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Performance Test of Spacex's Starlink: An Empirical Review

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Starlink, Internet Connectivity, Low Earth Orbit (LEO), Satellite Constellations, Network Performance.

Abstract: In recent years, there has been significant interest in the deployment of Low Earth Orbit (LEO) satellite constellations as a potential solution to provide broadband internet access to remote regions [1]. One such constellation, Starlink, run by SpaceX, promises fast internet connectivity via its constellation of satellites in low Earth orbit. In this study, a comprehensive analysis of Starlink's performance in Nigeria was given, assessing five performance metrics: latency, packet loss, throughput, routing strategy, and environmental influences. The tests were conducted for the various metrics using command-line tools like Ping (Packet Internet or Inter-Network Groper), tracert (traceroute), iperf3 (Internet Performance Working Group), and Python scripts which were used to both automating the test procedures and analysing the collected data. Our findings reveal that Starlink's latency was higher than advertised but still low compared to most Mobile Network Operators (MNOs) in Nigeria, making it suitable for the majority of internet users. On average, the study found that packet loss remained relatively low, jitter was within acceptable limits, and throughput exhibited variations but generally maintained satisfactory levels. Also, heavy rainfall was found to affect Starlink's performance, highlighting the impact of environmental factors.

1. Introduction

Access to high-speed internet has become more crucial for economic development, education, healthcare, and social connectivity in the 21st century [2]. However, typical broadband infrastructure often fails to reach remote and underdeveloped areas, leaving billions of people without dependable internet access [3, 4]. One of the initiatives that has

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attracted significant interest is Starlink, SpaceX's project aimed at providing global high-speed internet coverage through a constellation of Low Earth Orbit (LEO) satellites [4]. Initially deployed on May 23rd, 2019, Starlink aims to use its deployment of thousands of satellites, establishing a LSN (Low Earth Orbit Satellite Network) constellation, to provide worldwide coverage and foster the possibility of 6G networking [5].

In the 90s and early 2000s, internet connectivity was established by modems that were connected to telephone lines, necessitating a dial-up connection [6]. Since then, various technological advancements have been introduced and utilised to enhance internet connectivity and performance [7]. These include Digital Subscriber Line (DSL), fibre optics, satellite, and broadband over power lines. SpaceX's Starlink represents one of the most advanced and recent technologies for internet service. Its latest version, v2.0 includes optical inter-satellite links (ISLs) for communication between satellites, allowing for data transfer rates up to 20 Gbps full duplex, eliminating the need for ground stations, and offering better performance, faster data transfer speeds, and lower operating costs [5, 8]. Starlink v1.0 differs significantly from v2.0 in that it employs a bent-pipe strategy [8], where a LEO satellite transfers traffic to a Ground Station (GS) for additional routing [9], involving a single hop and only including the nearest GS before transitioning to the terrestrial network.

Novelty of the Study: This paper addresses a significant research gap by benchmarking Starlink's performance specifically for Mobile Network Operators (MNOs) in Nigeria, a context that has not been extensively examined. This study aims to offer a thorough empirical evaluation of Starlink's service in Nigeria, determining whether it fulfils its promises and meets the expectations of users in this region.

