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Assessment of rainfall rate and fade event duration for earth-space satellite links design in Nigeria

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The quest for advanced digitalized technology requires the knowledge of rainfall duration as a function of signal fading events. The assessment of events duration and rain rate for applications on Earth-space microwave links design are examined in the present work. The study has been carried out based on measurements along a set of rain gauge networks sited in five different locations across different regions in Nigeria. The degrees of the influence of rainfall rates for the outage period of the signals are tested along a direct-to-home Eutelsat satellite link operating at 12.25 GHz at one of the sites, Akure, Nigeria. The results would be useful in optimizing link budgeting, especially for the low-availability satellite systems over Nigeria. It would also serve as a benchmark for assessing the level of degradation that could be encountered in the switchover to digital broadcasting as well as 5G applications in Nigeria.

Keywords: Rainfall rate events, Fade event duration, Earth-space microwave links, Tropical climate

1 Introduction

Super high frequency which belongs to the microwave frequency (µF) band continues to gain more attention because of the numerous applications. It finds applications in the areas of point to point communication, radar transmitter systems, terrestrial digital data links and microwave radio links. Hence, the ability to deliver acceptable Quality of Service (QoS) to end users is vital to the system engineers and service provider. However, in the µF and other higher frequency band, rain has been recognized as one of the major causes of signal degradation along earth-space transmitting link in the form of fading[1,2]. A measure needed to ameliorate attenuation arises from the effect of precipitation on the transmitting link requires a deep knowledge of the characteristics of rainfall events, the duration and the fading due to the events. Also, for satellite systems operating in the low availability, the influence of fading on the transmitting links affect both the system design and subsequently the required QoS delivered to the customers[3].

Most of the researches on the radio links availability are based on the statistics of the rain rate, which often transforms to excessive design of the super high frequency systems[1,4]. However, with the recent transformation into 5G systems, it is expedient that the usual assessment of the intensity of rain may not be enough to accommodate poor performance due to latency, but the duration of rain events is vital in link designing[2,5,6]. The contributions of physical phenomenon such as reflection, absorption and scattering also impose different variations on the signal along the propagation path. The rate at which event of precipitation in a location is one of the key factors relating to the aforementioned phenomena[2]. Several reports from the temperate zones have modelled the event duration and its performances in the region[7-9], however, in the tropical regions, very few attempts have been made to model in this respect[2,10-13]. Some of the models developed using the temperate region data, when applied to the tropical region do not perform as expected due to the rain pattern in the tropical region which is highly convective with more of a thunderstorm. Among the work carried out on the subject matter in the tropical region is the work by Ajayi and Ofoche[10] onthe characteristics of tropical rainfall rate for extremely high frequency band applications in Nigeria. It was observed that at high rain rates, some of the return period observed was due to the trend in the rain rate within the rain cells and small mesoscale systems. This assertion was also corroborated in the work of Ojo[14].

Some other researchers[2] in the tropical region reported that the average number of cases of event

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duration in smaller integration time (one-minute) follows an exponential curve on the rain rate, while some other rain rates follows a power law relation. A study by Ojo and Olurotimi[15] on the characterization of the structure of rain rates over selected locations in the Southwestern part of Nigeria also shows the dependence of rain rate for the rain duration the selected locations with the minimum and the average rainfall intensity of about 8.59 mm/h and 1.51 mm/h. Alonge and Afullo[16] pointed out that in addition to the contemporary multiple power problems due to the algorithm routines at the base stations, the static provisions for such power demands in the link budget are mainly due to the propagation of radio waves and fade losses as a result of rain. Hence, with the advent of 5G wireless networks, especially at mm-waves frequency range, assessing the level of signal fading over tropical and equatorial countries such as Nigeria will require in-depth study of rain fade event duration so that good QoS can be delivered to customers.

