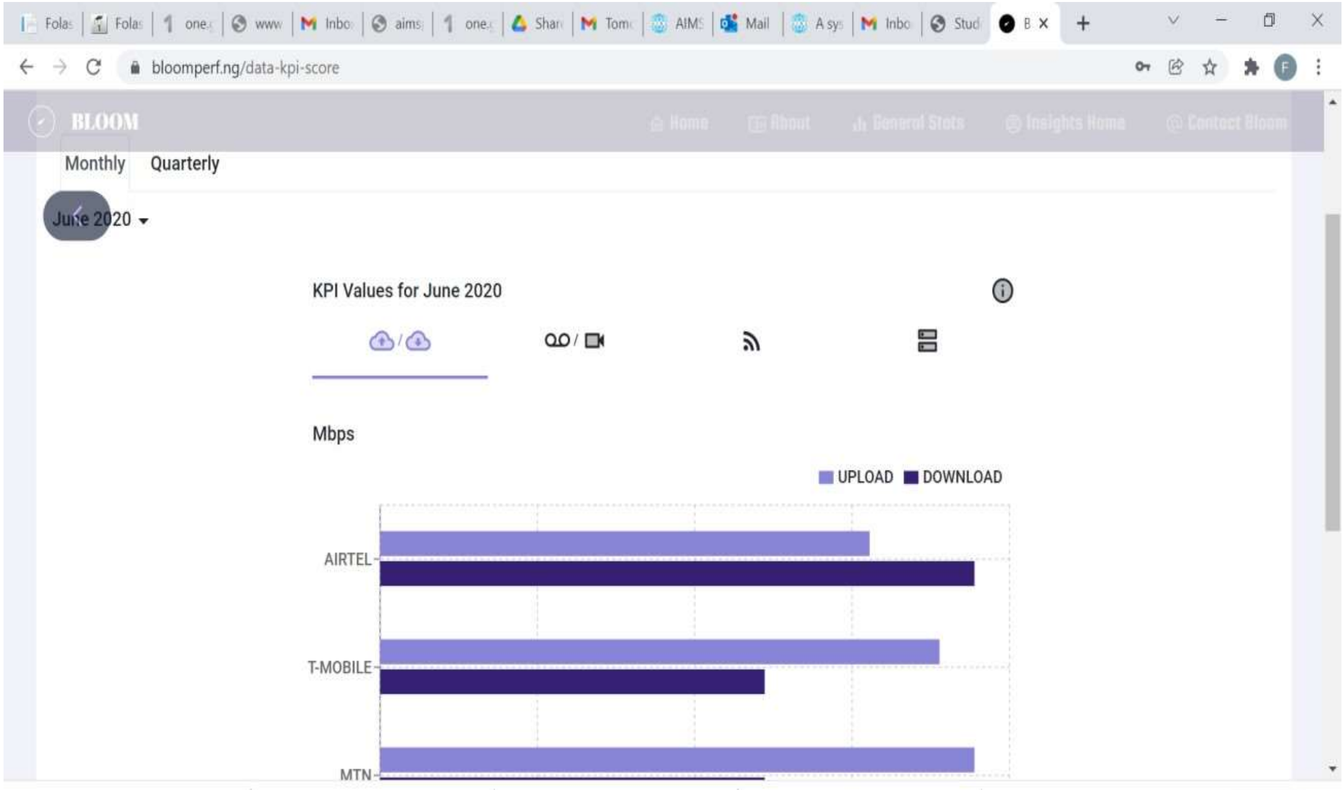

Figure D10: Online broadband data analytics page showing upload and download speed

