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Characterization of Worst Month Statistics for Satellite-Earth Links Performance in Tropical Locations

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Authors' contributions

This work was carried out in collaboration between all the authors. All authors designed the study as part of author OMD PhD research. Author OMD performed the statistical analyses, wrote the protocol and drafted the manuscript. Author JSO read, corrected and managed the analyses, result and literature searches. Authors MOA and JSO supervised of this study. Author MOA read and approved the final work carried out by author OMD.

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ABSTRACT

The increasing development in satellite technology has brought about several novel mobile satellite services and applications. Consequently, there is a pressing demand for seamless data transfer and accessibility to satellite-earth microwave links in SHF/EHF frequency bands. However, rain has been the major degradation parameter for the availability of satellite signals especially at frequencies greater than 10 GHz. In this paper, we present some statistical analysis of rainfall in two tropical locations in Nigeria – Akure (7°17’N, 5°1 8’E, 358 m) in the Southwest, and Jos Plateau (9°57’N, 8°58’E, 1192 m) in the north central. Rainf all intensities of one-minute integration time were measured for 19 months (June 2013 to December 2014). Predicted results showed that rain induced attenuation values above 30 dB occurred during the worst months, while clear sky values are below 2 dB. The worst month statistics obtained were largely different from those proposed by

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the ITU. Thus, for optimum link budgeting, the modified values of Q and ß should be adapted in these regions. The results will facilitate improved radio-communication planning in the region. More investigation on beacon measurements of rain-induced attenuation is required to corroborate these results.

Keywords: Rainfall variability; earth-satellite links; worst month statistics; attenuation; tropical region.

1. INTRODUCTION

The ever-expanding satellite technology offers novel applications and access to boundless terrestrial and satellite services – everywhere, anytime – just at the press of a button [1]. Mobile platforms available via satellite include e-defence, Tele-banking, Skype, e-learning and so on. Consumers continue to press for ubiquitous coverage, internet traffic by-pass, scalability and improved quality of service of communication systems. Inevitably, these pressing demands for flawless data transfer and audio-video communication spell the need to improve the reliability of satellite-earth communication links. Research shows that radio signals operating at frequencies above 10 GHz suffer more from rain attenuation [2-4]. In order to achieve good Quality of Service (QoS) for both down link and uplink frequencies, provision must be placed to mitigate attenuation due to rain especially at high frequency bands [5,6].

Rain induced attenuation may be measured directly from beacon experimental setups. Otherwise, it has to be predicted from rain-rate or raindrop size distributions [5,7]. To predict rain attenuation from rain rate along the link path, the statistics of point rainfall rate characteristics prevalent at the location of interest must be available [7,8]. To estimate path loss, the radio link planner requires statistical characteristics of rain rates distributions – annual, seasonal and monthly; as well as worst-month statistics [8-10].

The objective of this paper is to present results of experimental data showing seasonal variability of rainfall intensities at two locations in Nigeria. It also presents the relationship between the average worst month statistics and the average annual distribution of rain-induced attenuation for fixed satellite services predicted from ITU-R 618-11 [11] model. The rain characteristics are based on the statistical distribution of rain rates at 1% to 0.001% exceedance levels, seasonal variability, relationships among the average worst month statistics, the average annual distribution and predicted rain-induced attenuation. The analyses capture the annual, monthly and seasonal variability of rainfall intensities. The probabilities of annual average and worst month rainfall intensities (P and P_w) were converted to long-term statistics by computing the conversion parameters β and Q_1, and validated against ITU-R values.

