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CHARACTERIZATION OF RAINFALL STRUCTURE AND ATTENUATION OVER TWO TROPICAL STATIONS IN SOUTHWESTERN, NIGERIA FOR THE EVALUATION OF MICROWAVE AND MILLIMETER-WAVE COMMUNICATION LINKS

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Abstract: Characterization of rainfall structure and attenuation are some of the steps to be considered when analyzing microwave propagation. In this paper, 2-year rainfall data of 1-minute integration time obtained from the Nigerian Environmental Climatic Observatory Program (NECOP), Pro-weather station, over two tropical locations in southwestern Nigeria were analyzed for radiowave communication purposes. The results obtained were compared with existing rain rate models to characterize the rainfall structure. Rainfall attenuation over the terrestrial paths in the two regions was also investigated for the path-length not exceeding 20 km using three different rainfall attenuation models namely: ITU-R, Moupfouma and Crane Global model. Overall results obtained from this study will assist radio communication engineers to design systems with an improved quality service for terrestrial and Earth-space communication links in the region.

Keyword: Rainfall structure, rainfall-induced attenuation, year-wise variability, NECOP and microwave propagation.

INTRODUCTION

Accurate and high-resolution rainfall-rate statistics are important for the design and evaluation of both terrestrial and satellite microwave systems. Attenuation of microwave signals by rain is a common problem faced by telecommunication service providers all over the world. It has long been ascertained that rainfall is one of the important atmospheric parameters (hydrometeors) that causes signal degradation along both terrestrial and satellite paths at frequencies beyond 10 GHz (Mandeep *et al*., 2007; Jassal et al., 2011; Ojo and Falodun, 2012). Therefore, in planning reliable communication systems at any location of interest, the knowledge of the rain attenuation at the microwave frequency range is essential. Rainfall rate data of 1-minute integration is needed for predicting rain attenuation in accordance with the International Telecommunication Union Radio Regulation (ITU-R). 1-minute rain rate statistics also have application in the design and operation of aerospace, vehicles, radar systems and satellite sensors among others (Tattelman and Scharr, 1983; Mandeep and Hassan, 2008). It is also necessary to observe the 1-minute time interval of rainfall structure and rain attenuation characteristics due to the diversity in the expanding trend of digital communication through satellite systems operating in the higher frequencies (Choi *et al*., 2005). However, due to the shortage of the required rainfall and rain attenuation data at specific locations, models are needed to predict the location dependence of both rainfall rate and rain-induced attenuation.

In this paper, the characterization of rainfall structure and attenuation over two tropical stations in Nigeria are presented in order to understand the possible period of signal outage to be encountered by communication systems operating in such locations, so that a suitable mitigation technique can be proposed for the region. Rainfall rates of 1-minute integration time were used to study the cumulative distribution of rainfall, the year-wise variability, comparison with existing models, the threshold of rainfall, evolution of rainfall and attenuation due to rainfall on the terrestrial paths.

DATA AND METHODOLOGY

2-year rainfall data (1st January 2011 to 31st December 2012) was obtained from the Nigeria Environmental Climatic Observatory Program (NECOP) Pro-weather station using tipping bucket rain gauge with resolution and effectiveness of 0.2 mm per tip and aperture size of 400 cm^2. The NECOP facilities are installed at the Federal University of

Technology, Akure, Ondo State (FUTA) and University of Lagos, Lagos State (UNILAG), Southwestern, Nigeria among other stations. Details about the NECOP set up are available in the work of Ojo and Falodun, 2012. The 1-minute integration time corresponds to 0.002% of the year. The accuracy of the gauge is ±1% with a measuring range of a minimum of 2 mm/h to a maximum of 400 mm/h. The data logger samples the data at every 10 seconds and averaged the data at every 1-minute. The availability of the rain gauge in a year is about 99.5% and 99.2% in Akure and Lagos respectively. The 0.5 and 0.8% of unavailability of the equipment are due to calibration and battery failure of the solar panel. The calibration of the rain gauge is maintained by regularly cleaning the capillarity. The overall reliability of the gauge is extremely high due to the simple drop-forming mechanism. The reliability has to be ensured by regularly keeping it clean, so that dust particles do not obstruct the free flow water (Ojo and Falodun, 2012). The tipping bucket rain gauge is one of the instruments available for data collection in the NECOP set up. Table 1 presents the characteristics of the experimental sites.

