Assessment of Rain Attenuation for Terrestrial Communication Links in Kaduna State, Nigeria

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Abstract

Designing satellite and terrestrial communication links requires accurate predictions of rain rate and rain attenuation because rain-fade and its dynamic fluctuations have consistently been detrimental to received signals, especially in tropical regions known to be prone to heavy rainfall. Nigeria's rain is characterized by heavy rainfall, frequent rainfall occurrences and a greater abundance of large raindrops when compared to temperate regions. Research on prediction of rain attenuation has become a necessity in the study area, as the study of rain attenuation prediction in Kaduna State is minimal (if available). Also, research and forecast by NIMET indicated that the northwestern region of Nigeria is expected to face a significant rainfall event in the coming days, which could lead to flooding and hazardous conditions (signal attenuation) that requires preparedness and mitigation efforts by authorities and resident. This study looks into the effect of rain-induced attenuation on microwave and millimeter wave propagation for terrestrial communication links in Kaduna State, Nigeria. 36 years (1986-2022) daily rainfall (mm) data was obtained from the Nigerian Meteorological Agency (NIMET) Abuja. The rainfall accumulation (mm) was converted to 1 minute rain rate (mm/h) using the Chebil rain rate model, while rain attenuation values were computed using the ITU-R P. 530-17 rain attenuation model. The analysis shows that Kaduna State has a rainfall rate of 106.12mm/hr at 0.01% of time exceedance. For the rain attenuation analysis, higher attenuation values were recorded at higher frequencies. At 25 GHz and 20 km path length, values of 103 dB and 127 dB were predicted for vertical and horizontal polarisations respectively, while 165 dB and 188 dB were predicted for vertical and horizontal polarizations respectively at 40 GHz. Hence, the findings show that the attenuation become higher at horizontal polarisation than at vertical polarisation.

Keywords: ITU-R P. 530-17 model, rain attenuation, rain rate, micro-wave, millimeter wave

1 Introduction

Since the beginning of time, communication has piqued the interest of humanity. Communication over long physical distances has been made easier by the development of wireless communication[1]. Without a thorough understanding of radio propagation, it is impossible to design, construct, and implement radio systems, let alone reap the immense benefits from them. Because people need to connect with each other, exchange and acquire knowledge, and experience, the efficiency of communication networks is becoming increasingly important in our society. At higher frequencies, the channel for communication, known as communication link is usually affected by rain. Rain can affect electromagnetic energy transmission by polarisation shifting, signal attenuation, or increase in signal noise temperature.

For a radio link with any degree of efficiency, to be able to accurately estimate attenuation due to rain, the location of interest must have the rain rate, integration time, average rainfall cumulative data, and worst-month distribution provided[2]. Furthermore, millimetre-wave (mm-wave) spectrum is essential to 5G's ability to effectively address the issue of limited bandwidth. On the other hand, mm-wave signals are more susceptible to obstruction, absorption, dispersion, depolarisation, and diffractive effects from raindrops [3]. Many studies have been conducted in this regard by researchers worldwide

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regarding an appropriate prediction model for rain attenuation in a specific area, as the suitability of a model may vary depending on the area under study. This is due to the fact that certain models are not suitable for all rainfall data, especially when integration times are lowered to five minutes [4]. Rain-induced attenuation is an important propagation effect that needs to be considered in the design of both terrestrial and satellite communication systems, as weather, and especially rain has a significant impact on radio wave propagation between terrestrial and earth space links at frequencies above [5].

2 Background

2.1 Rainfall rate.

The measurement of the quantity of rain that falls per unit time is referred to as the "rainfall rate" in meteorology or climatology. It is usually expressed in terms of millimetres per hour or inches per hour (mm/hr or in/hr). Instantaneous rainfall intensity, also known as instantaneous rain rate, is sometimes stated in mm/h, even if the measurement period was much less than an hour. The goal of standardizing the unit of measurement is to make it easier to compare rainfall intensities worldwide. If the specific short-term rainfall rate had remained constant for an hour, rainfall rate may be considered as the amount of rain that would have fallen every hour [6].

2.2 Rain rate models

Attenuation of the propagating signal at microwave and millimeter-wave frequencies is a natural process caused by rain. Therefore, in order to maintain the quality of millimeter-wave and microwave communications, rain attenuation must be mitigated. Rain rate models are used to forecast how much electromagnetic radiation will be attenuated or weakened by rain. To evaluate the effect of rain on signal transmission, these models consider variables such as rainfall rate and raindrop size distribution.

2.2.1 Chebil Rain Rate Model

One method that is used to estimate the point rainfall rate ($R_{0.01}$) at any particular location was recommended by[7]. It allows the application of long-term mean annual accumulation M at an interest site. The power law relationship of the model is given by:

$$R_{0.01} = \alpha M^{\beta} \tag{1}$$

where α and β are the regression coefficients and are defined as $\alpha = 12.2903$ and $\beta = 0.2973$. M in equation (1) is the mean annual accumulation of rain for the location.