In this paper, assessment of the duration of events on rain rate over some selected locations in Nigeria has been reported. The selected locations have been chosen for the uniformity in the period of measurement. A model based on Wiebull distribution for characterizing events has also been developed for Nigeria, while a relation between rain event duration and the percentage occurrence of a certain precipitation level is formulated[3].

The rest of the paper is arranged as thus: the second section discusses the data and sites description, section three discusses the methodology adopted, results and discussion are presented in section four, while conclusive remarks are drawn in section five.

2 Data and sites description

Table 1 presents information on the experimental sites while Fig. 1 shows Nigeria map indicating the network of rain gauge used in this study.The assessments of the precipitation event duration were based on five years (2009 -2014) data over some selected sites (Lagos, Akure, Jos, Enugu and Port Harcourt) in Nigeria. The sites have been selected among the propagation measurement campaign by the Tropospheric Propagation Data Network (TRODAN) of the Center for Atmospheric Research (CAR), Ayingba, Nigeria. Each site is equipped with a unique standard tipping bucket rain gauge that is controlled by the automatic weather equipment. The rain gauges have similar specifications in all the sites with an accuracy of ±1% and measuring range between 2 mm/h and 400 mm/h at an average one-minute

Sites	Lat. (^{o}N)	Long. (^{o}E)	Altitude (m)	Equipment availability
Lagos	6.35	3.45	41	94%
Akure	7.10	3.05	303	97%
Jos	9.10	9.45	1217	92%
Enugu	6.30	7.30	139	98%
Port Harcourt	4.45	6.50	18	94%

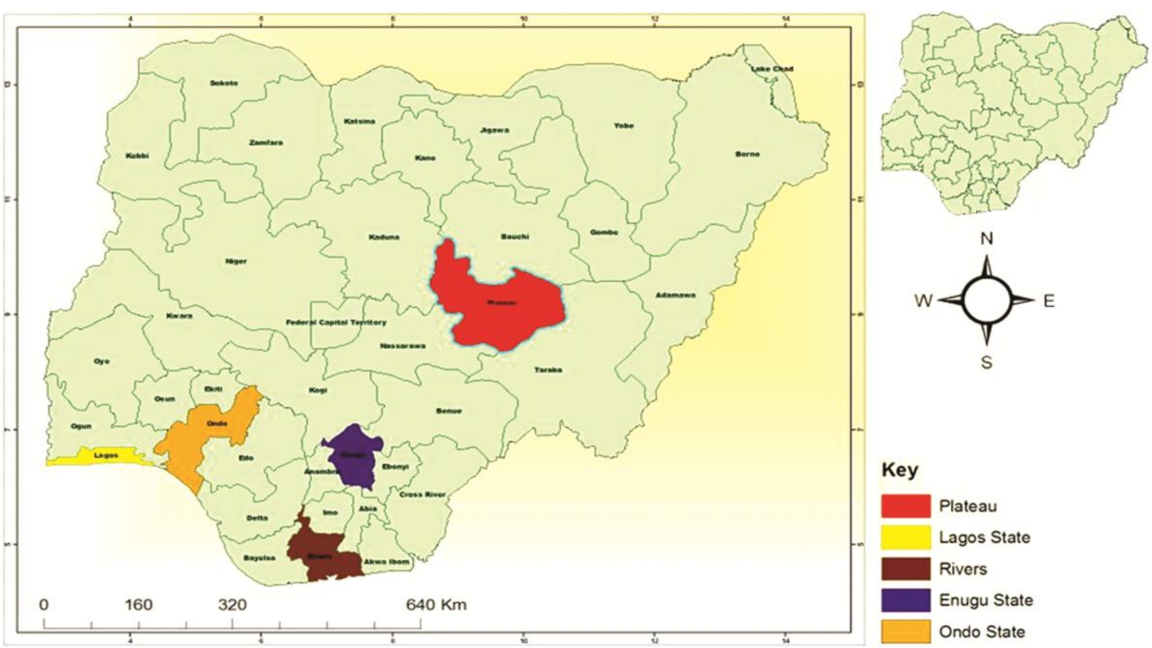

Fig. 1 — The network of rain gauge

integration time[17]. The availability of the rain gauge in a year for each site is as specified in Table 1. The percentage unavailability period arises due to calibration and the failure of the battery attached to the solar panel of the set up[18]. Dust particles are frequently removed to keep the gauge clean and avoid obstruction of the free flow of water.

