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Reducing Propagation Losses in Ku-Band Satellite Communication Using ITU-R Model

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Abstract: **In this work, a modified ITU-R model that maximizes the slant-path reduction, increases elevation angle and as a result, minimizes the rain attenuation has been developed. Attenuation losses are predominant phenomena in any signal propagation. These losses are more severe in wireless propagation, in which communication satellite is categorized. Various factors, such as rain attenuation, cloud attenuation, tropospheric scintillation, ionospheric scintillation, water vapour attenuation, rain and ice depolarization, contribute to these losses in different magnitude depending on the frequency of the signal propagation. In Satellite communication propagation above 10GHz, eg ku-band, Rain is the most outstanding contributor to the major signal impairment. ITU-R has put up models for predicting and/or reducing individual causes of propagation impairment. However, the existing ITU-R model for rain attenuation is "static" meaning that the modeling parameters of the ground stations are referenced to the longitude of the space segment. This, however, does not optimize the goal of reducing the slant-path, increasing the elevation angle and consequently reducing the rain attenuation efficiently. In this paper, rain attenuation is calculated using Modified ITU-R rain attenuation model. The outputs of the work are used to calculate the rain attenuation and comparison are made with the existing ITU-R model. The result shows that the proposed modified ITU-R model achieves significant improvement in rain attenuation reduction.**

Keywords: **Rain Attenuation, Elevation Angle, Slant Path, Ku-band, ITU-R, Model.**

I. Introduction

Ku-band is very popular for satellite communication services, because of its small component size; and its less interference at higher frequencies[1]. However, Propagation of radio wave via frequency band above 10GHz is severely affected by rain attenuation. Rain-induced attenuation is the major issue at frequencies above 10 GHz, more especially in tropical regions which experience heavier rainfall intensities [2]. Rain attenuation plays significant role in the design of terrestrial and Earth-satellite radio links especially at frequencies above 10 GHz . It is important to include rain fade margin when designing the satellite link budget. The rain fade margin is a component of the link margin and it is a calculation based on the expected rain attenuation over one year. The rain fade calculation takes into consideration the rainfall data, elevation angle ,rain attenuation, gaseous attenuation, free space path loss, system noise interference, depolarization, scintillation and slant range of an earth station from the satellite.

A lot of works have been done to Mitigate Propagation Impairments in Communication Satellite, and specifically in Ku-band. [3] carried out study on Atmospheric Propagation Model for Satellite Communications Which itemized impacts of each impairment factor and model for those factor. An improved ITU-R rain attenuation prediction model over terrestrial microwave links in tropical region" offered an improved approach of predicting rain attenuation cumulative distribution (CD) over microwave links. These studies achieved precedence on determining rain attenuation based on 0.01% rain rate attenuation and link availability of SATCOM. However, they did not account for the individual parametric contributions and consequences to rain attenuation. This study capitalizes on this shortcoming and proposed a modified ITU-R model that maximizes the slant-path reduction, increased elevation angle and as a result, minimizes the rain attenuation.

II. Theoretical Background

ITU-R Model: The ITU-R model calculates the rain statistics via data files which are indexed by latitude/longitude for giving clearer estimate for rain statistics rather than looking at the concept of rain region. The model divides rain on the earth on the basis of rain rate(denoted by A to P excluding I and O) aside from providing the probability of the given rain-rate being exceeded. The ITU model provides only the 0.01% rain statistics for predicting rain fade depth. ITU Rain attenuation model provides estimates of the long-term statistics of the slant-path rain attenuation at a given location for frequencies up to 55GHz. The method adopted by ITU to calculate the cumulative distribution of rain attenuation is extremely simple and require only the knowledge of the values of rainfall rate exceeded for 0.01% of time of an average year in the location of interest. The following parameters are required:

H_S=>height above mean sea level of the earth station(km)

$\theta_{elevation}$=>elevation angle(degrees)

α_{ES}=>latitude of earth station(degrees)

f =>frequency(GHz)

R =>radius of the earth(km)

The International Telecommunication Union (ITU) divided the globe into 15 rainfall climatic zones and categorized Nigeria as Region P, countries with very high rain precipitation. The knowledge of the mean and rainfall distribution and the climate will provide a broad view on the expected rain attenuation in order to calculate the rain attenuation prediction from the recommended measurements of local one-minute integration time of rain rate statistics are required.

