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Tropical Rainfall Structure Characterization over Two Stations in Southwestern Nigeria for Radiowave Propagation Purposes

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Abstract
Tropical rain structure characteristics are investigated over two stations in southwestern, Nigeria using 2-year rainfall data of 1-minute integration time obtained from the Nigerian Environmental Climatic Observatory Program (NECOP), Pro-weather station. This result was analyzed in order to present information about the detailed microstructure of rain rate in this region and their impact on satellite-Earth propagation link services. The statistical analysis of the data has been based on the cumulative distribution function (CDF), exceedence of rainfall intensity threshold values, integration time effect, dependence of rainfall on the event duration, worst month concepts as well as diurnal variability. Dependence of average rain rate on the duration of rain event shows that in Akure, the average rainfall intensity during the rain events is about 8.59 mm/h, the maximum rainfall intensity during rain events was 179.6 mm/h, while in Lagos the minimum rainfall intensity during rain events was 1.51 mm/h and the maximum rainfall intensity was 206.8 mm/h. In overall, the results obtained will assist in the successful planning of communication links to operate in the Ku and higher frequency bands in a tropical location like Nigeria.

Keywords: rainfall structure, tropical locations, threshold levels, rainfall evolutions, diurnal variability

INTRODUCTION

Rainfall is an important part of the global hydrological cycle, as it is the key entity to drive energy circulation in the atmosphere Kumar (2006). Rainfall is also a vital factor for consideration in the design of telecommunication systems. The effects of rainfall on microwave terrestrial and space communication systems, especially in tropical and equatorial zones, pose the most important problem for the telecommunication engineer at frequencies above 10 GHz (Moupfouma et al., 1990, Ojo et al., 2008, Ojo and Omotosho, 2013). Rainfall structure is very inhomogeneous both in terms of location and time. Its inhomogeneity shows distinct diurnal, seasonal, and yearly variations (Ajayi, 1996). In terms of location, rainfall structure depends on the movement of the Inter Tropical Discontinuity (ITD) which is determined by the variation of the Intertropical convergence zone (ITCZ). The ITD movement dictates the seasonal weather pattern in the tropics. Nigeria is one of the tropical countries that has two main seasons: wet (March-October) and dry (November - February of the following year). Also in Nigeria, heavy rainfall usually falls during the wet season and during this period the ITD moves across the country (Ojo and Falodun, 2012). The rainfall is known to be dominated by the convective type, which occurs in short time spell over shorter distances. The diurnal variation of the rainfall pattern experienced in the tropical region also depends on the temperature variation and aerosol activities among other factors (Das et al., 2013). Therefore, in order to obtain an optimum performance of satellite signals in the tropical locations, there is the need to critically test the structure of rainfall and its impingement on the microwave systems.

In this work, we investigate the temporal variability of rainfall structure in two locations Akure and Lagos in southern Nigeria using 2-years of measured rainfall data of 1-minute integration time. The study also examined the statistical durations and time interval between rainfalls spells; the diurnal variability, threshold levels as well as the usual rain rate cumulative distributions. The primary aim is to present information about the detailed microstructure of rain rate and their impact on radio propagation in order to plan an optimum link budgeting for satellite-Earth link services in the studied region.

SITE SELECTION, DATA BASES AND ANALYSIS

Table 1 presents the characteristics of the experimental sites. Each of the location is identified by its rainfall climatology. The Federal University of Technology, Akure, Nigeria, FUTA (henceforth be referred to as Akure) is located in the rain forest region of Nigeria and governed by the movement of the ITD, whereas, University of Lagos, UNILAG (henceforth referred to as Lagos) is on the coastal plane and governed by the same ITD movement. The maximum rainfall recorded per year in each of the location is also presented. Further details about these locations are given in the work of Ojo and Falodun (2012).

