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Measuring Mobile Broadband Quality of Service in Cellular Networks: A Case Study of South West Nigeria

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Abstract –Nigeria's Mobile Broadband (MBB) sector is battling with a significant Quality of Service (QoS) gap; with slow speeds, high latency, and inconsistent performance often falling short of advertised speeds and Service Level Agreements (SLAs) being common problems faced by mobile customers in the country. Often customers do not experience the advertised speeds offered by the Mobile Network Operators (MNOs) and MBB speeds are far slower than the worldwide average. To address these challenges, a robust QoS monitoring system was developed using a host and crowdsource-based approach. The methodology involves installing a custom made QoS MBB performance (MBPerf) application on 500 volunteers' Android smartphones to measure five selected MBB QoS metrics – Domain Name System (DNS) Lookup, download and upload speed, latency and received Signal Strength Indicator (RSSI) in real time. The coverage area includes the six South West (SW) states of Nigeria while the three major MNOs in Nigeria – AIRTEL, GLO and MTN were tested for a period of nine months. Exploratory Data Analysis (EDA) carried out reveal that mobile users experience the best Internet speed performance between 11 pm and 6 am, while a downward and variable trend is experienced from 6 am till late in the evening at 11 pm. Comparative analysis of latency results with the industry benchmarks shows that all the MNOs significantly fell short of the benchmark by at least 74%. Findings from the DNS analysis suggests that MNOs' DNS recursive servers are in general operating effectively and not adding significant delays to end users' queries.

Keywords- 4G LTE, 3G; quality of service; exploratory data analysis; crowdsourcing; mobile broadband

I. INTRODUCTION

MBB, a high-speed connection that provides Internet access and various data services through cellular networks has transformed global connectivity. Over the years, MBB has greatly increased Internet availability and has become the main mode of online access for much of the world's population [1]. By the last quarter of 2024, over 4.6 billion people worldwide were using mobile Internet [2]. In 2022, mobile technologies and services accounted for 5 percent of the global Gross Domestic Product (GDP), contributing about $5.2 trillion in economic value [3]. Mobile telephony has become the largest Information and Communication Technology (ICT) platform in history, driving notable developments in healthcare, education, business, social communication, entertainment, and news.

In Nigeria, MBB continues to be the primary means of Internet access for most citizens, representing over 99.6% of all connections. As of second quarter of 2024, it made a substantial economic contribution of 16.36% to the GDP [4]. In addition, Nigeria's teledensity grew substantially from 72.72% in May 2012 to 100.09% in April 2024; likewise, the broadband penetration rate as of January 2025 stands at 45.61% [4]. Besides, statistics of data usage in Nigeria indicate a profound growth of about 39% between August 2023 (655,880 Terabytes) and August 2025 (1,152,347 Terabytes) [4]. The MNOs too are expanding their networks for increased coverage. The preceding statistics undoubtedly suggest that Nigeria's broadband industry is expanding, and this trend is expected to continue as the National Broadband Plan for 2020–2025 projects a higher broadband penetration rate [5]. However, on the downside, QoS and user experience remain the primary impediments to broadband Internet access in the country, even though MBB has resulted in significant gains for all stakeholders in Nigeria's telecom sector. Customer happiness is hampered by poor QoS [6], which is necessary to maintain a competitive advantage in the market. According to [7], QoS is important in determining customer satisfaction because it determines if MNOs can provide qualitative services to their mobile consumers. It is evident from studies conducted by [6], [8], and [9] that MNOs are curious to know the strengths and weaknesses of their networks to respond quickly to problems and address customers' complaints. Any MNO that provides a higher level of QoS than its competitors may expect to keep existing customers as well as attract new ones for a long time. Besides, networks must keep up with the tremendous traffic growth and still offer subscribers optimum service quality.

Given these demands, MNOs must address key challenges such as ensuring consistent coverage, improved network performance and enhancing user Quality of Experience (uQoE) [10]. Consequently, monitoring and evaluating service quality are crucial tasks that all stakeholders must prioritize. In this study, a host and crowdsource-based measurement approach was used to provide a pool of unbiased data with the help of a custom-made mobile QoS application called MBPerf. The collected dataset was then analyzed to evaluate the approximate performance (QoS) available to mobile users within the coverage area.

MBPerf was developed to address the lack of transparency in MBB performance monitoring and reporting in Nigeria, where MNOs rarely release their QoS related datasets for independent evaluation and even when they do, the results are often biased toward protecting business interests. In addition, it has been observed that the regulator, NCC, only provides benchmark values for voice services without publishing regular and transparent performance reports on MBB services. These challenges put customers in a position of not being able to make informed decisions about their MBB needs and budget. MBPerf provides an unbiased, customer-centric, and continuous measurement system. The Android-based daemon runs in the background on customers' smartphones, measuring five key QoS metrics along with relevant metadata according to the testing schedule. The results feed the database (DB), allowing for regular, independent analysis of the QoS experienced by customers. Similar studies exist around the world, such as the FCC SpeedTest in the United States [11], [12], Ofcom's mobile performance effort in the United Kingdom [13], and crowdsourced platforms like OpenSignal [14], nPerf [15], and Ookla Speedtest [16], which have established the value of crowdsourced network performance data. However, MBPerf is unique in that it is tailored to the Nigerian market, with a customer-centric focus on unbiased data collection. Unlike some traditional apps that rely on users to manually trigger tests, MBPerf runs continuously in the background, ensuring that the data collected is more representative of actual user experiences. Beyond just offering raw performance figures, MBPerf generates research-grade datasets that can be used to drive academic inquiry, guide policy interventions, and empower consumers with accurate insights into the approximate QoS delivered by MNOs.

II. Literature Review

A. Mobile Broadband and its Evolution

There are two primary methods of accessing the Internet [17]: through a fixed-line connection at home or via mobile broadband, which offers portability. Broadband refers to high-speed Internet connectivity that supports data, voice, and video transmission, typically provided through land-based technologies like DSL or cable services. It is termed "broad" due to its ability to accommodate multiple service types across a wide bandwidth, while mobile broadband extends these services to mobile devices [18]. MBB operates by connecting to a mobile network via a SIM card, enabling users to access the Internet through a dongle, a portable Wi-Fi hotspot, a SIM-equipped tablet or laptop, or by tethering from a mobile phone. Over the past four decades, mobile networks have undergone remarkable evolutions [19]. The cellular concept began with the first generation (1G) networks in 1981. Figure 1 summarizes the evolution of MBB wireless networks and the specific features of each generation from the first to the fifth generation. MBB networks have grown tremendously in almost five decades and are classified into different generations. 2G was the most extensively used mobile communications technology worldwide from the early 1990s until it was surpassed by 3G and 4G between 2017 and 2019 [20]. 5G has passed through the design stage and is now in implementation. Today, the fifth generation (5G) technology has stormed the markets, and research on the sixth generation (6G) has begun. With the rapid change in broadband networks and Internet trends as well as the increasing growth in mobile traffic, issues relating to QoS must not be ignored [10].

B. Why Measure Mobile Broadband Performance?

The contextual QoS data that was collected from mobile users using a host-based approach, the numerous insights gained from it, and the rapid adoption and popularity of smartphones [2] justify this study. Furthermore, MBB performance monitoring plays a crucial role in shaping telecom sector policies, assisting regulators in making informed decisions. Additionally, by providing customers with insights into their Internet service performance, it empowers them to choose the most reliable and fastest network while balancing their data needs and budget effectively [22]. Furthermore, MBB performance monitoring fosters healthy competition among MNOs, ensuring they are held accountable for their advertised speed claims, thereby driving them to improve their services [23]. The outcomes of this study are expected to contribute to the advancement of MBB technology and have practical implications for MNOs, regulator, and end-users.