2. REVIEW OF WORST MONTHS STATISTICS

Since propagation conditions vary from month to month, the system designer has the additional objective to ensure at least 99% system performance and availability for the worst month of the year [3]. For accurate radio-meteorological data and propagation predictions, ITU-R recommendation P.581-2 [9] requires that the worst month for which a pre-selected threshold for any performance degrading mechanism be specified, using the conversion model of ITU-R.P.841-4 [10]. The conversion factor Q is defined by equations (1) and (2) in terms of worst month and as a function of two parameters β and Q_1 (that is, the regional climatic factor and the probability of occurrence, respectively) defined in [10,11].

$$P_w = Q \times P \quad (1)$$

$$P = {P_w}/{Q} \quad (2)$$

where, P and P_w are the probabilities of annual average and worst month rainfall intensities respectively; and Q is the conversion factor for converting from average annual percent to average annual worst month time percentage. With values varying from 1 to 12, Q is defined by its two parameters, Q_1 and β, as a function of annual average percentage, p% [10,11]. Parameters β and Q_1 can be obtained from tables in [10] for various regions of the world; and the values of β and Q_1 have been given for tropical and sub-tropical regions as 0.15 and 2.82 respectively, and the relationship is expressed in equation (3).

$$Q_{(p)} = 2.82P^{-0.15} \quad (3)$$

However, [12] observed that most ITU-R models were formulated from a database comprised mainly of data obtained from temperate regions with very little input from tropical regions. As such, the results using equation (3) tend to deviate from measured values. Therefore, to obtain the annual, seasonal and monthly variability of rainfall characteristics of the locality, this paper sets out to formulate models based on measurements at two low latitude tropical locations in Nigeria - Akure and Jos.

3. EXPERIMENTAL SITE AND METHODOLOGY

Measurements were taken from two sites: Department of Physics, the Federal University of Technology Akure (FUTA), South-west Nigeria; and Gold and Base, Jos in the midland, Plateau state Nigeria. The measurement set-up is the Davis Vantage Vue weather station equipped with a weather link data logger and an integrated sensor suite (ISS) which consists of sensors such as the rain gauge, temperature sensor, solar panel, and the timer and so on. It was used to measure and record one-minute rain-rates for a period of 19 and 15 months at Akure and Jos, respectively. Measured data were averaged over each calendar month to determine the distributions of rainfall intensities for both average year (AY) and average worst month (AWM) as prescribed by ITU-R recommendations [10]. The rainfall rates were used to formulate a model that relates the average worst month (AWM) to an average year (AY).

4. RESULTS AND DISCUSSION

4.1 Seasonal Variability of Rainfall Accumulation and Number of Occurrences based on different Rain Type

The average monthly rainfall accumulation in Akure and Jos, for the period of measurement and the variation of the rain regimes are shown in Figs. 1 and 2 respectively. The month of September had the highest accumulation of about 210 mm, and 199 mm, in 2013 and 2014 for Akure respectively, while for the Jos location the highest accumulation of about 323 mm was recorded in the month of July 2014 as presented in Fig. 1.