2-year rainfall data from January 2011 to December, 2012 with an up time well in excess of 99% are used in this work. Rain rate data of 1- and 5-minute integration time was used in the analysis. The rain rate data are obtained using tipping bucket rain gauge with resolution and effectiveness of 0.2 mm per tip and aperture size of 400 cm^2 of the Nigeria Environmental Climatic Observatory Program (NECOP) Pro-weather stations. The 1-minute integration time corresponds to 0.001% of the year, while 5-minute integration time corresponds to 0.002% of the year. The detailed set up of the NECOP is available in the work of Ojo and Falodun (2012). At the two sites, the rain gauges have similar specifications, accuracy of ±1% with the measuring range of a minimum of 2 mm/h to a maximum of 400 mm/h. The data logger samples the data in every 10 seconds and averaged the data at every 1-minute. The 5-minute values were obtained from 5 successive 1-minute measured values. 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 reliability of the data from the gauge has to be ensured by regularly, keeping it clean, so that dust particles do not obstruct the free flow of water.

RESULTS AND DISCUSSION

Mean Monthly Accumulated Rainfall Distribution

Improvement on quality of service requires a great deal more detailed information of a particular season and month. Fig. 1 presents the mean monthly accumulated rainfall amount over the observed 2-year period. The two locations, usually experience heavy rainfall during the wet-season (March – October). In this study, the result of the heavy rainfall downpour is considered as the seasonal variation. The month of September was observed as the worst calendar month of the year in Akure with a mean monthly accumulated rainfall of 98.1 mm. In Lagos, the month of June was the worst month with a mean monthly accumulated rainfall of 238.5 mm. This is an indication of worst calendar months of a radio link at the location. It could also be observed that the rain forest region (Akure) and the coastal region (Lagos) both recorded that peak average monthly rainfall accumulation in the same month when the worst month was experienced. Also, due to ITD movement, rain continues to fall even during the dry season in the rain forest and coastal region. These results agree with the work of Ojo and Sarkar (2008) that rainy period in a tropical location can fluctuate in length, time of occurrence, and severity.

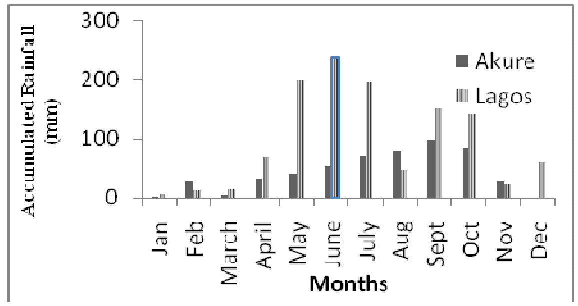


Fig. 1: The mean-monthly accumulated rainfall (mm) over the observed stations.

CDF of Rain Rate based on Different Integration Time

Fig. 2 (a and b) presents the results of 1- and 5-min rainfall rate distributions for Akure and Lagos respectively. It could be observed that for the 2-years of observation at the lowest percentage of 0.001% exceedance for Akure (Fig. 2a), rain rate of about 150 mm/h was continually exceeded for 5-minute integration time while the equivalent 1-minute integration time rainfall rate exceeded is about 184.58 mm/h. Also, at the higher percentage exceedance time of 0.01%, 5-minute integration time rainfall rate of about 80 mm/h was continuously exceeded while its 1-minute integration time equivalent is 98.45 mm/h. Also at 0.1% time, 40 mm/h of rainfall rate was exceeded in 5-minute integration time while it was about 43.10 mm/h for the equivalent 1-minute integration time. The same trend was observed in Lagos (Fig. 2b) although with different rain rate values. Generally, these results show that rainfall rate of 5-minute integration time does not give a true value of rain rate in a location. For example, in Akure and at 0.01% of time, 5-minute integration time rainfall rate underestimated the actual value by about 20%. Hence, rain-induced attenuation estimated using the 5-minute integration time rainfall rate will be underestimated in these locations.

