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Rain Attenuation Characteristics for Earth-Space Communication in parts of Northeast and Southwest Nigeria

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Abstract

The characteristics of rain attenuation for earth-space communication in three Northeast States (Adamawa, Gombe and Taraba) and three Southwest States (Lagos, Oyo and Ogun) of Nigeria are presented in this paper. 33 years rainfall data obtained from the Nigerian Meteorological Agency (NiMet) was utilised**.** Chebil rain rate model was used to compute the point rainfall rate, while the ITU-R P.618-12 model was used to compute the rain attenuation for the six locations. The point rainfall rate computed in the Northeast ranged between 90.34 mm/h and 96.2 mm/h, while higher rainfall rates that ranged between 99.7 mm/h and 108.2 mm/h were recorded in the Southwest. Elevation angles of 23°, 42.5° and 55° were considered. The computed rain attenuation for the Northeast States ranged between 10.22 dB and 37.14 dB, while that of the Southwest States ranged between 10.60 dB and 41.00 dB for time percentage exceedance of 0.01 at Ku-band. From the values of the rain attenuation predicted, availability of signal is possible at 42.5° and 55° elevation angles but impossible at 23° elevation angle.

1. Introduction

Rain attenuation is a serious atmospheric effect that can cause short-term and long-term impairments on radio signal communication links [1, 2]. For earth-space communication systems operating at higher frequency bands of 10 GHz and above, rain attenuation poses the greatest meteorological threat to system efficiency and dependability. While other climatic factors such as clouds, ice, fog and snow can also cause degradation, rain causes more damage [3-5]. Therefore, it is crucial to do a detailed analysis of how rain deterioration affects the effectiveness of systems that operate in these high-frequency bands [6-7].

Rainfall causes radio waves traveling at these high frequencies through the atmosphere to be either absorbed or dispersed, which reduces the signal [8]. Furthermore, scattering may result in radio path interference. Attenuation by absorption will outweigh that by scattering in the super high frequency (SHF) band, where the radio wave's wavelength is longer than the size of a raindrop. On the other hand, attenuation due to scattering will be more noticeable in the extreme high frequency (EHF) band and beyond, where the wavelength is shorter than the rain drop dimension [9]. Precise evaluation of the corresponding rain rate is crucial for rain attenuation study [10]. Several investigations on the frequency of rain have supported this claim [11-15].

Although a great deal of work has gone into creating rain rate and rain attenuation models, the precision of rain attenuation prediction provided by these efforts across a communication link still depends on the rainfall data that is observed locally [16].

The aim of this paper therefore, is to investigate rain attenuation on satellite communication links in three Northeast States (Adamawa, Jalingo and Gombe) and three Southwest States (Lagos, Ogun and Oyo) of Nigeria by estimating the rain attenuation at Ku frequency band and also comparing the extent of rain attenuation in the study area for different polarisations. Similar research works have recently been carried out in North Central Nigeria [17-19]. Results obtained will be beneficial to operators and intended consumers of services from various satellite outfits, especially the NIGCOMSAT-1R.

1.1 The Study Area

The study area for this work is three Northeast states and three Southwest states of Nigeria. These are Adamawa (with Yola as the State capital), Gombe (Gombe is the State capital), Taraba (Jalingo is the State capital), Ogun (Abeokuta is the State capital), Oyo (Ibadan is the State capital) and Lagos (Ikeja is the State capital). The study area has a tropical climate with two seasons: The dry season which spans from November to March; and the wet (or rainy) season which begins in April and ends in October every year for Yola, Jalingo and Gombe, while rainfall is experienced throughout the year in Abeokuta, Ikeja and Ibadan. Figure 1 shows the map of the 36 States of Nigeria with the study area highlighted.