Input Parameters for ITU-R Attenuation Model: Satellites in geostationary orbit are 35,800 km above the earth, and since rain only forms in the troposphere, which extends seven miles above the earth, a signal travelling through a rain cell will experience attenuation during only a small portion of its transmission path [4]. The important input parameters are azimuth and elevation which are computed from the absolute values of longitude and latitude. Rain attenuation is one of the most crucial factors to be considered in the link budget estimation for microwave satellite communication systems, operating at frequencies above 10 GHz [5].The elevation angle, altitude and latitude are used for calculating the slant path. The slant path is in turn used for calculating the rain attenuation for a particular region or location. The Input Parameters are listed here below:

Elevation Angle: The angle of elevation is the angle at which the satellite appears above the horizontal. If the angle is too small then signals may be obstructed by nearby objects if the antenna is not very high. For those antennas that have an unobstructed view there are still problems with small angles of elevation. The reason is that signals have to travel through more of the Earth's atmosphere and are subjected to higher levels of attenuation as a result. An angle of five degrees is generally accepted as the minimum angle for satisfactory operation. The elevation angle, also called the altitude, of an observed object is determined by first finding the compass bearing on the horizon relative to true north, and then measuring the angle between that point and the object, from the reference frame of the observer. Elevation angles for objects above the horizon range from 0 (on the horizon) up to 90 degrees (at the zenith). Sometimes the range of the elevation coordinate is extended downward from the horizon to -90 degrees .

Slant Path: Slant path means the total propagation length that radio signals would travel in the rainy medium. This is the line-of-sight distance between the satellite and the earth station. It is the length of the satellite-to-ground path that is affected by a rain cell as shown in figure 1b. The slant path delay is proportional to the difference between the travel time of a signal from a satellite to a ground-based receiver and the travel time that would occur if there was no atmosphere affecting the signal propagation [6].Rain attenuation is directly proportional to the slant path. The Slant-Path length, L (km), is represented in figure 1a as D_{RAIN}.

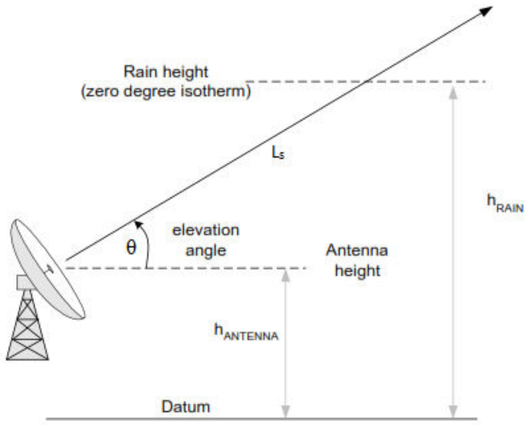
Specific Attenuation: The specific rain attenuation is a fundamental quantity in calculation of rain attenuation statistics for terrestrial and earth-space paths. The power-law relationship of specific rain attenuation y_R (dB/km) and rain rate R (mm/h), $y_R = kR^a$ is widely used and the values of k and a are usually tabulated for specific frequencies. Regression to determine the relationships between the parameters, k and a, and frequency has been done and the regressed expressions given in eqn 3

The point rain rate: R0.01 (mm/h). The rainfall during a given time interval (or often one storm) measured in a raingage, or an estimate of the amount which might have been measured at a given point. R0.01 (mm/h) exceeded for 0.01% of an average year may be obtained for one-minute integration rain rate data, from Nigeria Meteorological Agency.

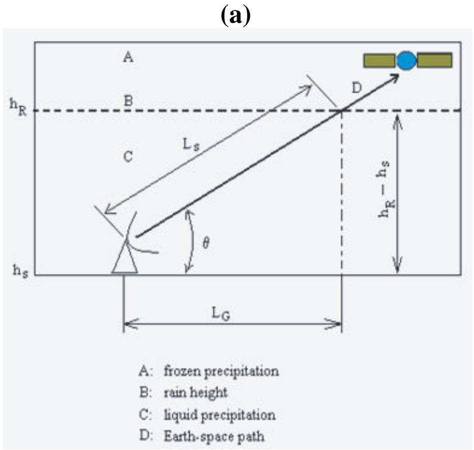
Rain Attenuation Model: To date, several rain attenuation models such as the Global Crane [7] and ITU-R P.618-8 [8] have been created to compute the rain fade figure for earth-space telecommunication systems. Rain models predict attenuation for a given frequency from site-related parameters such as rain intensity statistics, rain height and path-elevation angle. Most of the models available today are developed based on the data collected from temperate regions[9].

