Estimation of Attenuation due to Rain within Ka and Ku Bands in Oyo State, Nigeria

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Abstract- Rain-induced attenuation of microwaves poses a serious challenge to signal availability beyond 10 GHz frequencies. The challenges are even more pronounced in the subtropical and tropical regions with high intensities of rain which is more accompanied with thunderstorms. Nigeria has an equatorial and tropical climate, which is identified by controlling rainfall. Rain is the significant attenuation factor of various communication signal above 10 GHz frequencies. Therefore, for effective utilization of the microwave bandwidth during rainfall, it is required to form the correlation between this attenuation effect and the bandwidth at various rainfall rate and frequencies at a particular interest location. Therefore, using rainfall data for the period of five (5) years (January 2014 to December 2019), this study attempts to model the point rain rate cumulative distribution.

1 INTRODUCTION

Rainfall is a natural phenomenon with non-uniform structure. Its uncertainty in space, time, duration and frequency of existence gives the requirement for dynamics knowledge, especially as needed for quantifying its result on radio waves at beyond 10 GHz frequencies (Obiyemi et al., 2014). The scattering, absorbing and depolarizing impact on signal propagations in microwave and millimeter bands remain a major concern for satellite and terrestrial link designs. Atmospheric effect is the major factor to be considered in design of satellite-to-earth links operating at frequencies above 10 GHz. Raindrops absorb and scatter radio waves, leading to signal attenuation, thus reduce the system availability and reliability (Yussuff et al., 2018).

Rain is correlated with the atmospheric propagation characteristics and utmost greatly influence the satellite system. Attenuation by rain intensity depends on the millimetres rain rate of accumulation per hour and not on the total rain accumulation. Electromagnetic signal transmission is being affected by rain in three ways: signal attenuation, system noise temperature increment, and polarization change (Ezeh et al., 2014). Advantages of telecommunication systems that operate at higher frequencies include: large bandwidth, increased frequency reuse, small device size and wide range of spectrum availability. The major disadvantage to these frequency ranges is rain.

In recent years, the roll-out of fibre optic networks has not reduced the importance of satellite communication, specifically for rural, faraway and inland cities over the globe. The initial satellite networks operate at L, S, C, and X bands, while the recent ones start operating at Ku, K, Ka, and V bands (Yakubu et al., 2018). Rain attenuation prediction methods on microwave paths have been grouped into two classes: empirical and physical.

Empirical methods are placed on database measurement from stations in various locations and climatic zones; and physical methods which make a trial to yield the physical behaviour involved in the attenuation process. Nonetheless, when a physical approach is used not all the input parameters required for the analysis is accessible. Empirical method is therefore the more frequently used methodologies. In empirical method, a proper distribution of rain rate at integration time of 1-minute is required for the site investigation to forecast precisely the rain attenuation for the location. This is because rain rates estimated through longer integration time might not capture a high-intensity, short-duration rain event, and are not recommended for communication systems designs (Afahakan et al., 2016; Yakubu et al., 2018).

2 THEORETICAL BACKGROUND

2.1 RAIN-RATE PREDICTION MODEL

The point rain rate is the estimated rain rate at a point using a single rain gauge, as against being measured over the whole link. A procedure for the measurement of a cumulative rain-attenuation distribution from a point rain-rate distribution is then needed if predictions are to be formed. Some models exist for determination of the point rain rate cumulative distribution.

Rice and Holmberg (1973) developed a model for obtaining rain rate values using the cumulative distributions of rain and maximum monthly period. The result shows point rain-rate cumulative rainfall accumulation, and highest rates map expected for diurnal distribution rest on a class of parameters like; highest monthly rainfall accumulation observed in a set of 30-year period, normal number of thunderstorm days in an average year and the average annual accumulation obtained from the analysis of local rain accumulation data. This model has a global acceptability, because it is established on local data. It uses long-integration-time of local rainfall data to calculate the CDF of rain rates.