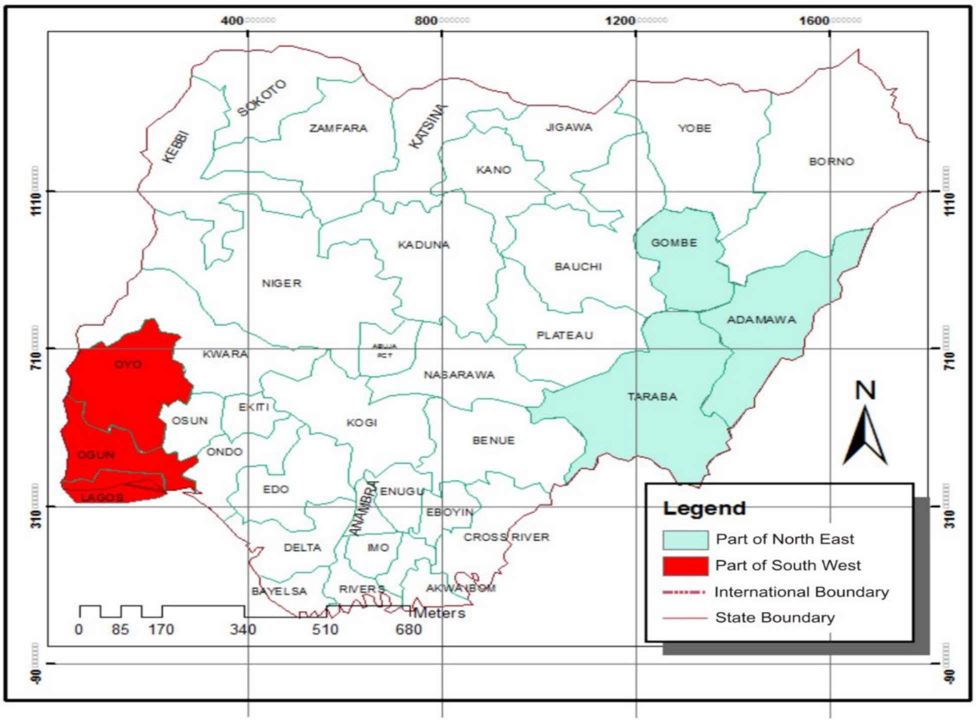


Fig. 1 *36 States of Nigeria with the study area highlighted*

2. Methodology

The instrument employed for the data measurement is the Casella tipping bucket rain gauge. Rainfall data of 33 years was collected from the Nigeria Meteorological Agency (NiMet). The data was analysed using Chebil rain rate model [20] given in equation 1, to calculate the rain rate, and ITU-R P.618-12 rain attenuation model [21] outlined in equations 2 to 13, to calculate the rain attenuation.

The Chebil rain rate model is expressed as:

$$R_{0.01}(mm/h) = \alpha M^{\beta} \quad (1)$$

where $R_{0.01}$ is the point rainfall rate exceeded at time percentage of 0.01, M is the mean annual accumulation of rain, while α and β are regression coefficients expressed as 12.2903 and 0.2973 respectively.
The rain attenuation computation for the locations using ITU-R.P 618-12 model was achieved through the following steps:
Step 1: Determine the rain height, H_R as:

$$H_R = h_o + 0.36 \text{ km} \quad (2)$$

where h_o is the 0°C isotherm height above mean sea level of the location

Step 2: Determine the slant path length L_s, below the rain height from:

$$L_S = \frac{H_R - H_S}{Sin\ \theta} \tag{3}$$

where θ is the elevation angle and H_S is the height of the location above sea level.

Step 3: Obtain the horizontal projection, L_G, of the slant path length from:

$$L_G = L_S \operatorname{Cos}\theta \tag{4}$$

Step 4: Obtain the point rainfall rate, $R_{0.01}$ (mm/h) exceeded for 0.01% of an average year.

Step 5: Obtain the Specific attenuation, $\gamma_{R0.01}$ (dB/km) for 0.01% of time:

$$\gamma_{R_{0.01}} = k\, R_{0.01}^{\alpha} \tag{5}$$

where parameters k and α are given in ITU-R P.838-3 [22].

