***AKSU Journal of Engineering and Technology*, 2026**
Vol. 1, No. 1, Pages 1-16
Published Online April 2026 in AKSUJET (http://www.aksujet.org   ISBN:978-978-53006-97

Etim, Edayeobong R[1]
Department of Electrical and Electronic Engineering
Akwa Ibom State University, Ikot Akpaden, Nigeria
raphetim@gmail.com

Ekpe, Unwana M[2]
Department of Electrical and Electronic Engineering
Akwa Ibom State University, Ikot Akpaden, Nigeria
unwanaekpe@aksu.edu.ng

Johnson, Enyenihi H[3]
Department of Electrical and Electronic Engineering,
Akwa Ibom State University, Ikot Akpaden, Nigeria;
enyenihijohnson@aksu.edu.ng

Corresponding author's email: ralphetim@gmail.com. +2348081133169

Satellite-Enabled 6G Networks: Bridging the Digital Divide in Hard-to-Reach Areas of Nigeria

ABSTRACT

In the face of Nigeria's expeditious urban digital growth, many rural and remote communities remain isolated from communication services. This paper analyzes how satellite-enabled sixth generation (6G) networks can revolutionize connectivity in Nigeria's hard-to-reach areas. These are rural areas and settlements in the Niger Delta, the Chad Basin, and mountainous areas bordering the Republic of Cameroun, where terrestrial cellular and cable-based networks do not currently provide service due to difficulties in installing ground-based telecommunications infrastructure. The paper examines the current satellite initiatives, especially how Geostationary (GEO) and Low Earth Orbit (LEO) satellite constellations can complement terrestrial networks using enabling technologies and policy frameworks to offer a roadmap for all-inclusive connectivity. This study employs a quantitative engineering approach to evaluate the role of satellite communication systems in extending mobile connectivity to hard-to-reach areas in Nigeria, with a focus on 6G integration. The key parameters to ensure ubiquitous 6G coverage are embedded in the link budget analysis. Using MATLAB and Excel-based modeling, satellite visibility, slant path geometry, and achievable throughput for GEO and LEO systems are examined. Four satellites (NigComSat-1R, Echostar 16, Astra 1A, and Echostar 6) were confirmed to be visible from the Niger Delta region, with Uyo, taken as a representative city. The elevation angles of the satellites ranged from 38.0° to 46.5° and the slant path distances were between 40,987.12 km and 41,550.88 km. NigComSat-1R's C-band service yielded downlink/uplink C/N ratios of 20.36 dB and 24.61 dB respectively, enabling Internet of Things (IoT) data rates of 134–266 kbps (DL) and 6.0–10.05 kbps (UL). In contrast, LEO-based Ku-band OneWeb services achieved 140–880 Mbps, validating their potential for community backhaul. The study affirms satellite integration as a technically viable solution for ubiquitous mobile coverage in 6G networks.

KEYWORDS: *6G, GEO, LEO, IoT, Non-terrestrial Networks, Satellite Communication.*

1. INTRODUCTION

Africa's most populous nation, Nigeria, faces a serious digital divide. While the urban centers enjoy expanding broadband access, rural and hard-to-reach areas struggle with limited and poor connectivity [1], [2]. The increasing demand for high-speed, reliable, and ubiquitous mobile communication has exposed the limitations of traditional terrestrial infrastructure, especially in regions with difficult terrain and low population density, where it may be economically unfeasible to deploy ground-based stations [3]. The emerging 6G framework emphasizes the inclusion of non-terrestrial networks (NTNs) to complement terrestrial infrastructure, and satellite-enabled platforms can meet this demand as they have been shown to achieve very wide coverage, relatively low latency, and appreciable throughput [3], [4]. This paper presents an analysis of satellite-based systems for enhancing connectivity in Nigeria's underserved areas, reflecting the need to urgently close the digital divide in the country.

2. THEORETICAL BACKGROUND AND REVIEW OF RELATED WORKS

Nigeria's digital divide is created by geography, income and infrastructure [1], [2]. According to the Nigerian Communications Commission (NCC), broadband penetration stood at 48.81% as of mid-2025, with rural areas lagging significantly behind [5]. The following sections provide an overview of the evolution of mobile communication systems, discusses how satellite networks are being integrated into terrestrial networks, and reviews some enabling technologies that make the integration possible before the review of some related works.

2.1. MOBILE COMMUNICATIONS: FROM 1G TO 6G

The evolution of mobile technology spans six generations. From the analogue first generation (1G) systems of the 1970s, each generation has introduced groundbreaking features. For example, second generation (2G) systems was anchored by the Global System for Mobile (GSM) communications technology. It ushered in digital services such as Short Message Services (SMS) and Multimedia Services (MMS). The third generation (3G) brought about mobile broadband capabilities based on the Wideband Code Division Multiple Access (WCDMA) and High Speed Packet Access (HSPA) technologies. The main fourth generation (4G) technology was the Long Term Evolution (LTE) and its advanced iteration, LTE-A. These technologies have significantly improved the throughput and latency capabilities of 3G, and the fifth generation (5G) promises even higher capabilities in terms of enhanced mobile broadband (eMBB), ultra-reliable and low-latency communications (URLLC), and massive machine-type communications (mMTC) [6]. The sixth generation (6G) is expected to build on present capabilities by integrating satellite and terrestrial systems for ubiquitous coverage.

2.2. SATELLITE COMMUNICATIONS NETWORKS IN NIGERIA

Satellites in Low Earth Orbit (LEO), Medium Earth Orbit (MEO), and Geostationary Earth Orbit (GEO) facilitate navigation, weather forecasting, and global communication. Nigeria's major satellite communication infrastructure is the NigComSat-1R, which is a GEO satellite with C-band and Ku-band transponders. A recent partnership between Eutelsat and the Nigerian Communications Satellite (NigComSat) Ltd aims to leverage on the OneWeb LEO constellation to deliver high-speed low-latency connectivity across the country [7]. The main frequency bands used in satellite communications are shown in Table 1, while Figure 1 shows a typical non-terrestrial communication network with space, air, and ground components [8]. The space-borne components are satellites in GEO and non-geosynchronous orbits (NGSO), while the air-borne platforms can be unmanned aerial vehicles (UAVs) or high altitude platforms (HAPs). The satellites can either be of the regenerative type, whereby digital signal process is carried out onboard the satellite, or of the bent-pipe (transparent) architecture. Both architectures are capable of supporting the next generation radio access network (NG-RAN).

