A Study of Rain-Induced Attenuation on Terrestrial Paths at Ku, K and Ka Bands Over Akungba-Akoko, Nigeria

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Rain attenuation is one of the main impairments that limit radio signals in high rain rate regions, especially at higher frequencies such as Ku, K and Ka frequency bands. Therefore, rain rate and rain attenuation predictions are some of the fundamental steps to consider when designing terrestrial line of sight communication links. The paper presents rain rates at 1 min integration for 0.01 percentage of time exceedance using Chebil, Lavergnat-Gole and power law conversion rain rate models for Akungba-Akoko, Ondo State, Nigeria. This was achieved using 5 min integration rainfall data for a period of three years. The rainfall data were measured by the Nigerian Environmental and Climate Observing Program (NECOP) instrumentation installed at the Adekunle Ajasin University, Akungba-Akoko. The estimated rain rates were used as input parameters to compute the total rain-induced attenuation at 0.01 percentage of time exceedance for 15 GHz, 23 GHz and 30 GHz through a path length of 10 km for vertical and horizontal polarizations, using Moupfouma, ITU-R and Lin attenuation models. Lavergnat-Gole conversion model gave the highest rain rate estimation in the region, while Lin attenuation model gave the highest estimation for total rain-induced attenuation, which is also closest to that of the ITU-R attenuation model. Generally, for all operating frequency bands and rain rates, the total rain-induced attenuation at horizontal polarization is higher compared to that at vertical polarization. Results from the analysis provide a broad knowledge of rain attenuation in the tropical region which can serve as a good preliminary design tool for terrestrial link engineers.

***Keywords*:** Electromagnetic waves, Rain attenuation, Rain rate, Integration time, Effective path length

Introduction

An electromagnetic wave, just as every other form of wave, is a disturbance which is capable of transferring both energy and momentum. The wavelength of

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electromagnetic wave depends on the period of time that a charged particle is accelerated, while its frequency is dependent on the number of accelerations completed in one second. However, in vacuum, all electromagnetic waves propagate at the same speed, irrespective of their frequencies and wavelength (Ghasemi *et al*., 2012).

Wireless communications use electromagnetic radiations to send and receive signals between transmitting antenna and receiving antenna through a certain distance. But the weak point of wireless communication is its inability to guarantee an impairment free communication link during rainfall (Cheon-In, 2006). When electromagnetic radiation meets water particles on its path, some of its energy is lost either in the form of absorption or scattering, hence the radiation is said to be attenuated. Radio wave propagation became a complex phenomenon as rain plays a momentous role in the undesired impairment of millimeter and centimeter wave propagations.

Over time, the rapid boom of the telecommunication market has resulted in a serious congestion in transmission at the lower frequencies; therefore, the desire for larger bandwidth and increased data rates has become very significant. But all radio frequencies above 10 GHz suffer from impairment due to rainfall. Hence, the need for providing impairment-free service has encouraged researchers into attenuation of radio waves by rainfall. Underprediction of total rain-induced attenuation could result in the designing of a system that is unreliable. On the other hand, overprediction of the total attenuation might lead to higher budgetary requirement for the link and waste of funds.

Theoretical Background

All electromagnetic radiations have fundamental properties and behave in conventional ways according to the basics of wave theory. According to James Maxwell, the speed (c) of an electromagnetic wave is given as:

$$c = \frac{1}{\sqrt{\varepsilon_o \mu_o}} \quad ...(1)$$

where ε_o is known as the permittivity of free space and μ_o is the permeability of free space. Since both ε_o and μ_o are universal constants, the speed of electromagnetic waves in free space is also a universal constant (m/s). In terms of frequency and wavelength,

$$c = f\lambda \quad ...(2)$$

where c is speed, f is frequency and λ is the wavelength of the wave.

