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AHMADU BELLO UNIVERSITY, ZARIA - NIGERIA

Proceedings of the 1st National Communication Engineering Conference 2018

Attenuation Analysis due to Rain at Satellite Frequencies

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ABSTRACT

Rain attenuation is a major source of signal degradation in microwave satellite communication resulting in unavailability of satellite reception during heavy rainfall. The knowledge of attenuation due to rain and its analyses is an essential consideration while setting up a satellite communication link in order to optimize system capacity and provides quality of service (QoS). In this project, a three year Rain rate data was obtained from the Nigeria Meteorological Agency (NIMET) database for all its centers in Northern Nigeria, the rain intensity was derived by converting the rain statistics obtain from NIMET, the converted data to rain intensity and the ITU-R recommended rain intensity models were used to estimate the deviation of rain attenuations at satellite frequencies (C, Ku and Ka-bands). The attenuation result at lower frequency spectrum especially C-band transponders (4-7.5) GHz are lower, while at higher frequencies above 10GHz, Ku-bands (10.7-12.75) GHz and Ka-band (20-30) GHz the attenuation are high, nevertheless, the research shows that rain attenuation is less severe in the Northern part of Nigeria and require lower fade margin for satellite link design purposes at all frequencies.

Keywords—Annual rainfall, rain intensity, satellite frequencies,

1. INTRODUCTION

The rapid growth in communication systems has brought saturation to the most desirable frequency bands (1 to 10 GHz). This fact has led to the utilization of higher frequencies extending the radio frequency spectrum from the cm into the millimeter wavelength region. (Khandaker L. and Mohammad M., 2014).

The presence of various forms of precipitation such as rain, snow, cloud and fog in a radio wave or microwave path is always capable of producing major impairment to terrestrial communications. Hydrometeors can introduce significant attenuation and depolarization, through their ability to absorb and scatter radio waves (Shoewu, O. and Edeko, F., 2011). Attenuation due to rain at microwave frequencies mainly leads to outages that compromise the availability and quality of service, making it one of the most critical factors in designing microwave link in tropical and subtropical regions. The design of new telecommunication systems requires the knowledge of rain fade in that region in order to optimize system capacity and meet quality and reliability criteria (Chebil, J. and Rahman, T., 1999).

For a reliable communication system, unavailability time during a year has to be kept at 0.01%. This corresponds to availability time of 99.99% during a year. Therefore rainfall with one-minute integration time is very important parameter to predict attenuation at 0.01% of time availability (ITU-R, P., 2003).

In this project, three years annual rainfall data was collected at various meteorological stations across Northern Nigerian States from the Agency Headquarter in Abuja. Common rain attenuation prediction methods require 1-min rain rate data, which is scarce in the tropical and subtropical regions. However, annual rainfall data are available at many meteorological stations. **A** method for converting the available rainfall data to the equivalent 1 min rain rate cumulative distribution (CD) was used. This allow for the usage of long-term mean annual rainfall data M at the location of interest (Khandaker L. and Mohammad M., 2014).

2. METHODOLOGY

The annual rainfall statistics (mm) collected from all the meteorological stations was converted first to rain intensity in order to calculate the rain attenuation; some selected rain models recommended by the ITU-R were used and integrated with the ITU-R model which is the most widely accepted international method and benchmark for comparative studies.

3. CONVERSION OF RAIN STATISTICS TO RAIN INTENSITIES

The Moupfouma model, a method for converting the available rainfall data to the equivalent 1 min rain rate cumulative distribution (CD) was used. Several studies have shown that the Moupfouma model with refined parameters can best describe the 1 min rain rate cumulative distribution in temperate and tropical regions. Moupfouma found that the 1 min rain rate CD could be expressed as (Khandaker L. and Mohammad M., 2014).

$$P(R \geq r) = 10^{-4}\left(\frac{R0.01+1}{r+1}\right)^{b} \exp(u[R_{0.01} - r]) \quad (1)$$

Where P is the probability of a rain event at 0.01%of the time, r (mm/h) represents the rain rate exceeded for a fraction of the time, $R_{0.01}$ (mm/h) is the rain intensity exceeded at 0.01 percent of time in an average year, and b is approximated by the following expression:

$$b = \left(\frac{r - R0.01}{R0.01}\right) \ln\left(1 + \frac{r}{R0.01}\right) \quad (2)$$