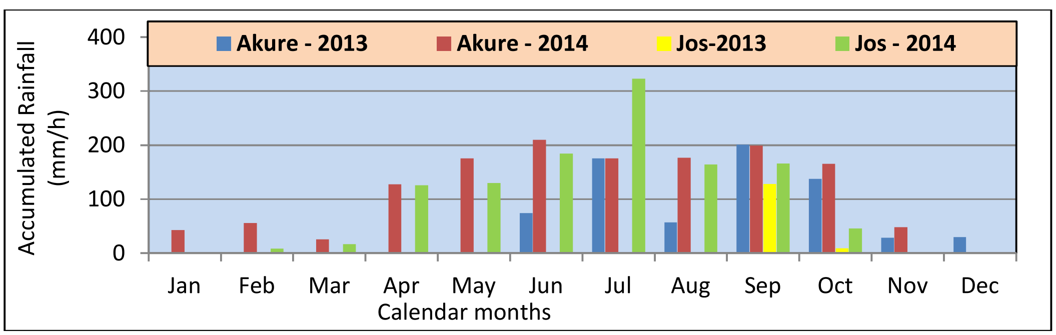

Fig. 1. Monthly accumulation of rainfall distribution in Akure and Jos

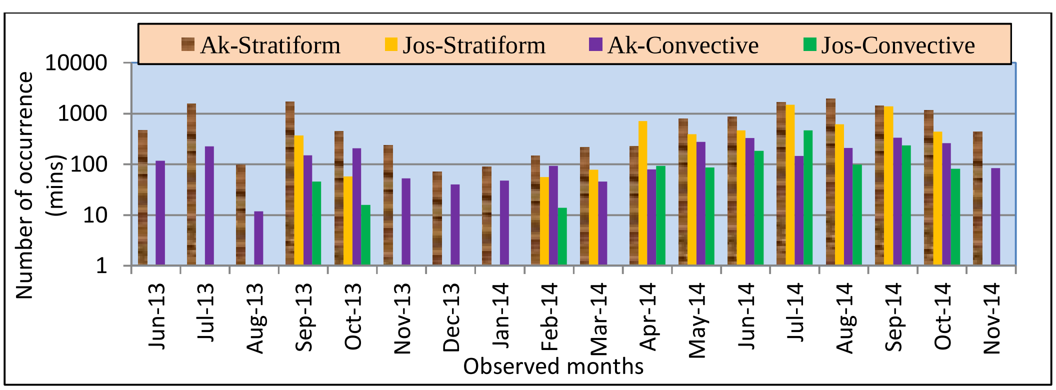

Fig. 2. Number of concurrences and monthly variation of rainfall intensities based on different rain types in Akure and Jos

The columns of monthly accumulation of rainfall show the double-peak and single-peak rainfall patterns in Akure and Jos – as typical of the tropical rain forest and Guinea savannah climates respectively. However, the annual variability between 2013 and 2014, is evident in the August break in Akure, which was more prominent in 2013 than in 2014 – when rainfall accumulation during August break in the respective years were about 50 mm and 170 mm. The observed annual variability is over 300% and this could result in worst month variations of over 25% [11]. This anomaly may be due to the general global warming and climate change, and highlights the significance of worst month statistics for power budgeting of microwave systems.

Considering the duration of occurrences based on rain type as presented in Fig. 2, convective rain type covers about 54% in Akure especially in 2014 as compared to occurrences in 2013. However, during the period of observation, stratiform rain type was prevalent in the two locations with more occurrence in Akure as compared to Jos. This should be expected considering the climatic characteristics of Akure, been a tropical location with more occurrence of rain.

4.1.1 Seasonal variability of rain rates distribution

The annual, seasonal and monthly variations of rainfall were captured in Figs. 3, 4 and 5 respectively. The rainy season in Nigeria was further classified into: onset (Feb -Mar), peak (April-Sept) and the end (Oct - Dec) as shown in Fig. 3. The classification is based on the number of rainy days in the specified month. At the onset of rains, there are less than 5 rainy days in the North and less than 10 in the south, but they are not intense. The months of peak rainfall each have more than 10 rainy days in both North and South. At the end, the rains are less frequent with shorter duration but more intense than at onset.

From the seasonal distribution of rain rates in Fig. 3, it is observed that Akure recorded high rain rates of up to 100 mm/h throughout the rainy season at 0.01% of time. This observation implies that, in planning the quality design objective for link availability, system designers need to mitigate the effects of high intensity rainfalls, throughout the rainy period in Akure; while in Jos, only the peak period requires such stringent controls. Low intensity rainfalls observed at the end of rains in Jos could be due to the mountainous topography of the region.

4.2 Relationship between AY and AWM

4.2.1 Selection of worst months

The "worst months" scenarios in Akure and Jos were also captured in Fig. 4(a) and 4(b). For example in Akure, six months were identified and selected as intense rainy months. The figures show that 3 months – May, July and October – stand out on the average as the worst months in Akure; while June and July are the observed months for Jos, the rain rates at 0.01% are above 150 mm/h in Jos, while others are below 140 mm/h. In the case of Akure, worst months have rain rates close to about 180 mm/h while others are below 150 mm/h. The average of rain rate distributions for all the calendar months of the years gives the value for the average year (AY) and is shown on Fig. 4 for each location.