Olsen *et al.* (1978) demonstrated the theoretical basis of a simple formula used to calculate the specific attenuation of radio waves by rain, which is given as:

$$\gamma = k R^{\alpha} \left(dB/km \right) \quad ...(3)$$

Attenuation Prediction Models

Prediction of rain-induced attenuation can be achieved using two methods:

- Physical method; and
- Empirical method

Physical Method: The physical method attempts to reproduce the physical conduct involved in the fading process. The method employs the use of climatic information such as yearly rain rate distribution, mean rain rate distribution, monthly and yearly accumulation of rain rate. Some acknowledged models for the physical method include the Rice-Holmberg (1973) model, Dutton-Dougherty (1979) model, Crane-DeBrunner (1978) model, physical-stochastic model (Lavergnat and Golé, 1998), ITU-R P.837-5 (ITU-R, 2007), and the EXCELL model (Capsoni *et al.*, 1997). However, physical methods are rarely used due to their intrinsic complexity.

Empirical Method: The empirical method is based on the correlation between observed attenuation distribution and the corresponding observed rain rate distribution, measured at one minute integration time. That is, the method relies on measured databases from different weather stations within given climatic region. The most essential input factor is rain rate of short integration time. Some of the most prominent authors include: Watson *et al.* (1982), Segal (1986), Burgueno *et al.* (1998), and Chebil and Rahman (1999), among others. The foremost challenge facing this method is the lack of sufficient rain rate data of short integration time, especially in the underdeveloped part of the world.

Conversion of Rain Rate into Short Integration Time

It has been found that a power law relationship exists between two equi-probable rain rates of different integration times (Ajayi and Ofoche, 1983). The power law relationship is given as:

$$R_{\gamma} = \alpha \left(R_T \right)^{\beta} \quad ...(5)$$

where R_{γ} is the integration time at which the rain rate is required and R_T is the integration time at which the rain rate is available; α and β are conversion factors.

According to Ajayi and Ofoche (Chris, 2006), the conversion factor C_R for the power law is given as:

$$C_R = \frac{R_{T(min)}}{R_{\tau(min)}} \quad ...(6)$$

where R_T is the integration time at which the rain rate is available and R_τ is the integration time at which the rain rate is required. This relationship is however best suited for cumulative distribution, in which the conversion factor can only be arrived at from the available data to be modeled.

Chebil and Rahman Rain Rate Model: Chebil and Rahman's (1999) model is used to convert rain amount obtained from any location to its equivalent rain rate data irrespective of the integration time of the available rain data. The model introduces experimental technique for estimating rainfall rate and conversion of the rainfall rate from any integration time into its equivalent one minute integration time at the same percentage probability of time. The model is a modification of the Segal method, as some conversion factors were introduced into the equation. It is expressed as:

$$R_{0.01} = \alpha M^{\beta} \quad ...(7)$$

where α and β are regression coefficients.

Lavergnat and Golé Rain Rate Model: Lavergnat-Golé (LG) model was developed starting from a physical basis (Emiliani and Luini, 2010). The method was developed as an application of stochastic process which was achieved by modeling the time interval between two consecutive raindrops as a renewal process using a disdrometer and it is acknowledged for good performance in all climatic regions (Emiliani *et al.*, 2009). The LG model introduces a conversion factor h to scale both the rain rate (R_T) and the probability (P_T). The model is expressed as:

$$R_1 = R_T / h^z \quad ...(8)$$

$$P_1(R_1) = h^z P_T(R_T) \quad ...(9)$$

where z is an empirical parameter, R_T is the available rain rate at integration time (T), R_1 is the rain rate at required one-minute integration time, while P_1 and P_T are the percentage probabilities at R_1 and R_T respectively. Thus, the advantage of the method is, it gives room for conversion between any integration time, while its weakness lies in its sole reliance on the empirical parameter z.

ITU-R Rain Attenuation Model: There are several recommendation models developed by ITU-R. For instance, ITU Recommendations P.1144-3 and P.837-4 are combined to obtain rain rate (mm/h). The models offer possibility of predicting the statistics of many propagation parameters such as attenuation, interference by rain scattering among others. In other words, the knowledge of the mean rainfall distribution and the climate will provide a broad view of the expected rain attenuation. To predict the total rain attenuation from recommended measurements, a 1 min integration time rain rate statistics is required. However, the major limitation of the model is that it performs better in the temperate regions compared to the tropical regions.