Studies have revealed that the Moufouma model with clarified parameters vividly explain the 1 min rain rate...
distribution (Afahakan et al., 2016). The model is good for both tropical and temperate regions, and can be shown by Equation (1) as:

\[ P(R \geq r) = 10^{-4} \left[ \frac{R_{0.01}}{r+1} \right]^b e^{\left( u\left[ R_{0.01} - r \right] \right)} \]  

(1)

Where \( r\text{(mm/h)} \) is the rain rate exceeded for a time fraction, \( R_{0.01}\text{(mm/h)} \) is the rain rate exceeded at 0.01 time percentage annually and \( b \) is calculated by the expression in Equation (2):

\[ b = \left( \frac{r-R_{0.01}}{R_{0.01}} \right) \ln \left( 1 + \frac{r}{R_{0.01}} \right) \]  

(2)

The specification \( u \) in equation (1) dictates the rain rate cumulative distribution slope, and depends on the climatic conditions which is given in Equation (3) as

\[ u = 4.110 \left( \frac{r}{R_{0.01}} \right)^{-\gamma} \]  

(3)

Where \( \lambda = 1.066 \) and \( \gamma = 0.214 \).

Therefore, the Moupfouma model needs three parameters; \( \lambda, \gamma \) and \( R_{0.01} \). While the first two parameters have been provided, \( R_{0.01} \), is estimated using the Chebil and Rahman’s model. Chebil and Rahman (1999) allows for the use of long-time mean annual accumulation, \( M \), at the location of interest. The power law correlation of the model is given by Equation (4):

\[ R_{0.01} = \alpha M^\beta \]  

(4)

In Equation (4), \( \alpha \) and \( \beta \) are the regression coefficients given as \( \alpha = 12.2903 \) and \( \beta = 0.2973 \).

Although, using the refined Moupfouma and Chebil model, the 1-minute rain-rate cumulative distribution can be evaluated from the long term mean annual rain data, and the model is being employed in this work.

2.2 RAIN ATTENUATION MODEL

There are distinct rain attenuation models utilized for the prediction of rain-induced attenuation for satellite-to-earth communication. About sixteen attenuation rain models published in COST 255 reports (Harris, 2002) claims universal applicability. To develop the map for rain attenuation over Nigeria, ITU rain attenuation model was used. It has been reported that ITU rain attenuation prediction model result was close to the average set prediction results obtained from the application of eight different methodologies (Yakubu et al., 2018).

Ryde (1946) proposed a rain attenuation model in his paper cited in (Crane, 1977) three decades later. Crane applied measured data to Ryde’s model to estimate the total matching between model predictions and measurements. Based on further analyses, Crane proposed a new revised model called two-component model (Crane, 1982).

The ITU rain attenuation prediction model gives valid results which have closeness to the standard prediction of a set of results obtained from the application of eight different methodologies (Moupfouma and Martin, 1995). Hence, this research work makes use of ITU-R model for rain attenuation prediction.

2.3 ITU-R ATTENUATION MODEL

The input parameters needed for this model are; height above sea level of the Earth station (km), point rainfall rate for the location for 0.01% of an average year (mm/h), elevation angle, frequency (GHz) and effective radius of the Earth (8500 km), latitude of the Earth station (degree).

3 METHODOLOGY

3.1 THE STUDY AREA

The study area is Ibadan, the capital of Oyo state and one of the six south west state in Nigeria. Ibadan has a tropical climate with two distinct seasons: The dry season which prevails from November to February and the wet season which commences from March and ends in October every year.

![Fig. 1: Map of Nigeria showing the state for the study area](https://example.com/nigeria_map.png)

3.2 PRINCIPAL SOURCES OF RAINFALL DATA

Principal sources of data for studying rainfall are represented by rain gauges and meteorological ground-based radars of the Nigerian Meteorological Agency (NIMET). The agency controls and stores measured hydro-meteorological data from its various forecasts offices located at airports and synoptic stations, spread across the country. Rain gauge data gives the utmost universal source of information about the rainfall in a site, available for long time periods for scheduled locations. The models for description of rain structure and the prediction of propagation impairments in this study, is thus based on rain gauge data daily recorded by NIMET weather stations for the study location.

3.3 APPROACH

3.3.1 Data Processing

The daily rainfall data was collected from NIMET for a period five years (January 2014 to December 2018). The monthly data is considered as a sum of daily data. Secondly, these 12 months data for five years were accumulated to get total annual fall rain data. The analysed yearly rain fall data is converted to one minute
rain rate data. Finally, ITU-R P.618-9 rain attenuation model is obtained from annual rain fall rate.