Step 6: Calculate the horizontal reduction factor, $r_{h0.01}$ for 0.01% of time using:

$$r_{h0.01} = \frac{1}{1 + 0.78\sqrt{\left(\frac{L_{G*}\gamma_{R_{0.01}}}{f}\right)} - 0.38[1 - \exp(-2L_G)]} \tag{6}$$

where f is the frequency in GHz

Step 7: Calculate the vertical adjustment factor, $v_{0.01}$ (km):

$$L_R = \frac{L_G r_{0.01}}{\cos\theta}, for\ \rho > \theta \tag{7}$$

Or

$$L_R = \frac{H_R - H_S}{\sin\theta}, for\ \rho \le \theta \tag{8}$$

where

$$\rho = \tan^{-1}\left(\frac{H_R - H_S}{L_G r_{h0.01}}\right) \tag{9}$$

Therefore,

$$v_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left[31\left(1 - \exp\left(-\frac{\theta}{[1+\sigma]}\right)\right)\frac{\sqrt{L_G\ \gamma_{R0.01}}}{f^2} - 0.45\right]} \tag{10}$$

where

$$\sigma = 36 - |\varphi|, for\ |\varphi| < 36° \text{ or } \sigma = 0, for\ |\varphi| \ge 36°$$

φ is the latitude of the station

Step 8: Compute the effective path length $L_{eff}(km)$ as:

$$L_E = L_R v_{0.01} \tag{11}$$

Step 9: Obtain the predicted rain attenuation exceeded for 0.01% of an average year from:

$$A_{0.01} = \gamma_{R0.01} L_E \tag{12}$$

Step 10: The attenuation for other percentage exceedances are obtained using:

$$A_p(dB) = A_{0.01}\left(\frac{p}{0.01}\right)^{-[0.655 + 0.033\ln(p) - 0.045\ln(A_{0.01}) - z\sin\theta(1-p)]} \tag{13}$$

where p is the percentage probability of interest, and z is given by

$$if\ p \ge 1\%,\ z = 0 \tag{14}$$

$$if\ p < 1\%, z = 0 \quad \text{if } |\varphi| \ge 36° \tag{15}$$

$$z = -0.005(|\varphi| - 36) for\ \theta \ge 25°\ and\ |\varphi| < 36° \tag{16}$$

$$z = -0.005(|\varphi| - 36) + 1.8 - 4.25 sin\theta, for\ \theta < 25°\ and\ |\varphi| < 36° \tag{17}$$

Table 1 presents the geographical parameters for the study area. These are parts of the input parameters used in computing the rain attenuation for the study area.

Table 1 *Geographical parameters for the study area*

Location	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
Longitude	12.27°	11.02°	11.30°	3.55°	3.9°	3.33°
Latitude	9.13°	10.19°	8.54°	6.42°	7.43°	6.58°
Isotherm height (km)	4.41	4.42	4.38	4.41	4.4	4.38

3. Results and Discussion

The computed point rainfall rate, $R_{0.01}$ is given in Table 2.

Table 2 *Point rainfall rate for the study area*

Locations	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
$R_{0.01}$ (mm/h)	90.34	94.40	96.20	99.70	104.80	108.20

The results in Table 2 show that higher rainfall rates at 0.01% exceedance was recorded in Abeokuta, Ibadan and Ikeja than in Yola, Gombe and Jalingo. This implies that higher rain attenuation is expected in the Southwest states than in the Northeast states.

The results for the step by step computation of rain attenuation for the locations using the ITU-R.P 618-12 model are presented in Tables 3 - 14, that is, from the derivation of the Specific attenuation to that of the Effective path length.