The 1-minute rainfall rate obtained was compared with the existing rain rate models namely: Rice and Holmberg, (1973); Moupfouma and Martins, (1995); Ito and Hosoya, (1999); ITU-R. Rec. P.837-6, (2012) and thereafter used to determine rainfall attenuation using three established models for terrestrial attenuation prediction. The models are: the ITU model (ITU-R, 530-12, 2012) the Crane Global model (Crane, 1996) and the Moupfouma model (Moupfouma, 1984). This is achieved by using $R_{0.01}$, defined as rainfall rate value at the outage probability value of 0.01% of the time, with a 1-minute integration time averaged over a period of 2-years for each of the location of study.

Rain rate prediction models were tested using the method recommended by ITU- R (2009) where for certain percentage of time ranging between 0.001% and 1% of the year for which data is available, the percentage of relative error between the predicted value and measured value are obtained using:

$$\%\ \text{relative error} = \frac{\text{Predicted }(p\%) - \text{Measured }(p\%)}{\text{Measured }(p\%)} \qquad \text{................ (1)}$$

The mean error, ì, and standard deviation,s, are used to determine the root mean square (rms) error, is defined as:

$$rms = \sqrt{\mu^2 - \sigma^2} \qquad \text{............... (2)}$$

RESULTS AND DISCUSSION

Distribution of Surface Rainfall Amount at the Locations

Figure 1 presents the monthly accumulated rainfall amount averaged over 2-year study period at the measurement sites. The average monthly rainfall in a location depends on the movement of the Intertropical Discontinuity (ITD). Precipitation occurs when air masses acquire moisture on passing over warm bodies of water, or over wet land surfaces. The moisture is carried upward into the air mass by turbulence and convection leading to lifting process that provides understanding of rainfall distribution across the globe. The ITD on its own part moves northward or southward with seasons. The discontinuity follows the sun northward during summer, as a result of this, more and more of the country (Nigeria) comes under the influence of the moisture-laden tropical maritime air. As period of summer wanes, the zone shifts southward, and bringing an end to the rainy season. Nigeria has two seasons: wet season (March - October) and dry season (November – February of the following year). Also, heavy rain usually falls during the wet season in the two locations and during this period, the ITD

Table 1: Site characteristics of the study locations

Station	Latitude (° N)	Longitude (° E)	Altitude (m)	Average annual rainfall (mm/year)	Region climate
FUTA- Akure	7.17	5.18	358	1598.5	Rain forest
UNILAG- Lagos	6.35	3.20	129	1861.45	Coastal

moves across the country. Based on the results from Figure 1 and Table 1, the average yearly rainfall total at UNILAG, Lagos and FUTA, Akure was about 1599 and 1862 mm respectively. Also from the measurements, September was the month in Akure with the mean monthly accumulated rainfall of about 198 mm, while the less ideal for microwave transmission month for Lagos was June with a mean monthly accumulation of about 239 mm. The minimum rainfall amount of about 1.5 mm (FUTA, Akure) and 5.6 mm (UNILAG, Lagos) occurred in December and January respectively due to ITD movement.