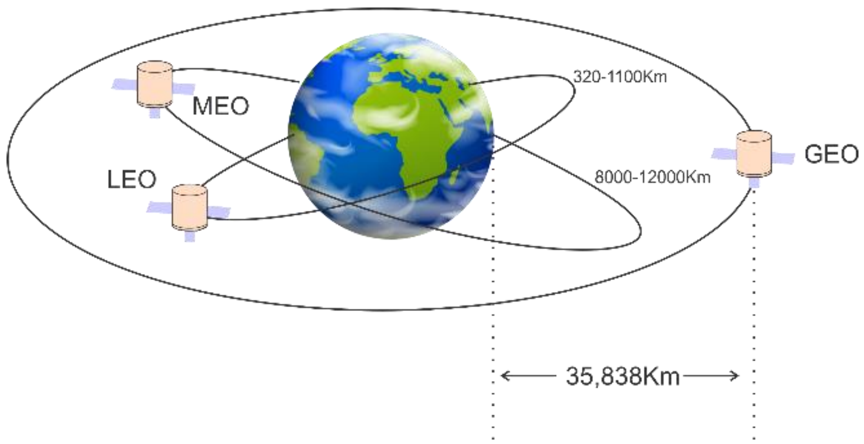


Figure 1: Satellite Constellations   Source: Author

2. Related work

Prior to LEO, satellites in Geostationary Equatorial Orbit (GEO) (as shown in Figure 1) were considered best for satellite internet provision due to their wider coverage area, and relatively stable and consistent communication links. However, performance tests of GEO internet connections exposed the problem of higher latency due to their high altitude [10]. This led to a shift in Satellite Network Operators (SNOs) towards LEO, as it tends to improve latency due to its shorter distance to the earth [11, 12]. Performance tests on Low Earth Orbit Satellite Networks (LEO SNOs), using Starlink as a reference, have been conducted using simulators. These tests primarily focus on physical layer behaviour and influential factors for countries such as the USA, Canada, and Belgium. Multiple studies have conducted an analysis of Starlink's satellite internet service by utilising real-world measurements and data collection. Michel et al. [13] conducted early research on Starlink's internet performance, comparing a Starlink user terminal, vs university fibre optics campus network vs a geostationary satellite internet connection (SatCom). Their findings showed Starlink's low latency of around 40ms and superior TCP throughput compared to SatCom, with averages of 178 Mbps and 20 Mbps respectively. Starlink also demonstrated faster web browsing with an average onLoad time of 167ms. The study emphasised the need for broader observations to assess Starlink's global performance comprehensively. They used a custom measurement platform for active measurements, employing the QUIC protocol for latency and throughput assessments. Packet loss and throughput were measured using Ookla SpeedTest, and web browsing performance was evaluated based on Load time and SpeedIndex time of popular websites.

Kaseem et al. [14] analysed Starlink's internet connection using browser extensions and dedicated measurement nodes. They gathered data from 28 users in 10 cities worldwide, including 18 Starlink users in the UK, measuring Page Load Time (PLT), latency, internet speed, throughput, and packet loss. The study revealed lower latencies for Starlink users but identified packet loss clusters during satellite handovers and noted performance variations due to weather conditions. To supplement browser extension data, volunteer measurement nodes were deployed, using Raspberry Pi connected to Starlink receivers for continuous network tests every 5 minutes. This comprehensive approach provided insights into Starlink's performance across different locations while addressing data collection limitations. Raman et al. [15] conducted a comprehensive study comparing Satellite Network Operators (SNOs), focusing on Starlink's technology versus LEO, MEO (Medium Earth Orbit), and GEO networks. They found that LEO networks like Starlink have higher throughput and lower latencies but exhibit higher jitter. GEO networks face data retransmission issues requiring Performance Enhancement Proxies (PEPs). The study utilised diverse data sources like M-Lab's SpeedTest for analysis, incorporating metrics like round-trip time (RTT) and jitter. To identify the different Satellite Network Operators (SNOs), Autonomous System Number (ASN) information was used due to limitations in the dataset. Their methodology combined public datasets, crowdsourcing, and traceroute measurements to analyse LEO satellite network performance and address data reliability and operator identification challenges.

Ma et al. [16] provides detailed insights into Starlink's performance, including latency, throughput, routing strategy, and environmental impacts. They found slightly higher latency compared to terrestrial networks but achieved a good average throughput of 80Mbps. Environmental conditions like obstacles affected performance, highlighting sensitivity to obstructions. The study also discussed potential upgrades and Starlink's application in motion, such as in recreational vehicles (RVs). The researchers employed various tools and methods, including iperf3 for throughput measurements and ping/traceroute for network characteristics. They automated data collection and measurements using Python scripts in their study.