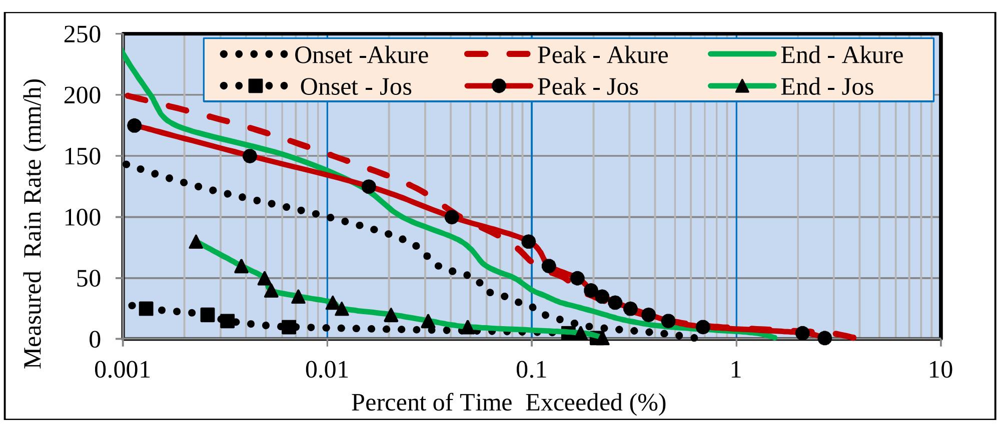

Fig. 3. Seasonal distribution of rainfall intensity during rainy season in (a) Akure and (b) Jos

