RAIN ATTENUATION PREDICTION FOR SATELLITE COMMUNICATION AT Ku-BAND IN NORTH CENTRAL NIGERIA

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Abstract

Prediction of rain attenuation for earth-space links in North Central Nigeria at Ku band is investigated using five of the best performing rain attenuation models: The ITU-R P.618 model, the Bryant model, the Simple Attenuation Model (SAM), the Garcia-Lopez model and the Svjatogor model. Two elevation angles are considered, 55^o and 23^o. The results obtained showed that the ITU-R, Garcia-Lopez and Bryant models performed best in this region. Also, attenuation ranges from 14 dB to 16 dB at 55^{o}elevation angle while it ranges from 20 dB to 22 dB at 23^o elevation angle at exceedance time percentage of 0.01% in all the stations implying that 99.99% (about 53 minute outage in a year) availability of signal is possible at 55^{o}elevation angle but not at 23^o elevation angle.

Key words: Rain Rate, Rain Attenuation, Ku band, elevation angle

1. Introduction

In the design of satellite-to-earth links operating at frequencies above 10 GHz, atmospheric effects play a major role. This is because raindrops normally absorb and scatter radio waves thereby causing signal attenuation and reduction of the system availability and reliability. The severity of rain impairment increases with frequency and also varies with regional locations (Choi *et al*., 1997). Rain attenuation depends on temperature, terminal velocity, size distribution and shape of the raindrops. Although, attenuation due to rain can be accurately measured by the use of satellite beacon signals and radiometers, since such propagation experiments are carried out only in very few places and for a limited number of frequencies and link geometry in the world, results obtained cannot be directly applied to all locations. Hence, various attenuation models based on empirical facts and the use of available meteorological data have been developed to provide enough inputs for system margin calculations in every region of the world (COST 225, 2002). This implies that accurate prediction of rain-induced attenuation on propagation paths is imperative when planning both microwave and terrestrial line-of-sight system links (Salonen and Poiares-Baptista, 1997).

Rainfall effect is more severe in tropical regions which are characterised by high rainfall intensity and the presence of large raindrops (Ojo *et al*., 2008; Moupfouma and Martin, 1995). High rainfall intensity is difficult to be recorded and measured experimentally, as well as highly variable from year to year. In systems design, it is the highest rainfall rates that are of great interest. Also, short integration time rainfall is the most essential input parameter in the prediction models for rain attenuation (Salonen and Poiares-Baptista, 1997).

Two broad classes of rain attenuation prediction on any microwave link exists: The analytical models which are based on physical laws governing electromagnetic wave propagation, and which attempt to reproduce the actual physical behaviour in the attenuation process; and the empirical models which are based on measurement databases from stations in different climatic zones within a given region. When a physical approach is used, not all the input parameters needed for the analysis are available. Therefore, empirical method is the most used methodology (Crane, 2003; Ramachandran and Kumar, 2005; Dutton, and Dougherty, 1979).

In Nigeria, the Nigerian Communication Satellite (NIGCOMSAT-1R) which was launched in 2011 and other satellite outfits like INTELSAT, EUTELSAT, ASTRA, NSS7 and SIRIUS which are linked to various digital television stations like DStv, HiTv, Multi Tv and MyTv Africa operate on Ku band. Therefore, knowledge of the degree of rain-induced degradation in different locations is very important, so as to guide satellite engineers and scientists on improving the quality of local communication networks (Isikwue *et al*., 2013).

For earth-space link design procedure, the margin for rain-induced attenuation must be estimated. It is therefore very important to calculate cumulative percentage of time yearly when rain attenuation on both the downlink and uplink exceeded 0.1% and 0.01% which correspond to about 9 hours per year and about 1 hour per year respectively (Ojo, 2009).

2. Literature Review

The point rainfall rate (mm/h) which is the main input parameter used for the prediction of rain attenuation is estimated from the mean annual rainfall accumulation by using Chebil's model. This model is expressed as:

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

where $R_{0.01}$ is the point rain intensity exceeded at time percentage of 0.01%, M is the mean annual accumulation of rain while α and β are regression coefficients given as 12.2903 and 0.2973 respectively. This simple approach by Chebil is more suitable for the estimation of point rainfall rate since it uses average annual rainfall accumulation, especially for the type of data used in this research. This rain rate model has been widely used for the prediction of rainfall intensity all over the world (Ajayi *et al*., 1996; Emiliani *et al*., 2004; Ojo *et al*., 2009; Obiyemi *et al*., 2014).