Year-wise Variability of Cumulative Distributions

Figure 2 presents the year-wise variability of cumulative distribution of average 1-minute rainfall rate over the two stations. The mean rain rate over the two years of measurement and the recent ITU-R rain rate model for each station (ITU-R, 2012) were compared. Cumulative distributions obtained were based on rainfall rates and percentage of time. The higher the rainfall rate, the lower the corresponding percentage of time recorded and the lower the rainfall rate the higher the percentage of time exceeded. Figure 2(a) shows that Akure with an average annual rainfall accumulation of 1599 mm recorded about 78 mm/h at 0.01% of time in the first year, while it was 98 mm/h at the same percentage of time in the second year. In the same vein, Lagos with an average annual rainfall accumulation of 1862 mm recorded about 185 mm/h at 0.01% of time in the first year, while it was 123 mm/h at the same percentage of time in the second year (Fig. 2b). The same trend could be observed in other percentages of time although with different values. Also, the cumulative distribution of rainfall rate was higher in year 2 when compared with year in Akure while the reverse is the case for Lagos. This shows how dynamic rainfall rate over the two locations could further be. Furthermore, it could be observed that the recent ITU-R model overestimated the rainfall rate at 0.01% exceedance of time by about 21% for Akure while it was underestimated by about 31% for Lagos.

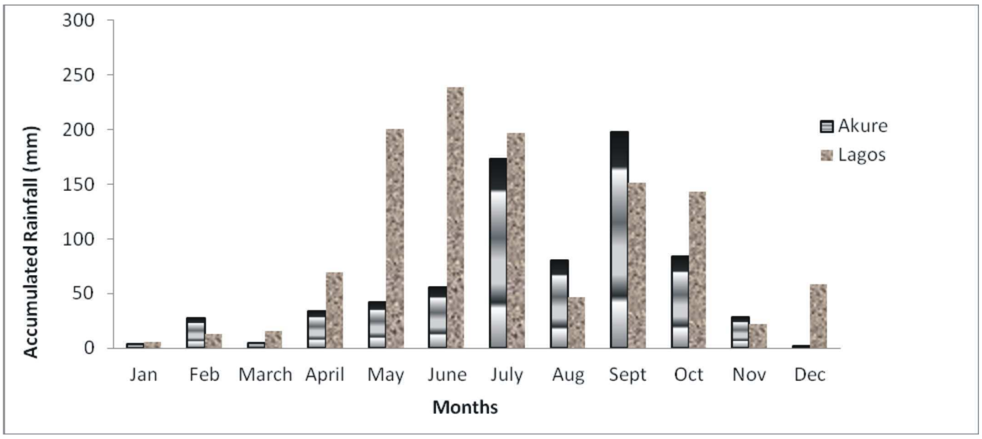
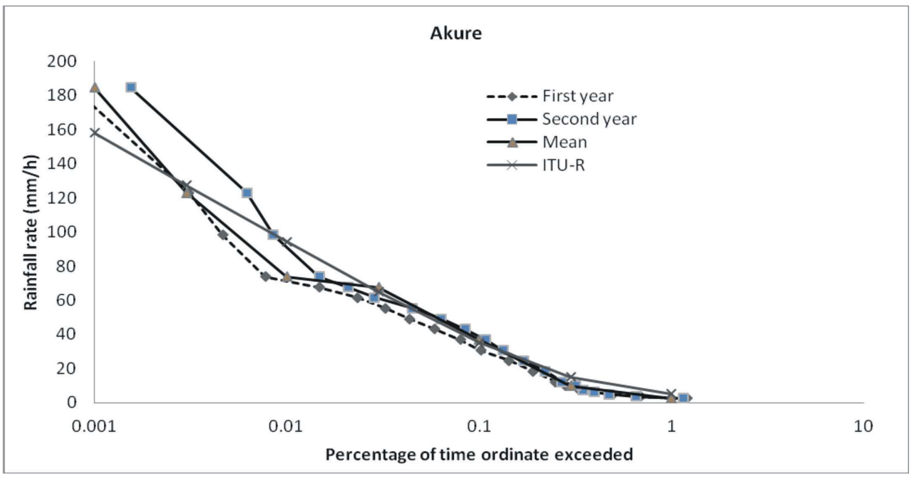
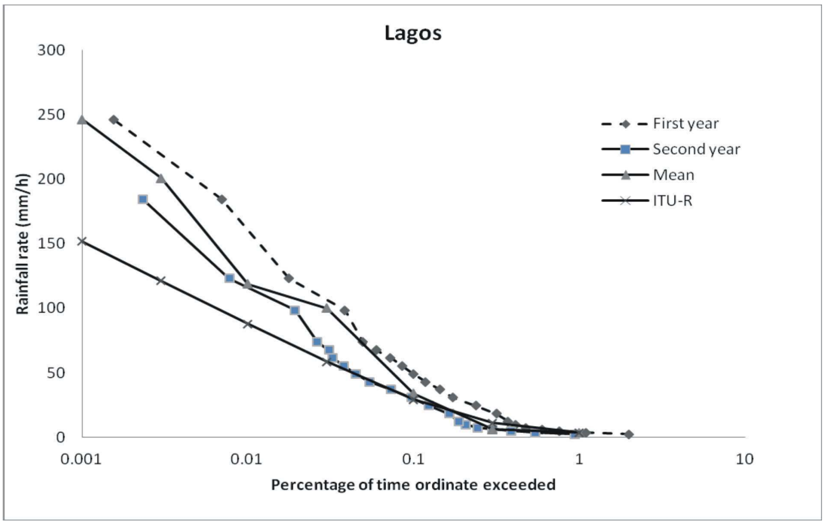