Table 3 *Specific attenuation for horizontal polarisation (dB/km)*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	4.20	4.43	4.53	4.39	5.03	5.22
14.00	6.33	6.66	6.80	6.60	7.50	7.78
20.00	10.69	11.20	11.43	11.11	12.51	12.94
40.00	22.02	22.88	23.25	22.73	25.05	25.75

Table 4 *Specific attenuation for vertical polarisation (dB/km)*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	3.24	3.41	3.48	3.38	3.85	3.99
14.00	4.99	5.22	5.33	5.18	5.84	6.04
20.00	8.10	8.46	8.62	8.40	9.38	9.68
40.00	18.96	19.68	19.99	19.55	21.49	22.07

Table 5 *Specific attenuation for circular polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	3.69	3.89	3.98	3.86	4.40	4.57
14.00	5.58	5.86	5.98	5.81	6.57	6.80
20.00	9.28	9.70	9.89	9.63	10.79	11.15
40.00	20.46	21.24	21.59	21.11	23.23	23.87

Table 6 *Horizontal reduction factor for horizontal polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	0.67	0.67	0.67	0.66	0.64	0.63
14.00	0.64	0.64	0.63	0.63	0.61	0.60
20.00	0.61	0.61	0.60	0.60	0.58	0.57
40.00	0.60	0.61	0.60	0.59	0.58	0.57

Table 7 *Horizontal reduction factor for vertical Polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	0.73	0.72	0.72	0.71	0.69	0.68
14.00	0.69	0.69	0.68	0.68	0.65	0.64
20.00	0.66	0.66	0.66	0.65	0.63	0.62
40.00	0.63	0.63	0.63	0.62	0.61	0.60

Table 8 *Horizontal reduction factor for circular polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	0.70	0.70	0.69	0.69	0.66	0.65
14.00	0.67	0.67	0.66	0.65	0.63	0.62
20.00	0.64	0.64	0.63	0.62	0.61	0.60
40.00	0.62	0.62	0.61	0.61	0.59	0.58

Table 9 *Vertical adjustment factor for horizontal polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	0.81	0.81	0.84	0.83	0.82	0.81
14.00	0.95	0.95	0.98	0.97	0.96	0.95
20.00	1.16	1.16	1.19	1.18	1.17	1.16
40.00	1.51	1.51	1.53	1.53	1.52	1.52

Table 10 *Vertical adjustment factor for vertical polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	0.81	0.81	0.84	0.83	0.82	0.81
14.00	0.95	0.95	0.98	0.97	0.96	0.95
20.00	1.16	1.16	1.19	1.18	1.17	1.16
40.00	1.51	1.51	1.53	1.53	1.52	1.52

Table 11 *Vertical adjustment factor for circular polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	0.83	0.83	0.86	0.85	0.84	0.83
14.00	0.97	0.97	1.00	0.99	0.98	0.97
20.00	1.18	1.18	1.21	1.20	1.19	1.18
40.00	1.52	1.52	1.53	1.53	1.53	1.52

Table 12 *Effective path length for horizontal polarisation*

Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	3.23	3.07	3.20	3.34	3.10	3.07
14.00	3.57	3.41	3.53	3.69	3.44	3.42
20.00	4.14	3.95	4.06	4.24	3.99	3.96
40.00	5.34	5.12	5.20	5.44	5.18	5.18

Table 13 *Effective path length for vertical polarisation*

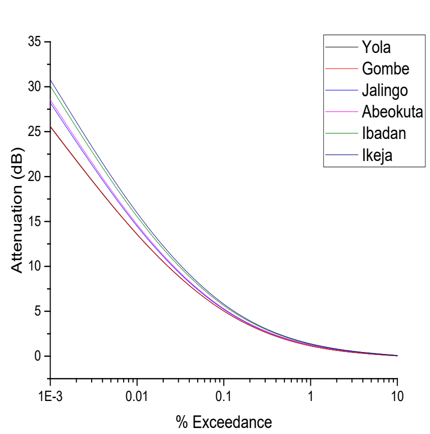
Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	3.67	3.50	3.64	3.80	3.54	3.51
14.00	4.01	3.83	3.96	4.14	3.88	3.86
20.00	4.68	4.48	4.60	4.81	4.54	4.53
40.00	5.66	5.42	5.52	5.76	5.51	5.51