TABLE 1: FREQUENCY BANDS FOR SATELLITE COMMUNICATIONS

Frequency Band	Downlink (GHz)	Uplink (GHz)
L	1.53–1.559	1.6265–1.6605
S	2.50–2.655	2.655–2.69
C	3.40–4.20	4.50–4.80; 5.725–7.075
X	7.25–7.75	7.90–8.40
Ku	10.70–12.75	12.75–13.25; 14.0–14.8
K	18.1–21.2	17.3–18.1
Ka/Q/V	37.5–40.5	27.0–31.0; 42.5–43.5; 47.2–50.2; 50.4–51.5

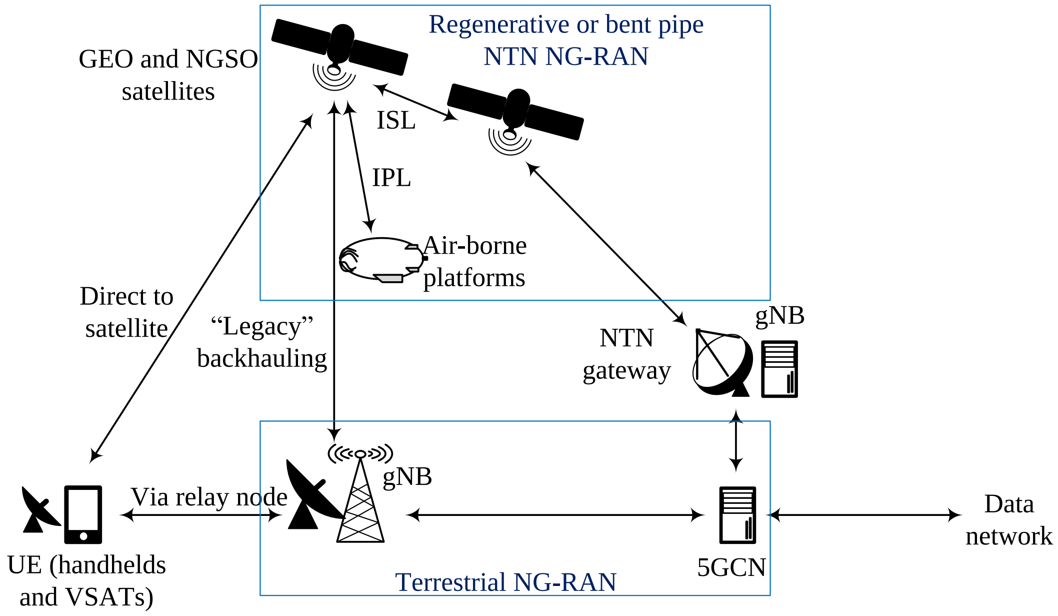


Figure 1: A non-terrestrial network showing space, air, and ground components [8]

2.3. INTEGRATION OF MOBILE AND SATELLITE SYSTEMS FOR 6G COMMUNICATIONS

The integration of non-terrestrial satellite and mobile terrestrial networks is central to 6G's vision and this is expected to deliver ultra-fast speeds, low latency and ubiquitous connectivity.

This will enable applications such as autonomous vehicles, holographic communications, and high-fidelity virtual reality [10]. Figure 2 depicts a

The ensuing hybrid networks would employ GEO satellites for wide coverage and LEO constellations for low latency while artificial intelligence (AI), edge computing, reconfigurable intelligent surfaces (RIS), and other enabling technologies would be leveraged to enable the networks to reach areas beyond traditional terrestrial network coverage [9]. multilayered integrated satellite-aerial-terrestrial RIS-empowered communication system [9].

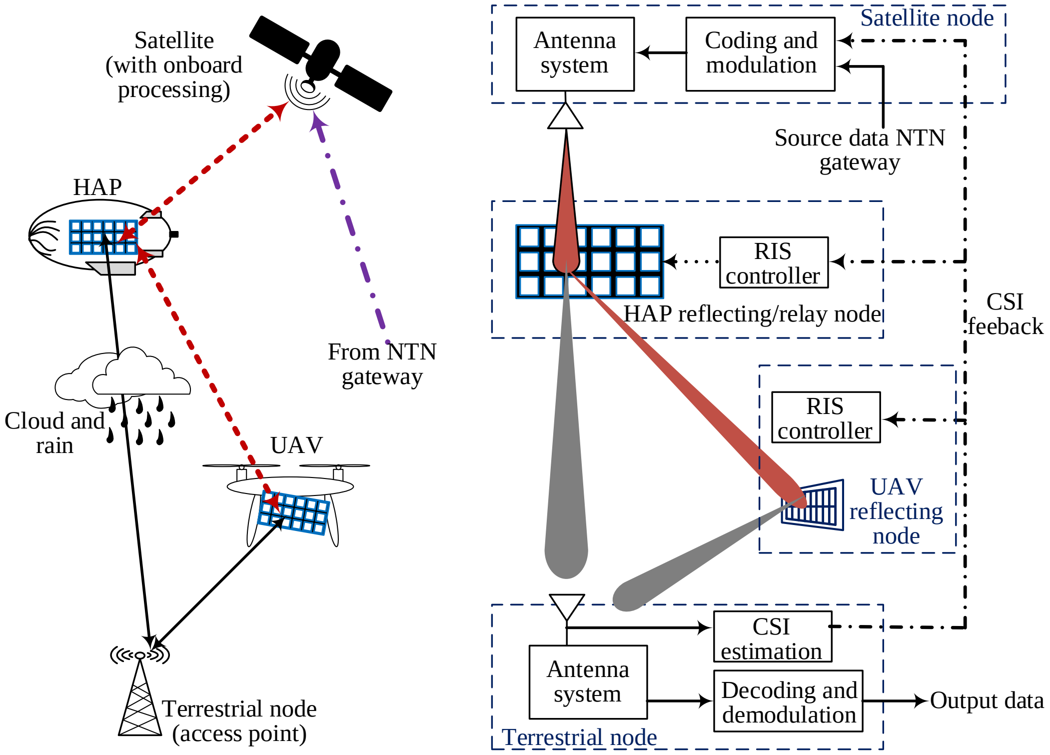


Figure 2: Integrated satellite-aerial-terrestrial RIS-empowered communication system pictorial and block diagram [9]

