Estimation of rain attenuation effect on radio wave propagation for broadband communication over northern Nigeria.

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Abstract: Rain induced effect on propagated signal was studied in this work. The weather parameters of two (2) locations representing two (2) climate zones in Northern Nigeria were employed, using the International Telecommunications Union (ITU-R P.618) rain attenuation model, to investigate the rain effect on strength of propagated signal ranging from Ku-band to V-band of the communication spectrum. The weather data were obtained from the Nigerian Meteorological Agency (NIMET) for a period of 10years (2009-2018) and assimilated into the model using 1-minute integration time rain rate. An elevation angle of 42.5^{o}, which is the conventional elevation angle of systems to NIGCOMSAT-1R over the Atlantic Ocean region, was used. The results showed that annual rainfall amounts trends varied slightly with the different locations and climate zones, having 2018 and 2010 as the highest rain years within the studied years at Maiduguri and Sokoto respectively. Also, the difference between maximum and minimum 0.01% attenuation for the two locations are 2dB-3dB, 3dB-6dB for horizontal polarization and 1dB-1.5dB and 2dB-4dB for vertical polarization respectively at the two locations respectively. Rain attenuation can be managed well for propagated Ku-band signal with sophisticated sensors but above Ku-band, signal strength attenuation induced by rain could be really alarming.

Keywords: Attenuation, communication spectrum, propagation, rain rate, exceedance probability.

1. Introduction

Many scientists have been interested in the absorption, transmittance, and reflective qualities of the earth's atmosphere in terms of electromagnetic radiation. A thorough understanding of these features will help physicists better comprehend the composition of the atmosphere, aid in the development of absorption theory, and contribute to the understanding of interactions between terrestrial radiations and atmospheric properties [1]. Because of the potential for additional communication channels, smaller antennas with a given resolving power, and lighter weight equipment, attenuation characteristics of the environment are significant to communication engineers interested in signal propagation at constantly increasing frequencies.

When microwaves pass through a medium that contains precipitations and gases, the signal strength is reduced due to two phenomena: (a) energy absorption by these particles and (b) energy scattering out of the beam by these particles. Atmospheric constituents absorb and scatter microwaves, especially at higher frequencies when the scattering effect is more severe. A major challenge facing satellite communication is that it is impossible to ensure communication when it rains or when the earth-space link is dampened [2]. An understanding of these characteristics is essential in setting up effective communication links.

Due to absorption and scattering by space particles, the quality of the radio frequency signal declines as it travels through the atmosphere and across the link [3]. This reduction in signal strength has a substantial impact on the information received, especially with recent improvements in satellite communication that demand a high data rate. The degree of deterioration is also determined by the link, meteorological conditions, sent signal, and receiver antenna specifications.

The troposphere and ionosphere are two different layers that make up the atmosphere. In these levels, however, the intensity of meteorological constituents varies. For example, in the troposphere, regions with high moisture content have high humidity, whereas places with dry surfaces have very little or no moisture content [4], [5], [6]. Rain has a significant role in influencing connection availability and dependability, and a good microwave network design significantly relies on the rain statistics of a certain deployment location [7].

Telecommunication service providers have given serious thought to moving or shifting to higher frequency propagation. This is owing to the network's high demand for C-band propagations. However, attenuation effects of rainfall and atmospheric gases on frequencies beyond 10GHz are a major source of concern, particularly in tropical locations such as Nigeria, where precipitation intensities are higher [8], [9]. Telecommunication providers have given moving or shifting to higher-frequency transmission serious thought. This is a result of the network's high demand from C-band propagations. The dampening effects of rainfall and atmospheric gases on frequencies above 10 GHz, particularly in tropical regions like Nigeria that suffer higher precipitation volumes, are a serious cause for concern. [8,9].

We tested the models using in-situ (ground-based) meteorological data from a tropical region because, despite the fact that ITU-R models have offered a systematic method for forecasting the rain attenuation on any terrestrial transmission medium, the models do not operate well in tropical zones because they are based on data retrieved from temperate regions

The IEEE (Institute of Electrical and Electronics Engineers) has defined standard communication frequency bands as follows;

Frequency	**Band**
8 – 12 GHz	X
12 – 18 GHz	Ku
18 – 27 GHz	K
27 – 40 GHz	Ka
40 – 75 GHz	V

The current situational increase in the conjunction of frequency bands is due to rapid expansion in telecommunications, reduction in the size of communication equipment, and ever-rising demand for bandwidth [10].