C. Review of Existing Research on Broadband Connectivity and MBB Performance Monitoring in Africa (2013 – 2024)

A summary of relevant studies relating to broadband connectivity and MBB performance monitoring in Africa between 2013 and 2024 is presented, highlighting technological growth, usage trends, challenges, and policy implications. [24] performed a first of its kind, systematic study on broadband performance in South Africa, using two tools – MySpeedTest on mobile phones and BISmark on home routers. Data was collected for a period of three months from 15 ISPs, focusing on upload/download throughput and latency of connections. Findings showed that customers in South Africa experienced broadband speeds that are less than what they pay for and this also contrast what is obtainable in the UK and US where ISPs generally deliver advertised speeds. In addition, mobile ISPs outperformed fixed-line ISPs in download speeds, though high latency persisted even when throughput improved. The study's limited duration and narrow QoS focus may have hindered its robustness. [25] on his part, explored Africa's progress in broadband connectivity and its integration into the global digital network. MBB had spread widely, slashing service costs from 2008 to 2010. The sector supported e-government expansion and economic development, contributing 8% of sub-Saharan Africa's GDP in 2021 to the tune of $140 billion and creating 3.2 million jobs. The economic contribution is projected to grow to $155 billion by 2025. Mobile banking in Nigeria and Kenya, and agricultural ICT services in Ghana, confirms broadband impact. Despite the visible gains, challenges still abound because broadband costs are still high, infrastructure is mainly urban-focused, rural access is limited, and local content is insufficient. Aikins advocated for national e-strategies, market liberalization, rural connectivity policies, public-private partnerships, and strategic spectrum management to sustain growth and close the digital divide. [26] used questionnaires to evaluate broadband performance in two rural (Ilesa, Oba-Ile) and two urban (Abuja, Lagos) areas in Nigeria. Findings revealed dominant use of wireless broadband and minimal video streaming by customers in the coverage area while MNOs are in transition to deploying 4G network technologies. The reliance on questionnaire-based data collection strategies raised concerns about accuracy due to potential misconceptions and misrepresentation. [10] adopted a Fuzzy Knowledge-Based approach with Triangular Membership Function to evaluate MBB performance delivered by three MNOs in the Niger Delta region of Nigeria. Data was collected using the software-based approach. The QoS parameters measured for 21 days include signal strength, packet loss, upload and download speeds. Results showed variance among MNOs' data. Also, the limited time and scope of metrics constrained the study's comprehensiveness. [27] conducted preliminary throughput measurements in Uyo and Eket, Nigeria. The study results show that the actual broadband throughput is several orders of magnitude lower than the expected theoretical values. The study suggested that broadband deployment and optimization in Nigeria needed enhancement. A testbed using Raspberry Pi was proposed for sustained data collection and robust performance evaluation. [1] surveyed broadband performance monitoring approaches, including hardware (Netbeez, BISmark, SamKnows) and software (Netalyzr, Speedtest, MobiPerf), along with crowdsource, active, and passive methods. The authors supported host-based technique because of its scalability, cost-effectiveness, and user-centric nature. Besides, the review highlights the transformative role of mobile broadband in Africa, linking its rapid expansion to increased smartphone availability and affordability as well as the increased rollout of networks and the adoption of newer, faster technologies. Despite the significant progress made in the broadband sector, the study points out that there is scarcity of research on the systematic and consistent monitoring, evaluation, and reporting of MBB performance in Africa. From the survey, several recommendations were provided to enhance cellular network performance in developing countries. Their findings and recommendations serve as a call to action for African governments, telecom regulators, and researchers to adopt more structured, empirical methods for evaluating broadband services, thereby improving the digital landscape for all. [28] analyzed 4G LTE quality across UNILAG, Ikorodu, and Oniru VI in Lagos. Data from a drive test facilitated the evaluation of Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Received Signal Strength Indicator (RSSI), and Signal-to-Noise Ratio (SINR) KPIs. Findings indicated that relying on one KPI (like RSRP) gives an incomplete picture of QoS. Poor network reception significantly worsened user experience, and the study recommended a thorough mapping and potential replanning of network routes. The study focused only on three locations and excluded newer technologies like 5G. Lastly, [20] emphasized MBB's expansion through device adoption and network improvements but noted lingering QoS concerns. They reviewed measurement techniques like drive tests, crowdsourced apps, and testbeds, each with limitations. The authors advocated for scalable, autonomous platforms to improve assessment accuracy and enhance future evaluations.

D. Summary of Gaps in Existing Studies

Broadband and MBB performance monitoring, evaluation, and reporting in Africa is significantly underdeveloped when compared to norms in developed countries such as the United Kingdom, the United States, Australia, and Canada, where regulatory bodies commission periodic and structured performance evaluations that are published quarterly, biannually, or annually. In contrast, African countries, including Nigeria, South Africa, Egypt, Kenya, Rwanda etc., lack such institutionalized and continuous performance monitoring systems. Additionally, there are no standardized benchmarks set by telecom regulators in Africa for MBB QoS metrics, despite the existence of such standards for voice KPIs. Existing studies across the continent exhibit several methodological limitations. Many of them were conducted over short duration, typically ranging from three weeks to three months, which limits their ability to reflect long-term performance trends. Besides, the coverage areas of these studies are often narrow, with measurements taken only in select urban or semi-urban areas, making the findings non-generalizable. Several of the studies rely on user-reported questionnaires or non-continuous testing methods, which are prone to bias and lack the rigor of standardized monitoring frameworks. Moreover, most studies examine only a limited set of QoS indicators, mainly throughput, upload and download speeds, latency and signal strength – without accounting for other crucial performance aspects such as jitter, packet loss, availability web browsing speed etc. There is an urgent need for unified evaluation metrics, as the complexity of network assessment is expected to increase with the expansion of 5G technology. The absence of a nationwide, scalable, consistent and autonomous monitoring system also hinders continuous data gathering and evaluation. Drive tests and crowdsourced techniques are used but are insufficient on their own for systematic assessment. Furthermore, the variety of tools and metrics used across studies creates difficulties in comparing results or establishing continent-wide performance baselines.

While MBB penetration has grown, due to increasing smartphone usage and improved infrastructure, policy and regulation have not evolved to match this growth. There is little to no regulatory pressure on MNOs to publish performance data, and customers remain largely uninformed about the actual broadband quality delivered to them. Finally, rural and underserved areas are notably absent from most measurement efforts, further deepening the digital divide and making it difficult to understand or address disparities in broadband access across regions.

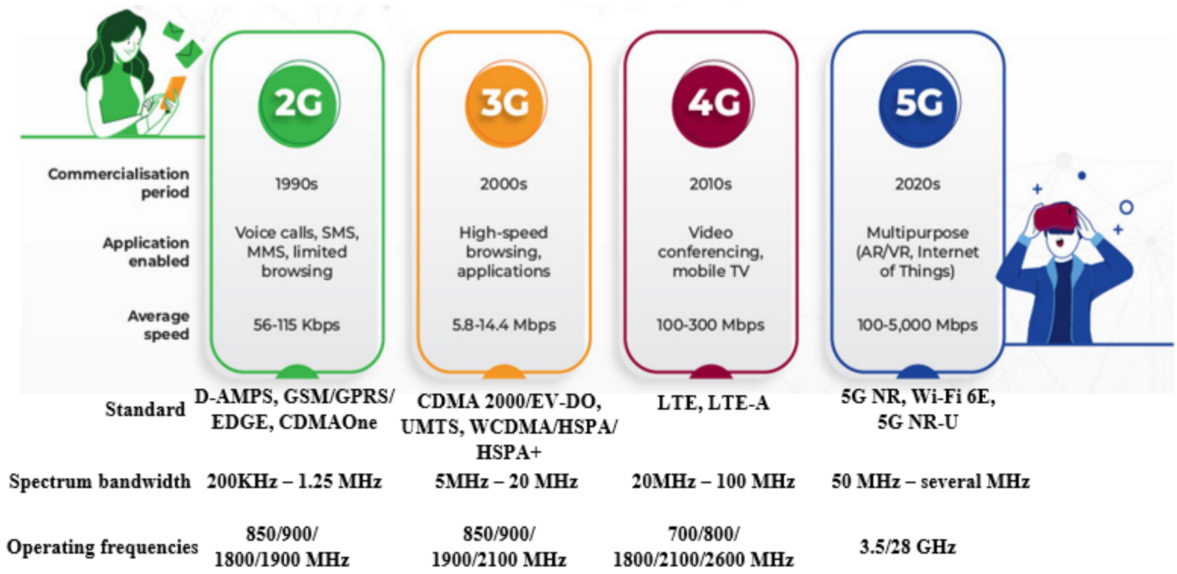


Figure 1. Evolution of MBB (Adapted from: [21])

III. METHODOLOGY

The methodology employed to achieve the research objectives is a host and crowdsource-based approach to MBB performance monitoring and evaluation which involves the development of MBPerf. MBPerf was validated with a known standard application. Thereafter, MBPerf was installed on volunteer devices and the collected data analyzed. The host-based methodology was selected because it is customer centric meaning that it allows data to be collected and characterized in the context of mobile users. Additionally, crowdsourcing enables the collection of numerous data points from a vast user base with minimal extra effort.

A. MBPerf Mobile Application

The client front-end of MBPerf data collection system consists of an Android smartphone and MBPerf QoS mobile application installed on it. The Android platform was chosen because of its market dominance globally and especially in developing countries like Nigeria. Focusing on the majority user-base allows for a larger impact and more extensive data collection. Besides, Android's open-source nature offers greater flexibility and control over app development, facilitating deeper integration with the device's capabilities and easier access to the required APIs.