Lin Rain Attenuation Model: This is one of the oldest versions of terrestrial line of sight link attenuation model. It is rarely used today due to its complex and detailed nature, which makes it relatively hard to follow (Dutton and Steele, 1982). The Lin model requires rainfall rate at five-minute integration time at *p*-percentage of time (Lin, 1975). According to Lin, prediction of signal attenuation by rain is quite complicated because of the nonuniform distribution of rainfall rate along the entire path length. In order to cater to the nonuniformity of the rain rate along a transmission path, the path is divided into small incremental volumes, in which the rainfall is approximately uniform. The rainfall rate in each small volume is associated with a corresponding attenuation called specific attenuation, and the product of the specific attenuation along the rainy path presents the total attenuation along the path.

$$A_{0.01} = \gamma \left(R_{0.01}\right) L_r \qquad \text{...(10)}$$

$$A_{0.01} = \kappa \left(R_{0.01}\right)^{\alpha} L_{eff} \qquad \text{...(11)}$$

where $A_{0.01}$ is the total attenuation at 0.01 percentage of time, $R_{0.01}$ is the 5 min rain rate at 0.01 percentage of time, r is the correction factor, L is the path length and L_{eff} is the effective path length.

Moupfouma and Martin Rain Attenuation Model: The Moupfouma and Martin model is said to be good for both tropical and temperate regions. It is expressed as (Moupfouma, 2009):

$$P\left(R \geq r\right) = 10^{-4} \left(\frac{R_{0.01}}{r+1}\right)^{b} exp\left(u\left[R_{0.01} - r\right]\right) \qquad \text{...(12)}$$

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

$$b = \left(\frac{r - R_{0.01}}{R_{0.01}}\right) \ln\left(1 + \frac{r}{R_{0.01}}\right) \qquad \text{...(13)}$$

The parameter u governs the slope of rain rate cumulative distribution and depends on the local climatic conditions and geographical features. For tropical and sub-tropical localities

$$u = \frac{4 \ln 10}{R_{0.01}} exp\left(-\lambda \left[\frac{r}{R_{0.01}}\right]^{\gamma}\right) \qquad \text{...(14)}$$

where λ = 1.066 and γ = 0.214.

Methodology

The Nigeria Environmental and Climate Observing Program's (NECOP) daily rainfall data was taken from the weather station in Adekunle Ajasin University Akungba-Akoko over a period of three years (July 2008 to June 2011), from which the cumulative distribution of rain rate will be determined (mm/h) at 0.01 percentage of time exceedance. Using Chebil's rain rate model, the rain rate would be calculated by:

$$R_{0.01} = \alpha M^{\beta} \quad ...(15)$$

where $R_{0.01}$ is the rain rate (mm/h), M is the mean annual rainfall accumulation, α and β are regression coefficients (Khandaker and Mohammad, 2014) and are given as:

α = 12.2903; and

β = 0.2973

On the other hand, rain rate (R) of any integration time (T) can be calculated (mm/h) by dividing the given rainfall data (M_p) by the observation time (T) and then multiplied by the number of minutes in an hour. This can be obtained using the formula:

$$R = \frac{M_p}{T} \times 60 \quad ...(16)$$

where M_p is the peak rainfall (mm) for an integration time T (min). The power law relationship between 5 min and 1 min rain rates of equal probability (p) of time is defined as:

$$R_{1min(p)} = aR^{b}_{5\,min(p)} \quad ...(17)$$

where $R_{1(minp)}$ and $aR^{b}_{5\,min(p)}$ are the 1 min and 5 min rain rate values (mm/h) at p-percentage of time, while a and b are the power law coefficients (Table 1).

