Telecommunications and Radio Engineering, 79(2):129-141 (2020)

ESTIMATION OF RAIN FADE DURATIONS ON COMMUNICATION LINKS AT Ka BAND IN EQUATORIAL AND TROPICAL REGIONS

M.E. Sanyaolu, O.F. Dairo,♦ A.A. Willoughby, & L.B. Kolawole

Redeemer's University, P.M.B. 230, Ede, Osun State 232102, Nigeria

♦Address all correspondence to: O.F. Dairo, E-mail: dairof@run.edu.ng

Duration of rain fade events is a major parameter to be considered when designing a communication link. Fading is a phenomenon responsible for intermittent fluctuations of radio signals observed in the tropical region. The prevalence of rain in the tropics accounts for the frequency of fading observed in this region. Despite, the efforts of researchers to help systems designers give due consideration to fade mitigation techniques in other parts of the world, there is still a dearth of fade duration data from the African equatorial and tropical regions. Hence, this study estimates the number of fade events per fade duration interval exceeding attenuation thresholds ranging from 1 dB to 18 dB at ka-Band (26.5 GHz–40 GHz), leading to nonavailability of satellite systems during raining events in the African equatorial regions. The range of fade durations is from 10 s to 5000 s. The International Telecommunication Union (ITU-RP) propagation model and data from the Tropospheric Data Acquisition Network (TRODAN) were used for the analysis. The eight TRODAN observatories, under the Centre for Atmospheric Research (CAR), cover the major climatic regions in the sub-Saharan region, namely equatorial, humid tropical and tropical zones (Geo. 4.82°N to 9.58°N). Fade duration decreases latitudinally as the attenuation threshold increases from low to higher latitudes. The equatorial region suffers the highest frequency of fade events while the tropical zones recorded the lowest. In addition, the 10 s fade duration recorded the highest occurrence of fade events. The implication is that heavy rains, causing higher attenuation, occur for a shorter time duration. Similarly, higher attenuation depends on raindrops size and rain intensity. Consequently, the number of fade events exceeding 1 dB threshold is higher than other thresholds with respect to the fade duration.

KEY WORDS: *fade durations, rain fade, radio propagation, rain attenuation, tropical regions, satellite communications, communication links, sub-Saharan climate*

1. INTRODUCTION

The increasing contents on the internet and other media around the world have continued to increase the use of available communication channels. With the growing volume of data comes the need for higher capacity and low latency communication networks [1]. The prediction of the behavior of radio wave propagation in a communication channel is sacrosanct to the design and modeling of the performance of earth-space links [2]. The time-varying characteristics of the received signal strength below a certain threshold on a communication link are termed fading. This challenging impairment is observed on both terrestrial and space signals transversing the atmosphere in the presence of fog, water vapor, rain and oxygen. Quite noticeable is the fading due to rain, which causes degradation on earth-space links at microwave frequencies [1,3]. In particular, the Ka-band may require mitigation techniques to make it suitable for long-distance communication in the tropics [4,5]. Being mindful of rain fade at the propagation frequency cannot be overemphasized in the design of reliable communication links. It is crucial for the accurate prediction of possible impairments to be encountered on a given propagation link [6-8].

Fade duration is calculated as a function of the interval of time between two successive crossings of the same fade depth threshold [9-11]. It indicates the period in seconds of exceedance of a given threshold value [12]. In particular, it estimates the stability of service quality such as signal to noise ratio, throughput and bit rate among others for high-frequency microwave links [13]. System designers have continued to pay attention to fade duration [14] for link budgeting vis-à-vis:

1. Downtime: Fade duration statistics gives information on the frequency and probability of downtime of a communication link for a given time duration [15,16].
2. Interference and fade mitigation techniques (IFMT): The implementation of IFMT, namely polarization, coding, power control, site diversity, path profile analysis and resource sharing, is necessary to avert system unavailability and total outages. The activation and duration of communication systems in the compensation configuration mode is achieved using fade duration statistics, depending on the link margin [6,17].
3. Coding and modulation: The choice of channel coding and the modulation regime takes into consideration the duration of fading events in the channel.