2.4 HARD-TO-REACH AREAS

Over 40% of the global population resides in rural or remote areas with limited or poor mobile coverage [11]. In Nigeria, some of such remote locations fall under the category of hard-to-reach areas, and examples can be found in the Niger Delta, the Chad Basin, and the mountainous areas bordering the Republic of Cameroun. These locations are mainly characterized by difficult geography and challenging terrain. In addition, some of the hard-to-reach areas are plagued with security concerns due to banditry and insurgency [12], high telecommunications infrastructure deployment costs, and a projected low returns on investments due to sparse population and low purchasing power of the locals. Where terrestrial mobile communications connectivity exists, service has been reported to be intermittent, unreliable, and unsatisfactory [13].

Fortunately, satellite networks can bridge the connectivity gap in hard-to-reach areas but face challenges such as high deployment cost of satellite infrastructure alongside high latency and spectrum congestion. This is especially the case for GEO-based systems. However, a viable solution to bridging the coverage gap is by integrating satellites into existing terrestrial networks [3], [14]. Some of the key enabling technologies for the convergence of terrestrial and non-terrestrial networks include Software Defined Radio (SDR) for flexible signal processing [15], Cognitive Radio (CR) for intelligent spectrum utilization, and Rate-Splitting Multiple Access (RSMA) for interference management and multi-user optimization [16]. Other important technologies include Network Function Virtualization (NFV) for cost-efficient deployment [17], Reconfigurable Intelligent Surfaces (RIS) [9], and massive MIMO [8] for enhanced connectivity.

2.5. RELATED WORKS AND RESEARCH GAPS

This section groups research works that have attempted to solve the hard-to-reach problem into interference management attempts, standardization, enabling technologies, coverage extension, mobility management, and security.

In terms of interference management, it has been identified that integrating satellites into terrestrial communication networks can solve the hard to reach problem. One of the research works that examined this solution is reported in [16]. This paper presented the emergence of RSMA as a powerful multiple access, interference management and multi-user strategy for next generation integrated satellite-terrestrial communication systems. It showed how RSMA can be used to manage interference in a multi-user 6G communications system. It contrasted the numerous benefits RSMA offers against the past generations of multiple access techniques.

Standardization being one of the main enablers for the integration of satellites and terrestrial networks has been extensively discussed in [18]. The paper presents an overview of the role that LEO satellite mega constellations would play in providing ubiquitous internet and communication services in the future. The paper reviews the 3GPP standardization activities for integrating such constellations into the 5G network and gives possible standardization directions for future 6G systems. It also reviews the standardization efforts of organizations other than the 3GPP, and went further to show how LEO satellite networks will provide wide-area coverage and support service availability, continuity and scalability.

There are several enabling technologies that can help address the challenges of hard-to-reach areas.

According to [17], solutions can be provided in terms of increasing service agility, and reducing the operating and capital expenses by leveraging virtualization technology to design, deploy and manage network services. It was shown in [17] that NFV effectively decouples the physical network equipment from the software that run on them. Other emerging enabling technologies that can solve the hard-to-reach problem include SDR, CR and RSMA and it has been shown that these can provide optimal low-cost connectivity solutions [15], [16], and [19].

In order to extend coverage to hard-to-reach areas, [20] looked into how new satellite-based services could be utilized to serve regions where conventional cellular coverage is absent. It discussed collaborative efforts by the Europe, Middle-East and African (EMEA) Satellite Operation Association (ESOA) to promote complementarity between terrestrial and non-terrestrial networks and encouraged the development of coverage-extending solutions. Also, [14] analyzed and discussed the technologies suitable for extending coverage to rural, poor and isolated areas. It highlighted the impact of the choice of technology on the challenges of connectivity in hard-to-reach areas. It also proposed an architecture for future networks, based on the existing solution to eliminate the coverage gap.

For mobility management in IP-based networks, the Internet Engineering Task Force (IETF) has introduced a number of protocols, such as Mobile Internet Protocol version 6 (MIPv6) and Proxy Mobile Internet Protocol version 6 (PMIPv6) [21]. However, such protocols were not designed to deal with the high topology change rate as is common in LEO satellite constellations. A number of approaches have been proposed by [18] to address this problem. Nevertheless, the concept of separating control plane and data plane of Software Defined Network (SDN) is a promising approach to efficiently manage the satellite network topology.

The integration of satellite and terrestrial networks brings unique security challenges due to the different system requirements and the incoherency of their security policies. Therefore, [22] provides insights into some security concerns and provides some potential mitigation techniques. It was noted that the overall integrated system will have a higher degree of vulnerability and face higher security threats if technologies with weak security and loopholes are integrated together. In conclusion, looking at the case studies reviewed in the literature, the related works did not take into cognizance the analyses of Nigerian scenario and this indeed is a research gap that this research work intends to fill.

3. METHODOLOGY

The three standard orbits used by communication satellites are LEO (500 km–1,500 km), MEO (between LEO and GEO), and GEO (35,786 km). NigComSat-IR is in GEO and its orbital slot is at 42.5^{o} E [23]. This gives the satellite an average slant path of 42,164.21 km when viewed from its network control center in Abuja, Nigeria. This study adopts a

Matlab-based modelling approach to uncover important parameters for integrating NigComSat-1R and other GEO satellites into a 6G network to bridge the digital divide in the country. The other GEO satellites used for the comparative analysis include EchoStar 16, located at 61.5°W, Astra, located at 5.2°E, and EchoStar 6, located at 72.7°W [24]. Geospatial computations were conducted in Matlab to evaluate satellite visibility, and compute slant path distances. Link budgets were calculated and validated using ITU-R recommended models.