There are different rain attenuation models employed for the prediction of rain-induced attenuation for Satellite to earth communication. Five amongst the best models are selected and used for the estimation in this work. These are the globally accepted ITU-R P.618 model (ITU-R, 2009), the Bryant model (Bryant *et al.*, 1999), the Simple Attenuation Model (Stutzman and Dishman, 1984)), the Garcia-Lopez model (Garcia-Lopez *et al*., 1988) and the Svjatogor model (COST 225, 2002). Only the ITU-R model is explained in detail here because of space constraint.

The ITU-R P. 618-9 Model

This model uses rain rate at 0.01% probability level for the estimation of attenuation and then applies an adjustment factor for the predicted rain attenuation depth for other probabilities.

The steps required for the analysis are given below:
Step 1: Determine the rain height, H_R as:

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

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:

$$L_S = \frac{H_R - H_S}{Sin\ \theta} \qquad (3)$$

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:

$$L_G = L_S \text{ Cos } \theta \qquad (4)$$

Step 4: Obtain the point rainfall rate, $R_{0.01}$ (mm/h) exceeded for 0.01% of an average year from one-minute integration rain rate data for the location

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

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

where parameters k and α are determined as functions of frequency in GHz as given in ITU-R P.838-3 (ITU-R, 2005).

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):

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

Otherwise,

$$L_R = \frac{H_R - H_S}{\sin\theta}, for\ \rho \leq \theta \tag{7b}$$

where $$\rho = \tan^{-1}\left(\frac{H_R - H_S}{L_G r_{h0.01}}\right) \tag{7c}$$

therefore, $$v_{0.01} = \frac{1}{1+\sqrt{\sin\theta}\left[31\left(1-\exp\left(-\frac{\theta}{[1+\sigma]}\right)\right)\frac{\sqrt{L_G\,\gamma_{R0.01}}}{f^2} - 0.45\right]} \tag{7d}$$

where $\sigma = 36 - |\varphi|, for\ |\varphi| < 36°$ or $\sigma = 0, for\ |\varphi| \geq 36°$

φ is the latitude of the station

Step 8: The effective path length $L_{eff}(km)$ through rain is calculated as:

$$L_E = L_R v_{0.01} \tag{8}$$

Step 9: The predicted rain attenuation exceeded for 0.01% of an average year is obtained from:

$$A_{0.01} = \gamma_{R0.01} L_E \tag{9}$$

Step 10: The attenuation for other percentage exceedances are thus obtained using the expression below

$$A_p(dB) = A_{0.01}\left(\frac{p}{0.01}\right)^{-[0.655+0.033\ln(p)-0.045\ln(A_{0.01})-z\sin\theta(1-p)]} \tag{10}$$

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

$$if\ p \geq 1\%,\ z = 0 \tag{10a}$$

$$if\ p < 1\%, \quad z = 0 \quad \text{if } |\varphi| \geq 36° \tag{10b}$$

$$z = -0.005(|\varphi| - 36) for\ \theta \geq 25°\ and\ |\varphi| < 36° \tag{10c}$$

$$z = -0.005(|\varphi| - 36) + 1.8 - 4.25\sin\theta, for\ \theta < 25°\ and\ |\varphi| < 36°. \tag{10d}$$

3. Methodology

The daily rainfall data used for this research work was acquired from the Nigerian Meteorological Agency (NIMET). The rainfall data was measured for a period of 33 years (January 1983 to December 2015) in the study area. The instrument employed in the data measurement is the Casella tipping bucket rain gauge (Figure 1).

The Casella rain gauge is a reliable transducer designed as a stand-alone sensor for operation within an existing logging system or data acquisition system. The body and funnel are made of aluminium alloy with an accurately machined septum ring at the top giving an aperture of 400 cm^2 and it is about 18 inches in height. Rain collects on one side of the bucket, which then tips when a predetermined volume of water has been collected. The tipping action discharges the collected water and repositions the opposite side of the bucket under the discharge nozzle ready for filling.