Another area of interest is characterizing the duration of a fade event as either short-term or long-term, particularly when the duration is longer than 10 s. Fade duration is also needed to develop the risk concepts in the delivery of telecommunication services [18].

The statistics of fade duration are estimated as the conditional distributions of fading events that exceed a specific duration, after crossing a set fade threshold. As a result, the percentage of system outages on a propagation link, for a specified exceedance and fade margin, can be estimated [14,19,20]. Cumulative distribution approach has been adopted as the basis of all fade duration statistics, whether for terrestrial or earth-space links, using the power-law, log-normal and two log-normal distributions [21,22].

The duration statistics such as the probability of rain fade duration at specific attenuation, time, rate of recurrence and the prediction of next time of occurrence are all vital to the understanding of the functioning, accessibility and quality of service (QoS) of the link [23]. Therefore, there is a crucial need for service providers to put these factors into consideration. Also, to apply the appropriate channel coding, modulation regime and the array of adaptive power optimization techniques when there is a severe rain fade event [24]. Hence, there is a need to analyze the distribution of rain fade durations on communication links at Ka-band in the equatorial and tropical regions with respect to given fade depth thresholds.

2. ITU-R FADE DURATION DISTRIBUTION MODEL

ITU-R model calculates the statistics of fade duration including the effect of scintillation, rain and other hydrometeors along a communication path. It analyses the fade duration for long-term performance using the log-normal distribution while the short-term events are estimated using power-law distribution. According to ITU-R, the duration statistics are defined by two conditional cumulative distribution functions (CDFs) [18]. The probability of a fade event of duration d greater than D(s), if attenuation a is greater A (dB). Hence, the $P\left(d > \frac{D}{a} > A\right)$ of d longer than D, if attenuation a (dB) rises above A, is calculated using Eqs. (1) and (2).

For $1 \le D \le D_t$

$$P\left(d > \frac{D}{a} > A\right) = D^{-\gamma}. \tag{1}$$

For $D > D_t$

$$P\left(d > \frac{D}{a} > A\right) = D^{-\gamma} \frac{Q\left(\frac{\ln(D) - \ln(D_2)}{\sigma}\right)}{Q\left(\frac{\ln(D_t) - \ln(D_2)}{\sigma}\right)}, \tag{2}$$

where γ is the power-law distribution exponent of the fraction of short-term fade duration and D_t the time interval in between the short and long duration of fade events. The ITU-R model details are provided in the methodology.

3. METHODOLOGY

Data from eight Tropospheric Data Acquisition Network (TRODAN) stations in Fig. 1, namely Lagos (Geo. 6.5°N, 3.5°E), Mowe (Geo. 6.73°N, 5.06°E), Port Harcourt (Geo. 8.99°N, 7.38°E), Minna, Nsukka, Akure, Yola (Geo. 9.35°N, 12.5°E) and Ayingba, with five-minute rain-rate integration time, were used for the analysis of rain fade durations. The Centre for Atmospheric Research (CAR) manages the TRODAN, being one of the centres of the National Space Research and Development Agency (NASRDA), a Federal Government Agency that supports the Earth-space sciences research community with several other services in Nigeria.

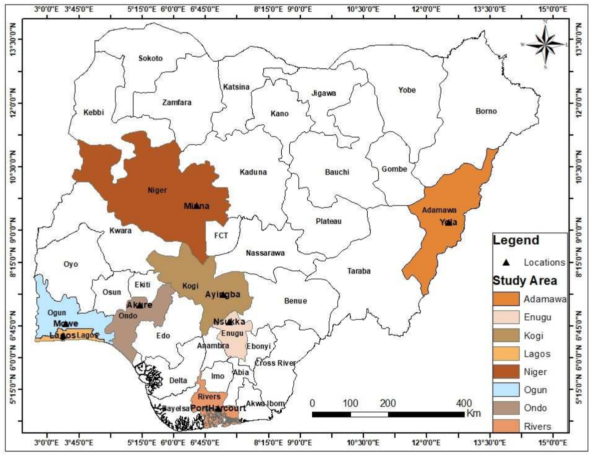

FIG. 1: Map of Nigeria showing study areas

This study used the Chebil and Rahaman [25] rain-rate model to convert the total accumulated rainfall data to one-minute integration time in Table 1 as expressed in Eq. (3):

$$R_{0.01} = \alpha M^{\beta}, \tag{3}$$

where M is the total accumulated rainfall at the location, $\alpha = 12.2903$ and $\beta = 0.2973$ are regression coefficients.