Mohan et al. [17] extensively analysed Starlink's performance using diverse measurement sources and publicly available data. They measured latency between global Points of Presence (PoPs) and Starlink ground stations (GSs) using RIPE Atlas probes, and crowdsourced geolocation data for GSs and PoPs. Additionally, they evaluated the impact of Starlink's bent-pipe operations on network performance, focusing on ground station deployment and satellite availability. Their study presented a global view of Starlink's last-mile performance analysis, illustrating latency between GSs and PoPs on a world map grouped by country. In summary, the collective body of research on Starlink's performance compared to traditional satellite internet technologies (GEO SNOs) reveals both advancements and limitations in satellite internet technology. These studies utilise real-world measurements, user data, and innovative approaches to explore various aspects of Starlink's performance, including latency, throughput, web browsing experience, and environmental factors. The findings highlight Starlink's potential for improved performance in terms of lower latencies, faster throughputs, and enhanced web browsing experiences, despite some unpredictability and susceptibility to external variables like satellite handovers and obstacles. These studies emphasise the need to assess Starlink's performance from multiple perspectives, considering factors such as its performance in different locations, user perspectives, and technological advancements, which collectively contribute to ongoing efforts to enhance satellite network capabilities and user experiences.

Rajiullah et al. [18] conducted a comparative test between a 5G Non-Public Network (NPN) in Karlstad and the Starlink network. Using Ookla's Speedtest, they assessed the throughput of the Starlink network by connecting to a server at the Swedish University Network (SUNET) using TCP multiple flow. Latency was measured using ping and the ICMP protocol. A modem named Cradlepoint-C17 was used for the 5G network test, incorporating Speedtest and ping. Additionally, the study conducted Netperf throughput tests on all four Cradlepoint modems in their 5G deployment at 30-minute intervals. This paper significantly contributes to the research on integrating 5G and LEO satellite systems. The testbed facilitates thorough empirical evaluations, promoting the development of use cases that integrate different technologies. Future research will explore other integration possibilities and performance enhancements.

In summary, the collective body of research on Starlink's performance compared to traditional satellite internet technologies (GEO SNOs) reveals both advancements and limitations in satellite internet technology. The findings highlight Starlink's potential for improved performance in terms of lower latencies, faster throughputs, and enhanced web browsing experiences, despite some unpredictability and susceptibility to external variables like satellite handovers and obstacles. These studies emphasise the need to assess Starlink's performance from multiple perspectives, considering factors such as its performance in different locations, user perspectives, and technological advancements, which collectively contribute to ongoing efforts to enhance satellite network capabilities and user experiences.

3. Methods and tools

3.1 Starlink User Terminal

A Starlink user terminal was installed and configured at the testing location to establish the connection with Starlink's satellite network. A view of the Starlink equipment can be seen in Figure 2.

Figure 2: Starlink Equipment

3.2 User PC

A standard PC was connected to the Starlink user terminal to simulate real-world user interaction and data transfer scenarios.

3.3 Starlink Device Review

Starlink consists of four major components: the Starlink satellite constellation (shown in Figure 3), the Ground station, Dishy (informal name for Starlink User Terminal) and the Router. There are currently about 5650 Starlink satellites which have been launched into the LEO [19], moving at an average speed of 27000 km/hr. For global coverage, it is predicted that Starlink requires over 10000 satellites of which more are launched at regular intervals and as at the time of writing, the most recent launch was on 17th April 2024 where 23 satellites were deployed [20]. Communication between the Dishy and satellite stations implement phase array technology in steering the beams for precise connection in the Ku and Ka bands as it would be impossible to mechanically steer the dish without initiating a mechanical failure [21]. Bent-pipe relay strategy is currently used for data transfer between the Dishy ground station (shown in Figure 4) and the satellite constellation causing reliance on ground stations [21]. Advancement on Starlink constellation as implemented in the recent version 2 of her satellite, has laser technology built for inter-communication in space thereby limiting the dependence on the ground station [22].