To accommodate the increased demand, radio link builders have been forced to create links employing higher frequencies in the Ku-, Ka-, and V- bands of communication [11]. As a result, it's distressing to note that communications above the Ku-band (10GHz) are severely dampened by hydrometeors [12].

To arrive at a full link budget, the attenuation model must take into account environmental factors that affect the radio signal propagation and, as a result, the channel's quality, the main emphasis being on the tropospheric effect.

2. Theoretical Background

Since the ITU-R P.618-12 model is broadly used worldwide, it is compared to emerging models to assess their dependability, particularly in situations where data collected are not accessible [13]. The model estimates attenuation using 0.01% level of probability rainfall rate and then adjusts for projected rain attenuation level for additional probabilities.

2.1 Rainfall Rate

A model was provided by [14] for converting measured rain data from any station to its rain rate data equivalent, regardless of the available rain data's integration time. It is calculated using a long-term annual mean accumulation, M, of rain amount for the study location, which is stated as:

$$R_{0.01} = \alpha M^{\beta} \qquad (mm/hr) \tag{2.1}$$

where α and β are coefficients of regression defined as: α = 12.290; and β = 0.297.

The rain rate (1 minute time integration)

The Ajayi and Ofoche model was adopted to convert rain rate from 3-minutes to 1-minute time integration values using:

$$R_{\pi} = aR_T^b \qquad (mm/hr) \tag{2.2}$$

where R = Rainfall rate, π = required rainfall rate time integration, T = is the available rainfall rate time integration, a and b are coefficients of integration for R_{π} given as a = 1.174 and b = 0.992. The coefficient "a" may not be dependent on climate but "b" may be dependent on the climate of location or can be further investigated [15].

2.2 Rain attenuation statistics from point rainfall rate

Considering frequencies of about 10 GHz to 55 GHz, the following procedures estimate the extended time prediction of slant-path rain attenuation at a particular site. The under-listed are required:

$R_{0.01}$: rainfall rate for the earth location for 0.01% of an average year (mm/h)
hs : height of the earth location above mean sea level (km)
θ : angle of elevation (degrees)
φ: latitude of the earth location (degrees)
f : frequency of propagation (GHz)
R_e : The Earth's radius (estimated at 8500 km).

The procedure for derivation of the model is as follows:
Step 1: Deduce the rain height, h_R, as presented in Recommendation ITU-R P.839:

$$h_R = h_0 + 0.36 \ (km) \tag{2.3}$$

where h_o is the annual average 0^0C isotherm height
Step 2: Determine the length of rainfall slant path and the horizontal projection as:
For θ≥5:

$$L_S = \frac{h_R - h_S}{sin\theta} \qquad (km) \tag{2.4}$$

For θ<5:

$$L_S = \frac{2(h_R - h_S)}{\left[sin^2\theta + \frac{2(h_R - h_S)}{R_e}\right]^{1/2} + sin\theta} \qquad (km) \tag{2.5}$$

The horizontal projection is evaluated by:

$$L_G = L_s cos\theta \tag{2.6}$$

Step 3: Deduce the rain rate, $R_{0.01}$, at 0.01% of an average year (with 1-minute time integration) using equations (2.1) and (2.2)
Step 4: Using the polarization coefficients (frequency dependent) as stated in Recommendation ITU-R P.838 and the estimations from Step 4, deduce the specific attenuation, γ_R, by using:

$$\gamma_R = kR_{0.01}^{\alpha} \quad (dB/km) \qquad \textbf{(2.7)}$$

Step 5: Estimate the horizontal reduction factor, $n_{0.01}$, for 0.01% time exceedance:

$$n_{0.01} = \frac{1}{1+0.78\sqrt{\frac{L_G \gamma_R}{f}}-0.38(1-e^{-2L_G})} \qquad \textbf{(2.8)}$$

Step 6: Estimate the vertical adjustment factor, $m_{0.01}$, for 0.01% time exceedance:

$$m_{0.01} = \frac{1}{1+\sqrt{sin\theta}\left[31(1-e^{-(\theta/1+\chi)}\sqrt{\frac{L_R \gamma_R}{f^2}}-0.45\right]} \qquad \textbf{(2.9)}$$

$$\zeta = tan^{-1}\left(\frac{h_R-h_S}{L_G n_{0.01}}\right) \qquad \textbf{(2.10)}$$