Figure 1: Monthly accumulated rainfall averaged over 2-year study period.



(a)



(b)

Figure 2: Year-wise variability of cumulative probability function of rainfall rate of 1-minute integration time over (a) Akure and (b) Lagos.

Comparison of Cumulative Distribution of Rainfall Rates with Existing Rain Rate Models

Figures 3(a and b) present the comparison of cumulative distribution of measured 1-minute rainfall rate and other models such as, Rice and Holmberg, 1973-RH model; Moupfouma and Martin, 1995-Moupfouma model; ITU-R model (1997) and Ito and Hosoya, 1999-Kitami model. The cumulative distribution is as usual based on rainfall rates and percentage of time. The higher the rain intensity the lower the corresponding percentage of time recorded, while the lower the rain intensity the higher the percentage of time. In Figure 3a, at the lowest percentage time of 99.999% that 0.001% exceedance, rainfall rate is about 200.6 mm/h, 174.2 mm/h, 158.1 mm/h, 159.6 mm/h and 184.6 mm/h for RH, Moupfouma, ITU-R, Kitami and the measured data respectively, while at the higher time percentage of 99.99% the rainfall rates are 120.4 mm/h, 106.8 mm/h, 94.4 mm/h, 95.3 mm/h and 98.5 mm/h for RH, Moupfouma, ITU-R, Kitami and the measured data respectively. Also, Figure 3b presented similar trend, where at 99.99% of time, rainfall rate is about 123 mm/h, 105.5 mm/h, 87.9 mm/h, 89.2 mm/h and 100 mm/h for RH, Moupfouma, ITU-R, Kitami and the measured data respectively. It is also about 200 mm/h, 172 mm/h, 151.7 mm/h, 152.1 mm/h and 169.1 mm/h at the lower percentage time of 99.999% for RH, Moupfouma, ITU-R, Kitami and the measured data respectively. These results indicated that over the two locations, Moupfouma model gives better prediction than other models when compared with the measured data.

In order to buttress the aforementioned assertion, Table 2 presents the statistical analysis of the cumulative distribution of the measured rainfall rates with the predefined models. The models were tested using the percentages of the relative error defined in equation (1.0) the Root Mean Square error (RMS) defined in equation (2.0) to judge the performance of each of the model. Since the regression models for attenuation prediction often use only rain rate at a single exceedance probability level, 0.01% of a year, the RMS values for that probability level are separately tabulated while exceedance probability levels for both 0.01 and 0.001% of the year are presented for the average relative error for multimedia purposes. Judging from figures 3a and 3b, nearly all the models agree well with the measured data up to 0.1% of the year (results not included in Table 2). However, results from Table 2 shows that RH model over estimated the measured data by more than 25% at exceedance probability levels for both 0.01 and 0.001% of the year in the two locations. This is because; the model was based on 5-minute average extreme rain rate observations and hourly rain rate empirical cumulative distribution functions (EDF's). They did not have 1 minute average rain rate EDF's for statistical analysis but engineered a plausible distribution from shape from the data then available. There is also uncertainty in rain rate distribution shape in the probability region between 0.001% of a year and 0.1% of a year (Crane, 1996).