Attenuation at 40 GHz was derived from the site data using the ITU-R [26] rain attenuation prediction model.

The Fade duration model recommended by the ITU-R [14], which applies to the tropical region, is used in this study. The model is employed for predicting the fade dynamics of a satellite link. Two different CDFs are used to describe fade duration:

1. $P\left(d > \frac{D}{a} > A\right)$ is the probability of the fade event of duration d greater than D (s) if the attenuation a is more elevated than A (dB). It is the fraction of the number of fade events of period higher than D to the total observed fade events, provided that the attenuation exceeds the maximum allowable A (dB).
2. $F\left(d > \frac{D}{a} > A\right)$ is the probability that the CDF is exceeded, or, equivalently, the proportion of fading time (bounded by 0 and 1) resulting from fade events of duration d greater than D (s), provided that the attenuation a exceeds A (dB).

The ratio of the total fading time to the total time of exceedance of the threshold is used to estimate this probability on the basis that fade events of duration *d* greater than *D*, provided that the threshold *A* is exceeded.

TABLE 1: Site characteristics of locations used

Stations	Latitude (°N)	Rain Rate ($R_{0.01}$)	Elevation Angle (θ)	Height a.b.s.l. (mm)	Annual Rainfall (mm/year)	Period of observation
Port Harcourt	4.82	123.47	55.9	7.52	2346.10	Jan 2009-Dec 2009
Lagos	6.52	110.72	51.5	10.75	1626.20	Oct 2007-Nov 2008
Mowe	6.82	74.83	50.5	19.00	430.50	Jan 2011-Dec 2011
Nsukka	6.84	106.52	56.1	414.40	1427.15	Jan 2008-Dec 2009
Akure	7.31	107.77	50.4	367.03	1485.60	Jun 2010-Jul 2011
Ayingba	7.49	70.11	55.5	377.42	349.60	Jul 2010- Jul 2011
Yola	9.08	94.33	60.7	282.63	948.50	Nov 2009-Dec 2010
Minna	9.58	90.15	54.2	273.30	814.33	Jan 2008-Dec 2009

The validity of this model is considered appropriate for fade events with period greater than 1 s. The factors considered necessary for the model are frequency, *f* (GHz), within the range of 10 GHz to 50 GHz; the elevation angle, ϕ (degrees), in the range of 5°–60°; and attenuation threshold, *A* (dB) is set at 5.5 dB, which is the worst-case value for downlink fade margin below which the link is considered inoperable.

The approach to calculating fade duration distribution using the ITU-R model: $P\left(d > \frac{D}{a} > A\right)$, the probability that fading of duration *d* longer than *D* will occur if the attenuation *a* is higher than *A* (*dB*), in Eqs. (1) and (2), is further illustrated by Eqs. (4) to (13).

$F\left(d > \frac{D}{a} > A\right)$, the cumulative probability of exceedance, i.e., the aggregate fraction of time of fade events of duration *d* longer than *D*, is estimated as:

For $1 \le D \le D_t$

$$F\left(d > D / a > A\right) = \left[1 - k\left(\frac{D}{D_t}\right)^{1-\gamma}\right]. \tag{4}$$

For $D > D_t$

$$F\left(d > \frac{D}{a} > A\right) = (1-k)\frac{Q\left(\frac{\ln(D)-\ln(D_0)}{\sigma}\right)}{Q\left(\frac{\ln(D_t)-\ln(D_0)}{\sigma}\right)} \tag{5}$$

the interval of duration D_t between short and long fades as:

$$D_t = D_0 e^{p_1\sigma^2 + p_2\sigma - 0.39} s; \tag{6}$$

where

$$p_1 = 0.885\gamma - 0.814; \tag{7}$$

$$p_2 = -1.05\gamma^2 + 2.23\gamma - 1.61 \tag{8}$$

the standard deviation σ of the log-normal distribution of the ratio of fade event time due to fades of longer duration is calculated as:

$$\sigma = 1.85 f^{-0.05} A^{-0.027} \tag{9}$$

the exponent γ of the power-law distribution of fading time ratio as a result of short-time fades is given as:

$$\gamma = 0.055 f^{0.65} A^{-0.003} \tag{10}$$

the average duration D_2 of the log-normal distribution of the probability of long duration fade events is derived as:

$$D_2 = D_0 \exp^{-\sigma^2} s \tag{11}$$

the average duration D_0 of the log-normal distribution of the ratio of time of fading occurrence for fades of longer duration, if the attenuation a is greater than A, is calculated as:

$$D_0 = 80\phi^{-0.4} f^{1.4} A^{-0.39} s. \tag{12}$$

The aggregate fade events of duration d longer than D at specified threshold A (dB) is derived from:

$$N(D, A) = P(d > D / a > A) N_{tot}(A), \tag{13}$$

where $N_{tot}(A)$ is the total number of attenuations.

4. RESULTS AND ANALYSIS

Figures 2-17 show the variation and number of fade durations exceeding the thresholds at 1, 3, 6, 9, 12, and 18 dB levels from the equatorial region to the tropical regions. The mean of the annual fade events of rain attenuation exceeding the specified thresholds was estimated for each location using the ITU-R prediction model [26].

Tables 2-4 show the typical frequency of occurrence of fade events with durations greater than the specified threshold within the range of 1 dB to 18 dB levels at Port Harcourt, Ayingba, and Yola, representing the equatorial, humid tropical and tropical zones, respectively.

TABLE 2: Typical fade duration events in Port Harcourt

Duration (s)	1 dB	3 dB	6 dB	9 dB	12 dB	15 dB	18 dB
10	2779	1271	1108	680	475	211	50
40	722	530	304	101	85	42	8
70	258	138	92	32	11	5	1
180	75	20	11	5	0	0	1
300	28	9	0	0	0	0	0
1600	7	3	1	1	1	0	0
2400	3	1	0	0	0	0	0
3600	1	0	0	0	0	0	0
5000	0	0	0	0	0	0	0

TABLE 3: Typical fade duration events in Ayingba

Duration (s)	1 dB	3 dB	6 dB	9 dB	12 dB	15 dB	18 dB
10	887	549	284	169	118	71	42
40	510	361	220	107	49	19	9
70	250	105	107	51	22	14	1
180	149	60	48	20	8	3	1
300	57	33	15	7	5	1	0
1600	32	10	1	0	0	0	0
2400	10	7	0	0	0	0	0
3600	2	0	0	0	0	0	0
5000	0	0	0	0	0	0	0

TABLE 4: Typical fade duration events Yola

Duration (s)	1 dB	3 dB	6 dB	9 dB	12 dB	15 dB	18 dB
10	418	226	156	112	82	43	16
40	286	161	109	73	41	12	7
70	134	76	31	17	8	4	1
180	101	12	9	5	1	0	0
300	92	39	1	0	1	1	0
1600	12	1	0	0	0	0	0
2400	8	0	0	0	0	0	0
3600	1	0	0	0	0	0	0
5000	0	0	0	0	0	0	0

From these Tables, it is evident that as the attenuation threshold increases the duration of fade events reduces in all the locations. In particular, the stations along the Atlantic coast in the equatorial region showed the highest frequency of fading events for each of the specified fade durations with respect to the attenuation thresholds. Considering 10 s fade duration, at 1 dB attenuation threshold, 2779, 887, and 418 fading events were estimated for Port Harcourt, Ayingba, and Yola, respectively. Similarly, at 6 dB attenuation threshold, 1108, 284, and 156 and at 18 dB threshold, 50, 42 and 16 fading events were estimated for Port Harcourt, Ayingba and Yola, respectively. This is in agreement with the prevalence of rain in the coastal region of the low latitudes relative to the reduced rain regimes that characterize the tropical zones in the higher latitudes. The frequency of fading events is lowest at 18 dB attenuation threshold level. This is because heavy rains causing high attenuation level occur over a short duration. Consequently, higher attenuation depends on the raindrop size and also the rain intensity [27].