MBPerf collected both passive and active data which are discussed in this section. MBPerf ran tests as a background service. Besides, there is an option for manual testing too. Measurements were taken every one hour via the Flutter WorkManager which can run tasks reliably even if MBPerf's session is closed or the device restarts. The passive data are divided into three parts, viz: device information, network information and location information. The active data measured and collected by MBPerf include the following QoS metrics. These metrics are standard technical parameters for accessing the quality of Internet services [29], [30], [31].

a) DNS look up: is the time taken in milliseconds (ms) by a wireless service provider to resolve a web domain name to an IP address. MBPerf measured the DNS look-up metric by using the InternetAddress.lookup() method in Flutter. DNS lookup is calculated as follows:

- Let the number of DNS server(s) visited by the $host = nDNS$ where $n = 1,2,3$ ....

- Each successive visit will incur a round-trip time of RTTI, where $i = 1,2,3 \ldots n$.

Hence, the total DNS Look-up time is given by equation (1) [32]:

$$DNS_T = \sum_{i=1}^{n} RTT_i \quad (1)$$

b) Download and upload speeds: the upload and download speed metrics measure the capacity of a user's MBB connection. The upload and download speed metrics are calculated using equation (2) [12]:

$$S = \frac{D}{T} \quad (2)$$

where S is the Speed (Bytes per second), D is the message length or number of bytes transferred within time T (Bytes) and T is time taken to transfer D (seconds).

c) Latency: Latency is the time from the source sending a packet to the destination receiving it. It is a measure of how responsive a network is. Latency was measured by using the Internet Control Message Protocol (ICMP) ping command, which sends sequentially 10 ICMP 'echo' request packets from MBPerf to the measurement server and then listens for the ICMP 'echo' response replies. The average Round Trip Time (or latency) that these packets take to complete this transport was then calculated using equation (3):

$$RTT = \frac{WS}{\tilde{\iota}(ms)} \quad (3)$$

where RTT is Round Trip Time in milliseconds, WS is TCP Window Size (64KB is a constant window size) and $\tilde{\iota}$ is Throughput or actual speed of packets in bits per second.

d) Received Signal Strength Indicator (RSSI): is a value that is useful for determining if a cell phone has enough signal to get a good wireless connection. RSSI measurements are indicated in negative values, which are relative. Usually, the closer the value is to zero, the stronger and higher the quality of the signal [33]. The estimated RSSI on a user's mobile device is calculated using equations (4) and (5) [34]:

$$P_r(dBm) = P_{min} - PLlog(d^{d_0}) \quad (4)$$

Taking the path loss exponent into account, we get equation (5):

$$P_r(dBm) = P_{min} - 10\gamma log(d^{d_0}) \quad (5)$$

where P_r is estimated received power (RSS) on a mobile device measured in dBm, γ is the path loss exponent with an average value of 4 for mobile networks, d is the distance between mobile device and BTS, d_0 is the mean radius of the cell tower and PL is the average path loss per decade for mobile networks. MBPerf returned the RSSI values to the user in decibel-milliwatt (dBm) by using the TelephonyManager() class to access the device's telephony information, including RSSI.

MBPerf was validated to ensure that the accuracy, consistency, and reliability of its dataset meet the Nigeria Communications Commission (NCC)/Federal Communications Commission (FCC) standard. Measurement results from Ookla Speedtest app, a widely recognized and reliable benchmark was used to validate MBPerf measurement results. Ookla Speedtest is recognized by the FCC in the US, International Telecommunications Union (ITU) and several ISPs and Telcos [16]. Ookla Speedtest is a definitive way to test the performance and quality of an Internet connection and Ookla, the company behind Speedtest is a global leader in fixed and mobile network testing applications, data and analysis [16]. Bi-hourly measurements of the download speed, upload speed and latency for a period of one month were collected via MBPerf and Ookla Speedtest apps for each of the three MNOs under evaluation. Correlation analysis was carried out on the measurement results and presented in TABLE I of section 4.

B. Data Collection

Appropriate sample size determination is required for appropriate analysis, thereby providing the desired level of accuracy. To calculate the number of users across the 6 states for the 3 MNOs tested, the sample size formula of equation (6) given by [35] was used.

$$Sample\ size\ (n) = \frac{\frac{z^2 * p(1-p)}{e^2}}{1 + \left(\frac{z^2 * p(1-p)}{e^2 N}\right)} \quad (6)$$

where z is the z-score, e is the margin of error, p is the standard deviation and N is the population size.

For the coverage area under investigation i.e. the South West (SW) region of Nigeria):

- $N = 61{,}741{,}836$ → active Internet subscriptions in the South West, First Quater (Q1), 2024 [36].
- $z = 1.96$ for 95% confidence level.
- $e = 5\% = 0.05$.
- Assuming $p = 50\% = (0.5)$, to be sure the group is large enough.
- Hence, $n = 384.16 \approx 384$ volunteers.

A total of 500 volunteers were selected as the sample size for robustness and improved reliability of data collected. Mobile customers who volunteered to participate in the study received MBPerf .apk file via various methods: Xender, WhatsApp or email attachment depending on their preference. Installation instructions were also provided to ensure a smooth setup process. MBPerf mobile application was installed on 500 volunteers' smartphones to measure five selected MBB QoS metrics in the six SW States (Ondo, Oyo, Ogun, Osun, Lagos and Ekiti) of Nigeria for a period of nine months. The total collected data which amounted to 6500 measurement instances were downloaded from the online database (Google Firestore) to the research Laptop (specification: Intel(R) Core (TM) i3-8130U CPU at 2.21 GHz, 8.00 GB RAM and x64-based processor) for further pre-processing and analysis. The block diagram of the QoS data collection system shown in Figure 2 consists of the current three major MNOs in Nigeria that participated in the study. One of the major services offered by MNOs is the World Wide Web (WWW) service. This network service was evaluated by analyzing the data collected by MBPerf. MBPerf's controller after executing a test scenario, collates the user-data and the measured QoS metrics.

The data is temporarily stored on the local storage of the user's mobile device and subsequently transmitted via the Internet to the online DB, where it is stored for future use. Raw data in JSON format pulled from the online DB and structured was subsequently pre-processed and analyzed using Python, Microsoft Power BI and Microsoft Excel statistical packages.

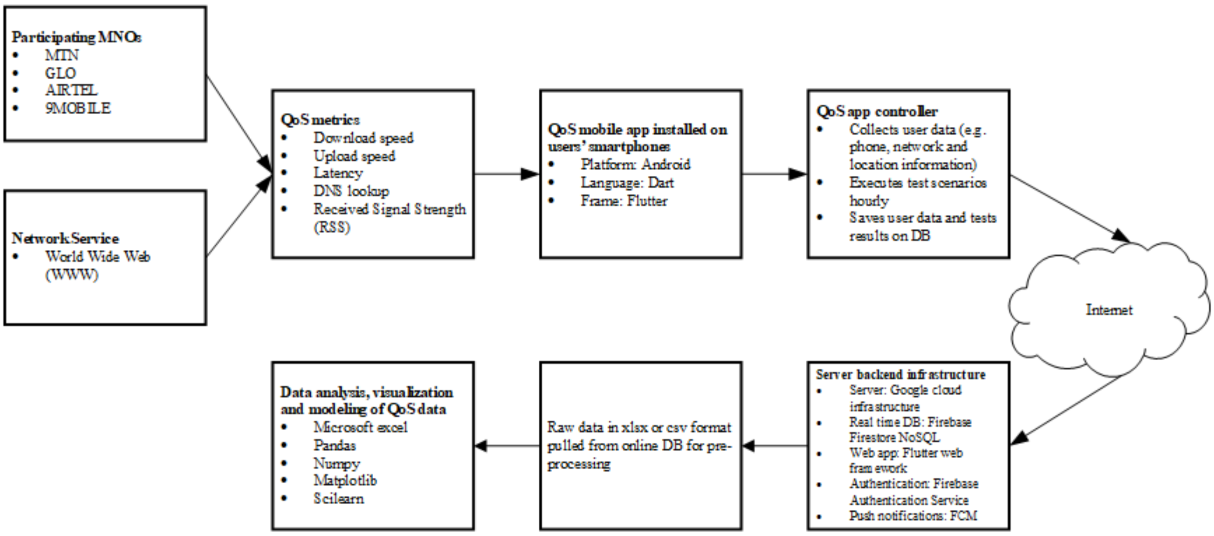


Figure 2. Block diagram of the MBPerf QoS data collection system

C. Exploratory Data Analysis

Raw data downloaded from Google Firestore was converted into .csv format and read on Microsoft Excel software in readiness for cleaning and subsequent analysis. Descriptive analysis, One Way Analysis of variance (ANOVA) Post Hoc Test via Least Significance Difference (LSD), correlation analysis, time series analysis and other relevant statistical analyses were employed to draw inferences relating to the performance of each MNO. Histograms, box plots, line graphs, column bar charts and area charts were used to graphically explain the analyzed dataset.