If $\zeta>\theta$

$$L_R = \frac{L_G n_{0.01}}{cos\theta} \quad (km) \qquad \textbf{(2.11)}$$

If $\zeta<\theta$

$$L_R = \frac{h_R-h_S}{sin\theta} \quad (km) \qquad \textbf{(2.12)}$$

If $|\varphi|<36^o$, then $\chi = 36 - |\varphi|$ (degrees)
If $|\varphi|>36^o$, then $\chi = 0$ (degrees)
Step 7: The effective path length is deduced using:

$$L_E = L_R m_{0.01} \quad (km) \qquad \textbf{(2.13)}$$

Step 8: The predicted attenuation for 0.01% time exceedance of an average year is estimated using:

$$A_{0.01} = \gamma_R L_E \quad (dB) \qquad \textbf{(2.14)}$$

Step 10: The projected rain attenuation for other time exceedances (percentages) of an average year, ranging from 0.001% - 5%, is deduced from the 0.01% exceedance rain attenuation for an average year:

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-[0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)sin\theta]} \quad (dB) \qquad \textbf{(2.15)}$$

If $p\geq1\%$ or $|\varphi|\geq36^o$: $\beta = 0$
If $p<1\%$ and $|\varphi|<36^o$ and $\theta\geq25^o$: $\beta = - 0.005(|\varphi|-(36)$
Otherwise: $\beta = - 0.05(|\varphi|-36)+1.8-4.25 \sin \theta$

3. Materials

3.1 Study Area

The study involved the use of meteorological data including rainfall amounts, air temperature, pressure and atmospheric density from two (2) locations in Northern Nigeria. According to Koppen's classification of Nigeria's climate, the selected locations are Maiduguri - representing the warm desert/highlands climate and Sokoto - representing the tropical dry/semi-arid climate [16]. The geographical locations and climatic features of the study area are shown in Table 1.

Table 1: Geography and climate features of study area

Stations/ Parameters	Maiduguri	Sokoto
Latitude	13.09°E	5.140°E
Longitude	11.50°N	13.035°N
Height above sea level (m)	353.8	350.8
Average annual rainfall (mm)	552.1	647
Average annual temp (°C)	27.4	28.9
Average rainy days/per	43	47
Average annual humidity (%)	30.2	48
Mean daily sunshine hours	8.3	8.8

3.2 Rainfall Pattern in Study Area

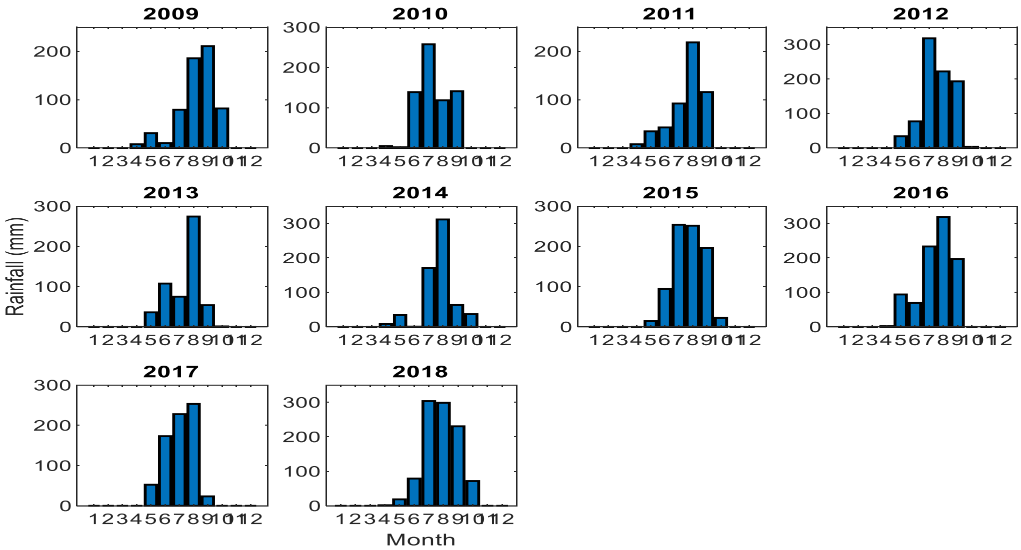

Figure 1: Monthly Accumulated rainfall in Maiduguri (2009-2018).