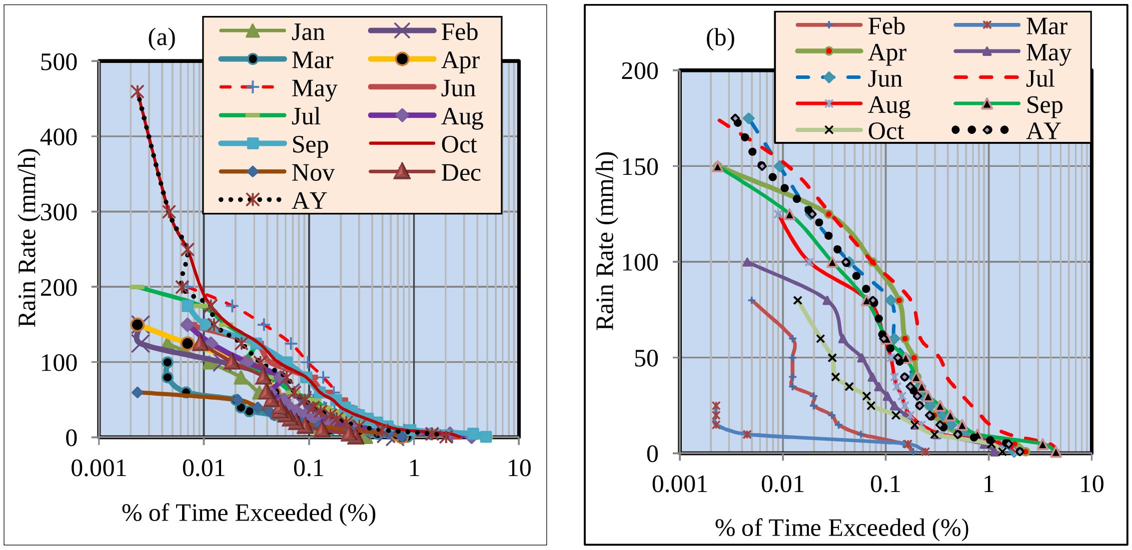

Fig. 4. Monthly variation of rain rates distribution in (a) Akure and (b) Jos

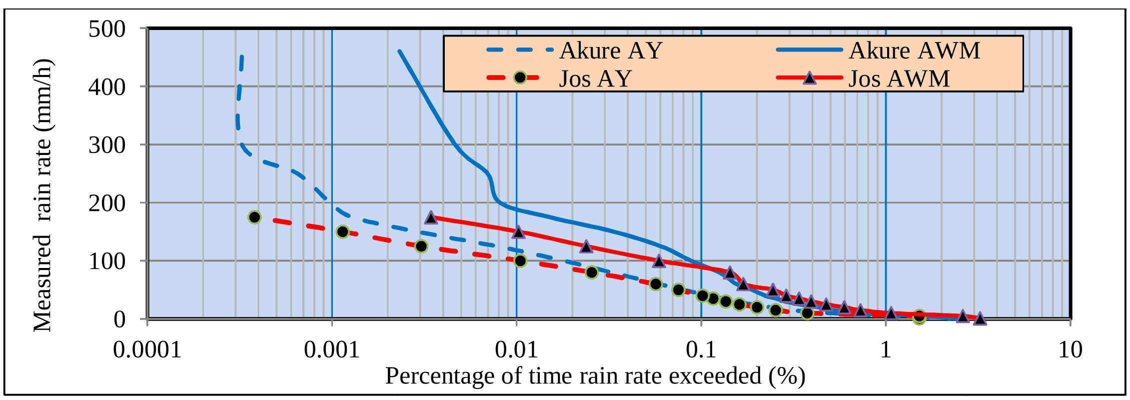

Fig. 5. Cumulative distribution of rain rates in average year and worst month for Akure and Jos

These values were used to derive the worst month statistics. The cumulative distribution of rainfall rates for all months and the worst months in Akure and Jos (Fig. 5) show that, in worst-months at 0.01% of time, rain rate of 178 mm/h was exceeded as against 120 mm/h in an average year in Akure.

Similarly, Jos shows worst-month exceedance of 150 mm/h, compared to 100 mm/h value for average year. The implication of this result provides a guide for system engineers for setting their monthly objectives and also for designing of worst scenarios and higher availabilities. For the worst month in Akure and Jos (which is May, and July respectively), increasing the fade margin by about 50% would result in accommodating much noise in the threshold. The only way out is for system planners to implement fade mitigation techniques such as the adaptive power control on the links [13].

4.2.2 Computation of AY to AWM relationship

The procedure in [8] was employed in deriving the power-law relationship between percentages of AY and AWM (Fig. 6), as defined in [9] and amended in [10], and for adjusting the worst month and annual percentages, P_w and, P_a. The correlation results from Fig. 5 show that there is very a strong relationship between the distribution of rain rate in the worst month and the annual distribution of rain rate distribution in both Akure and Jos, with determination coefficients of 0.992 each. However, the slope of the trend-line suggests that the dependence of rain rate characteristic is stronger in Akure than in Jos. The power law relation for the probability distribution over Jos and Akure are given in equations (4) and (5) respectively.

$$P_a = 0.5006\, P_w^{0.918} \quad \text{(Jos)} \quad (4)$$

$$P_a = 0.6763 P_w^{0.9576} \quad \text{(Akure)} \quad (5)$$

4.3 Evaluation of Performance of ITU-R P.841-4 [10]

The results obtained using ITU-R models in [10, 11] expressed in equation (6) for the relationship between AY and AWM are compared with values from other tropical regions and ITU as presented in Table 1. For ITU-R, percentage values between 0.001% 3.0% were applied to equation (7) to give the AWM percentages.

$$P_a = 0.3 P_w^{1.18} \quad (6)$$

$$P_w = 2.77407 P_a^{0.84746} \quad (7)$$

Similarly, in deriving the Q values, for Akure and Jos, percentage values between 0.001% 3.0% were applied to equations (4 and 5) to give the AWM percentages. All three curves gave perfect fits as shown in Fig. 7. The parameters were subjected to validity and stability tests against the models from measured data, using the root mean square error (RMSE) and CHI-square (CHI) statistics, respectively. The RMSE and CHI values (of 0.104, and 0.14 respectively) showed that the model fitted perfectly with measured data from Jos. Although the RMSE and CHI values (of 4.5 and 8.6 respectively) were high for Akure, the model passed the test at 95% validity. The high test values at Akure may have resulted from the fact that the rain climatic zone for Akure lies between ITU-R's N and P climates and not zone P – in agreement with earlier observations raised by [8]. Also, the values of the regional climatic factor and the probability of occurrence (β and Q_1) determined from measured data for Akure were, 0.372 and 1.060; while Jos had 0.207 and 2.042 (Fig. 7). The values deviated greatly from the one proposed by ITU-R (0.15 and 2.82), but is in agreement with previous observations for tropical regions by [14,15]. Hence for better accuracy, the values derived with local data should be adopted in Nigeria.