Figure 1: The Casella rain gauge

4. Results and Discussion

The rainfall analyses from the long-term daily rainfall data for the North Central States of Nigeria are presented. The data include non-rainy days and rainy days for the period of 33 years (January 1983 to December 2015). Relevant information for the understudied stations is shown in Table 1.

Table 1: Station Characteristics for North Central Region

Station	Latitude (^{o}N)	Longitude (^{o}E)	Elevation (m)	Average rainfall per annum (mm)
Minna	9.54	6.54	249	1201
Abuja	9	7.28	334	1457
Markudi	7.7	8.5	142	1179
Lokoja	7.47	6.44	204	1229
Ilorin	8.32	4.34	304	1232
Jos	9.58	8.57	1110	1239
Lafia	8.5	8.47	403	1339

Rainfall rate Analysis

The point rainfall rate, $R_{0.01}$ computed from equation 1 for the North Central region are 103.2 mm/h for Minna, 109.4 mm/h for Abuja, 103.9 mm/h for Lokoja, 102.7 mm/h for Makurdi, 104.2 mm/h for Jos, 104 mm/h for Ilorin and 106.7 mm/h for Lafia.

Rain Attenuation Prediction

The point rainfall rate predictions by Chebil model were used as initial input to predict the cumulative distribution of rain attenuation. The five rain attenuation models already mentioned in section two were used. The cumulative distributions of the rain-induced attenuation obtained at different percentages of time were compared for each of the station. 12.675 GHz, which is the Ku band high power downlink frequency, was used. Two elevation angles were considered, 55° and 23°.

The ITU-R model is the most widely accepted method for the estimation of rain attenuation on satellite communication system all over the world, hence the developed models were compared against it for reliability, especially when measured data are not available (Abayomi and Khamis, 2012). Results from experimental data has shown that the ITU-R rain attenuation prediction model which was derived based on lognormal distribution agrees closely with measured values (Choi *et al*., 1997; Emiliani *et al*, 2004; Mandeep and Allnut, 2007; Panchal and Joshi, 2016). This model uses rain rate at 0.01% probability level for the estimation of attenuation and then applies an adjustment factor for the predicted rain attenuation depth for other probabilities. As a result of this global acceptability of the ITU-R model, comparisons carried out in this work are based on the model.

Tables 2 and 3 give brief descriptions of the topographic and climatic features along with the geometrical parameters relevant to satellite links at Ku frequency band.

Table 2: Topographic, Climatic and Geometric features of Links to Satellites at 55° Elevation Angle and 12.675 GHz

Station	Latitude (ºN)	Longitude (ºE)	Elevation (km)	Rain Height (km)	Slant Path Length, LS (km)	Horizontal Projection, LG (km)	Effective Path Length, LE (km)
Minna	9.54	6.54	0.249	4.79	5.54	3.18	3.01
Abuja	9	7.2	0.334	4.76	5.40	3.10	2.88
Lokoja	7.8	6.73	0.204	4.75	5.55	3.18	3.03
Makurdi	7.7	8.5	0.142	4.76	5.64	3.23	3.07
Jos	9.87	8.9	1.11	4.76	4.45	2.55	2.69
Ilorin	8.48	4.58	0.304	4.78	5.46	3.13	2.99
Lafia	8.5	8.47	0.403	4.77	5.33	3.06	2.91

Table 3: Topographic, Climatic and Geometric features of Links to Satellites at 23° Elevation Angle and 12.675 GHz

Station	Latitude (ºN)	Longitude (ºE)	Elevation (km)	Rain Height (km)	Slant Path Length, LS (km)	Horizontal Projection, LG (km)	Effective Path Length, LE (km)
Minna	9.54	6.54	0.249	4.79	11.61	10.69	4.15
Abuja	9	7.2	0.334	4.76	11.33	10.43	3.98
Lokoja	7.8	6.73	0.204	4.75	11.63	10.71	4.20
Makurdi	7.7	8.5	0.142	4.76	11.82	10.88	4.27
Jos	9.87	8.9	1.11	4.76	9.33	8.59	3.74
Ilorin	8.48	4.58	0.304	4.78	11.46	10.54	4.15
Lafia	8.5	8.47	0.403	4.77	11.18	10.29	4.04