Each of the study site exhibited nearly same rain-bearing pattern except Port Harcourt, where the rainy season often begins in the month of April and can last till November period, while a few cases of rain even in the dry season months.Rain pattern is a combination of the stratiform and convective especially during the early rainy months (April to July), whereas the convective rain type dominates a late period of the rainy season (September to October) and is often accompanied by localized violent thunderstorms[10].

However, in Port Harcourt, rain continually falls throughout the year, but very minimal in January and December.

3 Methodology

Time series rain rate data of 5-year based on the sites separation distance was as depicted in Fig. 1. The assessment was carried out based on the period rain rate with rain rates exceeding specified range between 2 and 150 mm/h, using an average period of thirty seconds (30-s) by taking three consecutive rain rate samples above the specified threshold[19].

Based on this study, we have adopted a simple Weibull Distribution Function (WDF) that contains only two variables for modeling rain rate event duration. The model was adjudged to perform excellently well in the tropical and equatorial regions[3]. The Weibull distribution function can be expressed as:

$$P(D \geq D_r = \exp\left[-\frac{D_r}{\mu}\right]^{a} \qquad \ldots(1)$$

where, the rain event duration is represented as D and D_r is the reference duration, μ and α are the function parameters. Simplifying the event duration, follows a power law function. This can be achieved by fitting each curve in a best fit power form based on a selected range of rain rates in the form of:

$$D = a(p)R^{-b(p)} \qquad \ldots(2)$$

where, a and b are parameters that depend on a given percentage.

The other database used was obtained from the continuous measurement by beacon receiver at one of the sites; Akure, Nigeria collocated with the rain measurement instrument. A direct-to-home through Ku-band signal via the EUTELSAT W4/W7 satellite signal has been received since 2012 by the 90 cm offset parabolic dish, at an elevation angle of 53.3^{o} [20-22]. The Ku-band signal was made to pass through a SAT link meter and a digitalized spectrum analyser to monitor the signal level through a computer unit. Detailed analysis of the beacon data is not presented here because of the paucity of space, however, they are available in the work of Durodola *et al*[20], Ibiyemi *et al*[21] and Adegbindin *et al*[22].

4 Results and Discussion

Fig. 2 presents the variation of the 5-year temporal average rain fade duration with rain rate for a typical rain rate threshold of 50 mm/h for each of the 5 sites. Generally, we observed that for any given rain rate threshold, the duration of the rain rate decreases as the cumulative distribution of rain events increases. This result shows similar pattern within the study region with no significant variability except Port Harcourt with dynamic behaviour. The average precipitation varied with location, while Port Harcourt experienced the highest amount of rainfall per year. In other words, assessing rainfall rate duration remained unchanged within the same climatic zone as earlier observed in the report of Mitra *et al*[2], Ojo *et al*[17] and Coma *et al* [23].

By adopting the Weibull distribution function of Eq. (1), all the cumulative distribution curves in Fig. 2 were adjusted based on correlation coefficient above 94%. A typical comparison of rain rate event duration with measured for Akure site is presented in Fig. 3 for the chosen precipitation threshold of 50 mm/h. The corresponding values of μ and α are 427.1 and 0.18 respectively. Good agreement could be observed from the plot.