Table 1: Power Law Coefficients '*a* and *b*' for Rain Rate Conversion

Conversion from	*a*	*b*
5 min to 1 min	0.895	1.041
10 min to 1 min	0.730	1.114
20 min to 1 min	0.784	1.141
30 min to 1 min	0.528	1.276
60 min to 1 min	0.507	1.363

Source: Emiliani et al. (2009)

According to Lavergnat and Golé model (LG), a conversion factor h is employed to scale both the rain rate and the probability. For the rain rate,

$$R_{1min} = R_{5min} / h^{z} \qquad ...(18)$$

where R_{1min} and R_{5min} are rain rates for 1 min and 5 min integration times respectively, parameter z is an empirically derived coefficient and h is the conversion factor, which is described as the ratio of the integration time at which the rain rate is required (t – 1) to that at which the rain rate is available (t_{τ}).

$$h = \frac{t_1}{t_\tau} \quad ...(19)\text{hence,}$$

$$R_{(1min)t_1^z} = R_{(5min)t_\tau^z} \quad ...(20)$$

It was recommended that the parameter z was equal to 0.115 for ITU-R climatic zone E (France, 1999) and it was suggested that the parameter z is region-dependent. According to Emiliani and Luini (2010) and Chun and Mandeep (2013), the global value of parameter z is given as 0.1609 and 0.1634, respectively. For the tropical regions, parameter z (Emiliani *et al.*, 2009) is given as 0.143.

According to the revised Moupfouma's model, the reduction factor (r) is given as:

$$r_{(0.01)} = exp\left(\frac{-R}{1+(\xi \times R)}\right) \qquad ...(21)$$

where ξ is a correction factor that assumes the rain drops to be uniform throughout the propagation length. It is governed by the actual path length and is given as:

$$\xi = \left(\frac{44.2}{L}\right)^{0.78} \qquad ...(22)$$

for all L greater than 7 km (Isikwue *et al.*, 2013).

Hence, the effective path length can be defined as:

$$L(eff) = L \times exp\left(\frac{-R}{1+(\xi \times R)}\right) \qquad ...(23)$$

Recommendation ITU-R P. 530-14 (ITU-R, 2012) assumes that an equivalent rain cell of uniform rainfall rate and length L can model nonuniform rainfall rate along the propagation path. The reduction factor (r) is expressed as:

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Table 2: Frequency-Dependent Coefficients for Estimating Specific Rain Attenuation

Frequency (GHz)	Regression Coefficients			
	kH	***αH***	***kV***	***αV***
10.00	0.0122	1.2571	0.0113	1.2156
11.00	0.0177	1.2140	0.0173	1.1617
12.00	0.0239	1.1825	0.0246	1.1216
13.00	0.0304	1.1586	0.0327	1.0901
14.00	0.0374	1.1396	0.0413	1.0646
15.00	0.0448	1.1233	0.0501	1.0440
16.00	0.0528	1.1086	0.0590	1.0273
17.00	0.0615	1.0949	0.0680	1.0137
18.00	0.0708	1.0818	0.0771	1.0025
19.00	0.0808	1.0691	0.0864	0.9930
20.00	0.0916	1.0568	0.0961	0.9847
21.00	0.1032	1.0447	0.1063	0.9771
22.00	0.1155	1.0329	0.1170	0.9700
23.00	0.1286	1.0214	0.1284	0.9630
24.00	0.1425	1.0101	0.1404	0.9561
25.00	0.1571	0.9991	0.1533	0.9491
26.00	0.1724	0.9884	0.1669	0.9421
27.00	0.1884	0.9780	0.1813	0.9349
28.00	0.2051	0.9679	0.1964	0.9277
29.00	0.2224	0.9580	0.2124	0.9203
30.00	0.2403	0.9485	0.2291	0.9129

Source: ITU-R (2005)

$$r = \left(\frac{1}{1 + \left(\frac{L}{L_o} \right)} \right) \qquad \text{...(24)}$$

where L is the path length of the link and L_o is a rainfall rate-dependent factor which is given by:

$$L_o = 35e^{-0.015} R_{0.01} \quad ...(25)$$

Equation (25) is valid for all values of $R_{0.01}$ equal or less than 100 mm/h, while 100 mm/h is used for all values of $R_{0.01}$ greater than 100 mm/h (Fashuyi, 2006).