The study evaluated two primary use cases: GEO-based low data rate for fixed Internet of Things (IoT) services using Inmarsat NB-IoT standard and LEO-based community WiFi backhaul using OneWeb (Ku-band). The OneWeb use case assumes the utilization of flat panel antennas mounted on public or private infrastructure and interfaces with the ground network, with the aim of serving remote communities. The parameters include an orbital altitude of 1200 km, the service link utilizes 11.7GHz in the downlink and 14.5GHz for the uplink, and the satellites carry regenerative payloads [20]. The study area was Nigeria's territorial space, with Uyo (Latitude: 5.024295°, Longitude: 7.872312°) used as the ground station reference point. Figure 3 shows the geometry of a GEO satellite.

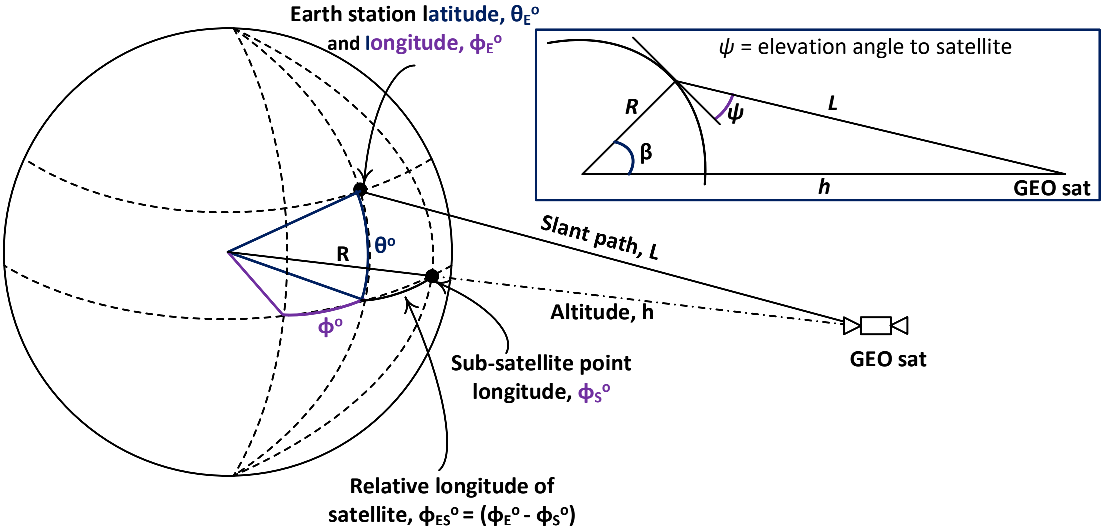


Figure 3: Geometry of a GEO satellite [25]

As can be observed in Figure 3, the slant path, L, can be determined in terms of the sub-satellite point longitude, φ_S, the earth station longitude, φ_E, and earth station latitude, θ_E. The relative longitude of the satellite is therefore given as

$$\varphi_{ES} = \varphi_E - \varphi_S \tag{3.1}$$

Other important parameters are the satellite altitude, h, satellite elevation angle, ψ and the radius of the earth, R. The radius of the satellite is therefore given as

$$R_s = R + h \tag{3.2}$$

The satellite elevation angle is given as

$$\psi = \tan^{-1}\left[\frac{\cos\beta - \sigma}{\sin\beta}\right] \tag{3.3}$$

where $\beta = \cos^{-1}(\cos\theta_E \cos\theta_{ES})$, and $\sigma = \frac{R}{R+h}$ (3.4)

The slant path to the satellite is given as

$$L = 35{,}786\sqrt{1 + 0.4199(1 - \cos\beta)}\ \text{km} \tag{3.5}$$

Having computed the slant path, it is necessary to determine the loss a signal suffers as it travels from the satellite to the hard to reach area. This is indicated as the free space loss and is given in decibels as

$$FSL = 20\,log\left(\frac{\lambda}{4\pi d}\right) \tag{3.6}$$

As a function of frequency and slant path, the free space loss is given as

$$FSL = 32.45 + 20\log(f) + 20\log(L) \tag{3.7}$$

In order for an earth station to be accessible to a satellite, the following condition must be satisfied.

$$\gamma \le \cos^{-1}\left(\frac{R}{R_S}\right) \tag{3.8}$$

In addition to free space loss, a propagating signal also suffers attenuation due to atmospheric effects, mainly due to hydrometeors such as rain, snow, and clouds. The long terms statistics of attenuation due to rain in the earth station-satellite slant path is dependent on the satellite elevation angle, latitude of the earth station, frequency of the propagating signal, height of the earth station above the mean sea level, h_S, and point rainfall rate where the earth station is located. The point rainfall rate, $R_{0.01}$is computed for 0.01% of an average year [26]. For satellite elevation angles, $\psi > 5^{\circ}$, the slant path range below the rain height is given by

$$L_s = \frac{h_R - h_S}{\sin\psi}\ \text{km} \tag{3.9}$$

Where h_R is the effective rain height and is calculated based on the latitude of the earth station [27]. For $\psi < 5°$, the following formula is used

$$L_s = \frac{2(h_R - h_S)}{\left(\sin^2\psi + 2(h_R - h_S)/R\right)^{1/2} + \sin\psi}\ \text{k} \tag{3.10}$$

It is also important to consider the effects of shadowing, which is caused by large obstacles which absorb and attenuate the propagating signals. The effects of shadowing is described statistically, and it follows a log-normal distribution.

A link budget accounts for all the gains and losses from the transmitter output to the receiving antenna. For example, the NigComSat-1R C-band transponder has the following parameters: a bandwidth, of 36 MHz, an output power,$P_t = 20$ W, a satellite antenna gain, $G_t = 20$ dB, receiving earth station antenna gain, $G_r = 49.7$ dB, and a slant range as computed using (3.5) [23]. Therefore, according to [28], the power received by an earth station is given as

$$P_r = \frac{P_t\, G_t G_r}{(4\pi L/\lambda)^2} \tag{3.11}$$

The receiver noise power is given as

$$P = kT_sB_n \qquad (3.12)$$

where k is Boltzmann's constant, T_s is the system noise temperature, and B_n is the noise bandwidth. The carrier to noise ratio is therefore given as

$$\frac{C}{N} = \frac{P_r}{kT_sB_n} \qquad (3.13)$$

The carrier to noise power ratio in the downlink is calculated based on the following equation

$$\frac{C}{N}_{DL} = EIRP_{SAT} + 20\,log\left(\frac{\lambda}{4\pi L}\right) + G_{RX} - 10\,log(kT_sB_n), \qquad (3.14)$$

where $EIRP_{SAT}$ is the effective isotropic radiated power of the satellite, G_{RX} is the gain of the antenna system in decibels, and other variables are as earlier defined in (3.12). Similarly, the uplink budget is calculated as follows.