The power law function of Eq. (2) can also be used to simplify event duration based on the cumulative

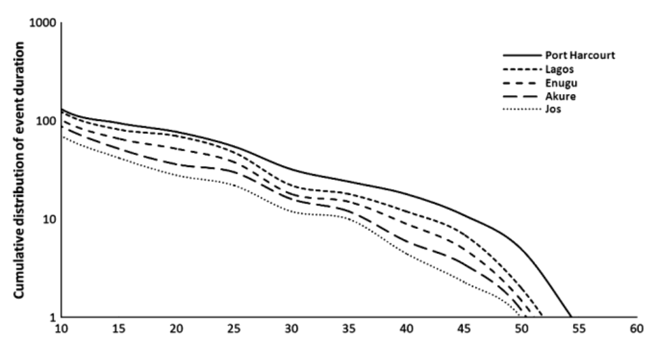

Fig. 2 — Rainfall event duration for the study sites

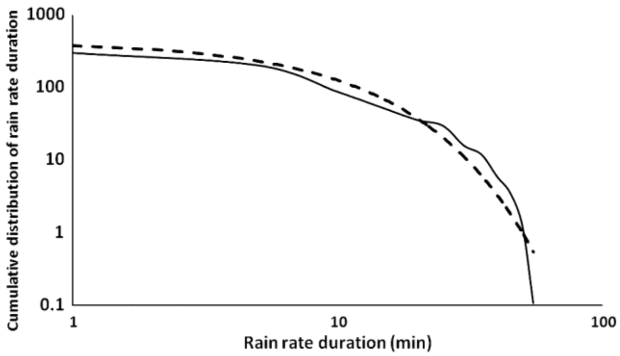

Fig. 3 — Comparison between the experimental data from Akure (broken line) and Weibull distribution function (solid line)

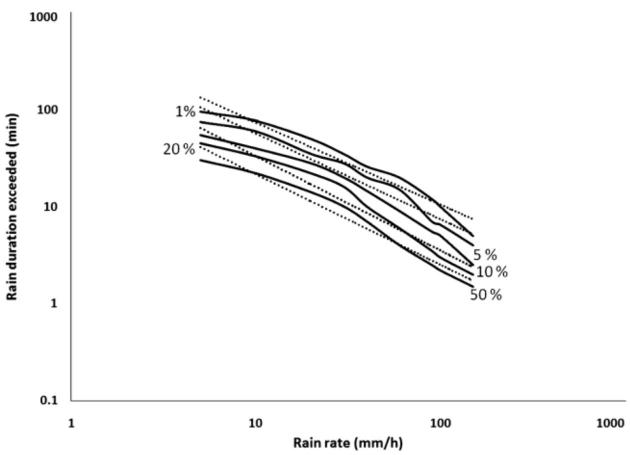

Fig. 4 —Comparison between rain rate duration at equal percentage time (solid curves), and empirical model (dashed curve) for Akuresite.