IV. RESULTS AND DISCUSSION

A. Coverage Mapping of the Coverage Area

The coverage area map of the six states in Nigeria's South West geopolitical zone, along with data points representing the various test locations where QoS data were collected is presented in Figure 3. The latitude, longitude and the signal strength values obtained per measurement for all volunteers were used to map the areas covered by MBPerf deployment in the six states. ArcGIS software developed by Esri generated this coverage map. The data points on the coverage map when compared with the signal strength power levels shown on the legend suggest that the tested MNOs can be said to have considerably good coverage in the study areas, since many of the signal strength values fall in the good and very good categories.

B. User interfaces of MBPerf Mobile Application and Online Dashboard

Some of the User Interfaces (UIs) of MBPerf QoS application are shown in Figure 4. The Home page shown in Figure 4a displays the results, menu and test buttons provided to help the user navigate through all the sections of MBPerf application. The test button when pressed launches a manual test. The progress being made during the manual test can be monitored on the test page shown in Figure 4b. The results page when pressed displays history of timestamped numerical and graphical results. Figure 5 displays one of the user interfaces (user management page) of the MBPerf's online dashboard. This page informs the administrator of the date and time measurements were taken and the history of all results (active and passive) collected from all users for each of the 5 QoS metrics measured. The Download data button on this page allows the administrator to download in excel format spreadsheet all the performance results.

C. MBPerf Data Validation

The correlation analysis results shown in Table 1 reveal strong positive correlations between MBPerf and Ookla Speedtest measurements. For download speed, the correlation coefficient, $r = 0.856$, for upload speed, $r = 0.884$ while for latency metric, $r = 0.755$. These results show that MBPerf measurements are significant and to a very large extent accurate and reliable.

TABLE I. CORRELATION RESULTS BETWEEN MBPERF AND OOKLA SPEEDTEST MEASUREMENTS

QoS Metrics	**MBPerf Download (Mbps)**	**Ookla Download (Mbps)**	**MBPerf Upload (Mbps)**	**Ookla Upload (Mbps)**	**MBPerf Latency (ms)**	**Ookla Latency (ms)**
MBPerf Download (Mbps)	1					
Ookla Download (Mbps)	**0.856**	1				
MBPerf Upload (Mbps)	0.667	0.595	1			
Ookla Upload (Mbps)	0.775	0.723	**0.884**	1		
MBPerf Latency (ms)	-0.600	-0.621	-0.691	-0.773	1	
Ookla Latency (ms)	-0.572	-0.607	-0.603	-0.697	**0.755**	1

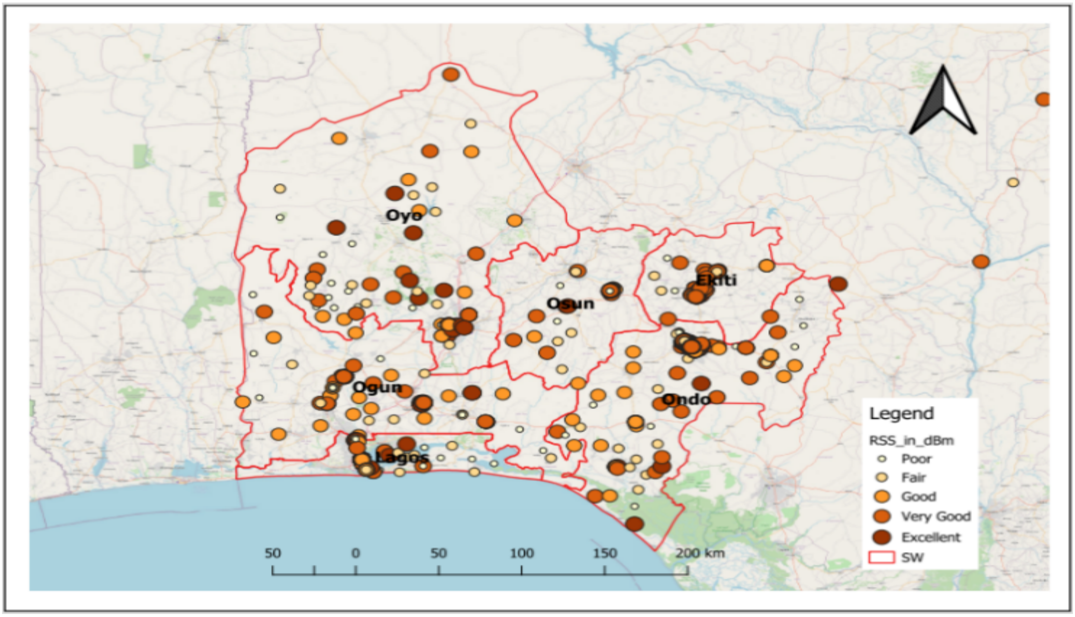
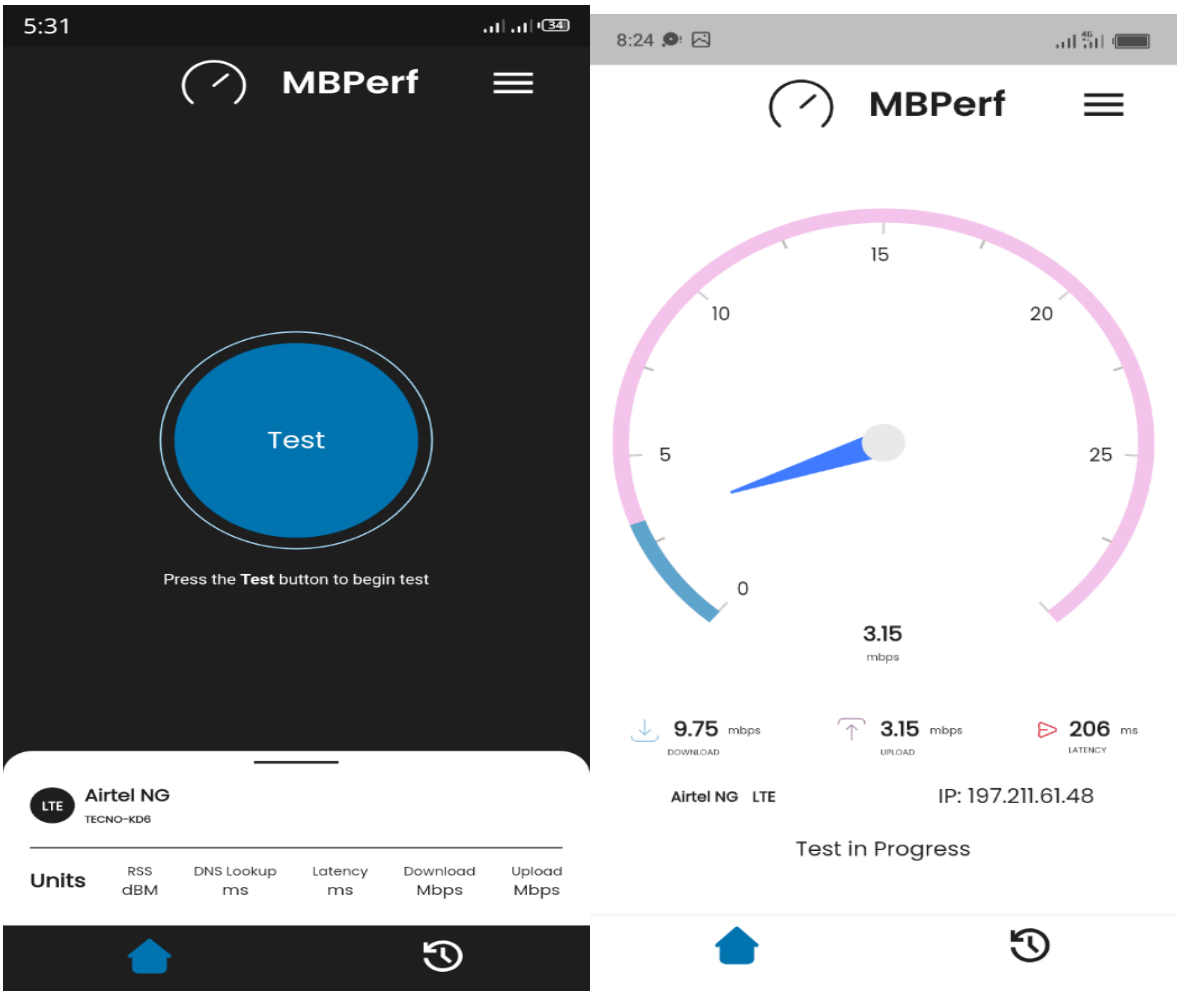