The principal objective of a rain attenuation model studied in this research is to achieve an accurate estimation of the attenuation level incurred by the signal due to rain which is key to realizing a reliable SATCOM system.

This rain attenuation model utilizes a methodology similar to ITU-RP.618-8,with the derivation of rain fall parameters such as the specific attenuation and path reduction factor being optimized to local data and findings. Together with the site-related parameters, the four key characteristics that influence the level of rain attenuation are as explained in fig.1 a and b below:



(a)



(b)

Fig.1: Diagram for attenuation predication

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Ku-band (and other frequency bands above 10GHz) satellite communication suffers Rain Fade as the dominant factor in path loss variation.

Rain fade margin is included when designing the satellite link budget. The rain fade margin is a component of the link margin and it is a calculation based on the expected rain attenuation. The rain fade calculation takes into consideration the rainfall data, elevation angle, rain attenuation, gaseous attenuation, free space path loss, system noise, interference, depolarization, scintillation and slant range of an earth station from the satellite.

This research describes the Modified ITU-R methods for calculating rain fade. The results can be used to relate the required availability of satellite circuits to the fade margin that must be included in the link budget.

III. Methodology

Ku-Band SATCOM Rain Fade Modeling by ITU-R

The Rain Attenuation Reduction in Db can be modeled by ITU-R by obtaining the product of Specific Attenuation (dB/km) and the Slant Path (km):

$$A_{RAIN}=\gamma_R D_{RAIN}$$

Where, A_{RAIN} is the rain attenuation loss in dB, D_{RAIN} is the path length through the troposphere in Km; γ_R is the specific attenuation(dB/Km)

Key Input Parameters

- Latitude and longitude of the earth station (degrees)
- The frequency of operation(GHz)
- Elevation Angle (θ) (degrees)
- Effective path length (D_{RAIN}) (Km)
- Specific Attenuation (γ_R)(dB/Km)
- Rain Attenuation (A_{RAIN})(dB)

Elevation Angle (degrees)

Elevation refers to the angle between the beam pointing direction, directly towards the satellite, and the local horizontal plane. Rain attenuation decreases with increase in elevation angle. It is the up-down angle. At low elevation angles, below 5 degree, the path through the atmosphere is longer and the signals are degraded by rain attenuation and rain thermal noise.

Step 1: Elevation Angle ($\theta_{elevation}$) Mathematical Model

The ITU-R Mathematical Model for Elevation Angle

ITU-R Mathematical Model for Elevation Angle is stated in the equation below:

$$\theta_{elevation} = \cos^{-1}\left[\sqrt{h^2 - 2R(h+R)[1-\cos(\alpha_{ES})\cos(\theta_{SAT}-\theta_{ES})]} \times \sqrt{1-cos^2 \times P}\right] \quad ...(1)$$

where $P= \alpha_{ES}cos^2(\theta_{SAT}-\theta_{ES})/(R+H)$

The elevation angles were calculated using ITU-R [Barclay,2003]

Modifying the Elevation Angle:

$$\beta = \begin{cases} \theta SAT\text{-}\theta ES; & if\ \theta SAT\text{-}\theta ES \le \theta ES \\ \theta ES; & if\ \theta SAT\text{-}\theta ES > \theta ES \end{cases}$$

where $\theta_{elevation}$ is the angle of elevation, *h* and R are 35786 km and 6378.1 km and are the distances of the geosynchronous orbit and the radius of the Earth respectively, α_{ES} is the latitude of the earth station, θ_{ES} is the longitude of the earth station and θ_{SAT} is the longitude of the satellite.

Slant-Path Length (km)

This is the line-of-sight distance between the satellite and the earth station. It is the length of the satellite-to-ground path that is affected by a rain cell as shown in figure 1b. The Slant-Path length, L (km), is represented in figure1b as D_{RAIN}. It is mathematically modeled as shown below.