Moreover, higher fade margin, which is less vulnerable to fading events, may be considered for satellite services requiring high service level agreement (SLA). On the other hand, lower fade margin from Tables 2-4 may make the link inoperable for high SLA services. However, lower fade margins may be useful for services such as periodical logging of meteorological data, wildlife and forestry monitoring requiring high integration time and low availability SLA. Hence, different fade margin regimes are applicable to different applications and SLAs.

The log-normal distribution of Figs. 2-17 show the aggregate fade events exceeding the given threshold of attenuation levels versus the corresponding fade duration (s) for all the locations. The frequency of fade events exceeding 1 dB threshold is higher compared to other higher thresholds. Similarly, the duration of fade events observed in the coastal cities is longer, especially for Lagos and Port Harcourt. This is attributable to the fact that the 18 dB threshold requires a higher intensity of rain, with longer duration compared to fade events exceeding a 1 dB threshold.

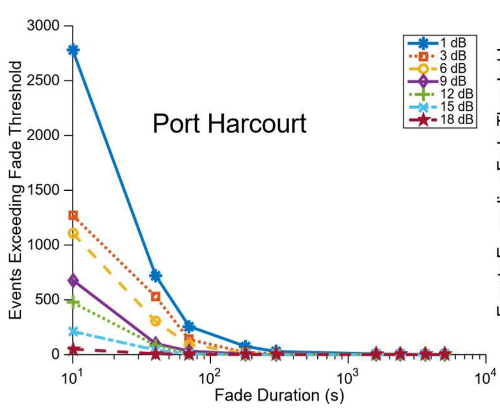

FIG. 2: Fade durations by attenuation levels in Port Harcourt

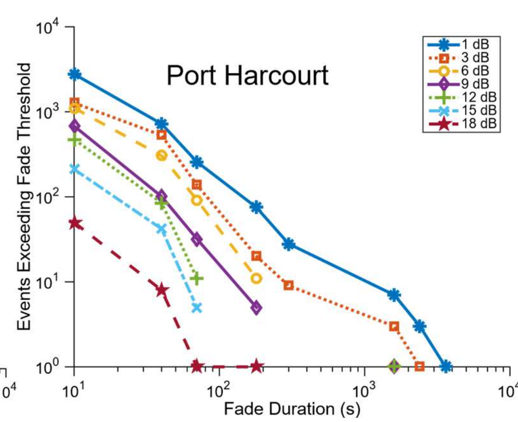

FIG. 3: The log-normal distribution plot of Fade durations in Port Harcourt

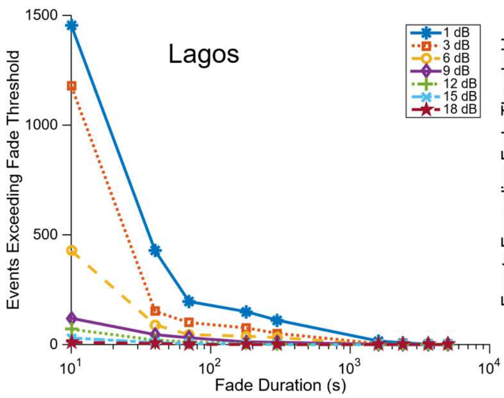

FIG. 4: Fade durations by attenuation levels in Lagos

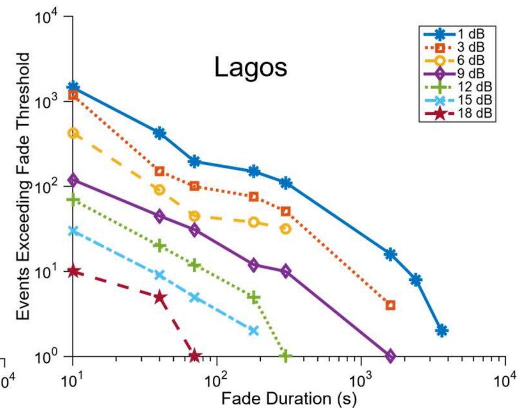

FIG. 5: The log-normal distribution plot of Fade durations in Lagos