2.3 Rain Attenuation

The product of the effective propagation path length (km) and the specific attenuation (dB/km) is known as rain attenuation. The effective path length of a microwave link is the product of the path reduction factor and the physical path length. It can also be defined as the ratio of rain attenuation to specific attenuation corresponding to the point rain rate, which is usually measured at one end of the link. Thus, one method of "averaging out" the spatial inhomogeneity of rain rate and, consequently, particular attenuation is through the concept of effective path length. Direct observations or forecasts based on long-term rainfall rate knowledge can yield attenuation [8].

2.3.1 The ITU-R P. 530-17 Attenuation Model

An estimate of the path attenuation exceeded for 0.01% of the time is given by:

$$A_{0.01} = \gamma_R d_{eff} = \gamma_R dr \quad \text{(dB)} \tag{2}$$

where γ_R is the specific attenuation, d_{eff} is the effective path length, d is the actual path length which was considered to be 1km, 2km, 4km, …20km. The parameter r is the distance factor. The steps for obtaining these parameters and the attenuation exceeded for other percentages of time can be obtained from ITU-R recommendation P. 530-17 manual as shown below.

An estimate of the distance factor is given by:

$$r = \frac{1}{0.477d^{0.633}R_{0.01}^{0.073.\alpha}f^{0.123}-10.579(1-exp(-0.024d))} \quad (3)$$

Where f (GHz) is the frequency and α is the exponent in the specific attenuation model from equation (2). The attenuation exceeded for other percentages of time p in the range 0.001% to 1% can be deduced from the following power law:

$$\frac{A_p}{A_{0.01}} = C_1\, p^{-(C_2+\, C_3\, log_{10}\, p)} \quad (4)$$

with

$$C_1 = (0.07^{C_0})\left[0.12^{(1-C_0)}\right]$$

$$C_2 = 0.885C_0 + 0.546\ (\ 1\text{-}\ C_0)$$

$$C_3 = 0.139C_0 + 0.043\ (1 - C_0)$$

where:

$$C_0 = \begin{cases} 0.12 + 0.4\left[log_{10}\left(\frac{f}{10}\right)^{0.8}\right] & f \geq 10\ GHz \\ 0.12 & f < 10\ GHz \end{cases}$$

3.0 Methodology

The Nigerian Meteorological Agency (NIMET), located in Abuja, provided the daily rainfall data for the research area. The Casella Rain Gauge, shown in Figure 1, was the equipment used to collect the daily rainfall data throughout the 36-year measurement period (1986–2022). These data was averaged annually mean annual rain accumulation M was computed to be 1320.7 mm.

Figure 1. Casella rain guage

3.1 Data analysis

The Chebil rain rate was used to calculate the rain rate as given in equation (1) and the result was used as an imput parameter for the rain attenuation prediction, while equation (2) was used to compute the rain attenuation values. Attenuation exceeded for other percentages of time was predicted using Equation (4)

4. Results and discussion

The analysis of rainfall rate and rain attenuation from the long term daily rainfall data are presented and discussed.

4.1 Rainfall rate distribution

The average rainfall rate for the 36 years is shown in Figure 2. The analysis shows that Kaduna state has a rainfall rate of 106.12 mm/h. this was predicted for 0.01% of time and illustrated in Figure (2)

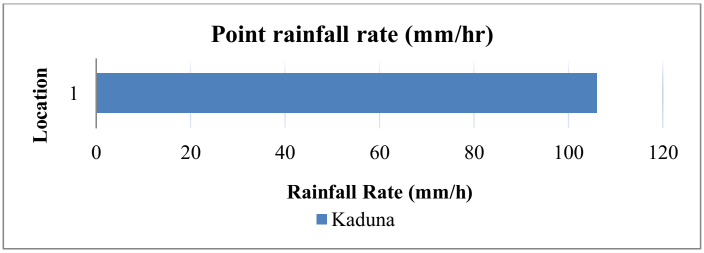

Figure 2: Point rainfall rate

4.2 Rain attenuation prediction

The rain attenuation from the ITU-R P. 530-17 rain attenuation model was predicted using the point rainfall rate computation by Chebil's model as the input parameter. A comparison and presentation are made of the cumulative distribution of the rain-induced attenuation measured at various time percentages and different path length for 25 GHz and 40 GHz frequencies.

The rain induced attenuation predicted exceeded for 0.01% for both vertical and horizontal polarisations at 25 GHz in Kaduna State is illustrated in Table 1 and Figure 3.

Table 1. Rain attenuation predicted at 25GHz

Path Length (km)	Vertical (dB)	Horizontal (dB)
1	17.62	22.28
2	25.1	31.66
4	37.02	46.54
6	47.38	59.39
8	56.91	71.17
10	65.85	82.17
12	74.28	92.5
14	82.21	102.2
16	89.66	111.29
18	96.62	119.78
20	103.09	127.66

Table 1 shows the rain attenuation exceeded at 0.01% predicted at 25GHz for both vertical and horizontal polarisations obtained using ITU-R P. 530-17. It can be observed that the attenuation is dependent on path length and therefore increases as the path length increases. For vertical polarisation, an attenuation of 17.62 dB was obtained at a path length of 1 km, but it becomes significantly high at 20 km with a value of 103 dB. Furthermore, at any given path length, higher rain attenuations are predicted for horizontal polarisation compared to vertical polarisation as shown in Figure 3.