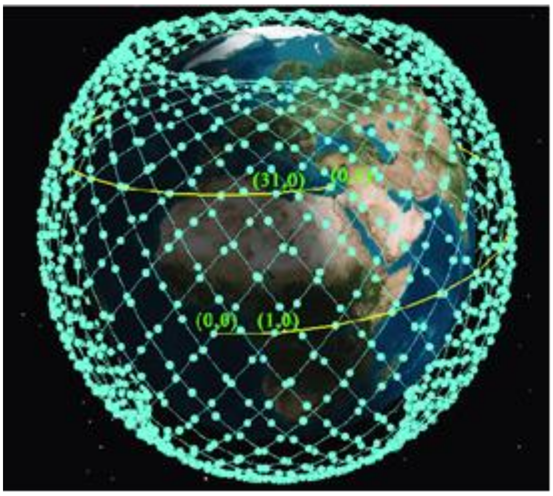


Figure 3: Starlink Satellite Constellations [28]

Starlink ground station or gateway provides the actual connection to the internet. Built to communicate directly with the satellite and earth fibre optic internet, it is required that the user of Starlink is located at least 100 km from the gateway. In Nigeria, as at the time of writing, there are two active gateways: one at Lekki (Lagos State) and another at Osun state [23].

Figure 4: Starlink Ground station [29]

3.4 Measurement Topology and Environment

Measurement for this project began in March 2023 and continued through February 2024, totalling twelve months of testing conducted at the University of Benin in Benin City, Nigeria. The choice of Benin City is significant as it provides insight into Starlink's performance in less saturated areas compared to larger Nigerian cities like Lagos and Abuja. A second generation (Gen 2) Starlink kit was set up, and performance tests were carried out using six parameters: (a) Latency, (b) Packet Loss, (c) Throughput, (d) Jitter, (e) Routing Strategy, and (f) Environmental Influence. These tests were conducted primarily through the

Command Prompt using HP Core i5 and Dell Core i5 laptops running Windows 10. A virtual server was set up on the HP Core i5 laptop via Hyper-V Manager for the throughput test.

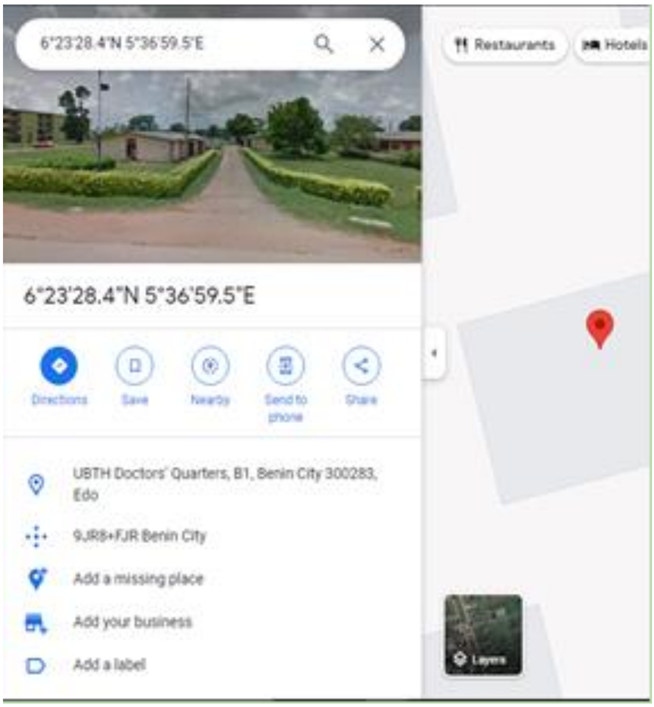


Figure 5: Test Location

3.5 Target Applications and Measurement Tools

Our latency and packet loss measurements were conducted using the 'ping' command, which operates in the network layer of the OSI model to check the availability and responsiveness of the IP address. Latency is determined by the time it takes to receive a response, while packet loss is also recorded, as shown in Figure 6