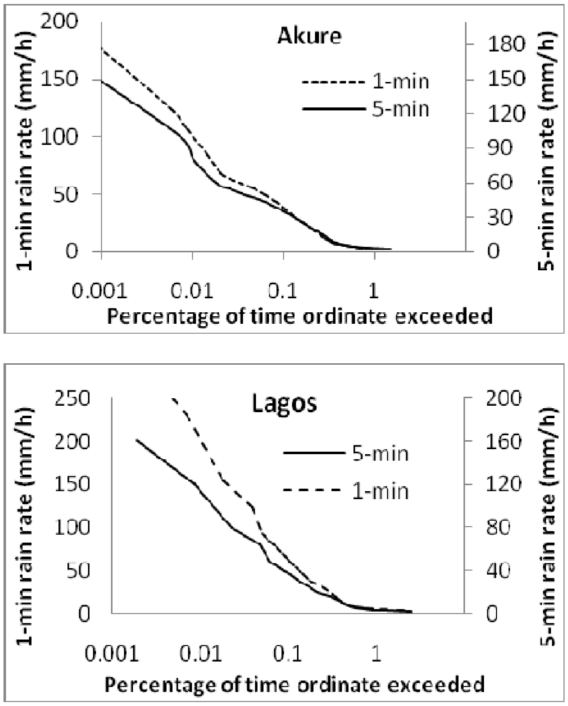
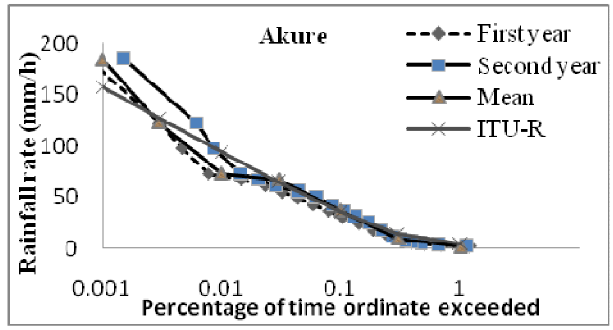


Fig. 2: Comparison of average 5-minute integration time rainfall data with 1-minute rainfall rate over the observed stations

Yearly Cumulative Distribution of Rainfall Rate

Fig. 3 (a and b) presents the year-wise variability of the cumulative distribution of averaged 1-minute integration time rainfall rate over Akure and Lagos respectively. The mean rain rate over the two years of measurement and the recent ITU-R P. 837-6 (2012) rain rate model for each station were compared. The cumulative distributions obtained were based on rainfall rates and percentage of time. The higher the rainfall rate, the lower was the corresponding percentage of time recorded and the lower the rainfall rate the higher the percentage of time exceeded. Fig. 3(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. 3b). 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 the second year when compared with the first year in Akure while the reverse was the case in Lagos. This shows how dynamic rainfall rate over the two locations could be. Furthermore, it could be observed that the recent ITU-R model overestimated the rainfall rate at 0.01% exceedence of time by about 21% for Akure while it was underestimated by about 31% in Lagos.



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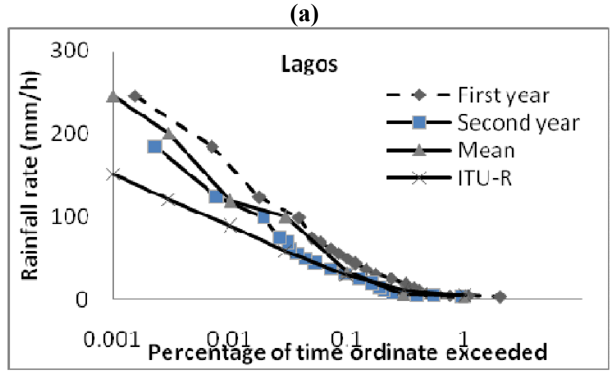
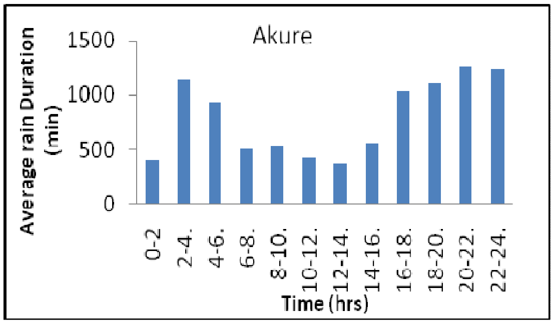