The ITU-R model agree with the measured rainfall rates for interval between 99% and 99.9% of time at both locations, but underestimated the measured data at Lagos while the measured data were overestimated at Akure using the average relative error at 99.99% most needed for rain attenuation prediction. The discrepancies might be due to the matrices used to obtain the parameters needed for the model. The model was actually based on the improved version of Salonen Baptisa model (1997). The Kitami model over estimate the measured value at 0.01% of the year at Akure, while it underestimates the measured data at this percentage of time as well as at 0.001% needed for multimedia applications. Kitami model was based on 1-minute rain rate distribution using thunderstorm ratio and average annual precipitation as regional climatic parameter from Kitami Institute of Technology data bank. The set back of the model is that some of the parameters needed are interpolated (Ojo and Falodun, 2012).

For the two locations considered, the Moupfouma model appears to fit best, the measured data judging from the lowest % RMS values as well as the average relative error. The model was developed based on intensity cumulative distributions for most of the hydro-meteorological zones of the world. It is also based on approximation of the log-normal distribution at the low rates and a gamma distribution at the high rain rates. This further confirms the work of earlier researchers (Ojo and Falodun, 2012; Mandeep, 2011, Mandeep and Hassan, 2008) that Moupfouma model can best be used to predict 1-minute rain rate in the tropical region.

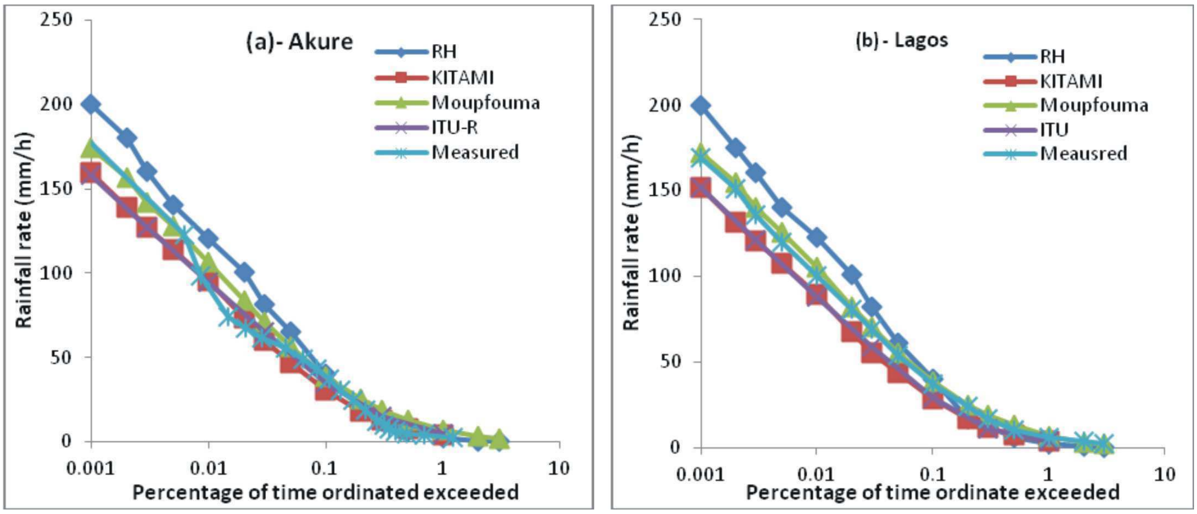


Figure 3: Comparison of averaged cumulative distribution of rainfall rate models with measured data over (a) Akure and (b) Lagos

Table 2: The statistical analysis of the cumulative distribution of the measured rainfall rates with the predefined models.