The cumulative distribution of the rain induced attenuation obtained for the Ku-band at 55º elevation angle for the stations using the different models were compared. Figures 2a and 2b show the result of the comparison for each of the stations. The Garcia-Lopez and Bryant models predicted closely with the ITU-R model. The SAM and Svjatogor models did not predict correctly as they recorded lower attenuation values. Attenuation values were virtually the same in all the stations since they are all under the same rain zone (the middle belt region of the country). For instance, the rain attenuation predicted by the ITU-R model for 0.001% unavailability of time which is important for internet multimedia applications is 25 dB for Minna, Abuja, Lokoja, Makurdi, Ilorin and Lafia while it is 23 dB for Jos. At this same percentage of time, Garcia-Lopez model predicted 23 dB for Minna, Lokoja, Makurdi, Ilorin, Jos, Lafia and 24 dB for Abuja while Bryant model predicted 24 dB for Minna, Abuja, Makurdi, 23 dB for Lokoja, Ilorin, Lafia and 20 dB for Jos. At 0.01%, the ITU-R model predicted 16 dB for all the stations except for Jos that had 14 dB. Garcia-Lopez model predicted 15 dB for the other stations and 14 dB for Jos while Bryant model predicted 15 dB for every other station except for Jos that recorded 12 dB. At 0.1% which corresponds to an average-year propagation objective (99.9 availability of time), the rain attenuation exceeded using ITU-R model is 7 dB for Minna, 6 dB for the other stations and 5 dB for Jos. The Garcia-Lopez model at this percentage of time predicted 6 dB for Minna, Makurdi, Jos, Ilorin and 7 dB for Abuja, Lokoja and Lafia. At this same percentage of time, the Bryant model predicted 7 dB for the other stations except for Jos that recorded 5 dB. The prediction from the other two models, the Simple attenuation model and the Svjatogor model were not at all close to the aforementioned predictions. These predictions were far lower as observed from the figures, for instance, the SAM predicted between 5 and 7 dB while the Svjatogor model predicted between 8 and 16 dB for the stations at 0.001%.

Figures 3a and 3b show the cumulative distribution of the rain induced attenuation for Ku-band at elevation angle of 23º. It is observed from these figures that there is significant increase in rain attenuation. This is because of the longer path length of the rain region at this lower elevation angle. Therefore, these high attenuation values imply that satellite links with lower elevation angles will suffer more rain attenuation than the ones with higher elevation angles.

From the results obtained, it can be concluded that the ITU-R, the Garcia-Lopez and the Bryant models can satisfactorily be used to predict rain attenuation in this region of Nigeria. Also, at 55ºelevation angle, attenuation generally ranges from 14 dB to 16 dB while it ranges from 20 dB to 22 dB at 23º elevation angle at time percentage of 0.01% in all the stations. These results reveal that at Ku band, 99.99% (about 53 minute outage in a year) availability of signal is possible at 55ºelevation angle since rain attenuation is less than 20 dB but impossible at 23º elevation angle since attenuation here is $\geq$ 20 dB. Therefore, there will be signal fade out at 23° elevation angle during rainfall in all the stations. This deduction is based on the fact that most satellites operating at 10 GHz and above are designed to withstand propagation losses that are ≤ 20 dB on its link because of limited carrier power at the output of the transmission amplifier which is about 150 W and minimal battery power onboard the spacecraft (Ippolito, 1986).