$$\frac{C}{N}_{UL} = EIRP_{ES} + 20\,log\left(\frac{\lambda}{4\pi L}\right) + G_{RX} - 10\,log(kT_sB_n) \qquad (3.15)$$

Satellite visibility parameters were derived using the standard geostationary-geometry model. The Earth's mean radius was taken as $R_e = 6371$ km and orbital altitude $h = 35786$ km, giving a satellite radius $R_s = R_e + h$. For a ground station at latitudeθ_E. Longitudeφ_E, and a satellite at sub satellite longitudeφ_s, the elevation angle E is:

$$E = tan^{-1}\left[\frac{\cos\theta_E.\cos\varphi_s - R_e/R_s}{\sqrt{1-[\cos\theta_E.\ \cos\varphi_s]^2}}\right] \qquad (3.16)$$

The slant-range distance S and surface-coverage radius r_c were computed respectively as:

$$S = \sqrt{R_s^2 + R_e^2 - 2R_sR_e cos\psi} \qquad (3.17)$$

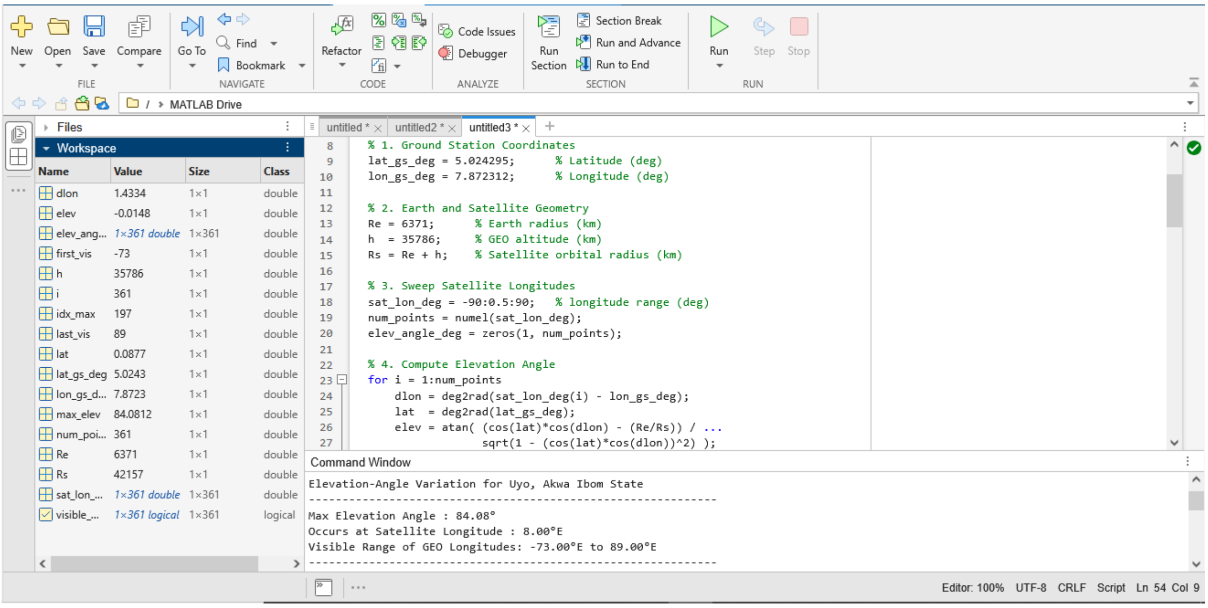
$$\psi = cos^{-1}(cos\theta_E \cos\varphi_s) \qquad (3.18)$$

$$r_c = R_e cos^{-1}\left(\frac{R_e}{R_s}\cos E\right) \qquad (3.19)$$

All trigonometric operations were performed in radians, and final outputs converted to degrees or kilometers as appropriate. The computations were verified in MATLAB (R2025b) and the elevation angles in Tables 3 and 4 agree, confirming geometric consistency between visibility and slant-path analyses. Figure 4 shows a screenshot of the MATLAB simulation environment.

The bandwidth for each link was chosen according to the standard channel spacing used in satellite IoT communication systems (200 kHz for downlink and 15 kHz for uplink, while spectral efficiency (η) was obtained from the selected modulation and coding scheme (QPSK with coding rates of 1/3 – 2/3, corresponding to 0.67–1.33 bps/Hz). These parameters were then applied in Equation (3.20), to compute the achievable data rates shown in Table 6.

$$R = \eta * B \qquad (3.20)$$



Name	Value	Size	Class
dlon	1.4334	1×1	double
elev	-0.0148	1×1	double
elev_ang...	*1×361 double*	1×361	double
first_vis	-73	1×1	double
h	35786	1×1	double
i	361	1×1	double
idx_max	197	1×1	double
last_vis	89	1×1	double
lat	0.0877	1×1	double
lat_gs_deg	5.0243	1×1	double
lon_gs_d...	7.8723	1×1	double
max_elev	84.0812	1×1	double
num_poi...	361	1×1	double
Re	6371	1×1	double
Rs	42157	1×1	double
sat_lon_...	*1×361 double*	1×361	double
visible_...	*1×361 logical*	1×361	logical

```
% 1. Ground Station Coordinates
lat_gs_deg = 5.024295;      % Latitude (deg)
lon_gs_deg = 7.872312;      % Longitude (deg)

% 2. Earth and Satellite Geometry
Re = 6371;      % Earth radius (km)
h  = 35786;     % GEO altitude (km)
Rs = Re + h;    % Satellite orbital radius (km)

% 3. Sweep Satellite Longitudes
sat_lon_deg = -90:0.5:90;   % longitude range (deg)
num_points = numel(sat_lon_deg);
elev_angle_deg = zeros(1, num_points);

% 4. Compute Elevation Angle
for i = 1:num_points
    dlon = deg2rad(sat_lon_deg(i) - lon_gs_deg);
    lat  = deg2rad(lat_gs_deg);
    elev = atan( (cos(lat)*cos(dlon) - (Re/Rs)) / ...
                 sqrt(1 - (cos(lat)*cos(dlon))^2) );
```

```
Elevation-Angle Variation for Uyo, Akwa Ibom State
------------------------------------------------------------
Max Elevation Angle : 84.08°
Occurs at Satellite Longitude : 8.00°E
Visible Range of GEO Longitudes: -73.00°E to 89.00°E
------------------------------------------------------------
```

Figure 4: Matlab simulation screenshot

4. RESULTS AND DISCUSSION

The results are presented and discussed in terms of satellite visibility and slant path analysis, link budget analysis in C-band, and data use estimation for IoT use cases.