(b)

Fig. 3: Yearly cumulative probability functions of rainfall rate of 1-minute integration time over (a) Akure and (b) Lagos.

Diurnal Variation of Rain

The diurnal rainfall patterns of each of the locations were also presented in Fig. 4. The 24-hour period is first divided into 12 sections of 2-hour duration. The total amount of rain duration encountered over the whole measurement period is then obtained from the database in each of these sections. It could be observed that the probability for rain occurrence as well as its intensity differs from time to time and this strongly depend on the climatology of each location. For example figure 4a shows that rainfall is relatively less in the morning and afternoon hours than other hours of the day. However, it is the reverse in case of Lagos (Fig. 4b). The lowest rainfall could be observed around 12-14 hrs local time while maximum rainfall is observed around 20-22 hrs local time at Akure. For Lagos, the lowest rainfall is observed around 14-16 hrs local time while maximum rainfall is observed around 02-04 hrs local time. In general, the two locations show high rainfall late in the evening and very early morning. The significance of these results is that high rain rate for shorter time duration can cause high fade since rain attenuation depends on rain rate (Das et al., 2013).



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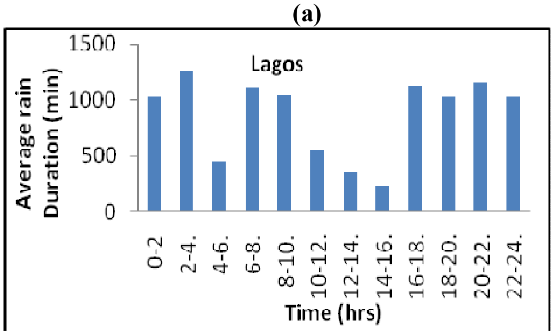


(b)

Fig. 4: Distribution of rain durations over (a) Akure and (b) Lagos

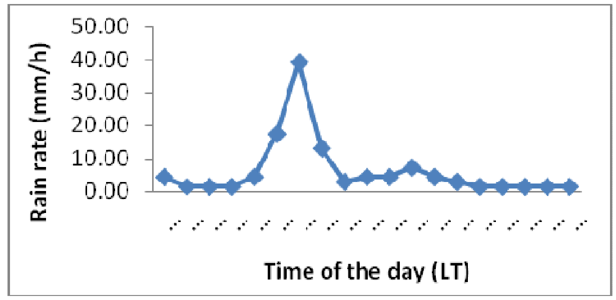
Examples of Intense Rainfall Events

This section presents the results of some rainfall events and their implication on radiowave signals.

Case study of Time series of Rainfall Rates

We selected some rain events to present the time series of rain rate during the month with the most intense rainfall rate at the two stations: September for Akure and June in Lagos. The first rain event of intense rainfall rate occurred in Akure occurred on 9 September, 2011 (Fig. 5a) between 13:30 and 20:50 pm local time. It was a convective shower event with a single intense peak and occurred for about 20 mins, and was followed by the stratiform event. Later in the evening, there exists about 40 consecutive minutes during which rain rates were below 2 mmh^{-1}. The second rain event occurred on 23 September 2011 (Fig. 5b). It is categorized by stratiform rain type followed by three convective showers. The stratiform rain events occurred in about 55 mins followed by about 50 mins of the first two convective showers and about 25 mins of the third one. The total duration of the convective showers is about 75 mins. It then showed that small drops contributed to rain rate in these rain events more than they did in the second events.