Locations	**Akure**	**Lagos**	**Akure**		**Lagos**	
	% of RMS error		**Average relative error**			
Model			**0.01%** of year	**0.001%** of year	**0.01%** of year	**0.001%** of year
RH	10.5	13.2	25.2	35.4	27.5	34.6
Kitami	9.8	10.2	6.2	-14.2	-7.4	-10.7
Moupfouma	4.5	6.5	5.3	3.4	4.5	3.6
ITU-R	7.5	8.4	5.8	-10.5	-7.2	-10.2

Thresholds of Rainfall

Knowing the particular rainfall rate that exceeded a particular value is very important for radio communication and satellite systems design. Figure 4 presents, the results of the number of exceedance and threshold of rainfall over the two stations. Twelve thresholds covering the rainfall rate from 3 to 200 mm/h were used. The results illustrated higher number of rainfall at all thresholds in Lagos than Akure and lower rainfall rate contributed most to the thresholds. This occurrence may be due to the fact that Lagos is a coastal region in Nigeria resulting in higher thresholds. The results indicated that when there is a higher threshold it signifies that system availability does not satisfy the specification unless an additional margin is considered (Karasawa and Matsudo, 1991; Ojo et al., 2009).

Dynamical Characterization of Rainfall Events

Examining the dynamical characterization of the rainfall intensity events over the two tropical stations is of huge interest to radio communication systems design. This makes us to understand the periods of the year that contributed most to the small exceedances. Figures 5 (a and b) present the evolution of rainfall intensity throughout an average day for the indicated outage period over Akure and Lagos respectively. The evolution is based on rainfall rate (mm/h) and hours of the day, local time (LT). The impact of convective rain contributing mainly to the small percentages of time could be observed, considering an average day for each exceedance. Results from Figures 5(a and b) show that evolution of low values (0.1% of time) of rainfall rate are completely independent of the hour of occurrence, whereas for very small percentages of time (0.001%), the values of rainfall rate are dependent on the time of the day. The result also shows that rain rates in excess of 50 mm/h occur more in the evening and some in early morning hours. However, the frequency of occurrence in the early hours of the day is higher in Lagos when compared with Akure. These hours comprise of the period for which communication services like transaction of businesses through internet, telephony, electronic banking takes place while in the evening hours, people are expected to enjoy direct-to-home Television services. System engineers therefore need to take into cognizance, the rainfall rate variations bearing in mind the volume of commercial activities taking place in the two cities (Lagos is the main industrial and commercial capital of Nigeria, while Akure is the capital city of Ondo state, Nigeria).