Figure 3. MBPerf deployment in Ondo, Ekiti, Osun, Ogun, Oyo and Lagos states



a) b)

Figure 4. MBPerf home and test pages

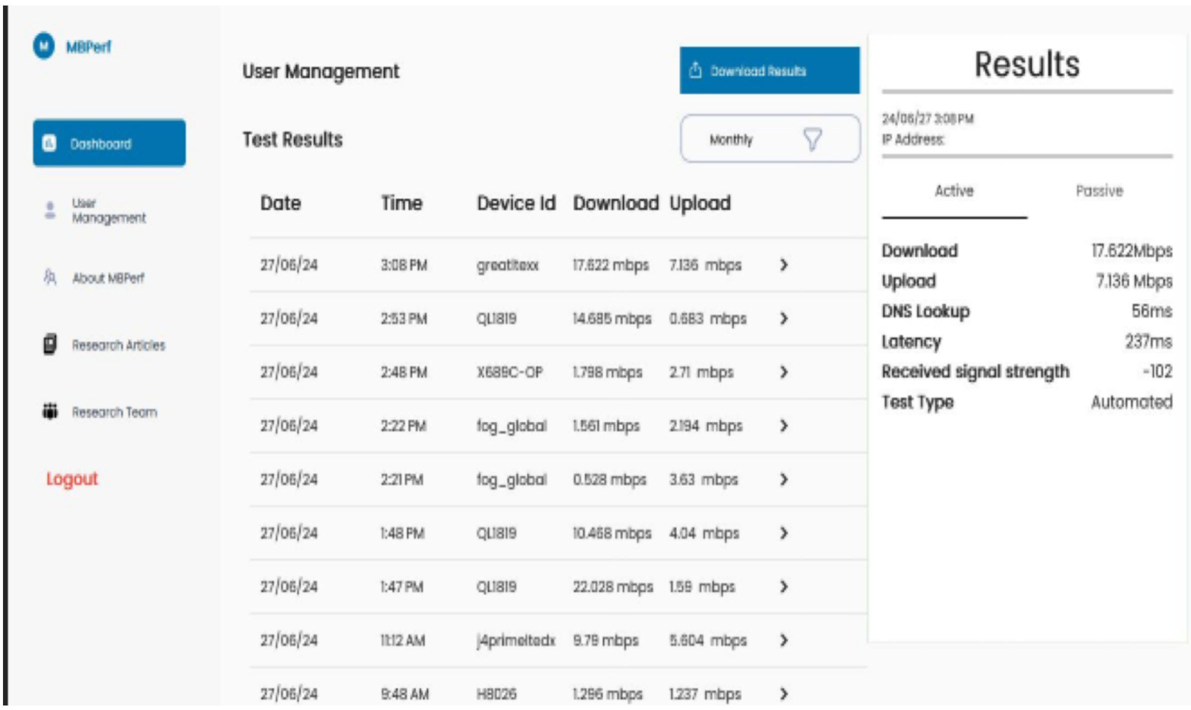


Figure 5. MBPerf online dashboard user management page

D. Analyzed Results of Mobile Broadband Network Performance, Q1 – Q3, 2024

This section graphically presents the analyzed results of QoS metrics outlined in methodology section of this paper. These results represent the mobile network performance from February to October 2024. To assure a fair comparison of the three MNOs, each MNO's performance based on the chosen QoS metrics were tested across a 24-hour profile at each location. Suffice to say that all the smartphones used were unbranded, unmodified and run the same OS (Android). It is important to note that the results are influenced by the diverse urban locations of the 500 volunteers who participated in this study. In addition, the type of smartphone and its hardware specifications influenced the QoS measurements.

E. Download Speed on 4G by Test Location and Network

As shown in Figure 6, the MNO with the fastest average 4G download speed recorded across all the sample sites tested was MNO-A in Lagos, at 16.1 Mbps while MNO-B in Oyo state had the lowest average 4G download speed at 4.7 Mbps. In Ekit state, there is no statistically significant difference between the speeds delivered by the MNOs. Unlike Lagos where the speed delivered by MNO-A (16.1 Mbps) is about three times that delivered by MNO-B (6.0 Mbps). In Ogun state, the MNO with the highest speed was MNO-A at 11.4 Mbps while MNO-B had the least speed at 6.6 Mbps. In Ondo state, there is no statistically significant difference between the 4G download speeds experienced by MNO-A (10.4 Mbps) and MNO-C (10.1 Mbps) users. MNO-B again had the lowest download speed of 6.8Mbps.

F. Matching Download Speed Performance with Industry Benchmark

The result of the exploratory analysis carried out to ascertain if the download speeds that MNOs achieve match the industry standard (benchmark) values – which lies between 10 and 50 Mbps [37] is shown in Figure 7. The box and whisker plot shows that MNO-A and MNO-C surpassed the lower limit of the benchmark by about 13% and 4% respectively but MNO-B, on the other hand fell short of the benchmark by about 25%. MNO-A outperformed MNO-C and MNO-B, with MNO-B having the worst performance as revealed by the mean values and the performance difference is significant.

G. Effect of Time of the Day on Download and Upload Speeds Performance

One of the possible explanations for inconsistent and variable Internet speed performance is that communication links exhibit different performance characteristics depending on the hour of the day [22], [38]. Figure 8 shows the download and upload speed metrics plotted against hours of the day. The time analysis shows that mobile users experience the best Internet speed performance between 11 pm and 6 am, while a downward and variable trend is experienced all throughout the day from 6 am till late in the evening at 11 pm.

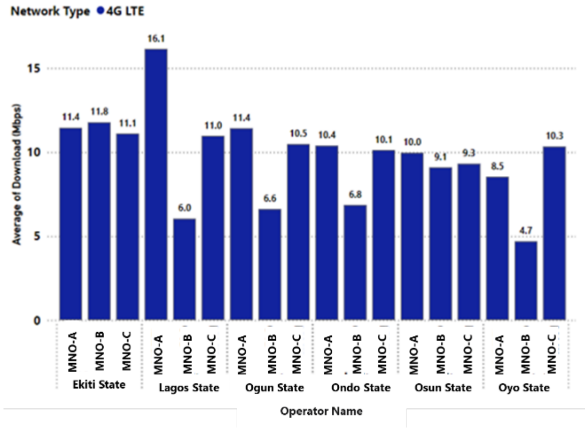


Figure 6. Average 4G LTE download by test location and network

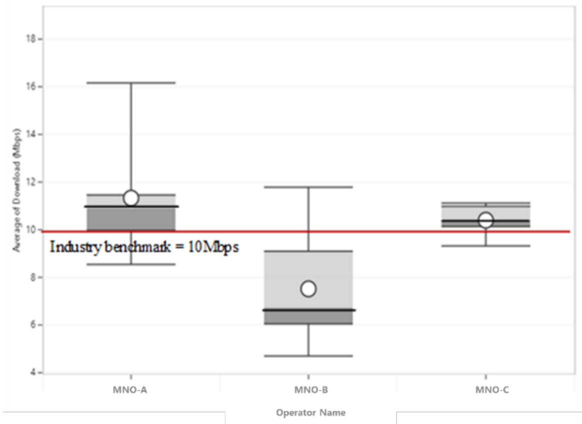


Figure 7. Download speed for each MNO compared with industry benchmark

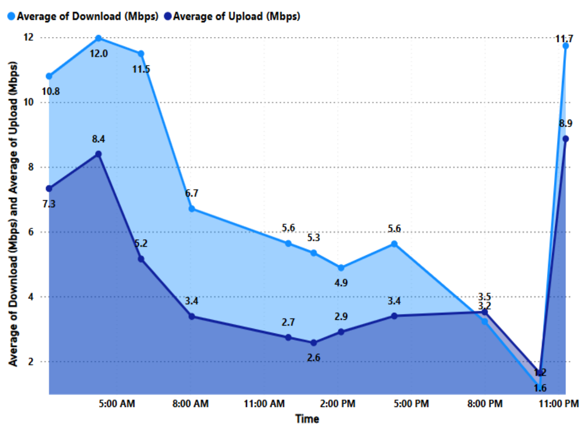


Figure 8. Effect of time of the day on download and upload speeds performance

H. Upload Speed on 4G by Network and Location

As illustrated in Figure 9, MNO-C in Osun recorded the fastest average 4G LTE upload speed across all tested sample sites, reaching 7.0 Mbps. Conversely, MNO-B in Lagos had the lowest average 4G LTE download speed, measuring 2.6 Mbps. The speed delivered by MNO-C (6.1 Mbps) in Oyo is twice the upload speed delivered by MNO-A (3.0 Mbps) and MNO-B (3.0 Mbps). In Ondo state, MNO-C had the highest upload speed at 5.6 Mbps while MNO-B again had the lowest upload speed of 3.4 Mbps and comparison of the speeds delivered by the three MNOs in Ondo state shows that they are statistically significant.