Step 2: The slant-path length Mathematical Model, L (km), represented in fig.1 as D_{RAIN}, below the rain height is calculated as:

$$D_{RAIN} = 42{,}643.7 \times 103 \times \sqrt{[1 - 0.29577 \times \{\cos(\alpha_{ES})\cos(\theta_{SAT} - \theta_{ES})\}]} \quad ...(2)$$

Modified as:

$$D_{RAIN} = 42{,}643.7 \times 103 \times \sqrt{[1 - 0.29577 \times \{\cos(\alpha_{ES})\cos(\beta)\}]}$$

$$\beta = \begin{cases} \theta SAT\text{-}\theta ES; & if\ \theta SAT\text{-}\theta ES \le \theta ES \\ \theta ES; & if\ \theta SAT\text{-}\theta ES > \theta ES \end{cases}$$

The Slant Path Length were calculated using ITU-R [Barclay,2003]

The specific attenuation (γ_R) (dB/km)

The specific attenuation for uniform rain γR (dB/km) at a given frequency may be obtained from the knowledge of the complex index of refraction of water at the temperature of the raindrops, the terminal velocity, the polarization and the size distribution of the raindrops

Step 3: Specific Attenuation (γ_R), (dB/km) Mathematical Model is calculated from:

$$\gamma_R=kR^{\alpha} \quad ...(3)$$

where the values of the *k* and *α* coefficients which differ according to polarization. The parameters *k* and *α* depend on frequency, rain temperature, raindrop size distribution, and polarization. Their values can be obtained from ITU-R P.838-3[10].Table 1 summarizes the values of *k* and *α* and the corresponding specific attenuation, γ_R.

Table 1: Values of the *k* and *α* coefficient used to determine specific rain attenuation, γ_R.

Rain Attenuation

Attenuation is a general term that refers to any reduction in the strength of a signal.

Step 4: Rain Attenuation (A dB): The predicted attenuation exceeded for 0.01% of an average year is obtained from [7]:

$$A_R=\gamma_R * D_{RAIN} \quad ...(4)$$

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IV. Results and Discussions

Data Collection and Results

Monthly rainfall, maximum temperature, and minimum temperature data for the selected cities were obtained from the Nigerian Meteorological Agency (NIMET), Oshodi Lagos, Nigeria; the agency responsible for the measurement, control, and storage of the hydro-meteorological data in Nigeria, and from Nigerian Communications Satellite Ltd (nig Comsat), Lugbe, FCT, Abuja, Nigeria; the commission that manages and exploits the commercial viability of the Nigerian Communication Satellite for the social economic benefit of the nation.

The nature of data collected are rainfall depth (mm) recorded for every month of the year and Longitude, Latitude and NigComSat 1-R longitude. For the analysis, the average of the monthly data were computed to give an average annual value. A summary of statistics for the meteorological variables is presented in Table 2

The design and simulation were done using MATLAB and Simulink as shown in fig 2. The rain attenuation experienced by the signals in the vertical polarizationatthe15locations of study predicted by the Existing Model ITU-R and by the modified ITU-R 618-10 with R0.01 are shown in Fig.3 and 4 respectively