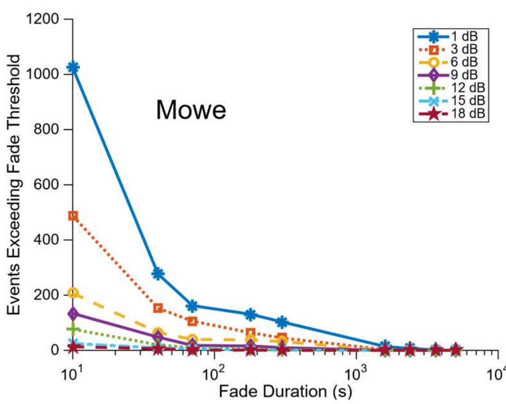

FIG. 6: Fade durations by attenuation levels in Mowe

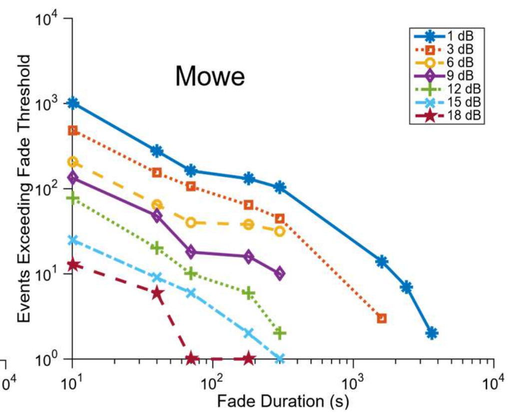

FIG. 7: The log-normal distribution plot of Fade durations in Mowe

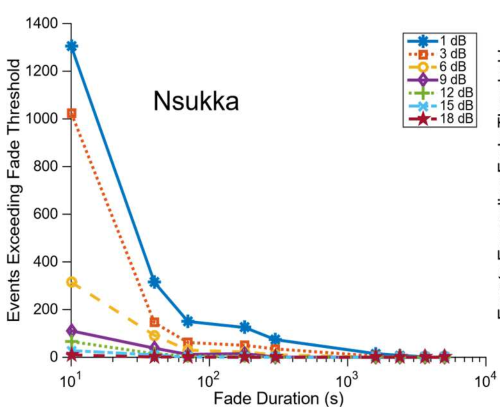

FIG. 8: Fade durations by attenuation levels in Nsukka

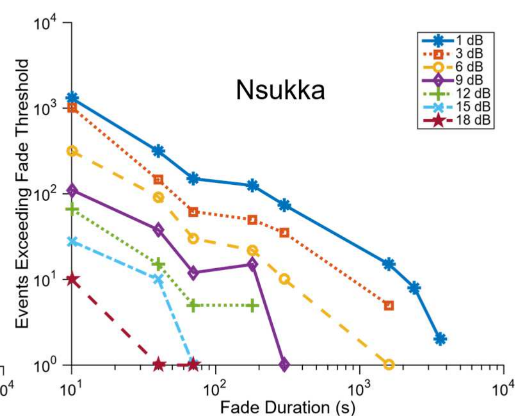

FIG. 9: The log-normal distribution plot of Fade durations in Nsukka

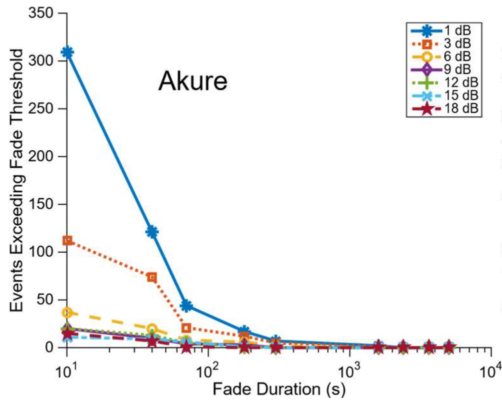

FIG. 10: Fade durations by attenuation levels in Akure

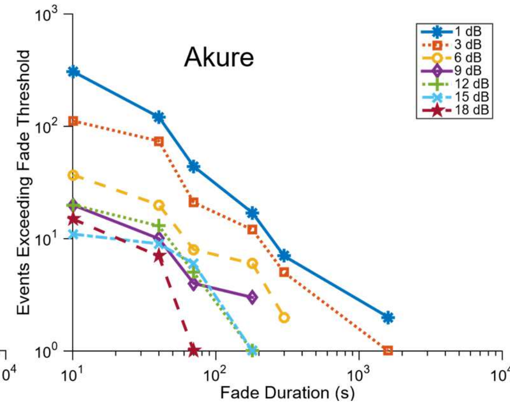

FIG. 11: The log-normal distribution plot of Fade durations in Akure

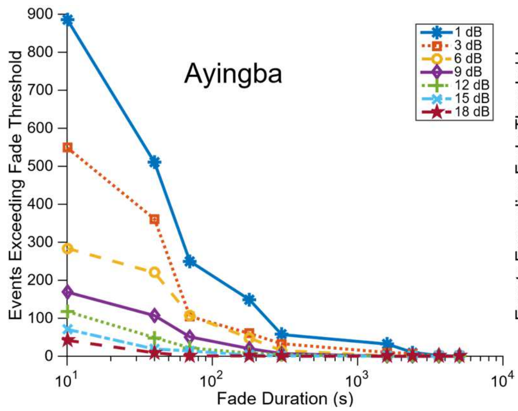

FIG. 12: Fade durations by attenuation levels in Ayingba

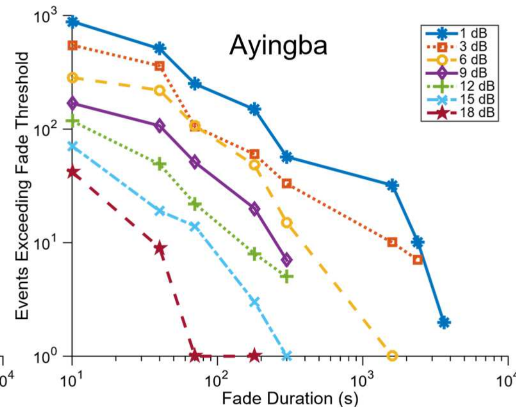

FIG. 13: The log-normal distribution plot of Fade durations in Ayingba

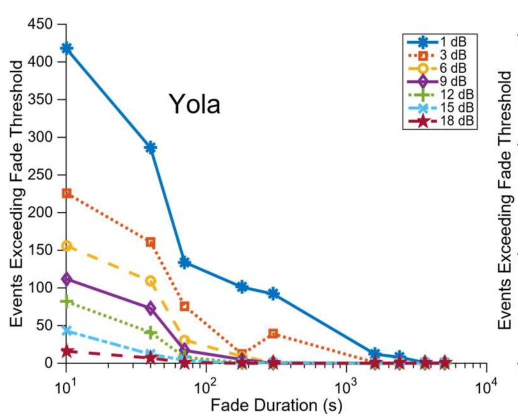

FIG. 14: Fade durations by attenuation levels in Yola

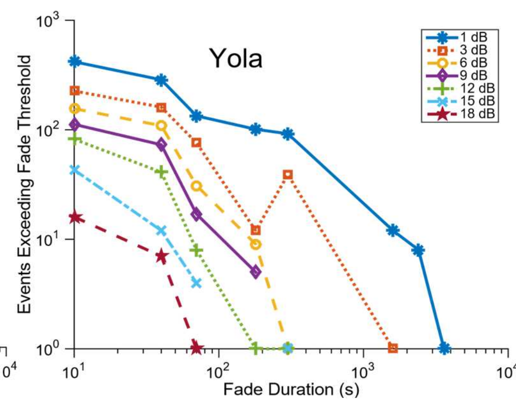

FIG. 15: The log-normal distribution plot of Fade durations in Yola

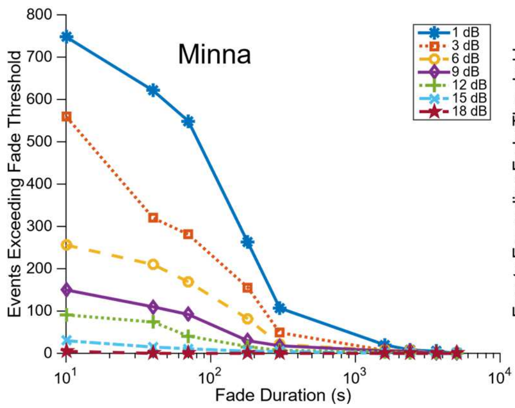

FIG. 16: Fade durations by attenuation levels in Minna

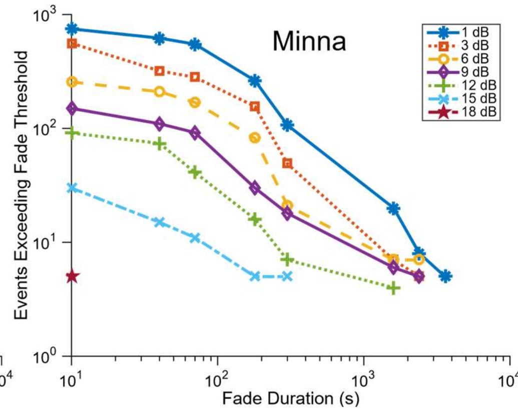

FIG. 17: The log-normal distribution plot of Fade durations in Minna

5. CONCLUSION

This study has provided information on features of rain fade durations at eight locations in the equatorial and tropical regions across Nigeria. The results of the ITU-R model show the pattern of distribution for both short and long fade durations.