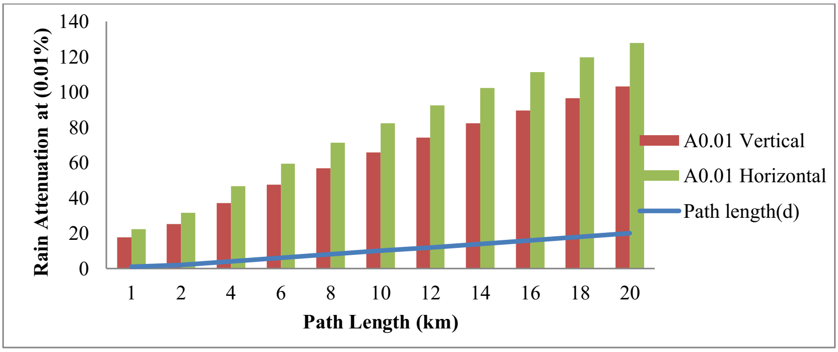

Figure 3. Rain attenuation at 25GHz

The attenuation exceeded for other percentages of time p in the range 0.001% to 1% is shown in Table 2.

Table 2. Rain attenuation predicted at 25GHz for 0.001%, 0.1% and 1%

Path length(km)	$A_{0.001}$		$A_{0.1}$		A_1	
	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
1	35.98	45.51	6.77	8.56	1.85	2.34
2	51.25	64.67	9.64	12.16	2.64	3.33
4	75.61	95.06	14.22	17.88	3.89	4.89
6	96.76	121.30	18.19	22.81	4.98	6.24
8	116.23	145.35	21.86	27.33	5.98	7.47
10	134.49	167.81	25.29	31.56	6.92	8.63
12	151.70	188.91	28.53	35.52	7.80	9.71
14	167.90	208.73	31.57	39.25	8.63	10.73
16	183.121	227.30	34.43	42.74	9.42	1169
18	197.34	244.62	37.11	46.00	10.15	12.58
20	210.55	260.71	39.59	49.03	10.83	13.40

It is noticeable from Table 2 that rain attenuation can also be a function of time exceedance. Attenuation becomes lower at higher percentage of time exceedance. Rain attenuation of 210.55dB and 260.71dB for vertical and horizontal polarisations respectively were predicted at 0.001% of time exceedance and at 20 km path length, while 10.83dB and 13.40dB for vertical and horizontal polarizations respectivelywere predicted at 1%of time exceedance and at the same path length.

The rain induced attenuation predicted exceeded for 0.01% for both vertical and horizontal polarisations at 40GHz is illustrated in Table 3.

Table 3: Rain attenuation predicted at 40GHz

Path Length (km)	Vertical (dB)	Horizontal (dB)
1	28.98	33.4
2	41.15	47.38
4	60.44	69.47
6	77.07	88.46
8	92.29	105.81
10	106.49	121.96
12	119.82	137.1
14	132.34	151.29
16	144.06	164.58
18	154.99	171.96
20	165.14	188.44

Comparing the values of attenuation at 25GHz and 40GHz, it can be observed that attenuation caused by rain is not just dependent on path length and percentage time exceedance, but also on frequency. The attenuation increases as frequency increases. At 25GHz and at a path length of 20 km, rain attenuation of 103.09dB and 127.66 dB were obtained for vertical and horizontal polarizations respectively at 0.01% time exceedance, while 165.14dB and 188.44dB were predicted at 40GHz for vertical and horizontal polarisations respectively at the same path length of 20 km and 0.01% time exceedance.

The attenuation exceeded for other percentages of time in the range 0.001% to 1% is shown in Table 4.

Table 4. Rain attenuation predicted at 40GHz for 0.001%, 0.1% and 1%

Path length(d)	$A_{0.001}$		$A_{0.1}$		A_1	
	Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
1	58.46	67.4	11.14	0.9	2.94	3.39
2	83.03	95.6	15.83	1.27	4.17	4.8
4	121.94	140.16	23.24	1.86	6.13	7.04
6	155.49	178.48	29.64	2.36	7.81	8.97
8	186.2	213.47	35.49	2.83	9.36	10.73
10	214.85	246.1	40.95	3.26	10.8	12.37
12	241.75	276.61	46.08	3.66	12.15	13.9
14	266.99	305.25	50.89	4.04	13.42	15.34
16	290.65	332.04	55.39	4.4	14.61	16.69
18	312.7	357.02	59.6	4.73	15.71	17.94
20	333.18	380.2	59.6	5.03	16.74	19.11

Conclusion

The rain induced attenuation analyzed in Kaduna State, Nigeria show that rain has significant effect on terrestrial links in this location which become severe at higher frequencies (10GHz and above). These attenuation predictions were made using ITU-R P. 530-17 model. The results obtained have shown that the severity of rain attenuation depends not only on frequency but also on the type of polarisation and path length. Also, rain attenuation at horizontal polarization is always higher than attenuation at vertical polarisation. In addition, it was observed that higher attenuation was experienced at lower percentage of time exceedance.

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