The parameter U in eqn. 1 governs the slope of rain rate CD, and depends on the local climatic conditions and geographical features. For tropical and subtropical localities

$$U = \frac{4 \ln 10}{R0.01} exp\left(-\lambda\left[\frac{r}{R0.01}\right]^{\gamma}\right) \quad (3)$$

Where λ and γ are positive constants and are given as
λ= 1.066 and γ = 0.214.
$R_{0.01}$ is the rain rate exceeded for 0.01% which is obtained using Chebil model.
Thus, the Moupfouma model requires three parameters; λ, γ and $R_{0.01}$. While the first two parameters λ and γ, have been provided. $R_{0.01}$, is estimated using the Chebil's model. This allows for the usage of long-time mean annual accumulation, M, at the location of interest.
The power law relationship of the model is given by Equation (4):

$$R_{0.01} = \alpha M^{\beta} \quad (4)$$

Where α and β are regression coefficients defined as
α= 12.2903 and β = 0.2973.

However, using the Chebil model, the 1-minute rain-rate cumulative distribution for 20 locations was fully determined from the long term mean annual rainfall data, as presented in table (1).

4. PROJECT PROCEDURES

The ITU-R 618-10gives summarized procedures for the computation of satellite path rain attenuation. In order to compute the slant-path rain attenuation using point rainfall rate, the following parameters are required:

$R_{0.01}$: point rainfall rate for the location for 0.01% of an average year (mm/h)
hs: height above mean sea level of the earth station (km)
θ: elevation angle (degrees)
φ: latitude of the earth station (degrees)
f: frequency (GHz)
Re: effective radius of the Earth (8500 km).

The following steps are used for estimating the long-term statistics of rain attenuation for the design of earth to satellite systems (Khandaker, L. and Mohammad, M., 2014).

Step 1: Determine the rain height, h_R, from the latitude of the earth station φ, from the formula
$h_R = h_0 + 0.36$ km(Recommendation ITU-R P.839).
Where;
$h_0 = 5.0$ for $0^o \leq \varphi < 23^o$ km (5)
$h_0 = 5.0 - 0.075(\varphi - 23)$ for $\varphi > 23^o$ km

Step 2: For $\theta \geq 5^o$ compute the slant-path length L_s below the freezing rain height from:

$$Ls = \frac{(hR - hS)}{\sin\theta} \text{ km} \quad (6)$$

For $\theta < 5^o$, the following formula is used:

$$Ls = \frac{2(hR - hS)}{\left[\sin^2\theta + \frac{2(hR - hS)}{Rs}\right]^{1/2} + \sin\theta} \text{ km}$$

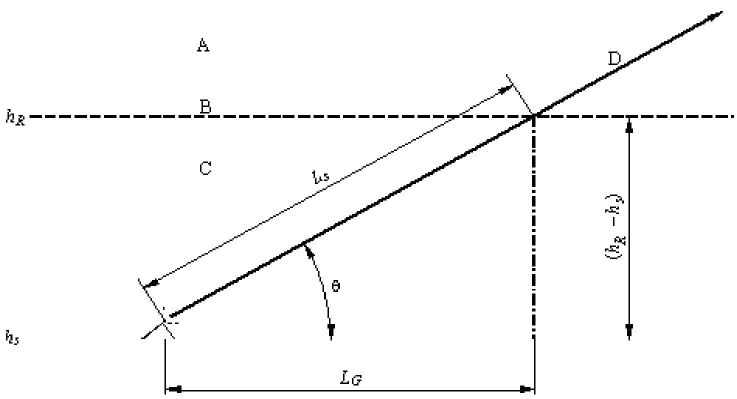

Fig 1: Schematic presentation of an earth-space path given the parameters to be input to the attenuation prediction process.

Where;
A: Frozen precipitation
B: Rain height
C: Liquid precipitation
D: Earth-space path

If $h_R - h_s$ is less than or equal to zero, the predicted rain attenuation for any time percentage is zero and the following steps are not required.

Step3: Calculate the horizontal projection, L_G, of the slant-path length from:

$$L_G = L_s \cos\theta \quad \text{km} \tag{7}$$

*Step4:*Obtain the rainfall rate, $R_{0.01}$, exceeded for 0.01% of an average year (with an integration time of 1 min).