The eight equatorial, humid tropical and tropical stations show that fade duration decreases latitudinally, from low to higher latitudes, and as the attenuation threshold increases. The equatorial region suffers fading the most with the highest frequency of fade events and the lowest in the tropical zone. Hence, the coastal stations in the equatorial region are the worst affected by fading compared to stations in the semi-arid tropical region. In addition, the 10 s fade duration recorded the highest occurrence of fade events with values of 1108, 284 and 156 for Port Harcourt, Ayingba, and Yola, respectively, at 6 dB attenuation threshold. The implication is that heavy rains, causing higher attenuation, occur for the shorter time duration. Similarly, higher attenuation depends on raindrops size and rain intensity. Consequently, the number of fade events exceeding 1 dB threshold is higher than other thresholds with respect to the fade duration.

The result of this study will assist system designers in the employment of mitigation techniques for designing reliable, operable and low latency broadband communication link in the equatorial and tropical regions. During the clear weather, the transmit power is reduced back to a nominal lower level so that excessive interference will not be generated. By this way, the broadband service providers will be able to ensure sustainable service operability and availability during rain events.

ACKNOWLEDGEMENTS

The following individuals, namely Prof. P.N. Okeke, pioneer Director, Centre for Basic Space Science (CBSS), Prof. A.B. Rabiu, Director, Centre for Atmospheric Research