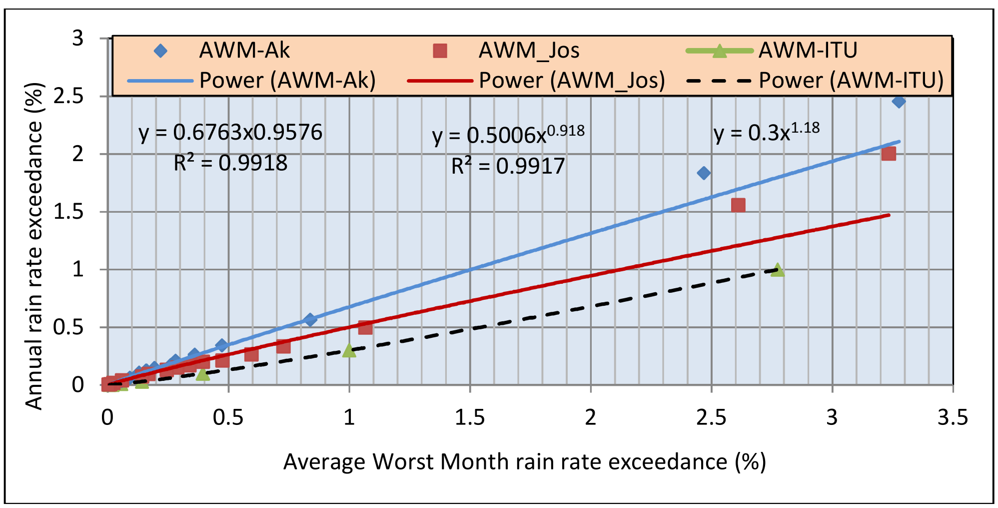

Fig. 6. Worst month model compared with ITU-R

Table 1. Worst month parameters for Akure and Jos compared with other Tropical regions and ITU

Location	α	β	*a*	*b*
Akure, Nigeria	1.060	-0.372	0.676	0.958
Jos, Nigeria	2.042	-0.207	0.501	0.918
USM, Malaysia (Yagasena, 2000)	1.398	0.293	-	-
UTM Malaysia (Yagasena, 2000)	1.22	0.28	-	-
Indonesia (Yagasena, 2000)	1.70	0.22	-	-
Kototabang, (Marzuki et *al*, 2016)	1.39	0.24	-	-
ITU	2.82	0.15	0.3	1.18