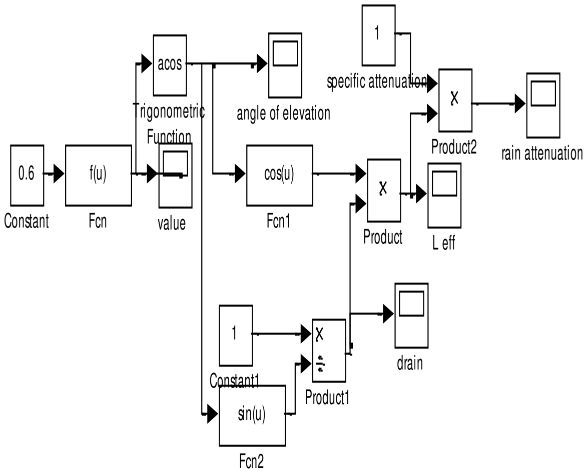

Fig.2: MATLAB Simulation of Modified ITU-R Rain Attenuation Model

Rain Attenuation Result Analysis

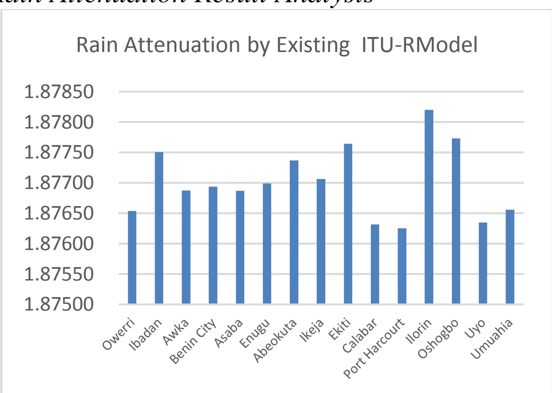

Fig.3: Rain Attenuation (dB) by Existing ITU-R Model

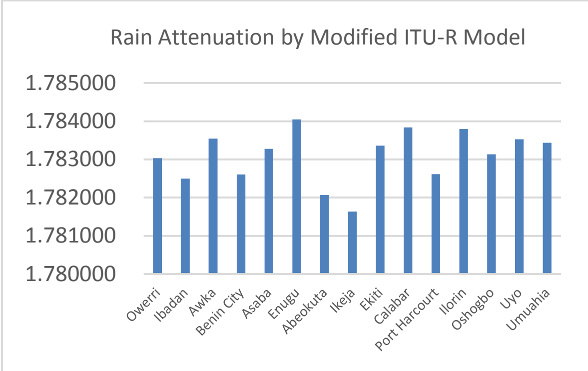

Fig.4: Rain Attenuation (dB) by Modified ITU-R Model

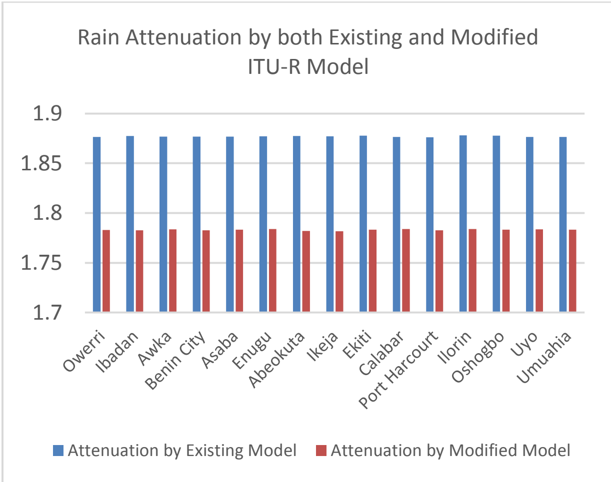

Fig.5 Comparison of Attenuation Reduction by Modified R Model relative with existing ITU-R Model

Fig.2: Rain attenuation (dB) for ku-band SATCOM by existing ITU-R Model for 15 different locations in the Southern Part of Nigeria. The maximum. The maximum attenuation occurs

Comparison of fig 3.with fig.4 for results obtained from Existing ITU-R model with the Modified ITU-R model for Ku-band SATCOM Rain Attenuation, show that significant reduction in Rain Attenuation across all the 15 locations understudy. There is, on the average, 5.00% Reduction in Rain Attenuation by the Modified ITU-R model relative to the Existing ITU-R model. Fig.5 shows the Percentage Rain Attenuation Reduction of the Modified Model when compared to the Existing ITU-R model.

There is an average of 14.25% increase in the Elevation Angle by the Modified ITU-R model when compared to the Existing ITU-R Model. This is shown in fig.6. Thus, the increase in Elevation Angle is consistence with the Reduction in Rain Attenuation.

As earlier outlined, the slant path of the Earth Station decrease with decrease in Rain Attenuation. In fig.7, the Slant Path of both the Existing and Modified ITU-R models are shown. There is an average 5.00% decrease in the slant path by use of the Modified ITU-R model when compared to the Existing ITU-R model.