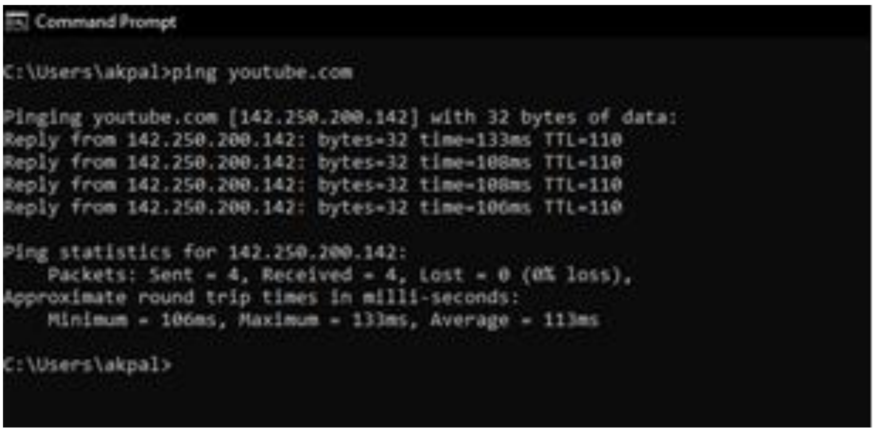


Figure 6: Ping Command

IPerf3 measures the TCP and UDP throughput in the transport layer. This was done by creating a virtual server using Hyper-V and sending 60 packets of data from the client system to the virtual server. Tracert, which functions at the network layer (Layer 3) of the

OSI model, was used to obtain the routing strategy of the network. This resulted in identifying the hops that were communicated with while travelling to the destination.

4. Results

The tests conducted on Starlink ISP in the Nigerian environment, evaluated various parameters such as latency, throughput, packet loss, environmental influences, routing strategy, and jitter. The tests were conducted for a period of one year, from the 1st of March 2023 to the 14th of March 2024. The results are presented in subsequent sections, providing insight into Starlink ISP's operational capabilities and potential areas for development.

4.1 Latency

The latency tests conducted during this study revealed that overall average latency was 119.56ms with the graph plotted in Figure 7. These tests were performed on several popular websites, including Facebook, YouTube, Twitter, Google, and Instagram, with servers located in the United Kingdom and the United States. Figure 6 illustrates the ping test results for YouTube as a sample example.

The calculated latency statistics over the one-year period are:

- Overall Average Latency: 119.56ms
- Maximum Latency: 162ms
- Minimum Latency: 102.85ms.

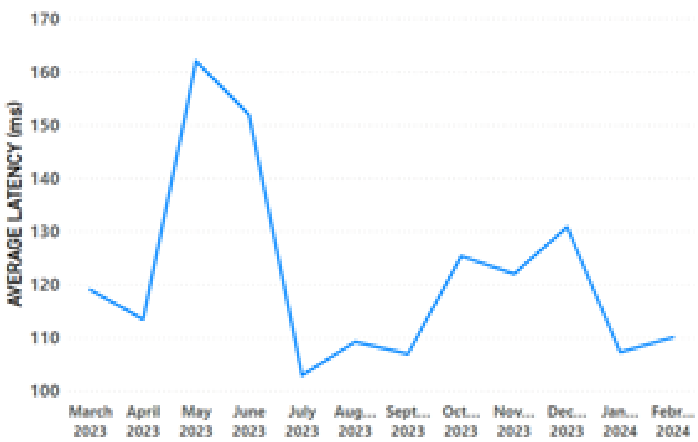


Figure 7: Monthly Latency Over 12 Months

The highest recorded latency was 162ms on the 3rd of March and the lowest at approximately 102.85ms on the 5th of March. This range suggests some variability in the network performance, with some months experiencing significantly higher latencies which could impact user experience. It should be noted that the measured values for latency differ from those advertised by Starlink as shown in Figure 8

Expected speeds per service plan:

SERVICE PLAN	STANDARD (FIXED)
AVAILABILITY	≥99%
DOWNLOAD	25-100 Mbps
UPLOAD	5-10 Mbps
LATENCY*	25-60 ms

Figure 8: Network Latency as Advertised by Starlink

Lower latency is preferred for better network performance. For example, in online gaming or real-time applications, latency should ideally be below 50ms for a smooth user experience [24, 25]. The latency which was measured to average 119.56ms is well over the 50ms recommendation, so there is bound to be some lag in low latency demanding tasks. However, this latency is better than most Mobile Network Operators (MNOs) in Nigeria. Popular MNOs like MTN and Airtel have measured average latencies of 122.49ms and 136.68ms, respectively, on their 4G networks [26]

4.2 Jitter

Jitter is the average delay time between packets' arrival. In other words, jitter refers to the variation in latency. To evaluate the jitter, we calculated the average time difference between the monthly latency values. The monthly average latency calculated over the one-year period and the absolute time difference can be shown in Table1. As can be seen from Table 1, the average Jitter measured from Starlink was an average of 24.83ms. Low jitter is essential to prevent packet loss and ensure stable communication. In scenarios like video conferencing or VoIP calls, jitter should be below 30 milliseconds to avoid disruptions [27]

4.3 Packet Loss

Packet loss occurs when one or more packets of data travelling across a computer network fail to reach their destination. This can happen due to various reasons such as network congestion, faulty hardware, or signal interference. Packet loss has several implications on network performance which include Reduced throughput, increased latency, poor quality of service and reduced reliability. From the numerous tests taken over the twelve months period, the packet loss can be shown statistically in Table 2.

Table 1: Statistical Evaluation of Jitter

DATE	Latency (ms)	Variation
March 2023	119.03	119.03
April 2023	113.40	5.63
May 2023	162.00	48.6
June 2023	151.83	10.17
July 2023	102.85	48.98
August 2023	109.23	6.38
September 2023	106.93	2.3
October 2023	125.31	18.38
November 2023	121.94	3.37
December 2023	130.78	8.84
January 2024	107.27	23.51
February 2024	110.06	2.79
AVERAGE		**24.83**

Table 2: Statistical Summary of Packet Loss Data

Statistic	Value (%)
Mean	0.6027
Standard Deviation	0.5179
Minimum	0.1333
25%	0.2187
50%	0.3750
75%	0.8408
Maximum	1.8462

This statistical summary shows the average, minimum and maximum packet loss over time. The average packet loss over the recorded period is approximately 0.60%. The standard deviation is about 0.52%, indicating some variability in packet loss from month to month. The maximum recorded packet loss is still quite low at approximately 1.85%, which does not significantly impact network performance, especially for real-time applications. Minimal packet loss is vital for data integrity and efficient transmission. Ideally, packet loss should be less than 1% to maintain a reliable network connection and prevent issues like dropped calls or slow page loading. As such, Starlink meets the requirement of minimal packet loss. A plot visualising the packet loss over time is shown in Figure 9

4.4 Throughput

Throughput is a measure of the volume of traffic a network can handle, usually expressed in terms of data bits per second. Network throughput refers to the overall data transfer rate within a network, while upload (UL) and download (DL) throughput specifically measure the data transfer rates for sending and receiving data, respectively. We utilised iperf3 (a command line tool for performing network throughput measurements) to conduct a series of network evaluations and simulations between two interconnected nodes, actively engaging in communication, to estimate the maximum achievable network throughput of the infrastructure. Additionally, we carried out random upload and download throughput tests using sites like Fast and Ookla Speed Test. The upload and download throughput we recorded reached as high as (8.5Mbps -27Mbps) upload and over (20Mbps - 300Mbps) download, respectively, which is still much better than most MNOs in Nigeria. For instance, most MNOs have average download throughputs ranging from 1.56Mbps to 18.01Mbps, and upload throughputs ranging from 4.63Mbps to 17.49Mbps on 4G Network [26]. The network throughput measured using iperf3 is illustrated in Figure 10 which shows the maximum achievable throughput between point-to-point connections but does not show speed test.