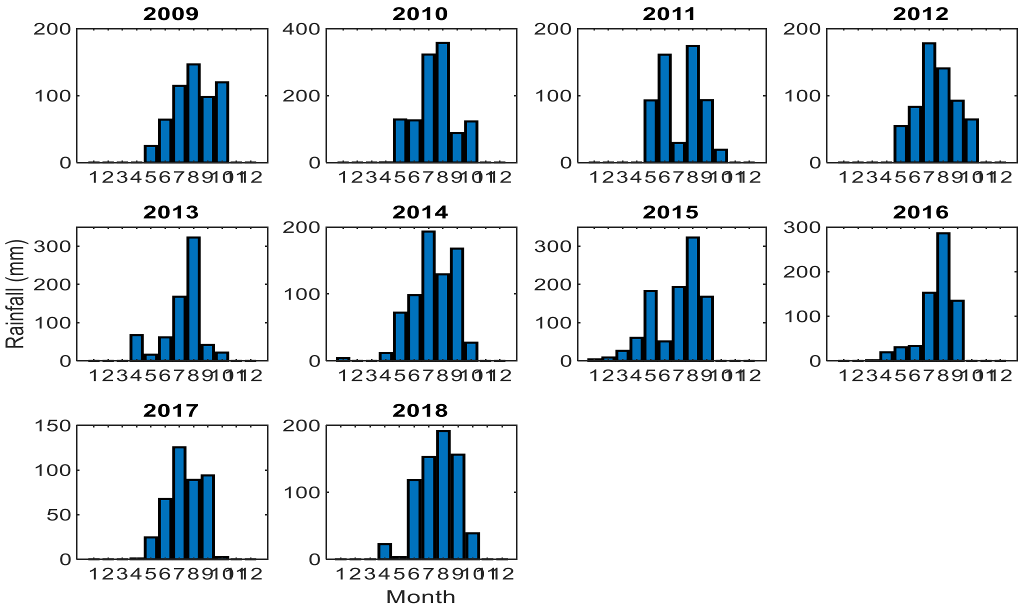

Figure 2: Monthly Accumulated rainfall in Sokoto (2009-2018).

Maiduguri represented in figure 1 is dominated by approximately eight (8) dry months (October - May) and four (4) months (June - September) with a maximum rainfall amount of 300mm in 2012 as against the higher values of 800mm observed by [17]. August break was observed only in 2010.

As seen in figure 2, Sokoto is dominated by approximately 7months of the dry season (October to April) and 5months of the wet season (June to September). It is observed that there has been an increased trend of rainfall in the area with time, shifting from four (4) wet months to five (5) wet months within the study period. This result does not agree with the results of [18] which posited that parts of Northern Nigeria could experience drought in the 21st Century. August break: 2014 and 2017 only.

The major factor responsible for this reduction of rainfall in the month of August/July for a wet and dry year, leading to August break as studied by [19] is Inter Tropical Discontinuity (ITD). The ITD is defined as the convergence zone between the two air masses (Tropical Continental air mass and Tropical Maritime air mass dominating the country's atmosphere) at the surface of moisture discontinuity.

4. Results and Discussion

The attenuation due to rain in a given area informs radio link planners about the rate at which the propagated signal will be affected by rain. Rainfall attenuation and signal availability criteria for the service on offer affect the operational frequency of a radio link.

The anticipated rain induced attenuation from the ITU-R model for rain attenuation utilized in this study was calculated using the point rainfall rate estimated using the Chebil and Rahman model as the input parameter. The Ka-band is 15GHz, and the V band is 45GHz, both of which are standard frequency bands created by the IEEE. We also used a 42.50 elevation angle, which is the standard radio station angle of elevation to NIGCOMSAT-1R for the region of the Atlantic Ocean. The ITU model, represented by equation (2.14) is most conventional procedure for estimating rain induced attenuation on radio propagation links across the world, especially where measured data is available [20]. The results of experimental data simulated into the ITU-R model for rain attenuation do not conflict with that of measured data. The horizontal and vertical polarization of rain attenuation were obtained and compared for the two (2) stations studied in this work over 10years.