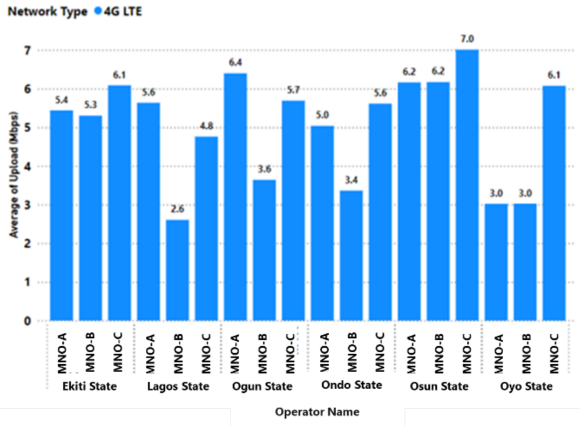


Figure 9. Average 4G LTE upload speed, by network and location

I. Asymmetric Internet Speeds

It was observed from Figure 10 that the aggregated download speed results for each MNO tested are typically higher than the upload speed counterpart. Considering MNO-B's network for instance, the 4G LTE download speed is 7.3 Mbps, which is more than 41% higher than its 4G LTE upload speed of 4.3 Mbps. For MNO-C, the percentage increase is 38% while that of MNO-A is more than 27%. The reason behind this is likely because most MNOs offer asymmetrical Internet connections, particularly for mobile end users. This means that the bandwidth allocated for downloading data is greater than that for uploading data. However, while typical consumer Internet plans favor higher download speeds due to usage patterns and infrastructure design, there are scenarios where upload speeds can be equal to or exceed download speeds, particularly in specialized contexts (such as in content creation and companies that rely on cloud services) or with certain types of Internet connections.

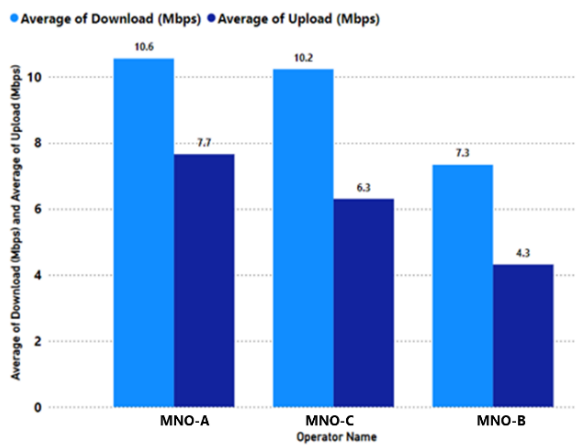


Figure 10. Overall average 4G LTE download and upload speeds, by network

J. Matching Upload Speed Performance with Industry Benchmark

The result of the exploratory analysis carried out to ascertain if the upload speeds that MNOs deliver match the industry standard (benchmark) values is shown in Figure 11. According to [37], the industry benchmark lies between 5 and 20 Mbps. The box and whisker plot shows that MNO-A and MNO-C surpassed the benchmark by 32% and 22% respectively while MNO-B fell short of the benchmark by about 14%. Just like for download speed, MNO-A again outperformed MNO-C and MNO-B with MNO-B having the worst performance, as shown by the mean values.

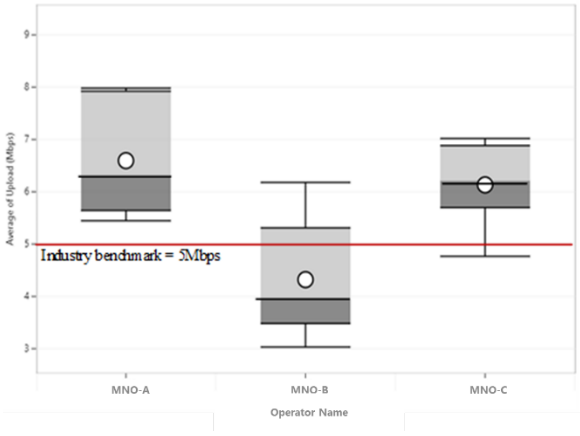


Figure 11. Upload speed for each MNO compared with industry benchmark

K. Latency on 4G LTE by Network and Location

MNO-C in Oyo recorded the fastest average 4G LTE latency across all tested sample sites, measuring 227 ms (Figure 12). However, MNO-B, in Lagos state had the lowest average 4G LTE latency of 2080 ms. In addition, significantly high latencies were recorded by MNO-B users in Ogun, Ondo and Oyo states at 868ms, 667 ms and 1554 ms respectively. MNO-A outperformed MNO-B and MNO-C in Ekiti, Lagos, and Ogun states while MNO-C outperformed other networks in Ondo, Osun and Oyo states. Comparison of the difference in latencies delivered by the MNOs in the six states shows that the results are statistically significant.

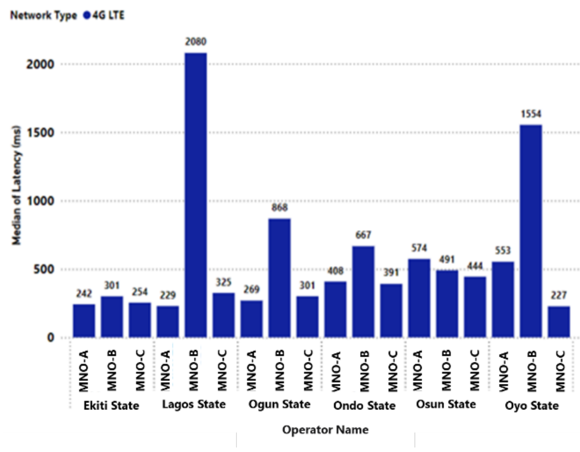


Figure 12. Average 4G LTE latency, by network and location

L. *Matching Latency Performance with Industry Benchmark*

Figure 13 shows the distribution of 4G LTE latencies to and from the measurement server for each MNO in MBPerf's deployment. The box and whisker plot shows that MNO-B users experience highly variable and inconsistent latencies towards the measurement server while MNO-C exhibited the most stable distribution of latency values, which is closely followed by MNO-A. Comparing the median latency for each MNO with the Industry benchmark, given by [37] as less than 100 ms, it can be deduced that all the MNOs significantly fell short of the benchmark. A significant performance problem is indicated by the high latency witnessed by the mobile users, which suggests that data packets are experiencing delays in their transmission between the user's device and the servers' hosting contents. Although testing toward an international server may have introduced significant bottlenecks, the measurements of download and upload speeds, as well as latency, still provide insights into the bottlenecks users encounter along a broader network path [38]. Furthermore, since most user-accessed contents are hosted on international servers, conducting tests on such infrastructure offers a more realistic assessment of performance [39]. To mitigate latency effects, governments can play a key role by promoting and supporting efforts to bring contents closer to customers. Additionally, optimizing interconnections and peering among MNOs and Internet Service Providers (ISPs) via regional and national Internet Exchange Points (IXPs) would help ensure network traffic follows the shortest and most direct route to its destination whenever feasible [1].

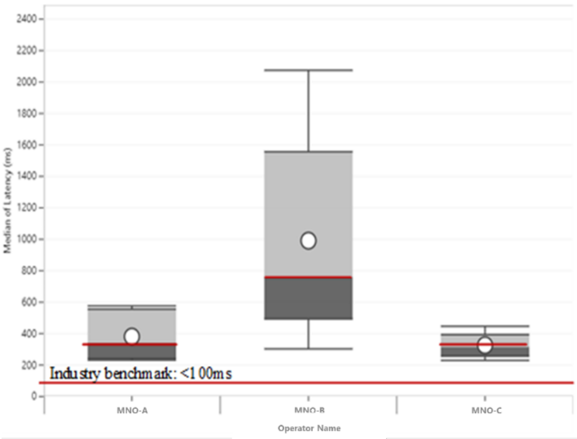


Figure 13. Latency for each MNO compared with industry benchmark

M. *4G LTE Latencies are Significantly Better than 3G Latencies*

Figure 14 presents a comparison of the overall average latency results for 4G LTE and 3G. As anticipated, the graph reveals that latency experienced by 4G LTE customers toward the measurement server was more than twice as low – resulting in faster and improved performance – compared to 3G. This is likely due to 4G LTE's superior access technology, which offers the advantage of reduced latency toward destinations [40].