Step5: Obtain the specific attenuation γ_R, using the frequency-dependent coefficients given in Recommendation ITU-R P.838 and the rainfall rate, $R_{0.01}$, determined from

Step4, by using:

$$\gamma_R = k\,(R_{0.01})^{\alpha} \quad \text{dB/km} \tag{8}$$

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

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{LG\,\gamma R}{f}} -- 0.3(1-e^{-2LG})} \tag{9}$$

Step 7**:** Calculate the vertical adjustment factor, $v_{0.01}$, for 0.01% of the time:

$$\zeta = tan^{-1}\left(\frac{(hR - hS)}{LG\,r0.01}\right) \text{degrees}$$

$$\text{For } \zeta > \theta,\ L_R = \frac{LG\,r0.01}{\cos\theta} \quad \text{km}$$

Else,

$$LR = \frac{(hR - hS)}{\sin\theta} \quad km$$

If $|\varphi| < 36^o$, $\chi = 36 - |\varphi|$ degrees

Else, $\chi = 0$ degrees

$$v_{0.01} = \frac{1}{1+\sqrt{\sin\theta}\left[31\,(1-e^{-(\theta/(1+\chi))})\sqrt{\frac{LR\ \gamma R}{f2}} - 0.45\right]} \tag{10}$$

Step 8: The effective path length is:

$$L_E = L_R V_{0.01} \quad \text{Km} \tag{11}$$

It is worth noting that the effective path length L_E can also be obtained by using the unified method for slant paths and terrestrial links model by skipping steps 6-8, where the effective path length can be extended for the slant path case by considering the rain height (Da Silva M., Marlene S., 2012).
The rain height is defined as a function of the zero degree isotherm height, which is mapped all over the world and given in Rec. ITU-R P.839-3.
For a slant path with an elevation angle θ, the effective path length will be given by;

$$L_E = (L) = \frac{1}{LG + LScos\theta}\int_{-LG}^{LScos\theta} Ls(x)dx = \frac{1}{1 + \frac{L_s\cos\theta}{L_G}} \cdot L_S \tag{12}$$

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

$$A_{0.01} = \gamma_R L_E \quad \text{dB} \tag{12}$$

*Step 10:*The estimated attenuation to be exceeded for other percentages of an average year, in the range 0.001% to 5%, is determined from the attenuation to be exceeded for 0.01% for an average year:

$$A_{\%P} = A_{0.01}\left(\frac{P}{0.01}\right)^{[0.065+0.033\ln(P) - 0.045\ln(A0.01\%) - \beta(1-P)\sin\theta]} \tag{13}$$

4. RESULT AND DISCUSSION

This chapter presents results obtained at each stage of this project in both tabular and graphical forms.
Table -1 shows how the long-term mean annual rainfall data M (mm/year) obtained from NIMET was converted to 1 min rain rate data $R_{0.01}$ (mm/h) using the Chebil's power law relationship. The model is applicable to both tropical and subtropical localities. Thus;
$R_{0.01} = \alpha M^{\beta}$
Where α and β are regression coefficients defined as α = 12.2903 and β = 0.2973.

Table 1: Measured mean annual rainfall and converted rain intensity(Nigerian Metrological Agency, 2018).

Stations location	Average annual cumulative rainfall data for 3 years M (mm/year)	Converted rain rate $R_{0.01}$ (mm/hr)
ADAMAWA	1489.5	107.9
ABUJA (FCT)	2184.9	120.9
BAUCHI	2153.5	120.4
BENUE	1805.3	114.3
BORNO	1328.5	104.3
GOMBE	1635.1	111.0
JIGAWA	2195.1	121.0
KADUNA	2315.5	123.0
KANO	1641.2	111.1
KATSINA	1192.7	100.9
KEBBI	1652.0	111.3
KOGI	1977.5	117.4
KWARA	2815.0	130.3
NASARAWA	1997.2	117.8
NIGER	1961.4	117.1
PLATEAU	1809.0	114.3
SOKOTO	1459.5	107.2
TARABA	1532.8	108.7
YOBE	1341.9	104.5
ZAMFARA	1569.7	110.0

5. COORDINATES AND ELEVATION ANGLES

The ground station look angle calculator in figure 4.1is a an online software used for calculating satellite azimuth and elevation angles. It was used in conjunction with the coordinates in table 4.2 obtained from the world atlas to calculate the elevation angles of each location.
The first parameters inputed into the calculator was the coordinate of Adamawa State, which has latitude of 9.208390˚ and longitude of 12.481460˚. The result displayed as the elevation angle was 71.7931˚.