Table 14 *Effective path length for circular polarisation*

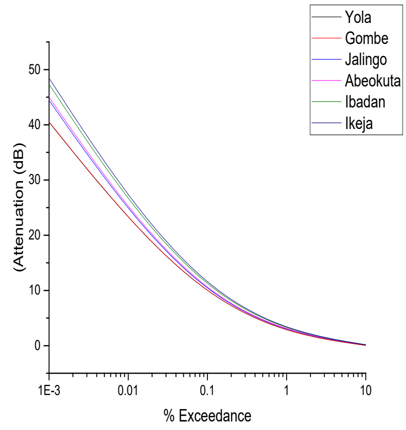
Frequency (GHz)	Yola	Gombe	Jalingo	Abeokuta	Ibadan	Ikeja
11.00	3.44	3.28	3.41	3.56	3.31	3.28
14.00	3.80	3.63	3.76	3.92	3.67	3.64
20.00	4.41	4.21	4.33	4.53	4.27	4.25
40.00	5.50	5.27	5.36	5.60	5.34	5.34

From these results, it is observed that the computed parameters generally increased as the frequency of propagation increased at all the stations. Also, a general increase in the computed values is observed in the Southwest states compared to the Northeast states. This is not unconnected to the differences in the geographical/geometrical conditions of these locations as given in Table 1, and the differences in the computed rainfall rate as presented in Table 2.

The results for the predicted rain attenuation at Ku frequency band (11 GHz and 14 GHz), three elevation angles (42.5°, 55°and 23°) and three polarisations (Horizontal, Vertical and Circular) are given in Figures 2 – 4.



(a)



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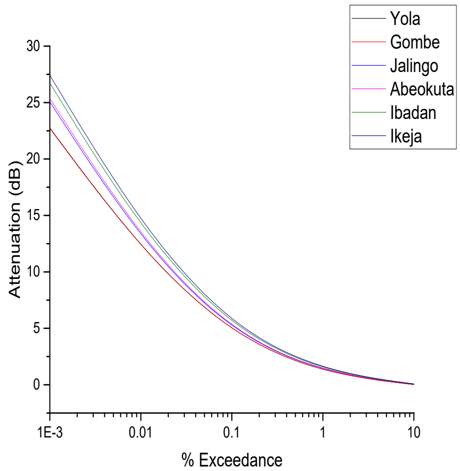

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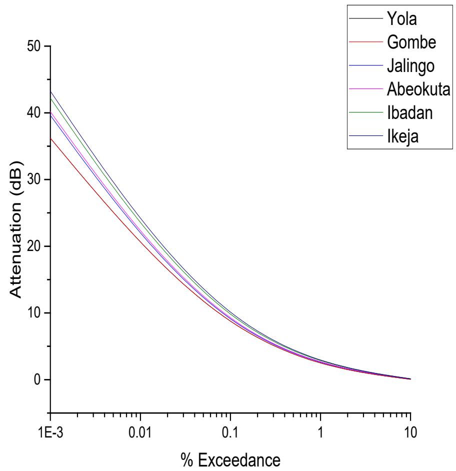

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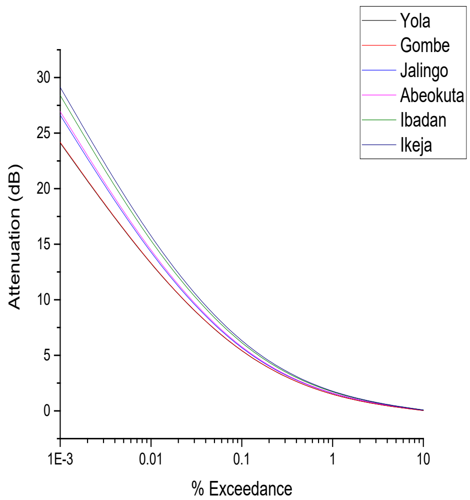