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Elevation Angle Result Analysis

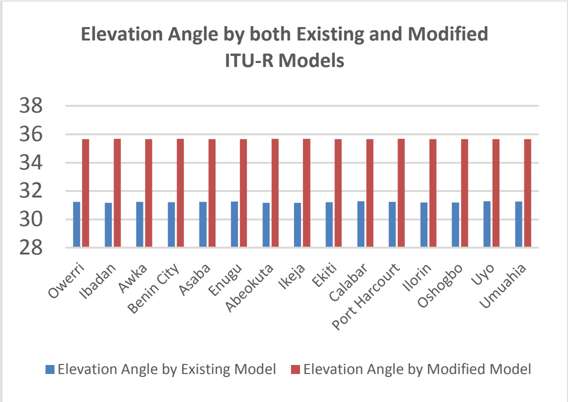

Fig.6: Elevation Angle by both Existing and Modified ITU-R Models

Slant Path Result Analysis

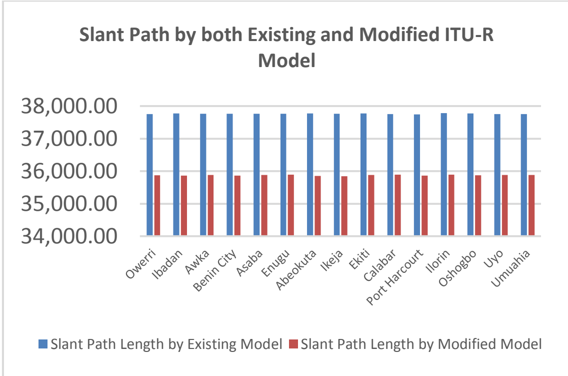

Fig.7: Slant Path (km) for both Existing ITU-R and Modified ITU-R models

Based on the results, it can be summarized that a major factor in reduction of Rain Attenuation by Modified ITU-R is the low elevation angle.

Table 1: Values of the k and α coefficient used to determine specific rain attenuation, γ_R.

Rain fall rate,R	Frequency (GHz)	Vertical Polarization			Horizontal Polarization		
		k	α	γ_R(db/km)	k	α	γ_R(db/km)
0.01	4.2	0.000648	1.095	0.00000418384	0.000724	1.2634	0.00000215248
0.01	11.2	0.01333	1.224	0.0000474080	0.01494	1.239	0.0000496993

Table 2: A summary of statistics for the meteorological variables

Earth Station	Maximum me-an mo-nthly rainfall Rate (mm)	Height above mean sea level, $h_{ANTENNA}$ (km)	Latitude North	Longitude East	Elevation angle, $\Phi_{elevation}$ (towards 42.8∘E) by Existing model	Elevation angle, $\Phi_{elevation}$ (towards 42.8∘E) by Modified model	Path Length L_S (km) by Existing Model	Path Length L_S (km) by Modified Model	Specific Attenuation γ_R (dB/km)	Rain Attenuation $A_{R\ (dB)}$ by Existing model	Rain Attenuation $A_{R\ (dB)}$ by Modified model	(%) Reduction
Owerri	2302	0.159	5.48	7.03	36.07	40.26	37,757.78	35,876.38		17.774032	16.748146	5.59
Ibadan	1091	0.239	7.39	3.91	36.03	40.29	37,777.30	35,865.60		17.745703	16.737271	5.68
Benin City	2003	0.08	6.34	5.63	36.11	40.29	37,764.56	35,886.67		17.735174	16.74437	5.59
Asaba	1784	0.055	6.2	6.73	36.04	40.27	37,765.85	35,867.81		17.744597	16.743648	5.64
Enugu	1690	0.248	6.44	7.49	36.09	40.28	37,764.46	35,881.22	4.184 E-06	17.737898	16.744425	5.6
Abeokuta	1232	0.067	7.15	3.35	36.15	40.31	37,766.87	35,896.88		17.730072	16.743083	5.57
Ikeja	1196	0.041	6.59	3.34	35.99	40.27	37,774.53	35,857.03		17.749981	16.738814	5.7
Ekiti	2181	0.456	7.62	5.22	35.96	40.25	37,768.42	35,848.19		17.754386	16.742218	5.7
Calabar	2597	0.099	4.95	8.32	36.09	40.32	37,780.03	35,883.04		17.736992	16.735744	5.64
Port Harcourt	2117	0.468	4.78	7.01	36.13	40.27	37,753.38	35,892.58		17.732221	16.750593	5.54
Ilorin	1058	0.29	8.5	4.55	36.04	40.24	37,752.07	35,867.94		17.744534	16.751325	5.6
Enugu	1690	0.317	7.77	4.57	36.13	40.36	37,791.28	35,891.73		17.732648	16.729471	5.66
Uyo	2071	0.196	5.03	7.93	36.08	40.32	37,781.87	35,878.46		17.739276	16.734723	5.66
Umuahia	2051	0.152	5.53	7.49	36.11	40.26	37,754.02	35,886.30		17.735361	16.750239	5.55