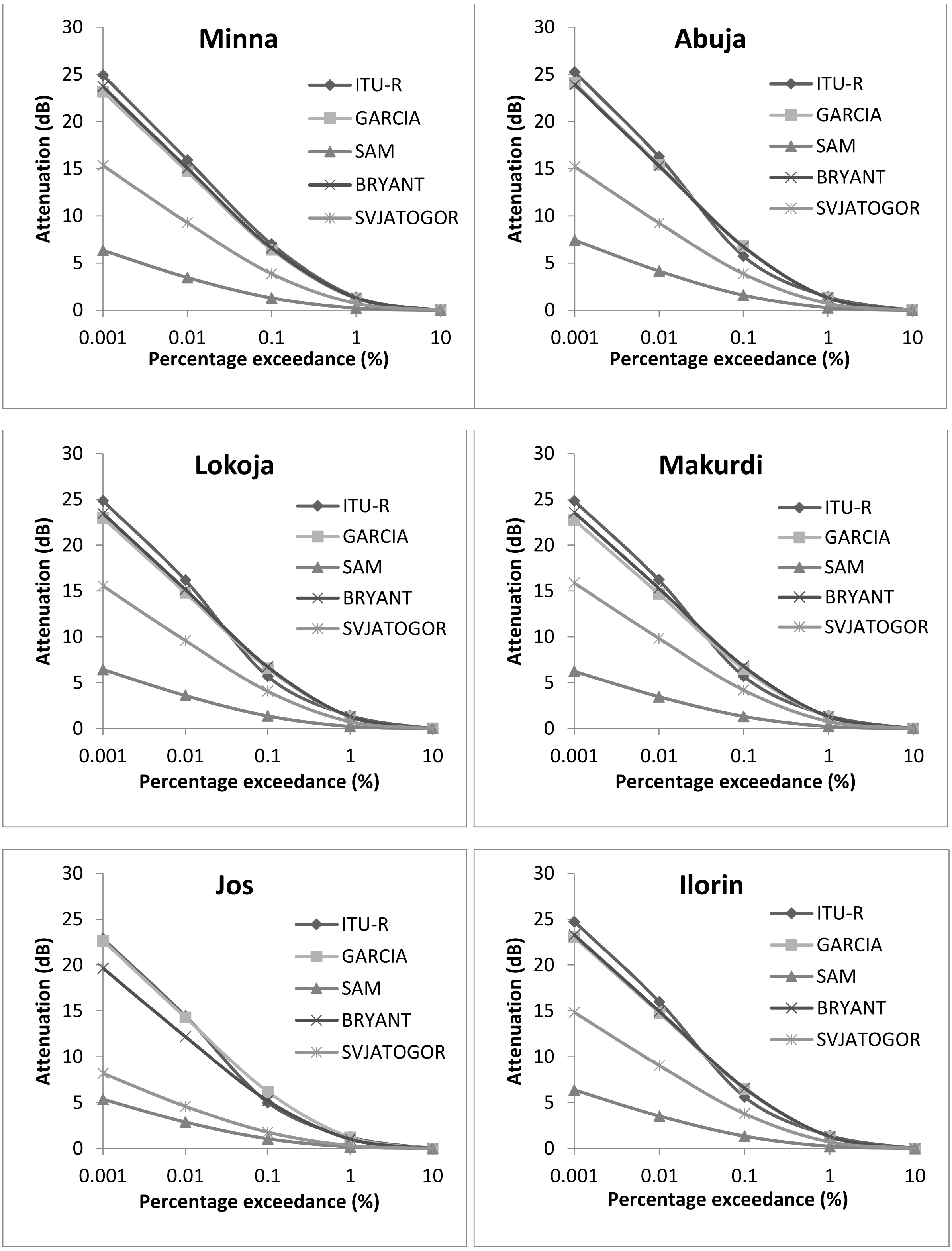

Figure 2a: Comparison of cumulative distribution of rain attenuation models at 55° elevation angle in Minna, Abuja, Lokoja, Makurdi, Jos and Ilorin.

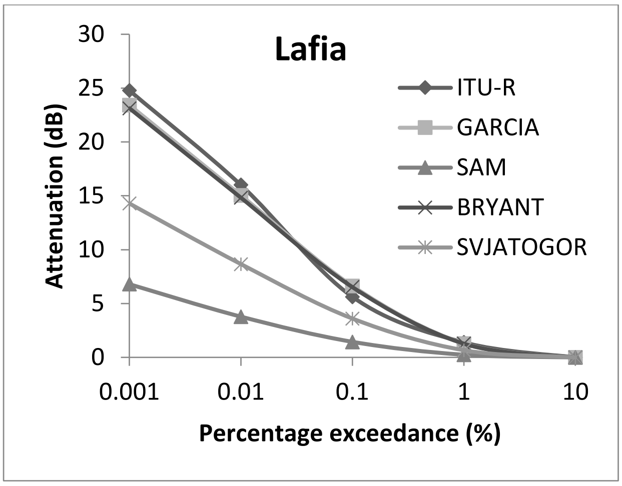

Figure 2b: Comparison of cumulative distribution of rain attenuation models at 55° elevation angle in Lafia