4.1. SATELLITE VISIBILITY AND SLANT PATH ANALYSIS

Satellite visibility was determined using the trigonometric models given in (3.1) to (3.5). As shown in Table 3, all four selected satellites had elevation angles greater than the 5° visibility threshold. The confirmation of line-of-sight connectivity implies that these satellites are viable candidates for delivering mobile communication services within the Nigerian territory.

Table 3: Satellite Visibility Results

S/N	**Satellite Name**	**Satellite Longitude (°)**	**Earth Station Lat (°)**	**Earth Station Long (°)**	**Elevation Angle (Computed)**	**Visibility Status**
1	NigComSat-1R	42.4	5.024295	7.872312	38.2	Visible
2	EchoStar 16	-61.5	5.024295	7.872312	41.7	Visible
3	Astra	5.2	5.024295	7.872312	46.5	Visible
4	EchoStar 6	-72.7	5.024295	7.872312	40.2	Visible

Table 4: Slant Path Distance Results

Satellite Name	Slant Range (km)	Coverage Radius (km)	Elevation Angle (°)
NigComSat-1R	38 404.7	8 170.5	38.21
EchoStar 16	37 956.8	8 546.1	41.73
Astra 1A	37 221.3	9 119.4	46.51
EchoStar 6	38 709.9	7 968.7	40.28

The slant path distances are shown in Table 4 and the values represent the geometric line-of-sight distances between satellite and ground station. The distances serve as critical input in link budget calculations, directly influencing free space path loss and, by extension, signal quality. The relationship between satellite elevation angle and slant path distance is shown in Figure 5.

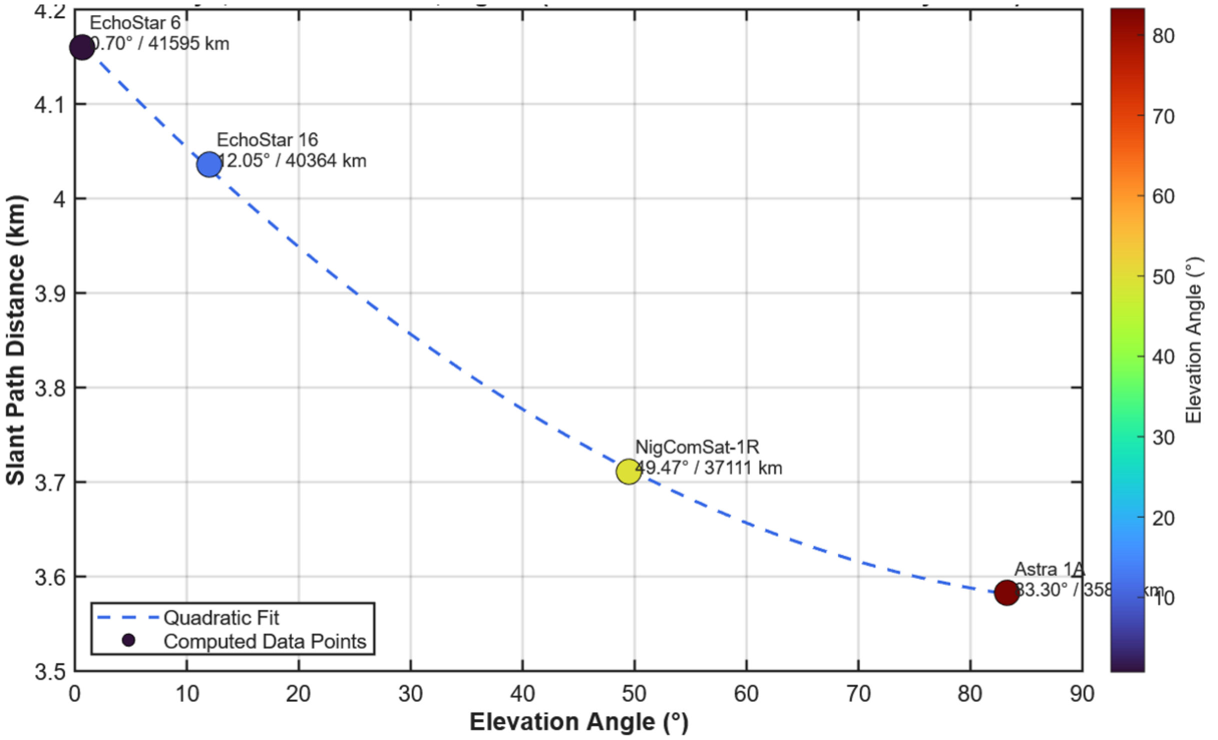


Figure 5: *Relationship between elevation angle and slant path*

4.2. LINK BUDGET ANALYSIS FOR NIGCOMSAT-1R (C-BAND)

As shown in Table 5, the downlink budget from NigComSat-1R to a typical Class 3 IoT device showed a C/N ratio of 20.36 dB, which is adequate for narrowband data transmission. The low receiver G/T of -3 dB/K reflects the limitations of IoT-class devices, but with sufficient EIRP and minimal atmospheric loss, the signal remains viable. The uplink results demonstrates a superior C/N ratio of 24.61 dB. This value is made possible by the satellite's high G/T (11 dB/K) and the manageable free space and atmospheric losses. The uplink performance exceeds downlink, highlighting the satellite's enhanced reception capabilities. Figure 6 shows the signal level diagram for the uplink and downlink paths.