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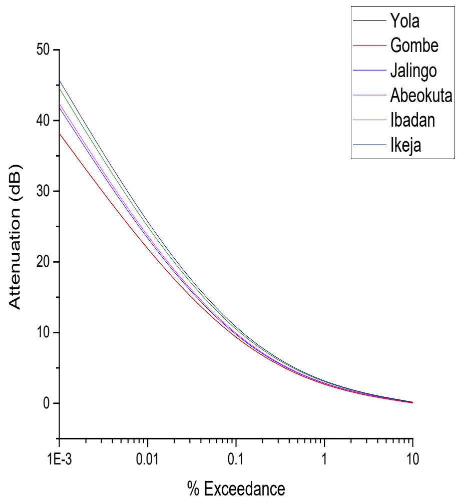

(f)

Fig. 2. *Rain attenuation at 42.5° elevation angle (a) 11 GHz, horizontal polarisation; (b) 14 GHz horizontal polarisation; (c) 11 GHz, vertical polarization; (d) 14 GHz, vertical polarization; (e) 11 GHz, circular polarization; (f) 14 GHz, circular polarisation*

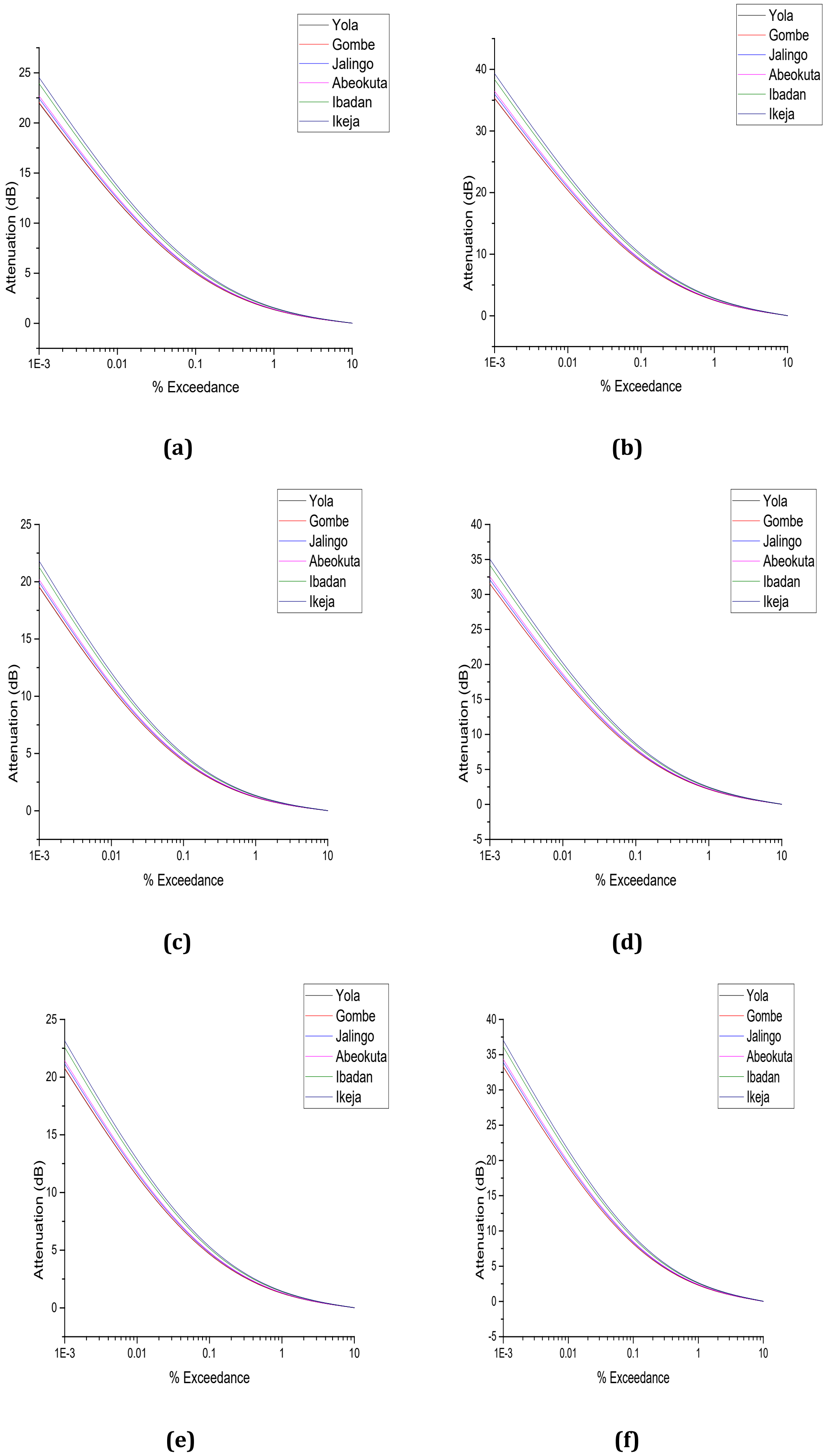

Fig. 3. *Rain attenuation at 55° elevation angle (a) 11 GHz, horizontal polarization; (b) 14 GHz horizontal polarization; (c) 11 GHz, vertical polarization; (d) 14 GHz, vertical polarization; (e) 11 GHz, circular polarization; (f) 14 GHz, circular polarization*