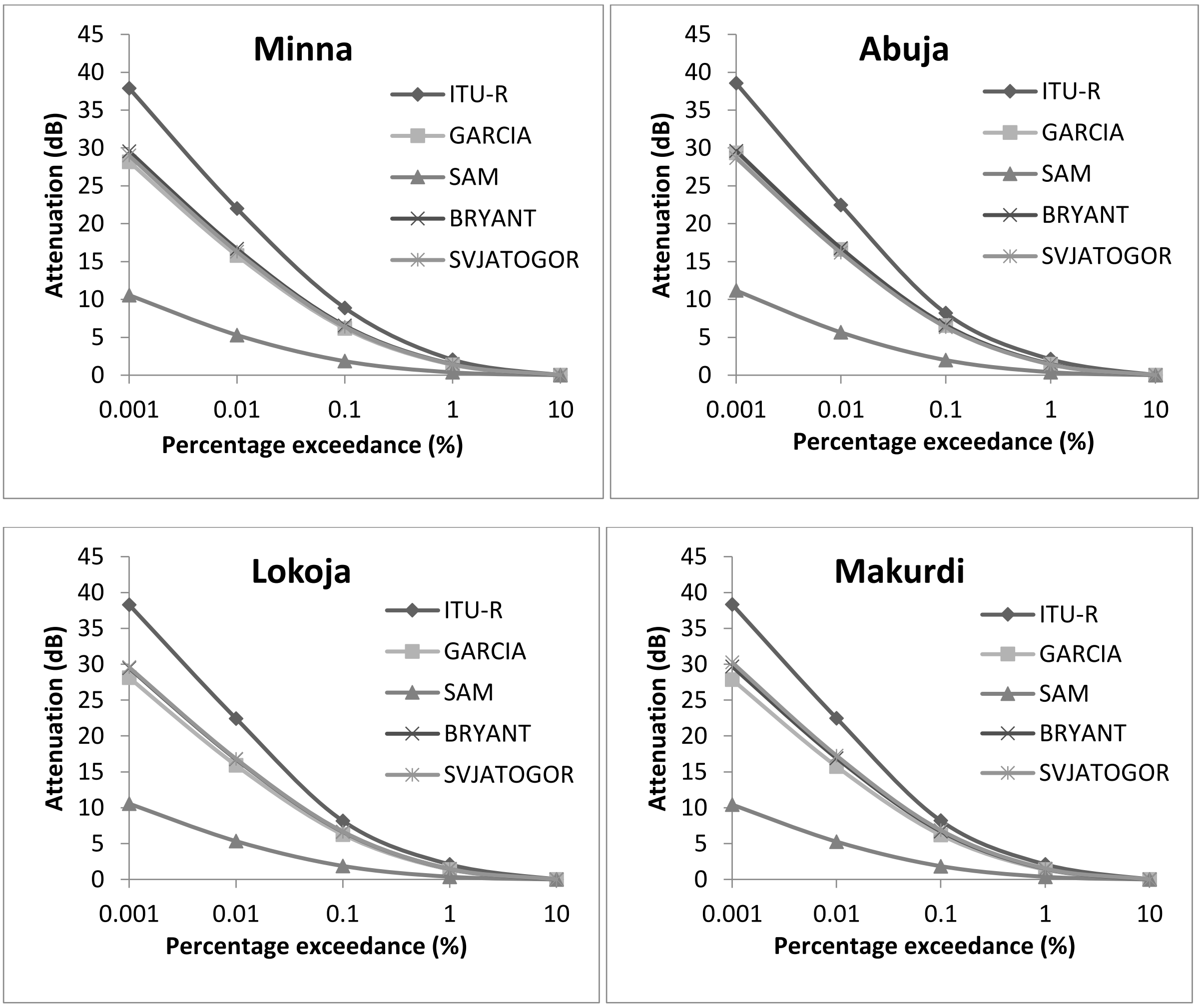

Figure 3a: Comparison of cumulative distribution of rain attenuation models at 23° elevation angle in Minna, Abuja, lokoja and Makurdi.