Table 3: Slant Path, Elevation Angle and Attenuation by Existing and Modified ITU-R Model

City	Slant Path Le ngth by Existing Model	Slant Path Length by Modified Model	(%) RReduction in Slant Path	Elevation Angle by Existing Model	Elevation Angle by Modified Model	(%) Increase in Elevation Angle	Attenuation by Existing Model	Attenuation by Modified Model	(%)Reduction of Attenuation
Owerri	37,757.78	35,876.38	4.9828	31.24	35.6676	14.172887	1.8765351	1.7830312	4.9827941
I Ibadan	37,777.30	35,865.60	5.0604	31.17	35.6742	14.450305	1.8775052	1.782495	5.0604493
Awka	37,764.56	35,886.67	4.9726	31.24	35.6613	14.152529	1.8768721	1.7835426	4.9726056
Benin City	37,765.85	35,867.81	5.0258	31.2	35.6731	14.336795	1.8769365	1.7826051	5.0258141
Asaba	37,764.46	35,881.22	4.9868	31.23	35.6647	14.2	1.8768672	1.7832717	4.9867939
Enugu	37,766.87	35,896.88	4.9514	31.26	35.655	14.059341	1.8769869	1.7840498	4.9514
Abeokuta	37,774.53	35,857.03	5.0762	31.16	35.6796	14.504525	1.8773676	1.782069	5.0761782
I Ikeja	37,768.42	35,848.19	5.0842	31.16	35.6854	14.523139	1.877064	1.7816302	5.0842082
Ekiti	37,780.03	35,883.04	5.0211	31.2	35.6633	14.305545	1.8776413	1.7833618	5.0211641
Calabar	37,753.38	35,892.58	4.9288	31.28	35.6572	13.993574	1.8763167	1.7838362	4.9288344
Port har-rcourt	37,752.07	35,867.94	4.9908	31.24	35.6729	14.189693	1.8762514	1.7826114	4.9907988
I Ilorin	37,791.28	35,891.73	5.0264	31.18	35.6576	14.360391	1.8782002	1.7837937	5.0264316
Oshogbo	37,781.87	35,878.46	5.0379	31.18	35.6661	14.387588	1.8777323	1.7831346	5.0378684
Uyo	37,754.02	35,886.30	4.9471	31.27	35.6612	14.042853	1.8763483	1.783524	4.9470679
Umuahia	37,758.21	35,884.58	4.9622	31.25	35.6624	14.119808	1.8765568	1.7834383	4.9622
Average Values			5.0036			14.253265			5.0036406

V. Conclusion

This study has presented the results on rainfall rate, and rain attenuation Ku-band Communication Satellite links. The relationship between effective specific attenuation, Path length, and rain attenuation by modified ITU-R predicted is investigated. The e results have clearly shown that the approach adopted by the current ITU-R method seems to be unsuitable for predicting rain attenuation. A new set of numerical coefficients was derived for improved rain attenuation predictions.

The applicability of this method was validated using rain measurements from 15 locations in Southern Part of Nigeria. When tested, the proposed method provided a significant improvement over the current existing method adopted by ITU-R Recommendations, for the prediction of rain attenuation. The test results presented have also shown that the proposed approach seems to provide a better and more reliable alternative to the ITU-R method in Southern Part of Nigeria, probably part of the country and probably other tropical climates in general. Results obtained are consistent with past studies that show that vertically polarized antennas are less likely to be affected by rain attenuation. The research study concluded that the elevation angle towards the satellite is a major factor in determining the quality of the signal in the Ku-band. The other factors that affected the receive attenuation of signal was the polarization, depth of rain, height above mean sea level, and difference in longitude.

The modeling of rain-fades for satellite links is very much alike to that for terrestrial links, although a bit more tedious and complex, since the applied model should hold true the variation in density of rain with altitude. To lower the effect of attenuation and other atmospheric phenomenon amounting to losses, the proposed ITU-R Modified Model, can be used for mitigation of rain fade. This model discussed hold true for Geo-stationary satellites (fixed elevation angle).The overall expected attenuation on an earth–space path ends up being dependent on angle of elevation, rain-rate(availability), and frequency only.

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