Table 5: Link Budget

Parameter	Downlink	Uplink
EIRP (dBW)	44	23.0
Free Space Loss (dB)	195.73	195.73
Atmospheric Loss (dB)	0.5	0.5
Receiver G/T (dB/K)	-3.0	11.0
C-band Bandwidth (GHz)	200	36
C/N Ratio (dB)	20.36	24.61

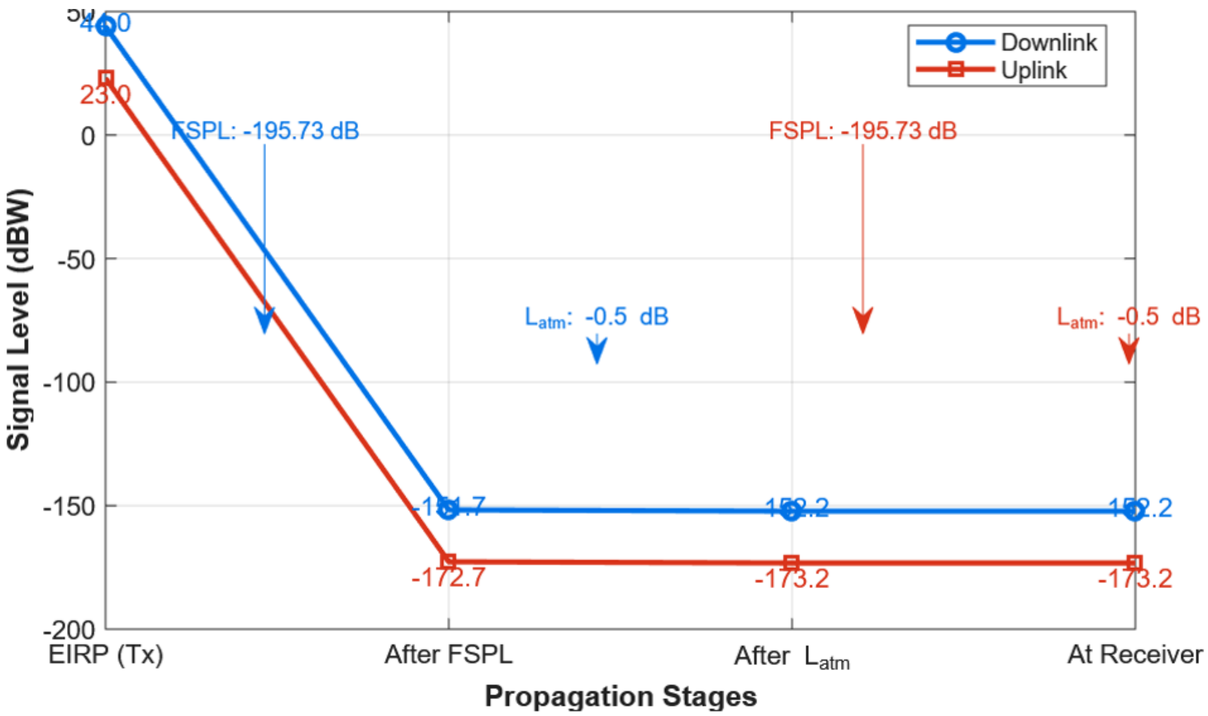


Figure 6: *Signal level diagram for uplink and downlink paths*

4.3. DATA RATE ESTIMATION FOR IOT USE CASE

Table 6 shows the data rates that NigComSat-1R can support for basic IoT services like smart metering and environmental monitoring. The configuration adopted nearly doubles the downlink data rate and delivers acceptable uplink rates for intermittent sensor data transmissions.

Table 6: Data Rates for IoT Devices

Link Direction	Bandwidth (kHz)	Spectral Efficiency (bps/Hz)	Data Rate (kbps)
Downlink	200	0.67	134.0
Uplink	15	0.67	10.05
Downlink (Opt.)	200	1.33	266.0
Uplink (Opt.)	3.75	1.60	6.0

4.4. THROUGHPUT ANALYSIS FOR ONEWEB (LEO, KU-BAND)

As shown in Table 7, the OneWeb LEO scenario achieved very high throughput, supporting real-time and bandwidth-intensive applications like community WiFi or cellular backhaul. The range between best and worst-case scenarios highlights the dependency on terminal G/T and satellite elevation but confirms the system’s flexibility in serving variable terrains and user densities.

Table 7: Data Rates for Community WiFi via LEO Constellations

Link Direction	Scenario Type	G/T (dB/K)	Data Rate (Mbps)
Downlink	Best Case	9	830
Downlink	Worst Case	7	140
Uplink	Best Case	9	880
Uplink	Worst Case	7	140

5. ENGINEERING IMPLICATIONS

From an engineering standpoint, the findings validate the potential of satellite systems to extend mobile communication to hard-to-reach areas. The slant path and elevation angle data confirm that GEO satellites can provide consistent coverage. The link budget calculations affirm the feasibility of stable communication links for narrowband applications. Furthermore, the high data rates demonstrated in the OneWeb case, makes LEO satellites suitable for backhaul and fixed wireless access in underserved regions. These insights are critical for engineers designing future 6G NTN-terrestrial hybrid systems.

6. CONCLUSION AND RECOMMENDATIONS FOR FURTHER WORK

This paper has presented a detailed engineering analysis of satellite-enabled 6G network communication systems as a means of addressing Nigeria's mobile coverage gaps in hard-to-reach areas. The work confirmed satellite visibility, computed feasible slant paths, developed and analyzed link budgets, and modeled real throughput for IoT and broadband use cases. Both GEO and LEO satellites proved capable of supporting varying classes of services, thus offering scalable solutions to connectivity challenges. Future work may integrate NS-3 dynamic simulations to explore delay, jitter, and multi-hop satellite-terrestrial routing performance under real-world conditions.

REFERENCES

[1] R. Adeleke, "Digital divide in Nigeria: The role of regional differentials," *African Journal of Science, Technology, Innovation and Development,* 2020.

[2] U. M. Ekpe, V. B. Umoh and N. S. Agbeb, "Eliminating the Digital Divide in Nigeria: Policy Direction and 5G Deployment Methodology," in *2021 1st International Conference on Multidisciplinary Engineering and Applied Science (ICMEAS)*, Abuja, Nigeria, 2021.