Hence, the effective path length, as defined by ITU-R (2012), is expressed as:

$$L_{eff} = L \times \left(\frac{1}{1 + \left(\frac{L}{L_o} \right)} \right) \quad ...(26)$$

On the other hand, the reduction factor, according to Lin (1975), is expressed as:

$$r_{0.01} = 1 + \left(\frac{1}{L(R)} \right) \quad ...(27)$$

where r is the reduction factor, L is the path length and $L(R)$ is the correction factor which is given by:

$$L(R) = \left(\frac{2636}{R - 6.2} \right) \quad ...(28)$$

hence,

$$r_{0.01} = 1 + \left(\frac{L}{\left(\frac{2636}{R - 6.2} \right)} \right) \quad ...(29)$$

and the effective path length,

$$L_{eff} = L \times \left[1 + \left(\frac{L}{\left(\frac{2636}{R - 6.2} \right)} \right) \right] \quad ...(30)$$

The (total) rain attenuation which is the product of specific attenuation (dB/km) and the effective propagation path length (km) is calculated for ITU-R (Moupfouma, 2009; and Lin, 1975) as follows:

According to Moupfouma (2009), total attenuation 'A' is given as:

$$A = {}_k R^{\alpha} \times L \times exp\left(\frac{-R}{1 + (\xi \times R)} \right) \quad ...(31)$$

ITU-R, the total attenuation 'A' is given by:

$$A = {}_{k}R^{\alpha} \times L \times \left(\frac{1}{1 + \left(\frac{L}{L_O} \right)} \right) \quad ...(32)$$

which can also be re-expressed as:

$$A = {}_{k}R^{\alpha} \times L \times \left(1 + \left(\frac{L}{L_O} \right) \right)^{-1} \quad ...(33)$$

According to Lin (1975), the total attenuation '*A*' is expressed as:

$$A = {}_{k}R^{\alpha} \times L \times \left(\frac{L}{\left(\frac{2636}{R - 6.2} \right)} \right) \quad ...(34)$$

Results and Discussion

The total rainfall accumulation (M_m) is 1,150.882 mm. The mean annual rainfall accumulation (M) is 383.63 mm. According to Chebil and Rahman (1999), $R_{0.01}$ = 72.07 mm/h.

The relationship between rain rate statistics with different integration times has been studied from the results. Conversion of the cumulative distribution of rain rate from five minutes integration time to equivalent one minute integration time at 0.01 percentage probability of time is achieved using power law (PL) and Lavergnat-Gole (LG) methods. The cumulative distribution of this relationship is given in Figure 2.

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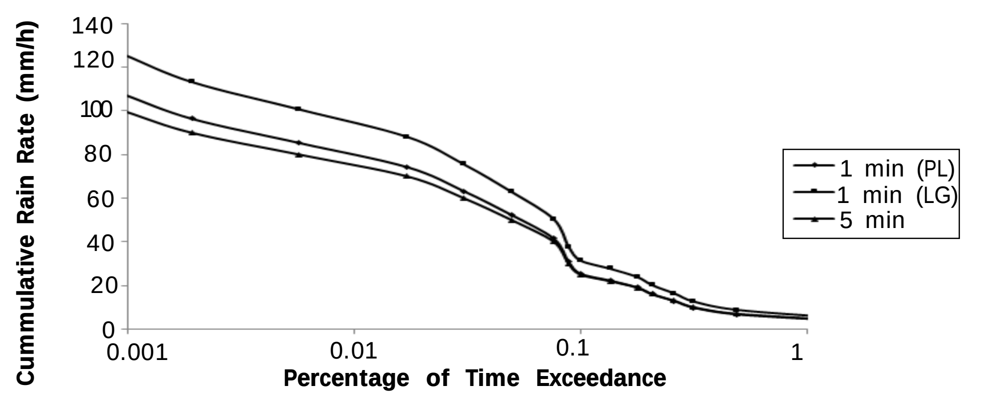
Figure 2: Relationship Between Cumulative Rain Rates and Percentage of Time Exceedance