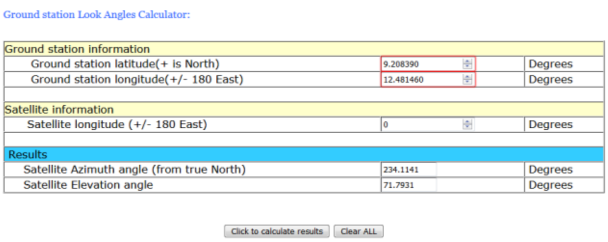

Fig 2: Ground station look angle calculator (Satcom, 2018).

Table 2: Result showing the coordinates and elevation angles obtained (world atlas, 2018).

Stations Location	Latitude $(N)^0$	Longitude $(E)^0$	Height Above Sea Level hs (m)	Elevation Angle (θ)
ADAMAWA	9.208390	12.481460	162	71.7931
ABUJA (FCT)	9.057850	7.495080	476	76.1586
BAUCHI	10.310320	9.843880	616	73.2531
BENUE	7.733750	8.521390	104	76.4498
BORNO	11.846920	13.157120	325	69.2649
GOMBE	10.289690	11.167290	460	72.1746
JIGAWA	12.453470	10.041150	359	71.2326
KADUNA	10.526410	7.438790	626	74.8364
KANO	12.000120	8.516720	484	72.7143
KATSINA	12.990820	7.601770	519	72.3176
KEBBI	12.453890	4.197500	234	74.5246
KOGI	7.796880	6.740480	53	77.8522
KWARA	8.496640	4.542140	320	78.6344
NASARAWA	8.493900	8.515320	179	75.844
NIGER	9.615240	6.547760	243	76.3007
PLATEAU	9.928490	8.892120	1,186	74.3291
SOKOTO	13.062690	5.243220	296	73.4397
TARABA	8.893670	11.359600	349	73.051
YOBE	11.713910	11.081080	427	71.0879
ZAMFARA	12.170240	6.664120	451	73.6825

6. RAIN HEIGHT, HORIZONTAL PROJECTION AND SLANT PATH LENGTH

Steps 2 and 3 from the project procedure was used to calculate the rain height, the minimum and maximum values of the horizontal projection and the slant height as shown in table 4.3;

Table 3: Rain height, horizontal projection slant path and lengths

h_R (km)	Ls at maximum rain rate (km)	Ls at minimum rain rate (km)	L_G at maximum rain rate (km)	L_G at minimum rain rate (km)
4.64	4.6	4.3	0.9	1.3

7. SPECIFIC RAIN ATTENUATION

The specific rain attenuation on satellite frequencies (C, Ku and Ka bands) for both the horizontal and vertical polarities were determined using the equation in step5 $\gamma_R = k\,(R_{0.01})^{\alpha}$

dB/km. The minimum and maximum values of rain rates $R_{0.01}$, (100.9 mm/hr) and (130.3 mm/hr) dB/km respectively and the ITU-R predicted rain rate 111.49 mm/hr served as an input.

The ITU-R recommended frequency dependent coefficients for estimating specific rain attenuation and the results obtained were as shown in tables 4 to 10.