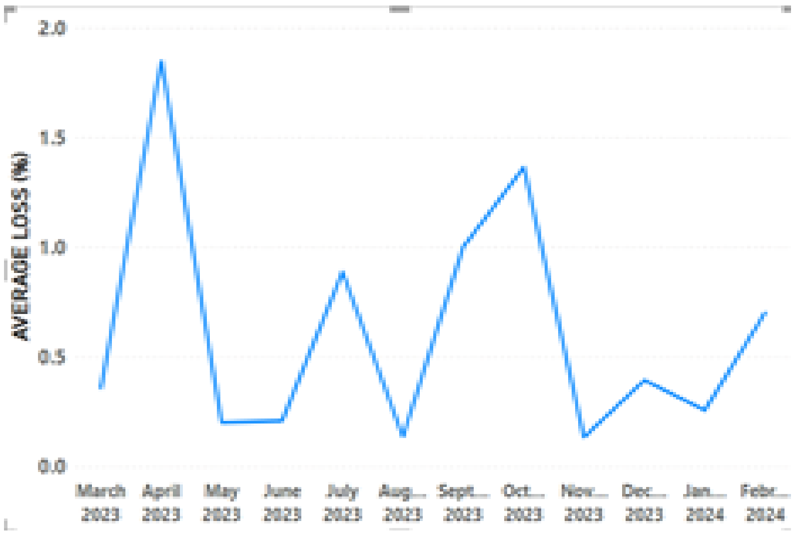


Figure 9: Monthly Packet Loss Over Twelve Months

Figure 10: Monthly Network Throughput Over Twelve Months

This graph shows the fluctuations in monthly network throughput values. The overall average throughput is shown to be: 939.93Mbps. The network throughput varies significantly over the period, with a maximum of approximately 1.091Gbps and a minimum of around 683Mbps. The variability indicates that the network throughput is not consistent, which could affect performance depending on the network load and other factors.

4.5 Routing Strategy

The Routing Strategy entails identifying the most efficient and optimal paths for data packets to travel from their source to their destination. Our testing reveals that Starlink networking typically traverses multiple servers to reach the final destination, often passing through two servers located in Lagos, Nigeria as illustrated in Figure 11.