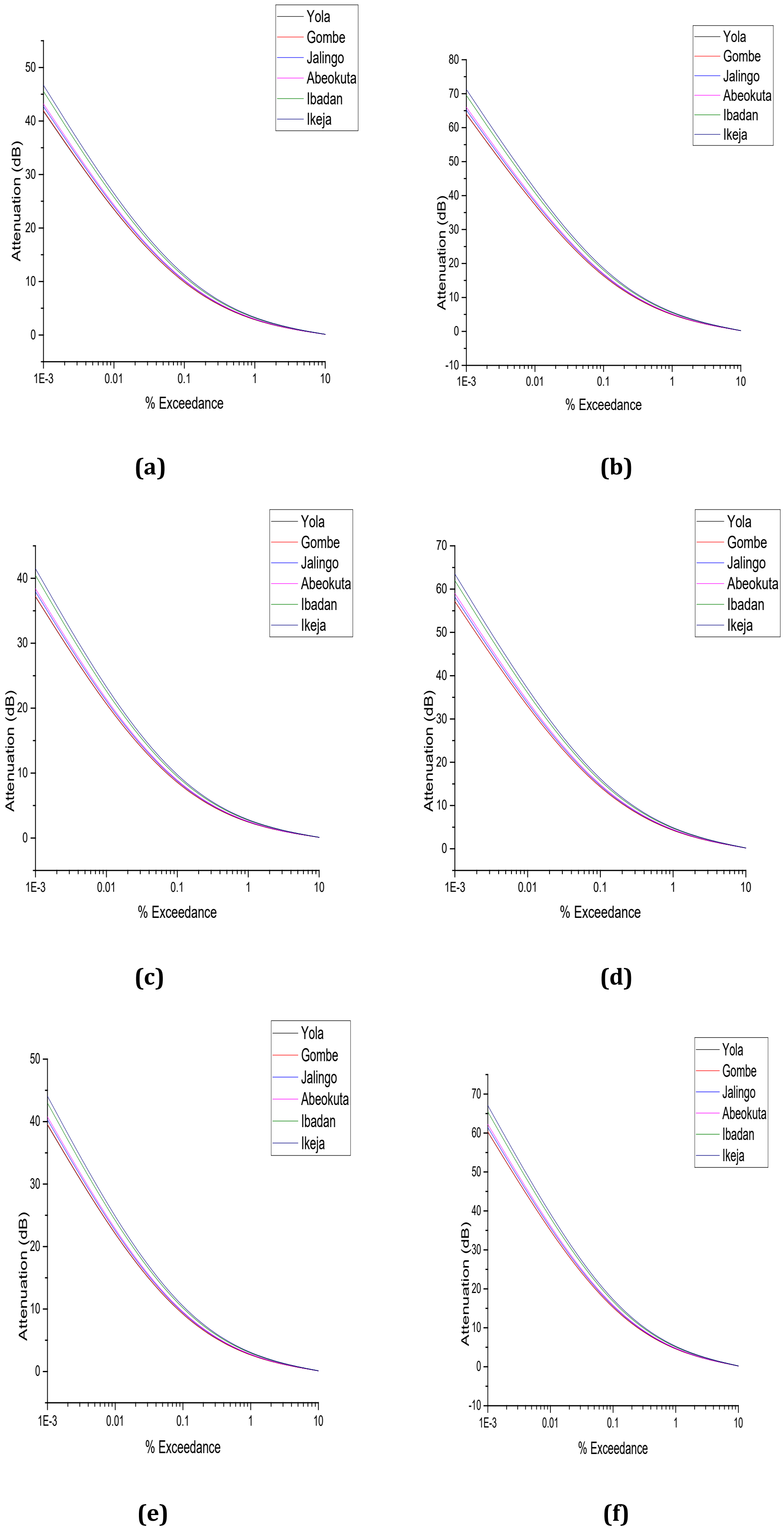

Fig. 4. *Rain attenuation at 23° elevation angle (a) 11 GHz, horizontal polarization; (b) 14 GHz, horizontal polarization; (c) 11 GHz, vertical polarization; (d) 14 GHz, vertical polarization; (e) 11 GHz, circular polarization; (f) 14 GHz, circular polarisation*

As observed in Figures 2 – 4, the Southwest region (Ikeja, Abeokuta and Ibadan) recorded higher rainfall attenuation in comparison to the Northeast region. For instance, at 0.01% time exceedance, attenuation values ranged from 14.66 dB in Abeokuta to 15.95 dB in Ikeja at 11 GHz downlink frequency for 42.5^{o} elevation angle and horizontal polarisation, while attenuation ranged from 13.54 dB in Yola to 14.48 dB in Jalingo at the same frequency, elevation angle and polarisation. At 14 GHz uplink frequency, the same trend is observed at the same time percentage exceedance of 0.01 for 23^{o} elevation angle and vertical polarisation. Here attenuation values varied from 32.05 dB in Yola to 32.71 dB in Jalingo, while attenuation varied from 33.21 dB in Abeokuta to 36.04 dB in Ikeja. Hence, more signal outages is expected to occur in the Southwest region than in the Northeast.

Also, from the computed attenuation, it is observed that horizontal polarisation had the highest amount of attenuation at all the operational frequencies. This was followed by circular polarisation, while vertical polarisation had the least amount of attenuation for both the uplink and downlink frequencies of Ku-band at the different elevation angles evaluated.