Table 4: Recommended ITU-R P.838-3 Frequency-dependent coefficients

Freq. (GHz)	k_H	α_H	k_V	α_V
1	0.0000259	0.9691	0.0000308	0.8592
1.5	0.0000443	1.0185	0.0000574	0.8957
2	0.0000847	1.0664	0.0000998	0.9490
2.5	0.0001321	1.1209	0.0001464	1.0085
3	0.0001390	1.2322	0.0001942	1.0688
3.5	0.0001155	1.4189	0.0002346	1.1387
4	0.0001071	1.6009	0.0002461	1.2476
4.5	0.0001340	1.6948	0.0002347	1.3987
5	0.0002162	1.6969	0.0002428	1.5317
5.5	0.0003909	1.6499	0.0003115	1.5882
6	0.0007056	1.5900	0.0004878	1.5728
7	0.001915	1.4810	0.001425	1.4745
8	0.004115	1.3905	0.003450	1.3797
9	0.007535	1.3155	0.006691	1.2895
10	0.01217	1.2571	0.01129	1.2156
11	0.01772	1.2140	0.01731	1.1617
12	0.02386	1.1825	0.02455	1.1216
13	0.03041	1.1586	0.03266	1.0901
14	0.03738	1.1396	0.04126	1.0646
15	0.04481	1.1233	0.05008	1.0440
16	0.05282	1.1086	0.05899	1.0273
17	0.06146	1.0949	0.06797	1.0137
17	0.06146	1.0949	0.06797	1.0137
18	0.07078	1.0818	0.07708	1.0025
19	0.08084	1.0691	0.08642	0.9930
20	0.09164	1.0568	0.09611	0.9847
21	0.1032	1.0447	0.1063	0.9771
22	0.1155	1.0329	0.1170	0.9700
23	0.1286	1.0214	0.1284	0.9630
24	0.1425	1.0101	0.1404	0.9561
25	0.1571	0.9991	0.1533	0.9491
26	0.1724	0.9884	0.1669	0.9421
27	0.1884	0.9780	0.1813	0.9349
28	0.2051	0.9679	0.1964	0.9277
29	0.2224	0.9580	0.2124	0.9203
30	0.2403	0.9485	0.2291	0.9129
31	0.2588	0.9392	0.2465	0.9055
32	0.2778	0.9302	0.2646	0.8981
33	0.2972	0.9214	0.2833	0.8907
34	0.3171	0.9129	0.3026	0.8834
35	0.3374	0.9047	0.3224	0.8761
36	0.3580	0.8967	0.3427	0.8690
37	0.3789	0.8890	0.3633	0.8621
38	0.4001	0.8816	0.3844	0.8552
39	0.4215	0.8743	0.4058	0.8486
40	0.4431	0.8673	0.4274	0.8421
41	0.4647	0.8605	0.4492	0.8357
42	0.4865	0.8539	0.4712	0.8296
43	0.5084	0.8476	0.4932	0.8236
44	0.5302	0.8414	0.5153	0.8179
45	0.5521	0.8355	0.5375	0.8123
46	0.5738	0.8297	0.5596	0.8069
47	0.5956	0.8241	0.5817	0.8017

Table 5: Specific attenuation (γ_R) for C, Ku and Ka bands on horizontal at ITU-R ($R_{0.01}$)

ITU-R Horizontal	C-band (4GHz)	Ku-band (12GHz)	Ka-band (20GHz)
α_H	1.6009	1.1825	1.0568
k_H	0.0001071	0.02386	0.09164
γ_R Db/km	0.2029	6.2882	13.3537

Table 6: Specific attenuation (γ_R) for C, Ku and Ka bands on horizontal at minimum $R_{0.01}$

Horizontal	C-band (4GHz)	Ku-band (12GHz)	Ka-band (20GHz)
α_H	1.6009	1.1825	1.0568
k_H	0.0001071	0.02386	0.09164
γ_R Db/km	0.1729	5.5881	12.0170

Table 7: Specific attenuation (γ_R) for C, Ku and Ka bands on horizontal at maximum $R_{0.01}$

Horizontal	C-band (4GHz)	Ku-band (12GHz)	Ka-band (20GHz)
α_H	1.6009	1.1825	1.0568
k_H	0.0001071	0.02386	0.09164
γ_R Db/km	0.2635	7.5612	15.7456

Table 8: Specific attenuation (γ_R) for C, Ku and Ka bands on vertical at ITU-R ($R_{0.01}$)

ITU-R vertical	C-band (4GHz)	Ku-band (12GHz)	Ka-band (20GHz)
α_H	1.2476	1.1216	0.9847
k_H	0.0002461	0.02455	0.09611
γ_R Db/km	0.0882	4.8554	9.9696

Table 9: Specific attenuation (γ_R) for C, Ku and Ka bands on vertical at minimum $R_{0.01}$