Figure 6 (a and b) presents similar results for Lagos. The first rain event with intense rainfall rate in Lagos occurred on 4 June, 2010 (Fig. 6a) while the second rain event occurred on 8 June, 2010. In Fig. 6 (a) for example, there are 3 cases of convective showers that lasted altogether for 30 mins and 2 cases of convective thunderstorm that lasted for about 20 mins. However, in Fig 6 b, the event was entirely convective showers that lasted consecutively for more than 45 mins.



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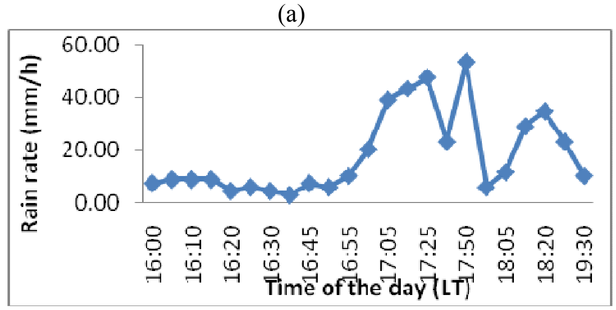

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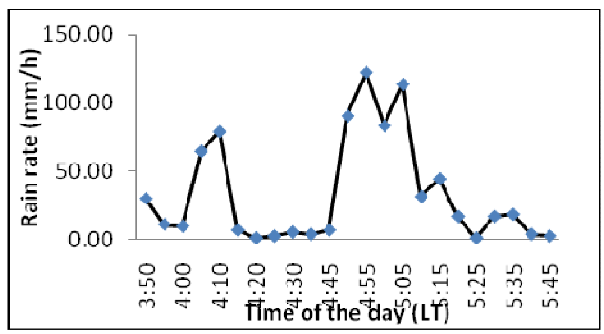
Fig. 5: Time series of rain rate during the rain events of (a) 9th September 2011, (b) 23rd September 2011 in Akure



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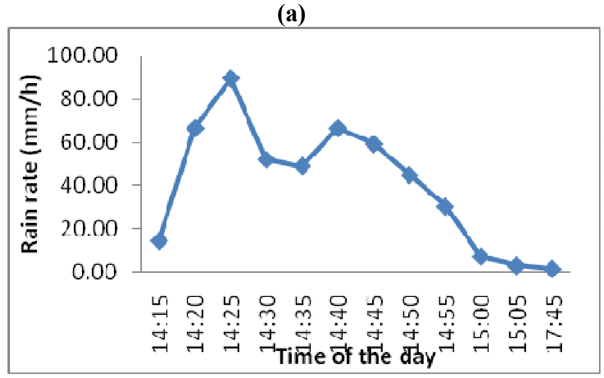


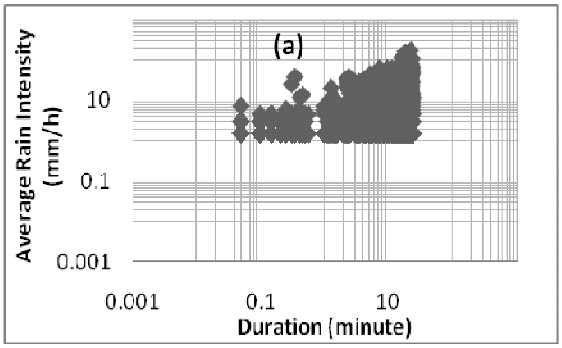
(b)

Fig. 6: Time series of rain rate during rain events of (a) 4th June 2010, (b) 8th June 2010 in Lagos.

Dependence of Average Rain Rate on the Duration of Rain Event

Figure 7 presents a typical scatter plot of the average rainfall rate event against the duration of rain events for all the rain events at both locations. In Figure 7a for example, the average rainfall intensity during the rain events is about 8.59 mm/h, the maximum rainfall intensity during rain events was 179.6 mm/h, while the minimum rainfall intensity was 1.51 mm/h. Also, the duration of the event was 14.60 min; the maximum rainfall event duration over the 2 years was 24 hours, while the minimum rainfall event duration was 0.05 min.