4. Conclusion

Rain attenuation characteristics for earth-space communication at Ku-band in parts of Southwest and Northeast Nigeria have been evaluated for some communication links, based on local input data. Chebil rain rate model was used to compute the rainfall rate, while the ITU-R P.618-12 rain attenuation model was used to compute the rain attenuation for 0.001% - 10% time exceedances. The results show that higher rainfall rates that ranged from 99.70 mm/h to 108.20 mm/h were recorded in the Southwest region, while lower rainfall rates that varied between 90.34 mm/h and 96.20 mm/h were observed in the Northeast region. Expectedly for the rain attenuation, computations for the Southwest region recorded higher values than the Northeast region. At 0.01% time exceedance, attenuation values ranged between 14.66 dB and 36.04 dB in the Southwest, while attenuation ranged between 13.54 dB and 32.71 dB in the Northeast for all the elevation angles, polarisations and frequencies (downlink and uplink) evaluated. This implies that more signal outages will be experienced in the Southwest region of Nigeria than in the Northeast region.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *K. C. Igwe;* ***data collection:*** *A. V. Samuel;* ***analysis and interpretation of results:*** *K. C. Igwe, A. V. Samuel;* ***draft manuscript preparation:*** *K. C. Igwe. All authors reviewed the results and approved the final version of the manuscript.*

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