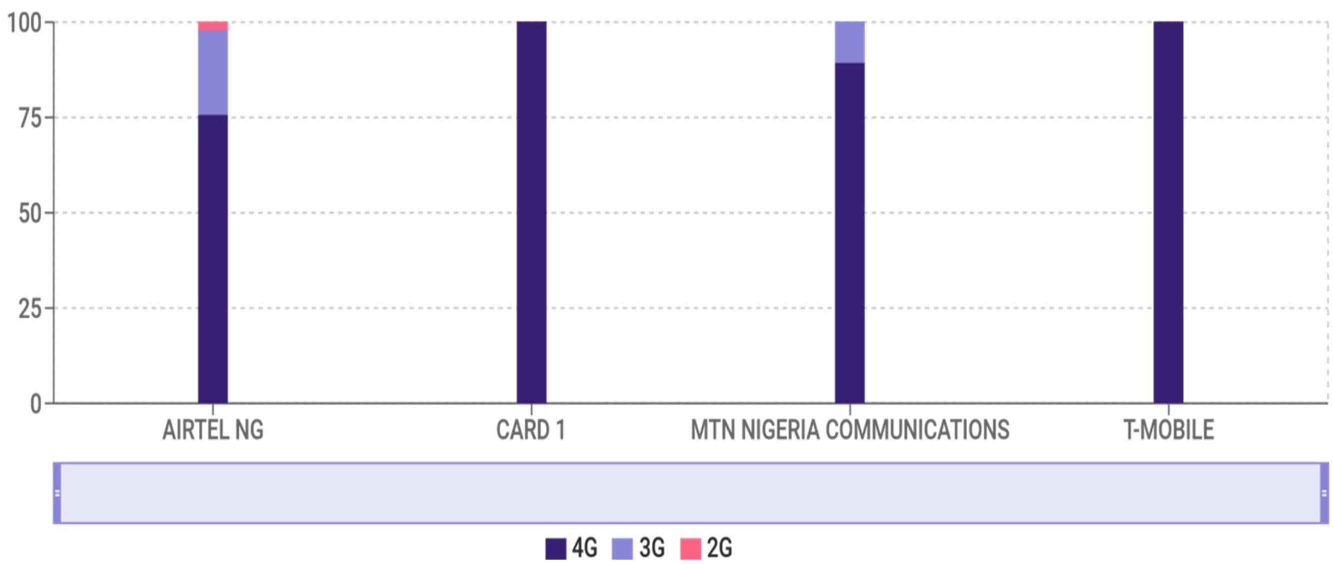

Figure D11: Online voice data analytics page showing network availability

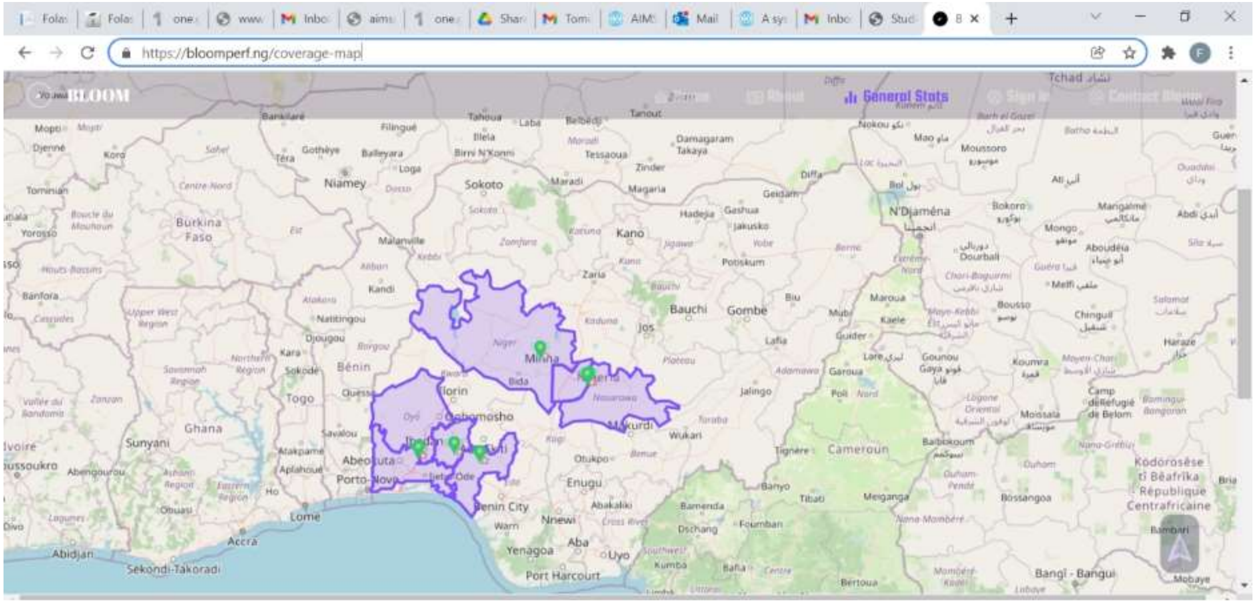

Figure D12: Network coverage map interface