The same trend could be observed in Lagos (Fig. 7b) where the minimum rainfall intensity during rain events was 1.51 mm/h and the maximum rainfall intensity was 206.8 mm/h. The average duration of the event was about 10.10 min; the maximum rain event duration over the 2 years was also 24 hours, while the minimum rain event duration was 0.05 min.



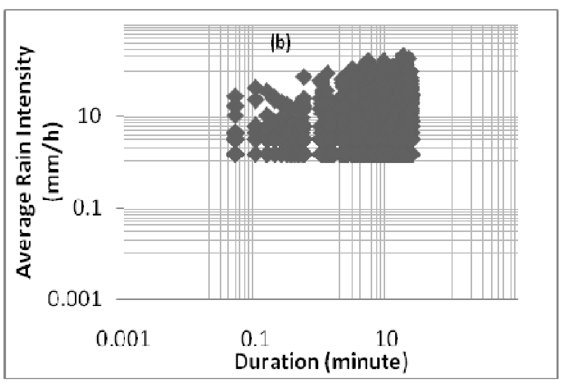
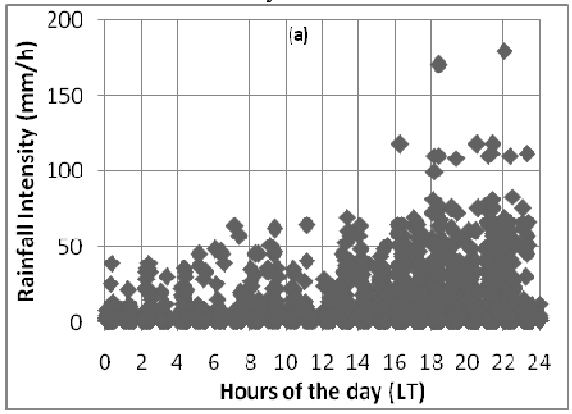


Fig. 7: Scatter plot of the dependence of average rainfall rate events (mm/h) on rain event duration for (a) Akure and (b) Lagos

Dependence of Annual Average Rainfall Intensity on Hour of the day

The dependence of annual average rainfall intensity on the hour of the day is important in determining the average rainfall rate over the time at which the peak of the event will occur. Figure 8a shows that the maximum rainfall rate transpired mostly in the evening and night time between 16 and 23 o'clock LT for the averaged 2-year rainfall in Akure. Figure 8b on the other hand shows that in Lagos, the maximum rain rate transpired mostly in the early hours of the day (5 – 9 am LT) and late in the evening (18 – 22 hours LT). These periods are the periods when people are supposed to enjoy direct to home services after the day's work.