3.3.2 Chebil and Rahman (1999) Rainfall Rate Model

The power law relationship of the model is given by the equation

\[ R_{0.01} = aM^\theta \]  

(5)

The regression coefficient \( a \) and \( \theta \) are defined as \( a = 12.2903 \) and \( \theta = 0.2973 \).

3.3.3 ITU-R Rain Attenuation Model

ITU-R model applies rain rate at 0.01% probability level for the attenuation estimation and then uses an adjustment factor for the predicted rain attenuation depth for other probabilities. The steps of the analysis are given below:

Step 1: Determine the rain height, \( H_R \) as:

\[ H_R = h_0 + 0.36km \]  

(6)

where \( h_0 \) 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:

\[ L_s = \frac{H_R - H_S}{\sin \theta} \]  

(7)

where \( \theta \) is the elevation angle and \( H_S \) is the height of the location above sea level.

Step 3: Obtain the horizontal projection, \( L_H \), from:

\[ L_H = L_s \cos \theta \]  

(8)

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, \( Y_{R_{0.01}} \) (dB/km) for 0.01% of time as given by:

\[ Y_{R_{0.01}} = kR_{0.01}^\alpha \]  

(9)

where parameters \( k \) and \( \alpha \) 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, \( r_{H_{0.01}} \) for 0.01% of time using

\[ r_{H_{0.01}} = \frac{1}{1 + \frac{H_R - H_S}{L_H} \sqrt{\frac{\theta}{2\pi}} \exp \left( \frac{-0.38(1-\exp(-2L_H))}{\exp(-2L_H)} \right) \}} \]  

(10)

where \( f \) is the frequency in GHz and \( \phi \) is the frequency in GHz.

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

\[ L_R = \frac{L_H v_{0.01}}{\cos \theta} \]  

for \( \phi > \theta \)  

(11)

Otherwise,

\[ L_R = \frac{H_R - H_S}{\sin \theta} \]  

for \( \phi \leq \theta \)  

(12)

where \( \phi = \tan^{-1} \left( \frac{H_R - H_S}{L_H r_{H_{0.01}}} \right) \)  

(13)

therefore,

\[ v_{0.01} = \frac{1}{1 + \frac{r_{H_{0.01}}}{L_H} \sqrt{\frac{\theta}{2\pi}} \exp \left( \frac{-0.38(1-\exp(-2L_H))}{\exp(-2L_H)} \right) \}} \]  

(14)

For the entire period, rainfall was generally low during the dry season (November-February) while the wet season (March-October) expectedly recorded higher amount of rainfall. September had the highest average rainfall data of Ibadan are presented. The data were obtained for a duration five years (January 2014 to December 2018).

4.1 Rainfall Distribution

The average monthly precipitation for 5 years for the study area is shown in Fig. 2.
precipitation while January recorded the lowest average precipitation. The months of observed peak rainfall are indicative of worst months of a satellite link in the various locations (Igwe et al., 2019).

### 4.3 Rain Attenuation Calculation for the Locations Using ITU-R P.618-9 Model.

ITU-R model uses rain rate at 0.01% probability level for the attenuation estimation and then applies an adjustment factor for the predicted rain attenuation depth for the remaining probabilities. Table 1 shows the Topographic and experimental parameters of Ibadan.

<table>
<thead>
<tr>
<th>Table 1. Topographic and experimental parameters of Ibadan</th>
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</thead>
<tbody>
<tr>
<td>Lat(°N)</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>7.21</td>
</tr>
<tr>
<td>Operating frequency</td>
</tr>
</tbody>
</table>

The rain attenuation for study area (Ibadan) is thus calculated in the following manner.

**Step 1:** Determination of the rain height, $H_R$

$H_R = H_o +0.36k$; where $H_o$ is the $0\,^\circ C$ isotherm height above mean sea level of the location and is given as 4.402 km. Hence, $H_R =4.760$ km

**Step 2:** Determining the slant-path length $L_s$. $\theta$ is the elevation angle which is $42.5^\circ$. $L_s = 6.8473$ km

**Step 3:** The horizontal projection, $L_c$, of slant-path length is calculated below. Where $\theta = 42.5^\circ$, $L_c = 5.0484$ km