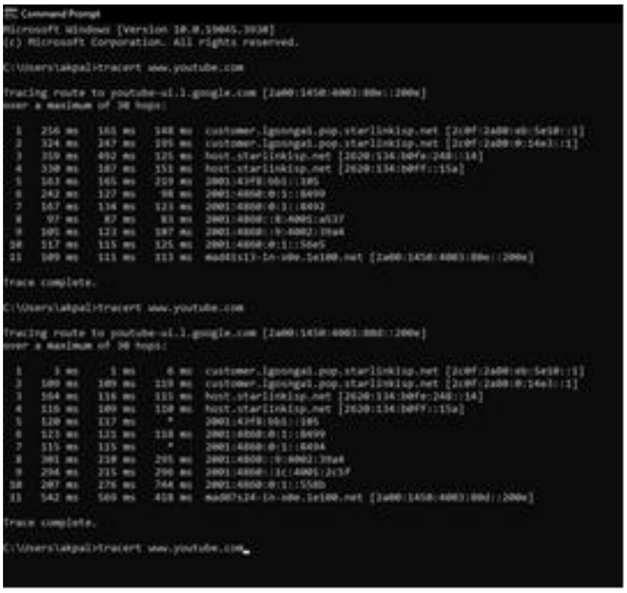


Figure 11: Routing Strategy Results

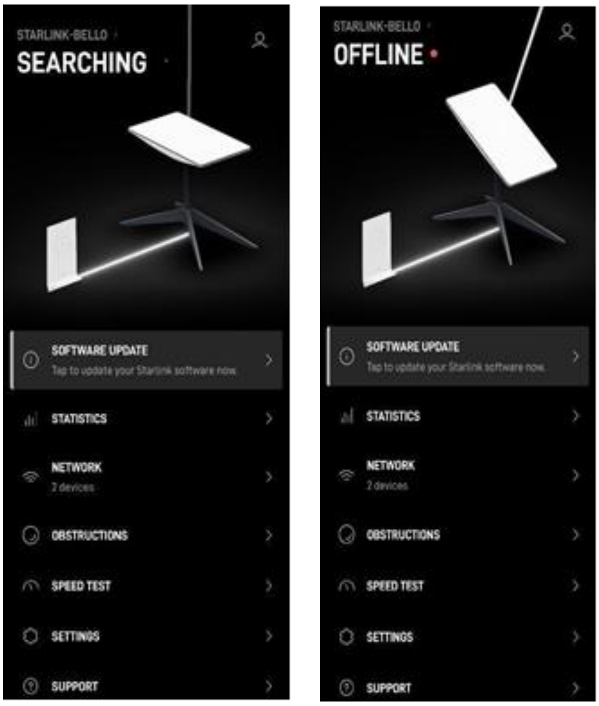
Using ipaddress.com, we were able to find the location of the other servers it went through. This is illustrated in table 3 below.

Table 3: Locations of IP Addresses in YouTube's Routing Path

IP ADDRESS	Location
2c0f:fb50:4002:808::200e	Kenya
2c0f:2a80:f:c910::1	Lagos
2c0f:2a80:0:1762::1	Lagos
2620:134:b0fe:248::56	United States
2620:134:b0ff::156	United States
2001:43f8:bb1::105	Nigeria
2001:4860:0:1::8499	United States
2001:4860:0:1::8492	United States
2001:4860::9:4003:518	United States
2001:4860:0:1::801d	United States
2001:4860:0:1::750b	United States
2c0f:fb50:4002:808::200e	Kenya

4.6 Environmental Influences

The Starlink connection was evaluated during rainfall. During light rainfall or drizzle, there was no apparent disruption in the internet connection. However, it was noted that heavy rainfall resulted in prolonged service downtime and internet disconnection, as the rainfall caused an obstruction in the Dishy's connection with the satellites in orbit. Figures 12(a) and 12(b) showcase the connectivity as perceived from the Starlink mobile app during heavy rainfall.



(a) (b)

Figure 12: Effect of Heavy Rainfall on Starlink Connectivity

5. Discussion/Conclusion

This paper presents an empirical analysis of Starlink's performance in Nigeria, focusing on latency, throughput, and packet loss. The findings indicate that Starlink is a viable alternative to traditional Mobile Network Operators (MNOs) in the region. With an average latency of 119.56ms, Starlink is well-suited for latency-sensitive applications, outperforming popular MNOs having latency as high as 243.43ms [26]. Packet loss was minimal at 0.60%, indicating strong data integrity.

Network throughput analysis revealed peaks up to 1.091Gbps using iperf3 software, with upload and download speeds reaching 26.7Mbps and over 300Mbps using fast and Ookla Speed Test, respectively. These figures surpass the typical performance of MNOs, which offer download speeds between 1.56Mbps and 18.01Mbps, and upload speeds between 4.63Mbps and 17.49Mbps [26]. However, connectivity was impacted by heavy rainfall, suggesting environmental factors should be considered in satellite internet performance.

Abbreviations

GEO	Geosynchronous Equatorial Orbit
GS	Ground Station
ISPs	Internet Service Providers
LEO	Low Earth Orbit
LSN	Low Earth Orbit Satellite Network
MEO	Middle Earth Orbit
MNOs	Mobile Network Operators.
PEP	Performance Enhancement Proxies
PLT	Page Load Time.
PoP	Point of Presence
RTT	Round Trip Time.
SNO	Satellite Network Operator
TCP	Transmission Control Protocol
UDP	User Datagram Protocol

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