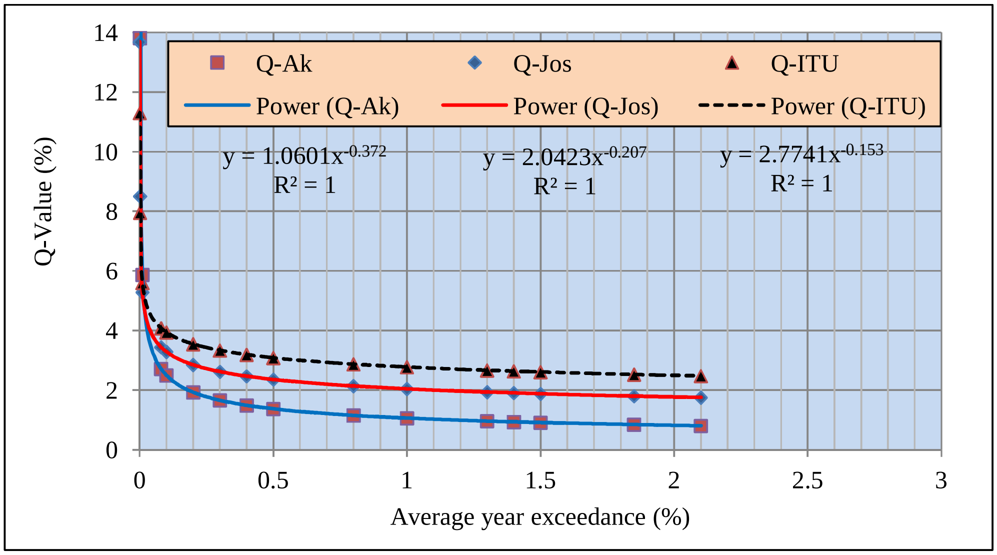

Fig. 7. Determination of conversion factors, β and Q_1

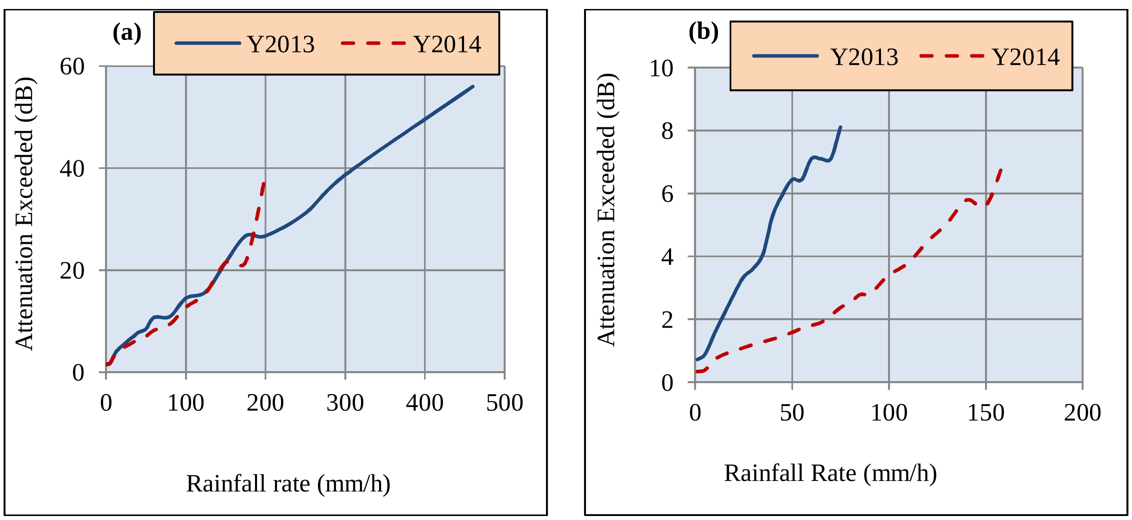

Fig. 8. Annual predicted Attenuation for (a) Akure and (b) Jos (ITU-R P.618 (2013))

4.4 Predicted Attenuation during Worst Months based on ITU-R P.618-11 [11]

Predicted attenuation results using methods prescribed by ITU [11], were between 6.5 dB and 21.5 dB, for rain rates in the range 30 mm/h to 150 mm/h for Akure, (Fig. 8 above) while clear sky attenuation in most tropical regions is less than 2 dB. The predicted rain attenuation for Jos and Akure at worst month rain levels (150 mm/h and 178 mm/h respectively) are about 6.5 dB and 28.5 dB. The attenuation levels predicted at the various rain rates indicate the level of fades and outages due to rain attenuation. This information will be useful to system planners and operators for estimating the fade margin to be budgeted to achieve the desired link availability.

5. CONCLUSION

In this paper, the degrading effect of rainfall intensities was highlighted in the statistics of worst month and monthly variations in rain rates along Ku-band signal paths in the study locations. The paper has revealed crucial considerations that affect the quality objectives of telecommunication systems. The results show that AY and AWM can be safely estimated from measured data of one minute integration time, and modeled with ITU-R recommended values. However, it is recommended that the worst-month design criteria of 178 mm/h and 150 mm/h for Akure and Jos, be considered as the actual design goal. Also, the relationship between the worst-month and average year has been given by β and Q_1 parameters, as 0.372 and 1.060 for Akure, and 0.207 and 2.042 for Jos. The worst month statistics derived would serve as essential planning tool for the system link designer for fade analysis and site diversity implementation; and eventually result in better availability of radio-communication systems in the region. Rain fade levels in worst month in both study locations are about 50% higher than levels in the average year, which suggests the need for alternative methods of mitigating rain fade such as adaptive power control schemes. The authors are carrying out more research work to corroborate and/or validate these results with beacon measurements of rain-induced attenuation as has been done in more advanced countries such as [16,17].

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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