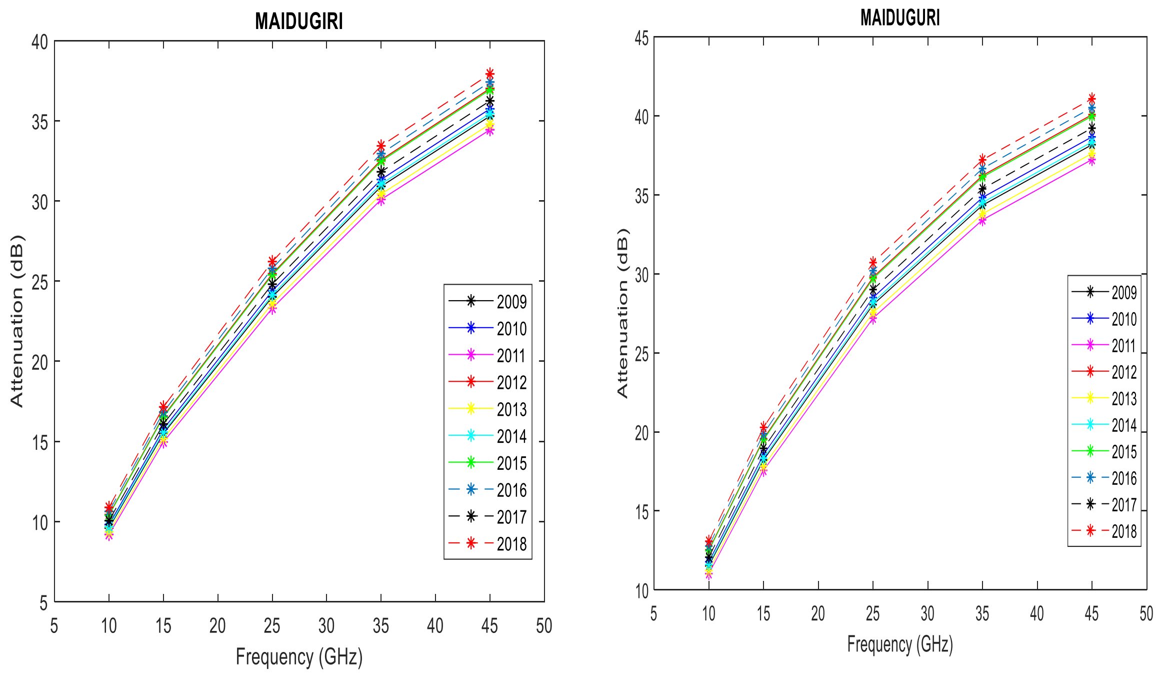

Figure 3: Attenuation at 0.01% exceedance for Maiduguri (horizontal and vertical polarization).

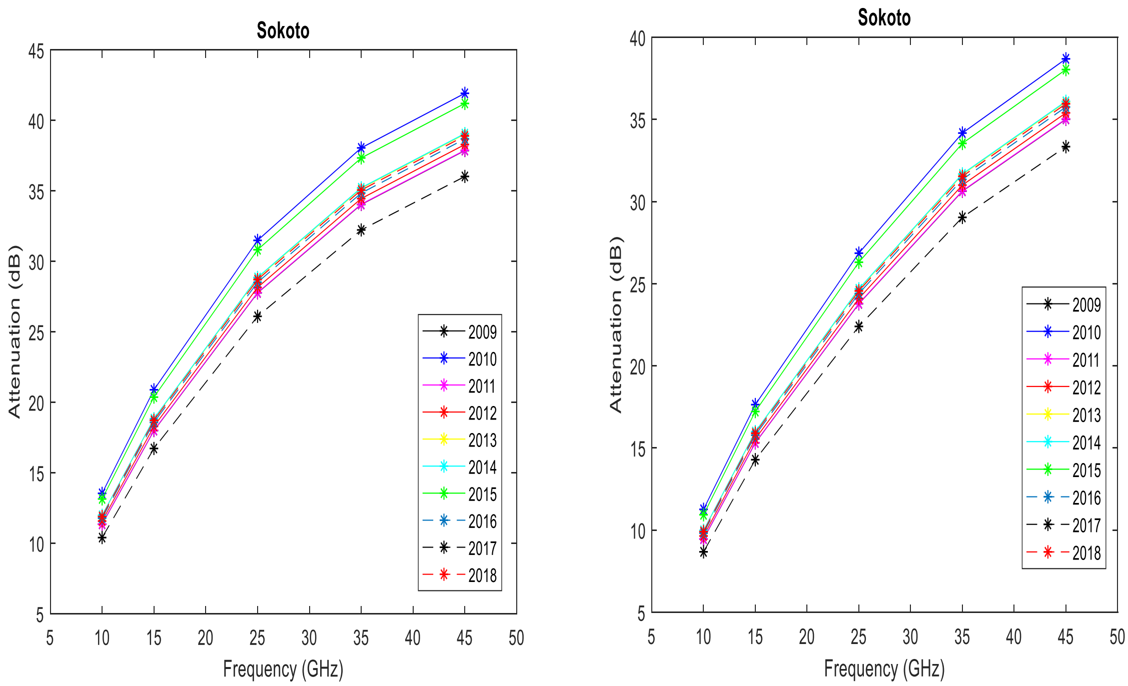

Figure 4: Attenuation at 0.01% exceedance for Sokoto (horizontal and vertical polarization).