**Step 4:** The $R_{0.01}$ (mm/h) for Ibadan, exceeded for 0.01% of an average year is obtained from one minute integration rain rate as $R_{0.01} = 108.2708$ mm/hr; Where $\alpha = 12.2903$, $\beta = 0.2973$ and mean average rainfall (M) = 1508.1 mm

**Step 5:** Calculate the specific attenuation, $\gamma_s$, using the frequency-dependent coefficients and $R_{0.01}$.

For 11GHz, $\gamma_{0.01} = 3.9336$ dB/km
For 14GHz, $\gamma_{0.01} = 5.9550$ dB/km
For 20GHz, $\gamma_{0.01} = 10.1659$ dB/km
For 40GHz, $\gamma_{0.01} = 23.9602$ dB/km

**Step 6:** The horizontal reduction factor, $\rho_{0.01}$, is calculated as:

For 11GHz, $\rho_{0.01} = 0.5995$
For 14GHz, $\rho_{0.01} = 0.5672$
For 20GHz, $\rho_{0.01} = 0.5349$
For 40GHz, $\rho_{0.01} = 0.5060$

**Step 7:** The vertical adjustment factor, $v_{0.01}$, is:

For 11 GHz, $v_{0.01} = 0.7906$
For 14 GHz, $v_{0.01} = 0.9099$
For 20 GHz, $v_{0.01} = 1.0850$
For 40 GHz, $v_{0.01} = 1.3533$

**Step 8:** The effective path length $L_e$:

For 11 GHz, $L_e = 3.2455$
For 11 GHz, $L_e = 3.5338$
For 20 GHz, $L_e = 3.9739$
For 40 GHz, $L_e = 4.6884$

**Step 9:** Predicted attenuation exceeded for varying frequencies are:

For 11 GHz, $A_{0.01} = 12.7664$
For 14 GHz, $A_{0.01} = 21.0434$
For 20 GHz, $A_{0.01} = 40.3983$
For 40 GHz, $A_{0.01} = 112.3351$

Table 2 gives the rain attenuation variation with respect to percentage of time exceeded. From Table 2 it is evident that an increase in frequency leads to a significant increase in the attenuation. Also, rain attenuation varies due to different rainfall rate experienced in the various locations.

<table>
<thead>
<tr>
<th>Table 2. Variation of rain attenuation with respect to % time exceeded at 42.5° elevation angle for Ibadan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (GHz)</td>
</tr>
<tr>
<td>0.001</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>14</td>
</tr>
<tr>
<td>20</td>
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<tr>
<td>40</td>
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Fig. 3: Rain attenuation at 11 GHz (Ku-downlink frequency).

Rain does not occur all the time in a year and its rate does not remain same either all the time, thus, the level of rain fade margin needed to compensate rain effects varies with time. Figure 3 gives a graphical representation of the rain attenuation at 11 GHz Ku
downlink frequency. At 0.01%-time exceedence, the rain attenuation level is, 12.76 dB.

Similarly, Figure 4 also presents rain attenuation at Ku-band uplink frequency 14 GHz at 0.01% of time exceedence is 21.04 dB.

Figure 5 gives the graphical representation at Ka-band downlink frequency 20 GHz, showing that at 0.01%-time exceedence, the rain attenuation is 40.39 dB.

Lastly, Figure 6 gives the rain attenuation at Ka-band uplink frequency 40 GHz, which also shows that the rain attenuation for the study area is 112.33 dB. As it is observed, increase in frequency leads to a correspond increase in attenuation. These indicate that attenuation is more pronounced at 40 GHz.

5 Conclusion

The effects of rainfall on satellite communication link at Ku-band and ka-band have been investigated for links to Nigerian communication satellite-1 Replacement (NIGCOMSAT-1R) based on local input data. Rain rate and rain attenuation graphs were developed for 0.001-10% of time using the (Chebil & Rahman, 1999) rain rate model for the rain rate graph and ITU-R P.618-9 rain attenuation model for the rain attenuation graphs over Ibadan. The result shows that an increase in attenuation was experienced at 40 GHz with a value of 112.33 dB and the least is at 11 GHz with a value of 11.76 dB. Hence pronounced rain attenuation is experienced in Ibadan at both the downlink and uplink frequencies of ka-band. Results achieved will be helpful to communication engineers and proposed consumers of services from various satellite outfits.

References