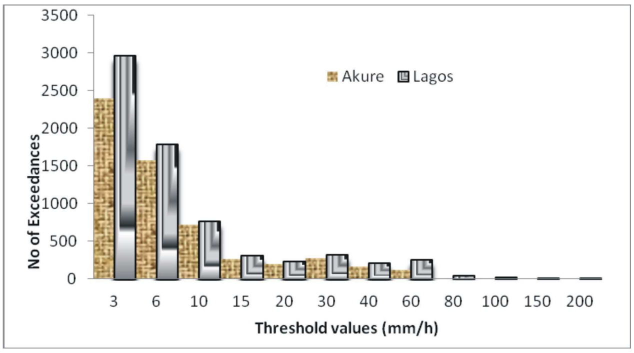


Figure 4: Thresholds of rainfall

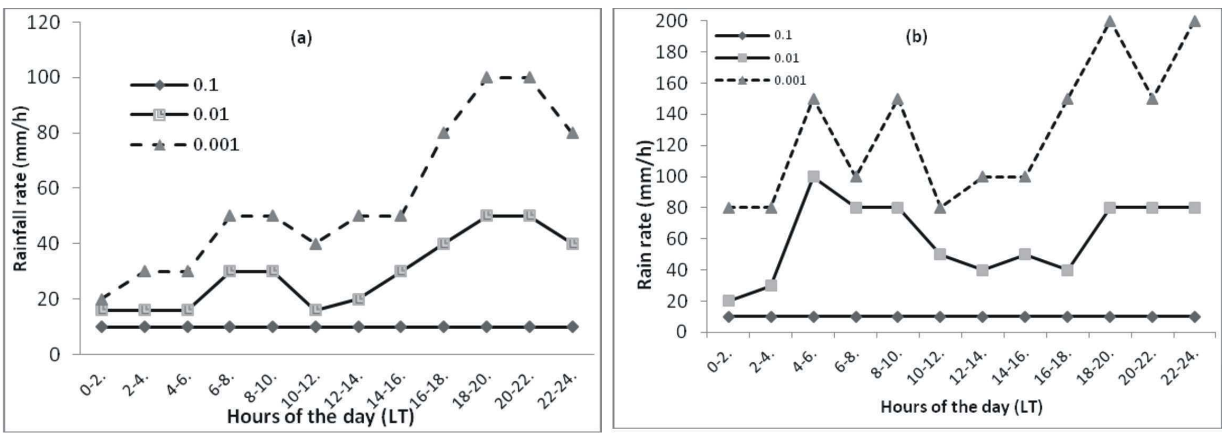


Figure 5: Evolution of rainfall intensity throughout an average day for indicated exceedance over (a) Akure and (b) Lagos

Attenuation Exceeded for 0.001 and 0.01% of Time on Terrestrial Paths in the Locations.

Figures 6 and 7 present plots of the predicted attenuation using various models for terrestrial line-of-sight (LOS) links against path lengths at percentage time exceedance of 0.001% and 0.01% respectively. Details of these models are available in Crane, 1996. Four frequencies within the Ku and Ka-band over the two stations were considered namely: 12 GHz, 20 GHz, 30 GHz and 40 GHz. In all the frequencies considered attenuation of the three models increase as the propagation path increases.

In figure 6 (a) for example, Moupfouma model gives the highest attenuation values in all the frequencies considered while Crane Global model curve which tends to give the lowest attenuation values at 4 and 8 km propagation path lengths, disperses a bit and intersect with the ITU-R model at path length greater than 15 km. The ITU-R model curve flattens more as the frequency and path length increases. In Lagos at 0.001% of time (Figure 6b), similar trends could be observed except at frequencies 12 GHz and 20 GHz where Crane Global models gives the lowest attenuation values while ITU-R models became closer as the propagation path length increases.

Figure 7a shows that in Akure, the ITU-R model gives the lowest attenuation values at all the frequencies while the Crane Global model which provides the highest attenuation values at the initial stage, bends more than that of Moupfouma model at path length 4, 6 and 8 km. It further intersects the Moupfouma model at these path lengths except at the frequency of 40 GHz where the Crane Global model gives the highest attenuation values throughout the propagation path. Figure 7b (Lagos) reveals that Moupfouma model provides the highest attenuation values at all frequencies while Crane Global model gives the lowest attenuation values in all the frequencies considered, Crane Global model which tends to provide the lowest attenuation values spread out and intersects with ITU-R model at path length greater than 5 km.