Vertical	C-band (4GHz)	Ku-band (12GHz)	Ka-band (20GHz)
α_V	1.2476	1.1216	0.9847
k_V	0.0002461	0.02455	0.09611
γ_R Db/km	0.0779	4.3412	9.0365

Table 10: Specific attenuation (γ_R) for C, Ku and Ka bands on vertical at maximum $R_{0.01}$

Vertcal	C-band (4GHz)	Ku-band (12GHz)	Ka-band (20GHz)
α_V	1.2476	1.1216	0.9847
k_V	0.0002461	0.02455	0.09611
γ_R Db/km	0.1071	5.7833	11.6239

8. THE EFFECTIVE PATH LENGTH

Table 11 shows the average effective path length which was calculated using the formula in step 8, values obtained earlier for the elevation angle, the horizontal projection and slant height length at minimum and maximum rain rates served as inputs for the equation.

Table 11: Effective path length (L_E) calculated at minimum rain rate

L_E minimum (km)	L_E maximum (km)	L_E average (km)
1.0183	0.7598	0.8891

9. Estimated rain attenuation compared with predicted ITU-R values

Tables 12 and 13 shows the estimated rain attenuation obtained using the formula $A_{0.01} = \gamma_R L_E$,in step10, for measured minimum and maximum rain rates ($R_{0.01}$) values at Katsina and Kwara states respectively on both horizontal and vertical polarization as compared with predicted ITU-R values.

ITU-R recommendation P.837-6 contains annexes and maps of meteorological parameters that have been obtained using the European Centre for Medium-Range Weather Forecast (ECMWF) ERA-40 re-analysis database, which are recommended for the prediction of rainfall rate statistics with a 1-minute integration time, when local measurements are not available. The model uses a database of parameters (Pr6, Mt and β), available from the ITU's 3M Group, each of which is matched to a pair of longitude and latitude. This model was used to measure rain rate for comparison purposes (Afahakan I., Udofia K., and Umoren M., 2018). From ITU-RP837-6 mm/hr (A), the recommended rain rate is 111.49 which was used in calculating the attenuation at the predicted ITU-R predicted rain attenuation, while he maximum and minimum rain rates were obtained using rain rates from Kwara mm/hr (130.3) mm/hr and Katsina (100.9) mm/hr respectively.

Table 12: Estimated rain attenuation for all three frequency bands at horizontal polarization

Frequency	$A_{0.01}$ (dB) at Measured Minimum $R_{0.01}$	$A_{0.01}$ (dB) at Measured Maximum $R_{0.01}$	ITU-R Predicted values
4 GHz	0.1538	0.2343	0.1804
12 GHz	4.9683	6.7226	5.5908
20 GHz	10.6844	13.9995	11.8728

Table 13: Estimated rain attenuation for all three frequency bands at vertical polarization

Frequency	$A_{0.01}$ (dB) at Measured Minimum $R_{0.01}$	$A_{0.01}$ (dB) at Measured Maximum $R_{0.01}$	ITU-R Predicted values
4 GHz	0.0693	0.07674	0.0784
12 GHz	4.4207	3.8597	4.3169
20 GHz	9.2019	8.0344	8.8640

10. ATTENUATION

The graphical display showing the results obtained for the attenuation at minimum and maximum measured rainfall as compared with predicted ITU-R values as given in figures 3 to 5.

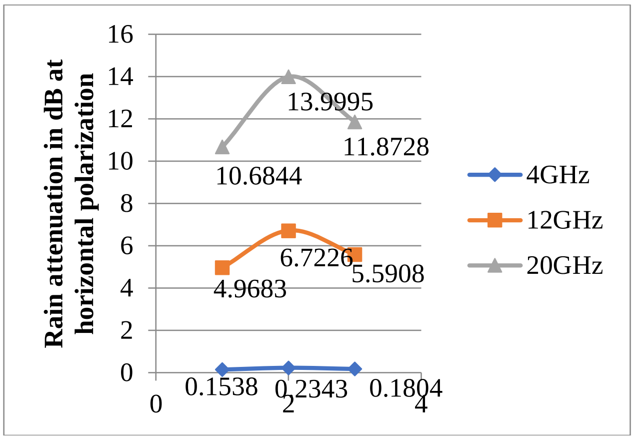

Fig 3: Estimated rain attenuation at minimum and maximum rain rate on horizontal polarization.