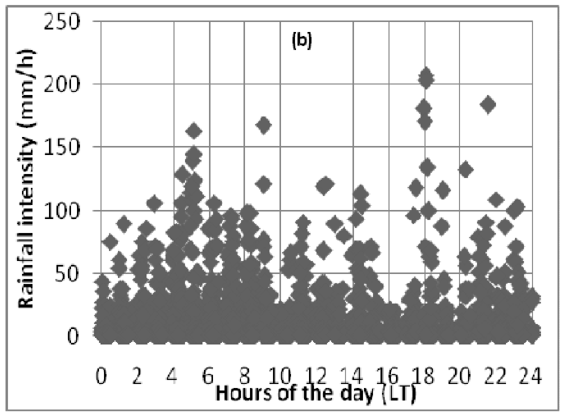


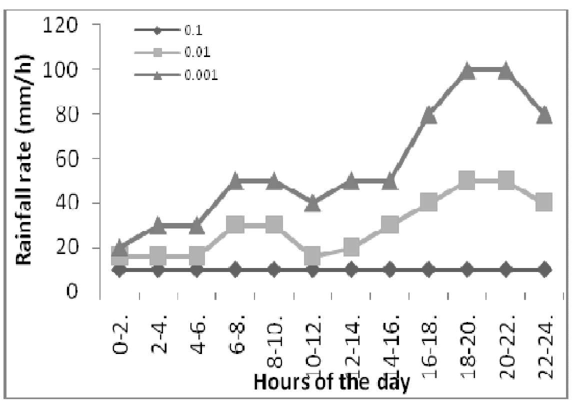
Fig. 8: Diurnal variability of annual average rainfall rate events over (a) Akure and (b) Lagos

Dynamical Characterization of Rainfall Events in Akure and Lagos

Examining the dynamical characterization of the rainfall rate events over the two tropical stations (Akure and Lagos) is also of huge interest to radio communication system designers. This is important for understanding the periods of the year that will contribute the most to the small exceedences. Figure 9 presents the evolution of rainfall intensity throughout an average day for the indicated outage levels over Akure and Lagos respectively. The evolution is based on rainfall rates (mm/h) and hours of the day. The impact of convective rain contributing mainly to the small percentages of time could be observed, considering an average day for each exceedence. Results from figure 10 therefore shows that low values of rainfall rate correspond to 0.1% of the time are completely independent of the hour of the occurrence. On the other hand, and for very small percentages of time (such as 0.001%), the values of rainfall rate in excess of about 50 mm/h are very dependent on the time of the day respectively. Nevertheless, 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 and so on 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).

Table 1: Site characteristics of the study locations

Sites	Coordinate	Alt. (m)	Average number of events	Average Annual Rainfall (mm/yr)	Climatic Region
Akure	7.17 (^{0}N) 5.18 (^{0}E)	358	1789	1598.50	Rain Forest
Lagos	6.35 (^{0}N) 3.20(^{0}E)	129	1903	1861.45	Coastal



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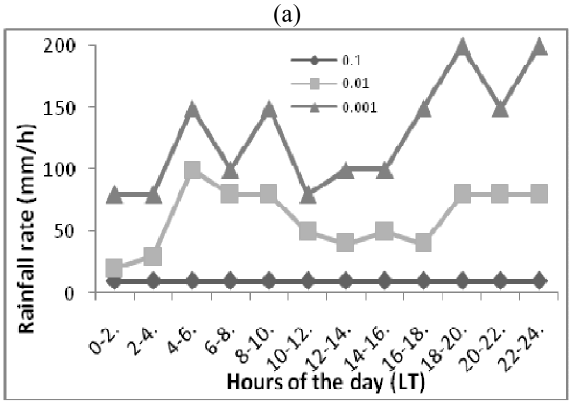

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Fig. 9: Evolution of rainfall intensity throughout an average day for the indicated exceedance over (a) Akure and (b) Lagos

CONCLUSION

In this study, spatial variability of rainfall structure in two locations Akure and Lagos in southern Nigeria using 2-years of measured rainfall data of 1-minute integration time are presented to assist in the design and evaluation of propagation effects on microwave and millimeter-wave communication systems. It was observed that the rain forest region (Akure) and the coastal region (Lagos) both recorded their peak average monthly rainfall accumulation in the same month when the worst month was experienced. Comparison of measured data with ITU-R data shows that the recent ITU-R model overestimated the rainfall rate at 0.01% exceedence of time by about 21% for Akure while it was underestimated by about 31% for Lagos. The results of threshold of rainfall illustrated higher numbers in Lagos when compared to Akure and that the lower rainfall rates contributed the most to the thresholds. Dependence of average rain rate on the duration of rain event shows that in Akure, the average rainfall intensity during the rain events is about 8.59 mm/h, the maximum rainfall intensity during rain events was 179.6 mm/h, while in Lagos the minimum rainfall intensity during rain events was 1.51 mm/h and the maximum rainfall intensity was 206.8 mm/h. 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 and so on 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).

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