[3] X. Zhu and C. Jiang, " Integrated Satellite-Terrestrial Networks Toward 6G: Architectures, Application," *IEEE Internet of Things Journal,* vol. 9, no. 1, pp. 437-461, 2022.

[4] W. Abderrahim, O. Amin, M.-S. Alouini and B. Shihada, "Latency-Aware Offloading in Integrated Satellite Terrestrial Networks," *IEEE Open Journal of the Communications Society,* vol. 1, pp. 490-500, 2020.

[5] F. Ulebor, "Nigeria has achieved 79.65% teledensity, 48.81% broadband penetration – NCC," 17 July 2025. [Online]. Available: https://www.vanguardngr.com/2025/07/nigeria-has-achieved-79-65-teledensity-48-81-broadband-penetration-ncc/. [Accessed 1 November 2025].

[6] S. Yrjola, M. Matinmikko-Blue and P. Ahokangas, "The Evolution of Mobile Communications," in *The Changing World of Mobile Communications*, Palgrave Macmillan, 2023, pp. 13-43.

[7] Satnews, "Eutelsat and NIGCOMSAT's multi-year, multi-million-dollar partnership," 23 January 2025. [Online]. Available: https://news.satnews.com/2025/01/23/eutelsat-partners-with-nigcomsat/. [Accessed 1 November 2025].

[8] U. M. Ekpe, A. L. Imoize and W. Montlouis, "Massive MIMO for Non-terrestrial Wireless Communication Systems," in *Massive MIMO for Future Wireless Communication Systems: Technology and Applications*, John Wiley & Sons, 2024, pp. 371-402.

[9] U. M. Ekpe, "RIS-Empowered Terrestrial and Non-terrestrial Wireless Communication Systems," in *Reconfigurable Intelligent Surfaces for 6G and BEyond Wireless Networks*, Wiley, 2025, pp. 525-550

[10] O. Kodheli, E. Lagunas, N. Maturo, S. K. Sharma, B. Shankar and J. F. M. Montoya, "Satellite Communications in the New Space Era: A Survey and Future Challenges," *IEEE Communications Surveys & Tutorials*, vol. 23, no. 1, pp. 70-109, 2021.

[11] World Bank, "World Bank Open Data - Rural Population," 2023. [Online]. Available: https://data.worldbank.org/indicator/SP.RUR.TOTL.ZS. [Accessed 1 November 2025].

[12] U. M. Etian and P. T. Bemgba, "Banditry in Northern Nigeria: Terrorists or Marauders?," *International Journal of Social Science, Management, Peace and Conflict Research,* vol. 9, no. 1, pp. 96-109, 2025.

[13] A. A. Felix, F. M. Dahunsi and S. O. Oluwatoki, "A Systematic Review on the Quality of Service of the Nigerian Communication System," *International Journal of Advances in Engineering and Management,* vol. 6, no. 8, pp. 199-212, 2024.

[14] I. S. Tognise, J. Degila and A. D. Kora, "Connecting Rural Areas: A Solution Approach to Bridging the Coverage Gap," in *IEEE 12th Annual Ubiquitous Computing, Electronics & Mobile Communication Conference,* New York, 2021.

[15] T. F. Collins, R. Getz, D. Pu and A. M. Wyglinski, Software-Defined Radio for Engineers, Artech House Publishers, 2018.

[16] B. Clerckx, Y. Mao, E. A. Jorswieck, J. Yuan, D. J. Love and E. Erkip, "A Primer on Rate-Splitting Multiple Access: Tutorial, Myths, and Frequently Asked Questions," *IEEE Journal on Selected Areas in Communications,* vol. 41, no. 5, pp. 1265-1308, 2023.

[17] R. Mijumbi, J. Serrat, J.-L. Gorricho, N. Bouten, F. D. Turck and R. Boutaba, "Network Function Virtualization: State-of-the-Art and Research Challenges," *IEEE Communications Surveys & Tutorials,* vol. 18, no. 1, pp. 236-262, 2016.

[18] T. Darwish and G. K. Kurt, "LEO Satellites in 5G and Beyond Networks: A Review from a Standardization Perspective," *IEEE Access,* vol. 10, pp. 35040 - 35060, March 2022.

[19] M. A. Abir, M. Z. Chowdhury and Y. M. Jang, "Software-Defined UAV Networks for 6G Systems: Requirements, Opportunities, Emerging Techniques, Challenges, and Research Directions," *IEEE Open Journal of the Communications Society,* vol. 4, pp. 2487-2547, 2023.

[20] A. Khan, M. Jaffar, S. Yaghmour, S. Watts, N. Chuberre and S. Mugnaini, "Extreme Long-Range Communications for Deep Rural Coverage: Non-Terrestrial Networks Position Paper," NGMN Alliance, 2019.

[21] F. T. Zohra, S. Azam and M. M. Rahman, "Overview of IPv6 Mobility Management Protocols and their handover," *International Journal of Computer Sciences and Engineering,* vol. 2, no. 3, pp. 121-129, 2014.

[22] I. Ahmad, J. Suomalainen and P. Porambage, "Security of Satellite-Terrestrial Communications: Challenges and Potential Solutions," *IEEE Access,* vol. 10, pp. 96038-96052, September 2022.

[23] NigComSat, "NigComSat-IR Technical Manual 2012 Edition," NIGCOMSAT, Abuja, 2012.

[24] E. Johnston, "List of Satellites in Geostationary Orbit," 24 October 2025. [Online]. Available: https://www.satsig.net/sslist.htm.

[25] U. M. Ekpe, *Satellite Communication Fundamentals Lecture Notes,* Ikot Akpaden: Department of Electrical and Electronic Engineering, Akwa Ibom State University, 2023.

[26] ITU-R, "Propagation Data and Prediction Methods Required for the Design of Earth-Space Telecommunications Systems," International Telecommunications Union, Geneva, July 2010.

[27] P. T. Thompson, "Propagation considerations relating to satellite communication systems," in *Satellite Communication Systems, 3rd Ed*, London, The Institution of Electrical Engineers, 2000, pp. 99-115.

[28] B. G. Evans, "Satellite systems planning," in *Satellite Communication Systems, 3rd Ed*, London, The Institution of Electrical Engineers, 2000, pp. 199-222.