As presented in figure 3 (a & b), the attenuation in Maiduguri observed at 15GHz was minimum with a value of 17.56dB in 2011 and maximum with value of 20.29dB in 2018 for the horizontal polarization as suggested by [19] for stations located in same zone as Maiduguri. The vertical polarization showed a relatively lesser value than the horizontal polarization, having its minimum attenuation value of 14.97dB in 2011 and maximum value of 17.15dB in 2018. At 25GHz K-band, minimum and maximum values of 27.20 and 30.71 were observed respectively for horizontal polarization while 23.31dB and 26.22dB minimum and maximum values were obtained respectively for the vertical component in the same year as in 15GHz. As simulations were also done for 35GHz and 45GHz frequencies, minimum and maximum values of 33.4dB and 37.22dB, 37.24dB, and 41.08dB were obtained respectively for horizontal polarization. The values of 30.09dB and 33.44dB; 34.45dB and 37.93dB were obtained respectively for vertical polarization. The difference between the minimum and maximum values of rain attenuation for the study years at Maiduguri ranges between 2dB to 3dB for both horizontal and vertical polarization respectively. These observations show that there were higher rain events in 2018 and lesser rain events in 2011 than other years studied for Maiduguri station.

The results showed in figure 4 (a & b) indicate the same trends of difference in rain attenuation for the selected frequencies under study. In the case of Sokoto, minimum attenuations were observed in 2017 while maximum values were observed in 2010. The difference between the maximum and minimum values, for the years studied, ranges between 4dB to 6dB for the horizontal component also between 3dB to 5dB for the vertical component. The 0.01% rain attenuation results for Sokoto and Maiduguri considering the different bands studied agrees with [20] in which they studied different other locations in Northern Nigeria.

In general, the horizontally polarized signal are predicted to experience higher attenuation than vertically polarized signal [11], for the bands of frequency employed in this study. Also, the estimated attenuation values at elevation angle of 42.5° for 0.01% exceedance probability show that about 99.999% availability, that is approximately 53 minutes signal outage in an average year, is possible for Ku band hence the predicted values of attenuation are less than 20 dB, but total signal outage is expected for the Ka and V band propagations during rainfall in the two earth stations. This is because the predicted attenuation values for those bands are greater than 20 dB. The above inference is made because a large number of satellites links designed for 10 GHz propagation and above are built to resist propagation dampening that are greater than or equal to 20 dB on its link, due to less availability of signal carrying power at the output of the signal strength amplifier [21].

5. Conclusion

This study was carried out using weather and rain parameters of two (2) locations representing the two (2) climate zones in Northern Nigeria. The International Telecommunications Union (ITU-R P.618) rain attenuation model was also used to investigate the rain effect on strength of propagated signal ranging from Ku-band to V-band of the communication spectrum. The weather data were made available by the Nigerian Meteorological Agency (NIMET) over a period of 10years (2009-2018) and assimilated into the model using 1-minute integration time rain rate. An angle of elevation of 42.5^o, which is the conventional angle of elevation of systems to NIGCOMSAT-1R over the Atlantic Ocean region, was used. Results from the study show that Maiduguri experienced maximum and minimum annual rainfall amounts of 1004mm in 2018 and 510.7mm in 2011 respectively. Meanwhile, Sokoto recorded the highest amount of 1146.7mm annual rainfall in 2010 and the lowest amount of 404mm in 2017. Maximum and minimum rain rates were obtained for a 1-minute integration time as 108.60mm/hr in 2018 and 88.96mm/hr in 2011 for Maiduguri; 112.93mm/hr in 2010 and 82.02mm/hr in 2017 for Sokoto; using the Chebil and Rahman rain rate model. The results of rain rate obtained were due to rain intensities observed in the years (2009-2018) of the study

The results from Maiduguri and Sokoto show that rain attenuation at 0.01% exceedance probability affects frequencies at K-band (25GHz), Ka-band (35GHz), and V-band (45GHz) respectively for horizontal and vertical polarization of signal. Also, the difference between maximum and minimum 0.01% attenuation for the two locations are 2dB-3dB, 3dB-6dB for horizontal polarization and 1dB-1.5dB and 2dB-4dB for vertical polarization respectively at the two locations respectively. The Ku-band (15GHz) signals would escape rain attenuation for both polarizations if well managed.

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