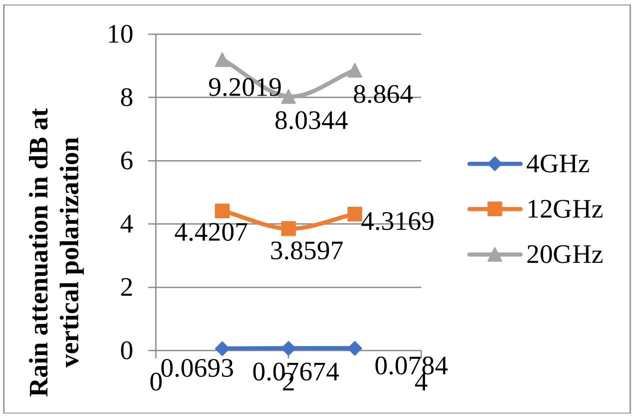

Fig 4: Estimated rain attenuation at minimum and maximum rain rate on vertical polarization.

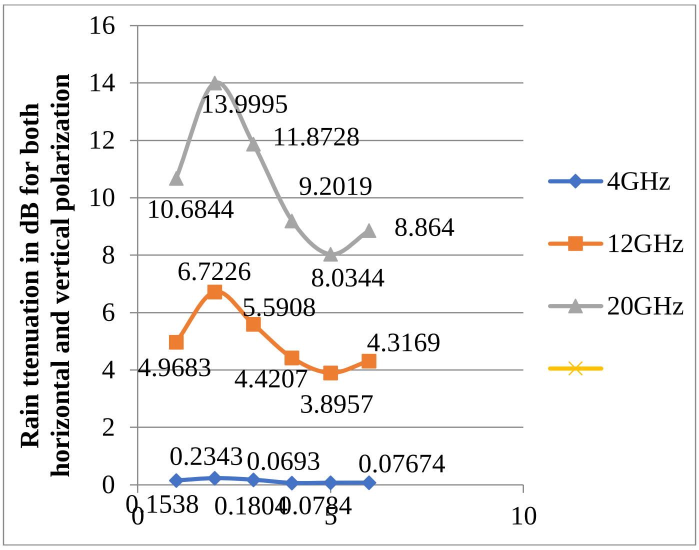

Fig 5: Comparison with predicted attenuations on both horizontal and vertical polarizations

For all the three bands, rain attenuation was estimated and compared with the ITU-R recommended rain attenuation for those regions. It is obvious that attenuation is lower at C-band on both horizontal and vertical polarization than the higher frequencies at Ku-band and Ka-band respectively.

The vertical polarization shows lower attenuation at all frequencies as compared to the horizontal polarization.

Hence to design a reliable microwave link, it is very critical because of higher attenuation at Ku and Ka- bands and needs careful and accurate estimation of rain attenuation, Kwara state has the highest rainfall cumulative distribution and rain rate at (130.3 mm/hr) with Katsina state having the lowest at (100.9 mm/hr) while the recommended ITU-R rain rate is 111.49 mm/hr.

10 CONCLUSION

Rain is a dominant source of attenuation at satellite frequencies in tropical and subtropical regions. Therefore accurate estimation of rain fade is very essential in order to design reliable microwave links in such regions. This was based on the cumulative rainfall data collected for three years in different parts of Northern Nigeria. Using appropriate conversion model, the long-term annual rainfall data was converted to rain intensity data. The rain intensity proposed by the International Telecommunications Union and Radio (ITU-R) as well as the converted data was used to investigate rain attenuation for microwave propagation in these regions at all frequencies.

From the results presented in tables and graphs in chapter 4, it is obvious to note that the level of attenuation due to rain on satellite frequencies was very small on lower frequency (C-band), while it was significantly high on higher frequencies (Ka and Ka) bands, It also shows that attenuation was less on the vertical polarization as compared to the horizontal polarization.
Attenuation at those frequencies was lower in the Northern region as compared to the Southern part of this country, which may serve as a good location to site Fixed Satellite Earth Station.

11 RECOMMENDATION

There was lot of difficulties and delay associated with sourcing data from the Nigerian Metrological Agency to execute this project. Long time research and rain studies should be deployed in future in order to get a more accurate effect of attenuation due to rain on satellite frequencies, also project of this nature needs funding.

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