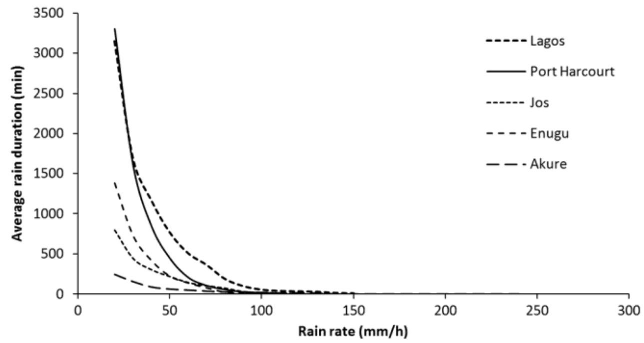

Fig. 5 — Average rain rate duration as a function of rain rate

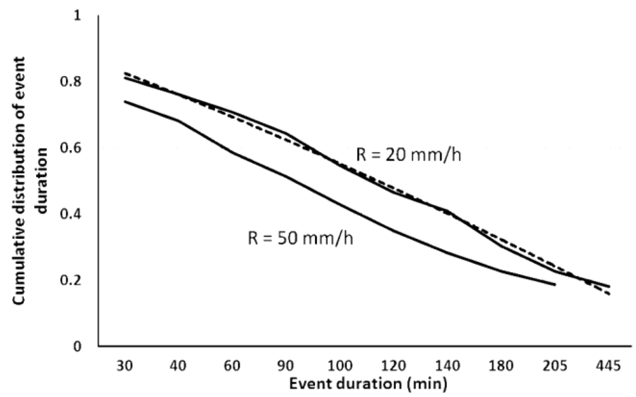

Fig. 6 — Comparison between rain rate duration and event duration due to fading

distribution of rain rate. We have plotted the event duration against rain rate for fixed probability level ranges between 1 and 50%. The result is presented in Fig. 4 for rain thresholds between 5 and 150 mm/h. By expressing each curve using the best fit power curve at the specified rain rates value, parameters *a* and *b* of Eq. (2) were obtained. A set of new parameters *Q* and *M* were also obtained for the respective percentage level based on the method adopted by[2, 5], where the relations are expressed as:

$$Q(P) = \left(a + bP^{-0.5} \ln p\right)^{-1} \quad \ldots (3)$$

$$M(P) = c + d \exp\left(\frac{p}{e}\right) \quad \ldots (4)$$

where, the parameters (*a*-*e*) are represented as thus:

a = 3.234 x 10^{-4}, b = 8.434 x 10^{-3}, c = 8.211 x 10^{-1}, d = 2.116 x 10^{-2} and e = 2. 948 x 10^{-1}

The set of empirically determined values aligned well with the measured values for all the selected probabilities as indicated by the thin-dashed lines in Fig. 4 for Akure. The expression presented in (2) also fits the measured data very well, especially for the selected time percentages. We also observed a little difference of about 0.2 min when compared measured data with the derived durations at 50% time percentages for 60 mm/h. The metric measure shows an absolute difference between the measured event durations and empirically fitted durations as 0.4 min and RMS value of 0.9 min for the system of curves.

Fig. 5 further presents the effect of average event duration on the rain rate for all the sites. During the worst month scenario, the critical percentages when rain rates are exceeded are usually between 0.1% and 0.01% especially for low availability satellite systems[14]. Based on the measurements in Akure, Nigeria $R_{0.1}$ and $R_{0.01}$ are 48 and 128 mm/h respectively[21]. Thus, in designing satellite systems with improved good QoS for this region, system engineers must utilize event duration of average values between 1 and 4-minute. These values are in agreementwith the experimental results of rain-induced attenuation obtained along a direct to home Eutelsat satellite link operating at 12.25 GHz at Akure, Nigeria.

Using the experimental results on Akure site, Fig. 6 presents a typical correlation result between the rain rate duration and event duration due to fading for rain intensity of 20 and 50 mm/h, respectively (linear). The dotted lines are obtained from event duration due to fade above 6 dB as measured using 12.25 GHz Eutelsat satellite link at Akure, Nigeria. A good agreement could be observed between rain rate duration and event duration due to fading.

We also noticed a direct relation between the rain rate and number of events. Also, for a particular value of rain rate, the duration increases as the number of events decreases. This shows that moderate rainfall rate (20 mm/h for example) can fall for a longer period, while; the higher rainfall rates are restricted to a shorter period. Therefore, statistical analysis of the period of events for specific rainfall rates will provide better understanding to communication system designers especially for the 5G applications.

5 Conclusion

Assessment of rainfall rates and event duration has examined in the tropical environment using 5-year data of time- series rain rate. The measured data have provided a better understanding on the statistical behaviour of the period of rain event, adoption of WDF to characterize the aforementioned events and adaptability of a power law model to simplify event duration based on the cumulative distribution of rain rate. It also gave insight into the specific average period of event for designing fade mitigation techniques, especially for the new switchover to 5G application for satellite systems in Nigeria. The overall results will provide the necessary benchmarks for designing communication satellite systems for 5G applications in the tropical regions

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