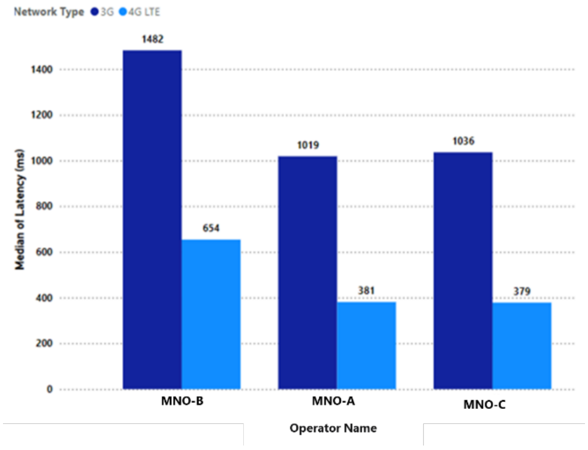


Figure 14. Average 4G LTE and 3G latency

N. *Effect of Time of the Day on Latency Performance*

Previous studies, including those conducted by [22], [38], [41] have shown that users experience inconsistent performance due to network congestion, which tends to increase during peak hours. The line graph displayed in Figure 15 confirms this previous finding. Based on the 4G LTE latency dataset, the average median latencies to the measurement server across all MNOs displayed significant instability and variability between 9 am and 9 pm, with the poorest performance observed around 9 pm. In contrast, latencies remained consistently stable during the early morning hours, from 12 am to 8 am. After these times, the latencies keep fluctuating throughout the day till late in the evening with some high peaks recorded in-between.

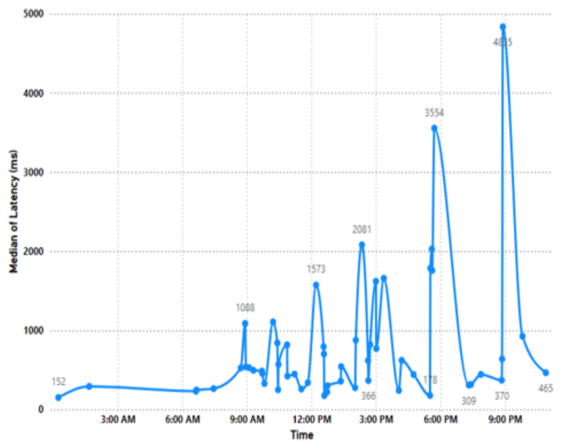


Figure 15. Median latency data plotted in relation to local time of the day

O. *DNS Lookup Analysis*

DNS converts domain names that are easily understandable by humans into machine-friendly IP addresses. Figure 16 shows that MNO-A recorded the lowest time in resolving DNS queries at 31 ms. This value is closely followed by MNO-C at 36 ms and then MNO-B at 37 ms. There is no significant difference between the DNS lookup time for MNO-A and that for MNO-C. Taking a closer look at Figures 16 and 17, it is observed that the aggregated DNS lookup times are significantly lower than 100 ms for the 3 MNOs and also considerably lower (better) than their latency counterparts (shown in Figures 13 and 14). These findings suggest that, at large, MNOs' DNS recursive servers are operating efficiently and not adding substantial delays to customers' queries because according to the submission made by [30]; "in theory, a good DNS deployment should provide DNS resolution time and failure rates better than or equal to the latency and packet loss figures." Besides, a benchmark of 100 ms is commonly accepted in the industry as a general guideline for optimal DNS performance [42]. Figure 17 shows that all the MNOs met and significantly surpassed the 100 ms benchmark. In terms of variability, MNO-C as revealed by the whiskers had the highest, followed by MNO-B. MNO-A on its part had the most consistent distribution of DNS lookup times.

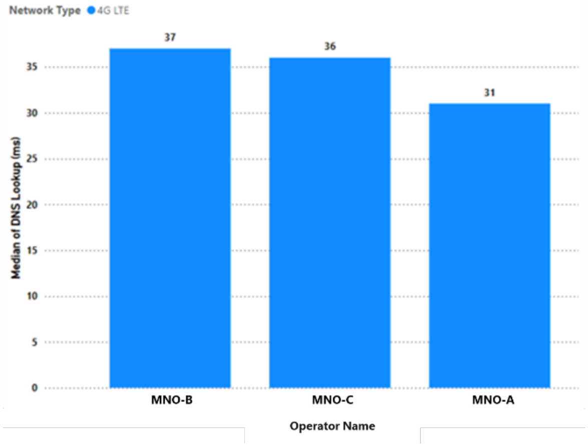


Figure 16. Average 4G LTE DNS lookup, by network

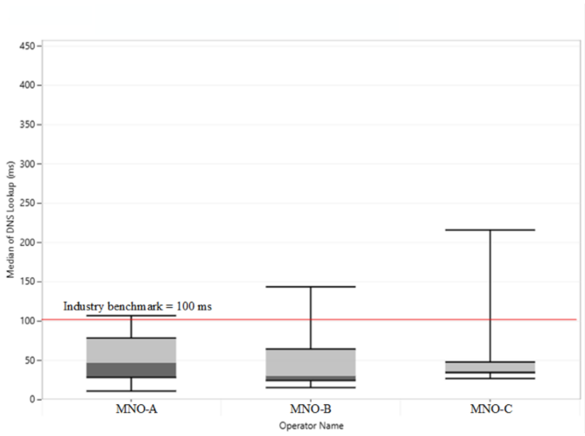


Figure 17. 4G LTE DNS lookup for each MNO compared with industry benchmark

P. *Difficulties Faced in Measuring MBB Performance in an Emerging Country – Insights from MBPerf Experience*

The following are the challenges encountered in the development and deployment of MBPerf in this study:

- **Privacy concerns**

Enlisting volunteers proved challenging, as many were skeptical about MBPerf's claim of not collecting their private data. Additionally, some customers cited limited phone storage as a reason for refusing to install the application.

- **Android OS restrictions on background service and inconsistent data connectivity**

MBPerf was designed to minimize disruptions to volunteers' Internet connections by running brief measurement cycles (under two minutes) as a background service. However, factors such as smartphone OS restrictions on background tasks, inconsistent data connectivity due to volunteers not enabling data services, and their forgetfulness to initiate manual tests significantly reduced the amount of data collected.

- **Data usage concerns**

MBPerf, like other QoS testing tools, requires significant data usage, raising concerns for volunteers with limited data plans. While large-scale measurements are essential for robust and representative performance dataset, software-based approaches face challenges such as inconsistent user participation and potential bias. To address these issues, volunteers were informed about data usage, encouraged to manage their data, and incentives in form of data were offered to some of the volunteers to encourage them to participate in the QoS measurements, thereby contributing to the volume of the collected QoS data.

CONCLUSION

In this study, MBPerf was developed to measure five (5) QoS metrics. The results, along with data related to the customer's network, device, and location were stored in an online database (Firestore) for further analysis. The dataset which emanated from this study after being explored has given powerful insights into the level of QoS delivered by MNOs across the six (6) SW states of Nigeria. The QoS monitoring system developed serves as a reliable standard framework, offering stakeholders a foundation to build upon for future evaluations of MBB QoS in Nigeria and more broadly, across Africa. This paper is part of a wider initiative of employing Machine Learning (ML) techniques to predict the QoS delivered to customers' devices based on measured QoS metrics, network, phone and location information of mobile customers in Nigeria [43]. In addition, the task of evaluating the effect of different smartphone brands on QoS, which has to do with the analysis of contextual data containing technical features of smartphone will also be addressed in future publication.

ETHICAL STATEMENT

Ethical approval was obtained from the Center for Research and Development (CERAD), The Federal University of Technology, Akure (FUTA), Nigeria before conducting this research.

CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

REFERENCES

[1] Akinlabi, A. A., and Dahunsi, F. M. (2021). Mobile broadband quality of service analysis using host-based performance measurements. African Journal of Science, Technology, Innovation and Development, 1–19. https://doi.org/Mobile

broadband quality of service analysis using host-based performance measurements.

[2] GSM Association. (2024). The State of Mobile Internet Connectivity 2024 (pp. 4–7). GSMA Intelligence.

[3] GSMA. (2023). The Mobile Economy 2023 (pp. 1–50). https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-economy/wp-content/uploads/2023/03/270223-The-Mobile-Economy-2023.pdf

[4] NCC. (2025). Industry Statistics. Industry Statistics. Retrieved January 5, 2025, from https://www.ncc.gov.ng/statistics-reports/industry-overview#market-share-gsm.