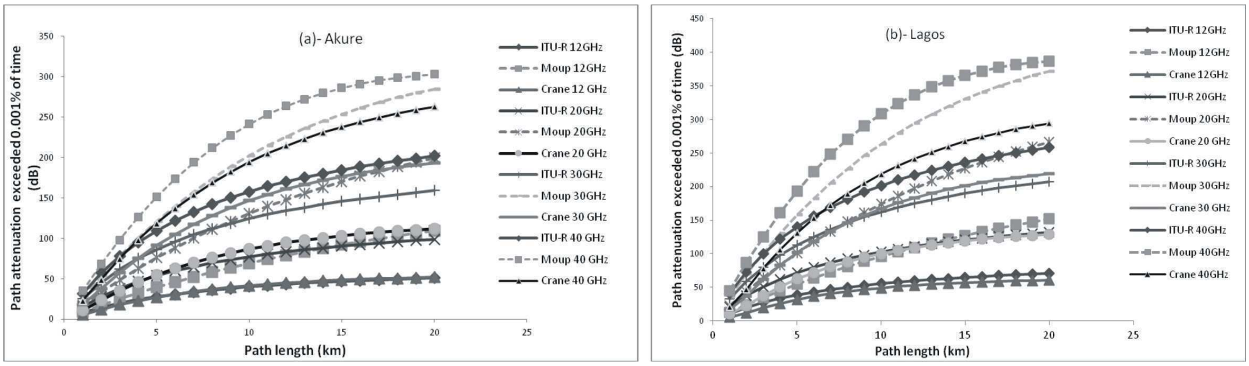


Figure 6: Rain-induced attenuation prediction models exceeded 0.001% of time for terrestrial line of sight at Ku and Ka-band frequencies (a) Akure and (b) Lagos.

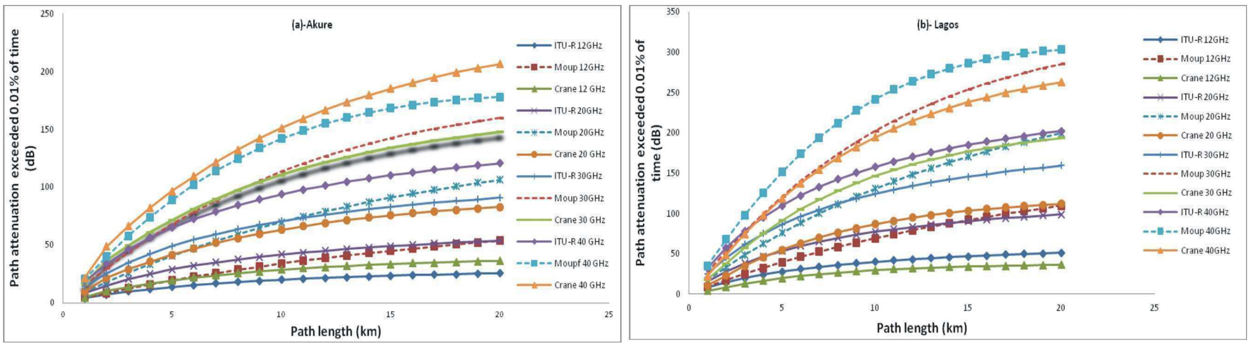


Figure 7: Rain-induced attenuation prediction models exceeded 0.01% of time for terrestrial line of sight at Ku and Ka-band frequencies (a) Akure and (b) Lagos.

CONCLUSIONS

In this study, rainfall structure and attenuation over two tropical stations in Southwestern, Nigeria are presented to assist in the design and evaluation of propagation effects on microwave and millimeter-wave communication systems. Measured rain rates are compared with the existing rainfall models. The cumulative distribution of rainfall rate when compared with the ITU-R model reveals that the model overestimated the rainfall rate exceeded for 0.01% unavailability of time by about 21% in Akure but underestimated it by about 31% in Lagos. It was also found that Moupfouma model show the closest fit to the measured data for low, medium and high rainfall rates based on statistical analysis with lowest values of RMS and average relative error. The RH model overestimated the measured data at exceedance probability levels of 0.01 and 0.001% of the year, the Kitami model over estimated the measured value at 0.01% of the year at Akure, while it underestimates the measured data at this percentage of time as well as at 0.001% needed for multimedia applications. The thresholds of rainfall showed higher rain rate values in Lagos when compared with Akure. It is also observed that high rain rates occur more in the evening and in the early morning hours over the two locations. However, the frequency of occurrence in the early hours is higher in Lagos when compared with Akure. Also, the rain-induced attenuation predictions obtained from the three different existing attenuation models on terrestrial line of sight for 0.001% and 0.01% of time gives variation in attenuation. These results will be of great interest to system engineers for the design and evaluation of microwave and millimeter-wave transmission of high data rate communication systems when higher link availability is required.

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