It is observed that the peak activities of rain rates are recorded at the lower integration times. At 0.01 percentage of time exceedance, the estimated rain rate for 5 min integration time is 70.00 mm/h. At one minute integration, power law and Lavergnat-Golé models estimated the rain rate to be 74.23 and 88.12 mm/h respectively. Specific and total rain-induced attenuations are determined at operating frequencies of 15 GHz, 23 GHz and 30 GHz, respectively, for both horizontal and vertical polarizations, using each of Chebil, Power law and Lavergnat-Golé rain rate conversion models at the same percentage probability of time exceedance. A summary of the results is presented in Tables 4, 5 and 6. Specific and the total rain-induced attenuation increases with increasing propagating frequencies and rain rates. It is also polarization-dependent which is higher for horizontal polarization compared to vertical polarization. Table 4 shows that prediction of total rain-induced attenuation using Moupfouma rain attenuation model, and Lavergnat-Golé rain rate conversion model gave the highest predicted attenuation, while the use of Moupfouma rain attenuation model with Chebil rain rate conversion model gave the least predicted attenuation at the same probability of time exceedance.

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Table 4: Rain-Induced Attenuation Using Moupfouma Model

Frequency	Quantity	CH Vert	CH Hori	LG Vert	LG Hori	PL Vert	PL Hori
15 GHz	Specific Attenuation (dB/km)	4.36	5.47	5.37	6.86	4.49	5.66
23 GHz		7.9	10.16	9.59	12.47	8.13	10.47
30 GHz		11.38	13.9	13.67	16.81	11.69	14.29
15 GHz	Total Attenuation (dB)	31.86	40.03	39.31	50.17	32.87	41.39
23 GHz		57.77	74.29	70.12	91.23	59.46	76.58
30 GHz		83.2	101.62	99.97	122.98	85.5	104.54

Table 5: Rain-Induced Attenuation Using ITU-R Model

Frequency	Quantity	CH Vert	CH Hori	LG Vert	LG Hori	PL Vert	PL Hori
15 GHz	Specific Attenuation (dB/km)	4.36	5.47	5.37	6.86	4.49	5.66
23 GHz		7.90	10.16	9.59	12.47	8.13	10.47
30 GHz		11.38	13.9	13.67	16.81	11.69	14.29
15 GHz	Total Attenuation (dB)	42.34	53.18	52.22	66.65	43.66	54.98
23 GHz		76.76	98.70	93.16	121.20	78.98	101.73
30 GHz		110.55	135.02	132.81	163.38	113.57	138.86

Table 6: Rain-Induced Attenuation Using Lin Model			
Frequency	Quantity	Polarization	
		Horizontal	Vertical
15 GHz	Specific Attenuation (dB/km)	5.30	4.23
23 GHz		9.86	7.68
30 GHz		13.52	11.08
15 GHz	Total Attenuation (dB)	65.77	52.51
23 GHz		122.45	95.40
30 GHz		167.87	137.58

Table 5 shows that the behavior of ITU-R rain attenuation model with the rain rates conversion models. The highest attenuation is recorded for Lavergnat-Golé model, followed by the power law model, while Chebil and Rahman's (1999) model recorded the least attenuation at the same percentage probability of time exceedance. Tables 7 and 8 show the behavior of ITU-R and Moupfouma rain attenuation models with Chebil, Lavergnat-Golé and power law rain rate conversion models in comparison with Lin rain attenuation model which requires rainfall rate at five-minute integration time, at the same probability of time exceedance.