[5] Federal Ministry of Communications and Digital Economy. (2020). Nigerian National Broadband Plan 2020 - 2025.

[6] Ojo, O. J., Popoola, J. J., Oyetunji, S. A. and Olasoji, Y. O. (2019). Performance Evaluation of a selected Cellular Mobile Operator in Ibadan Metropolis, Nigeria. 6(5), 10115–10124.

[7] Popoola, J. J., and Areo, A. E. (2020). Modeling and Development of a Novel Quality of Service Prediction Model for Global System for Mobile Communications Network using Artificial Neural Networks. Journal of Applied Science & Process Engineering, 7(2), 510–523.

[8] Casas-Hernandez, P., D´Alconzo, A., Wamser, F., Seufert, M., Gardlo, B., Schwind, A., Tran-Gia, P., and Schatz, R. (2017). Predicting QoE in Cellular Networks using Machine Learning and in-Smartphone Measurements. In 9th International Conference on Quality of Multimedia Experience (QoMEX 2017) https://doi.org/10.1109/QoMEX.2017.7965687.

[9] Alhammadi, A. El-Saleh, A. and Shayea, I. (2021). MOS Prediction for Mobile Broadband Networks Using Bayesian Artificial Intelligence, 2021 International Conference on Artificial Intelligence and Computer Science Technology (ICAICST), Yogyakarta, Indonesia, 2021, pp. 47-50, https://doi.org/10.1109/ICAICST53116.2021.9497834.

[10] Umoren, I. J., and Inyang, S. J. (2021). Methodical Performance Modelling of Mobile Broadband Networks with Soft Computing Model. International Journal of Computer Applications, 174(25), 7–21.

[11] Burger, E. W., Krishnaswamy, P., and Schulzrinne, H. (2023). Measuring Broadband America: A Retrospective on Origins, Achievements, and Challenges. ACM SIGCOMM Computer Communication Review, 53(2), 11–21.

[12] Samknows. (2013). Quality of Broadband Services in the EU (pp. 1–103). European Commission.

[13] Ofcom. (2024). Mobile Matters: Using crowdsourced data to assess people's experience of using mobile networks (pp. 1–30).

[14] Opensignal. (2023). Opensignal Methodology Overview (pp. 1–16). https://cdn.opensignal.com/public/pdfs/opensignal_methdology_overview_jan_2023.pdf?utm

[15] nPerf. (2024). Barometer of mobile Internet connections in Switzerland. (pp. 1–14).

[16] Ookla. (2024). Speedtest. Speedtest. https://www.speedtest.net/about

[17] Kim, M., Park, J., Jee, K. and Lee, S. (2006). Mobile Broadband Deployment Strategies for Korea and Demand Analysis 2006. Technology Management for the Global future - PICMET 2006 Conference, pp. 1977-1982.

[18] Ergen, M. (2009). Mobile Broadband Including WiMAX and LTE (1st ed.). Springer Science+Business Media LLC 2009.

[19] Jaiswal, S., Kumar, A., and Kumari, N. (2014). Development of Wireless Communication Networks: From 1G to 5G. International Journal of Engineering and Computer Science (IJECS), 3(5), 6053–6056.

[20] Umoh, V., Ekpe, U., Davidson, I., and Akpan, J. (2023). Mobile Broadband Adoption, Performance Measurements and Methodology: A Review. Electronics (MDPI), 12, 1–25. https://doi.org/doi.org/10.3390/ electronics12071630

[21] Sood, R., and Garg, A. (2014). Digital Society from 1G to 5G: A Comparative Study. International Journal of Application or Innovation in Engineering and Management (IJAIEM), 3(2), 186–193.

[22] Dahunsi, F. M., and Akinlabi, A. A. (2019). Measuring mobile broadband performance in Nigeria: 2G and 3G. Nigerian Journal of Technology, 38(2), 422–436.

[23] Ofcom. (2015). Measuring Mobile Broadband Performance in the UK: 4G and 3G Network Performance. In Research Document (Issue April). https://www.ofcom.org.uk/__data/assets/pdf_file/0033/79629/ofcom_mbb_performance_report_ april_2015.pdf

[24] Chetty, M., Sundaresan, S., Muckaden, S., Feamster, N., and Calandro, E. (2013). Investigating Broadband Performance in South Africa. Proceedings of the 4th Annual Symposium on Computing for Development, ACM DEV 2013 (Vol. 2). researchICTafrica.net.

[25] Aikins, S. K. (2015). Leveraging Broadband for e-Government and Development in Africa: Opportunities and Challenges. International Journal of Public Administration in the Digital Age, 2(3), 1–23. https://doi.org/10.4018/ijpada.2015070101

[26] Kuboye, B. M. (2017). Evaluation of Broadband Network Performance in Nigeria. International Journal of Communications, Network and System Sciences, 10(09), 199–207. https://doi.org/10.4236/ijcns.2017.109011.

[27] Umoh, V. B., Ubom, E. A., Umoh, J. B., and Ekpe, U. M. (2021). A Framework for a User-Centric Determination of Mobile Broadband Performance in Nigeria. 2021 1st International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS), 1–5.

[28] Imoize, A. L., Isabona, J., Lee, C.-C., and Udeji, F. (2023). Optimizing the Quality of Service of Mobile Broadband Networks for a Dense Urban Environment. Future Internet. https://doi.org/10.3390/fi15050181.

[29] Waturu, D. K. (2010). ITU-T Recommendations and other International Standards Relevant to QoS/QoE. Workshop on Delivering Good Quality Telecommunications Service in a Safe Environment in Africa, Nairobi, Kenya.

[30] European Commission. (2012). Quality of Broadband Services in the EU, A Performance Study Report Prepared by SamKnows for the European Commission, 2012. Luxembourg, Europe: SamKnows Ltd, pp. 1-106.

[31] Richard, H. (2012). Overview of Quality of Service (QoS): APT-ITU workshop on the International Telecommunications Regulations. APT-ITU workshop on the International Telecommunications Regulations, Bangkok.

[32] Jean-Claude, F. (2022). Data Communication and Networks. Computer Science Department Courant Institute of Mathematical Sciences. https://cs.nyu.edu/~jcf/classes/CSCI-GA.2262-001/handouts/Homework2Solutions.pdf

[33] Teltonika. (2024). What Do RSSI and RSRP Mean in Your Network Setup? https://teltonika-networks.com/newsroom/what-do-rssi-rsrp-mean-in-your-network-setup

[34] Figueiras, J., and Frattasi, S. (2011). Mobile Positioning and Tracking: From Conventional to Cooperative Techniques. Wiley.

[35] Sawyer, S. (2017). Analysis of Variance: The Fundamental Concepts. The Journal of Manual and Manipulative Therapy, 17(2), 27–38. https://doi.org/DOI: 10.1179/jmt.2009.17.2.27E

[36] NBS. (2024). Telecoms Data: Active Voice and Internet, Porting and Tariff Information (Q1, 2024) (pp. 1–11).

[37] Ilya, G. (2013). High Performance Browser Networking: What Every Web Developer Should Know about Networking and Web Performance. (Courtney Nash, Ed.) (1st ed.), Sebastopol, USA: O'Reilly Media, Inc.

[38] Sundaresan, S., Teixeira, R., Feamster, N., Pescapè, A., Crawford, S. and De Donato, W. (2011). Broadband Internet Performance: A View from the Gateway. In Proceedings of the ACM SIGCOMM 2011 Conference, Vol. 41, No. 4, pp. 134–145.

[39] Feamster, N. 2014. "BISMark: A Broadband Internet Service Benchmark." March 21, 2014. https://devpost.com/software/bismark-a-broadband-internet-service-benchmark.

[40] Grigorik, I. (2013). 1. Primer on Latency and Bandwidth: High Performance Browser Networking. Sebastopol: O'Reilly Media Inc. Retrieved April 2, 2017, from

https://www.safaribooksonline.com/library/view/high-performancebrowser/9781449344757/

[41] Sundaresan, S., De Donato, W., Feamster, N., Teixeira, R., Crawford, S., and Pescapè, A. (2012). Measuring Home Broadband Performance. Communications of the ACM, Vol. 55, Issue 11, pp. 100–109. ACM New York, NY, USA: ACM Press.

[42] DigiCert. (2024). DNS Performance Analytics and Comparison. DNSPerf. Retrieved April 5, 2020, from https://www.dnsperf.com.

[43] Akinlabi, A., Dahunsi, F., Popoola, J., and Okegbemi, L. (2025). Real-time mobile broadband quality of service prediction using AI-driven customer-centric approach. Advances in Computing and Engineering, 5(1), 1-19. doi:https://dx.doi.org/10.21622/ACE.2025.05.1.1332.