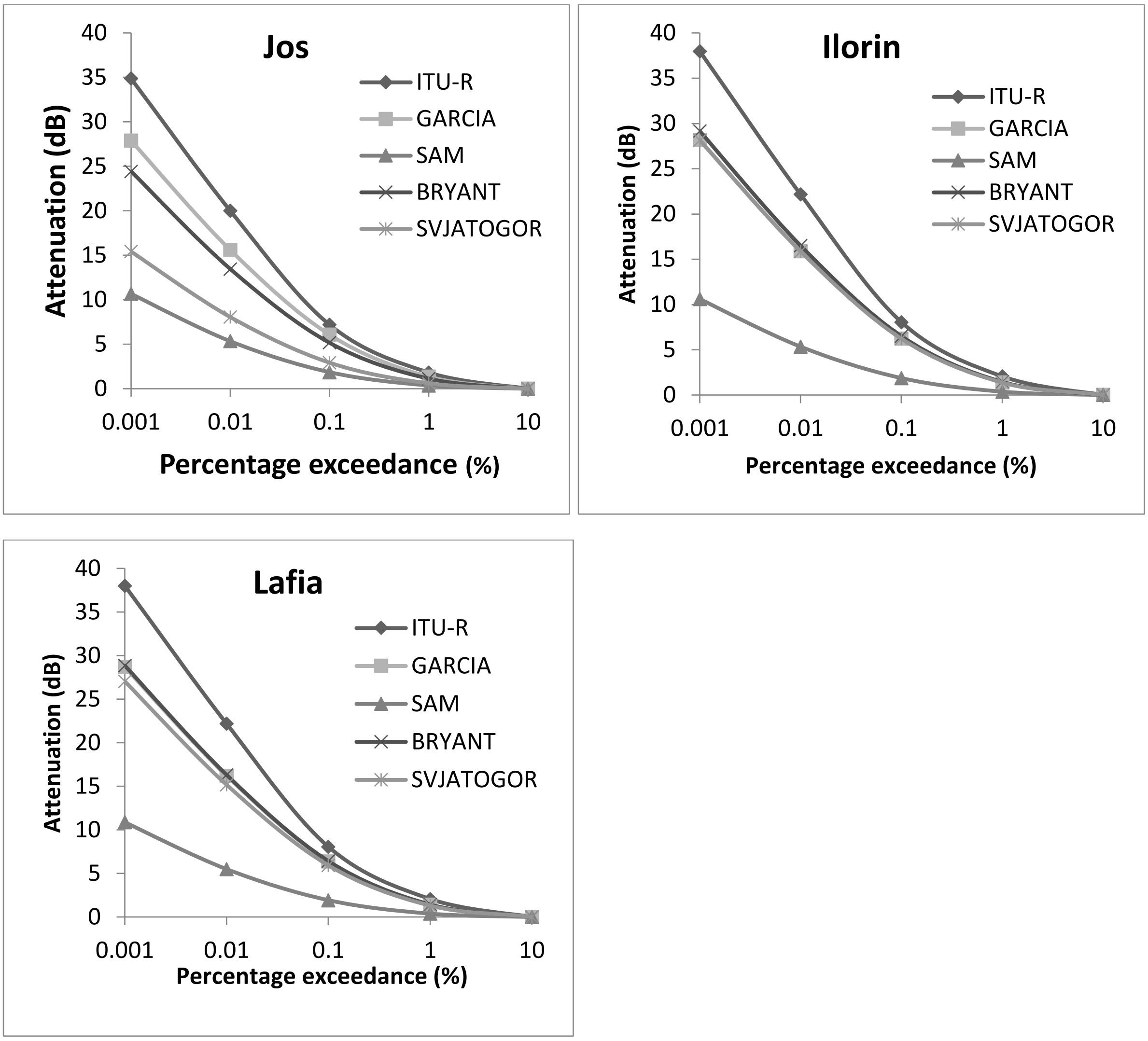

Figure 3b: Comparison of cumulative distribution of rain attenuation models at 23° elevation angle in Jos, Ilorin and Lafia.

5. Conclusion

The prediction of rain attenuation and its effects on satellite communication at Ku band for the North Central region of Nigeria has been investigated for satellite links operating at 55º and 23º elevation angles. This predictions were made using five different rain attenuation models and the results obtained has shown that the ITU model, the Garcia-Lopez model and the Bryant model can satisfactorily be used to predict rain attenuation in this part of Nigeria. From the values of attenuation predicted at time percentage of 0.01% unavailability which is equivalent to 99.99% (about 53 minute outage in a year), availability of signal is possible at 55ºelevation angle but impossible at 23º elevation angle thereby implying signal fade out at 23º elevation angle during rainfall in all the stations.

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