Table 7: Comparison Between ITU-R, Lin and Moupfouma Rain Attenuation Models for Vertical Polarization

Frequency (GHz)	Lin	MP (CH)	MP (LG)	MP (PL)	ITU-R (CH)	ITU-R (LG)	ITU-R (PL)
15	52.51	31.86	39.31	32.87	42.34	52.22	43.66
23	95.40	57.77	70.12	59.46	76.76	93.16	78.98
30	137.58	83.2	99.97	85.5	110.55	132.81	113.57

Table 8: Comparison Between ITU-R, Lin and Moupfouma Rain Attenuation Models for Horizontal Polarization

Frequency (GHz)	Lin	MP (CH)	MP (LG)	MP (PL)	ITU-R (CH)	ITU-R (LG)	ITU-R (PL)
15	65.77	40.03	50.17	41.39	53.18	66.65	54.98
23	122.45	74.29	91.23	76.58	98.7	121.2	101.73
30	167.87	101.62	122.98	104.54	135.02	163.38	138.86

Table 7 shows that the predicted total rain-induced attenuation is highest for Lin rain attenuation and the model is closest to that predicted using the combination of ITU-R rain attenuation model and Lavergnat-Golé rain rate model for all frequencies. Table 8 shows that the combination of ITU-R rain attenuation model and Lavergnat-Golé rain rate model predicted the highest attenuation to be 66.65 dB at 15 GHz, while at 23 GHz and 30 GHz, Lin rain attenuation model predicted the highest attenuation, which is still the closest to the values recorded for the combination of ITU-R and Lavergnat-Golé rain rate conversion model.

Conclusion

The study is on rain rate and rain-induced attenuation prediction for terrestrial radio communication links using three years' rainfall data from Akungba Akoko, Nigeria. It describes how the measured rainfall intensity from a pluviometer can be converted into rain rate using Chebil, power law and Lavergnat-Golé methods. ITU-R, Moupfouma and Lin rain attenuation models are considered as the most pertinent rain attenuation models for terrestrial line-of-sight links in the tropical regions. From the results, it is confirmed that rain-induced attenuation increases with increasing rain rate and transmitting frequency. Considering ITU-R rain attenuation model as the standard and Lavergnat-Golé rain rate conversion model as a suitable model for the tropical region, Lin attenuation model that employs rain rate at five minutes integration time is equally good for the prediction of rain-induced attenuation in the tropical regions.

References

1. Adel A A, Mohammed A A and Mustafa A S (1986), "Rain Map for Radio Wave Propagation Design in Saudi Arabia", *International Journal of Infrared and Millimeter Waves*, Vol. 7, No. 11, pp. 1780.

2. Ajayi G O and Ofoche E B C (1983), "Some Tropical Rainfall Rate Characteristics at Ile-Ife for Microwave and Millimetre Wave Application", *Journal of Climate and Applied*, American Meteorological Scoiety, Published Online, https://doi.org/10.1175/1520-0450(1984)023<0562:STRRCA>2.0.CO;2.

3. Burgueno A M, Puigcever M and Vilar E (1998), "Influence of Rainguage Integration Time on the Rain Rate Statistics used in Microwave Communication", *Annals of Telecommunications*, Vol. 43, Nos. 9&10, pp. 522-527.

4. Capsoni C, Fedi F, Magistoni C and Paraboni A (1997), "Data and Theory for a New Model of the Horizontal Structure of Rain Cells for Propagation Applications", *Radio Sci* (USA), Vol. 22, No. 1987, p. 359.

5. Chebil J and Rahman T A (1999), "Rain Rate Statistics Conversion for the Prediction of Rain Attenuation in Malaysia", *Electronic Letters*, Vol. 35, No. 12, pp. 1019-1021.

Author pl chk ref 1, 20 are not cited in text

ProvideVol, No, pp for ref 6, 8, 11, 13, 18, 19, 20, 28

No for ref 10, 25, 26

pp for ref 21

6. Cheon-In O (2006), "Analysis of the Rain Fading Channel and the System Applying MIMO", *IEEE Journal* (ISCIT).

7. Chris T M (2006), "Rain Attenuation Modelling for Southern Africa", October 2006 Report, *Student Journal*, pp. 1-2.

8. Chun O W and Mandeep J S (2013), "Empirical Methods for Converting Rainfall Rate Distribution from Several Higher Integration Times into a 1-minute Integration Time in Malaysia", Original Scientific Paper UDC 551.508.85

9. Crane R K and DeBrunner W E (1978), "Worst-Month Statistics", *Electronics Letters*, Vol. 14, No. 2, pp. 38-40.

10. Dutton E J and Dougherty H T (1979), "Year to Year Variability of Rainfall for Microwave Applications in the USA", IEEE Trans Communication (USA), Vol. 27, p. 829.

11. Dutton E J and Steele F K (1982), "Bibliography and Synopsis of Literature Concerned with Microwave and Millimeter Wave Propagation Effects", IEEE Trans Communication.

12. Emiliani L and Luini L (2010), "Evaluation of Models for the Conversion of T-Min Rainfall Distributions to an Equivalent one-minute Distribution to be Used in Colombia", Rev. Fac. Ing. Univ. Antioquia N.° 56.

13. Emiliani L D, Luini L and Capsoni C (2009), "Analysis and Parameterisation of Methodologies for the Conversion of Rain-Rate Cumulative Distributions from Various Integration Times to One Minute".

14. Fashuyi M O (2006), "Study of Rain Attenuation on Terrestrial Paths at Millimetric Wavelengths in South Africa", Thesis: Masters in Electrical Engineering in Telecommunications and Information Technology Telecommunications and Information Technology, University of KwaZulu-Natal.

15. France (1999), ITU-R Study Groups Doc. 3J/59, 26.

16. Ghasemi A, Abedi A and Ghasemi F (2012), "Propagation Engineering in Wireless Communications, Basic Principles in Radio Wave Propagation", Vol. XVII, No. 2, p. 434.

17. Isikwue B C, Ikoyo A H and Utah E U (2013), "Analysis of Rainfall Rates and Attenuations for Line-of-Sight EHF/SHF Radio Communication Links Over Makurdi, Nigeria", *Research Journal of Earth and Planetary Sciences,* Vol. 3, No. 2, pp. 60-66.

18. ITU-R (2007), "Propagation Data and Prediction Methods Required for the Design".

19. ITU-R Recommendation P.530-14 (2012), "Propagation Data and Prediction

Methods Required for the Design of Terrestrial Line-of-Sight Systems", International Telecommunication Union.

20. Kesavan U, Tharek A R, Abdulrahman A Y and Abdulrahim S K (2011), "Comparative Studies of the Rain Attenuation Predictions for Tropical Regions".

21. Khandaker L B and Mohammad M R (2014), "Performance Analysis of Rain Fades on Microwave Earth-to-Satellite Links in Bangladesh", *International Journal of Engineering and Technology,* Vol. 4, No. 7.

22. Lavergnat J and Gole P (1998), "A Stochastic Raindrop Time Distribution Model", *AMS Journal of Applied Meteorology*, Vol. 37, No. 8, pp. 805-818.

23. Lin S H (1975), "A Method for Calculating Rain Attenuation Distributions on MicrowavePaths", *BSTJ,* Vol. 54, No. 6, pp. 1051-1086.

24. Moupfouma F (2009), "Electromagnetic Wave Attenuation Due to Rain, A Prediction Model for Terrestrial or LOS SHF/EHF Radio Communication Links", *Journal of Infrared Millitera-Hz Waves*, Vol. 30, No. 3, pp. 622-632.

25. Olsen R L, Rogers D V and Hodge D B (1978), "The aRb Relation in the Calculation of Rain Attenuation", *IEEE Trans. Antennas and Propag*., Vol. 26, pp. 547-556.

26. Rice P L and Holmberg N R (1973), "Cumulative Time Statistics of Surface-Point Rainfall Rates", *IEEE Trans. Commun. (USA) Com,* Vol. 21, p. 1131.

27. Segal B (1986), "The Influence of Rainguage Integration Time on Measured rainfall Intensity Distribution Functions", *J. of Atmospheric Oceanic Tech.*, Vol. 3, No. 4, pp. 662-671.

28. Watson P A, Gunes M, Potter B A, Sathiaseelan V and Leitao J (1982), "Development of a Climatic Map of Rainfall Attenuation for Europe", Final Report of ESA/ESTEC Contract No.4162/79/NL/DG/ (SC), Report 327.

Reference # 70J-2018-08-0X-01