(CAR), Anyigba, and Dr. S.O. Mohammed, Director-General and Chief Executive Officer, National Space Research and Development Agency (NASRDA), are appreciated for their support to access the TRODAN data and Mr. Olumide Julius Ademuyiwa for his GIS input.

REFERENCES

1. Chodkaveekityada, P. and Fukuchi, H., (2017) Differences in the dynamic properties of rain fade between temperate and tropical regions, *Advances in Space Research*, **59**(5), pp. 1321-1329. doi:https://doi.org/10.1016/j.asr.2016.11.038.
2. Nuroddin, A.C.M., Ismail, A.F., Abdullah, K., Badron, K. et al., (2013) Rain Fade Estimations for the X-Band Satellite Communication Link in the Tropics, *International Journal of Computer and Communication Engineering*, **2**(4).
3. Timothy, K.I., Mondal, N.C., and Sarkar, S.K., (1998) Dynamics properties of rainfall for performance assessment of Earth/space communication links at Ku and Ka bands, *International Journal of Satellite Communications*, **16**, pp. 53-57. doi:10.1002/(SICI)1099-1247(199801/02)16:1<53::AID-SAT594>3.0.CO;2-H.
4. Ramachandran, V. and Kumar, V., (2007) Modified rain attenuation model for tropical regions for Ka-band signals, *International Journal of Satellite Communications and Networking*, **25**(1), pp. 53-67. doi:10.1002/sat.846.
5. Yeo, J.X., Lee, Y.H., and Ong, J.T., (2014) Rain Attenuation Prediction Model for Satellite Communications in Tropical Regions, *IEEE Transactions on Antennas and Propagation*, **62**(11), pp. 5775-5781.
6. Badron, K., Ismail, A.F., Din, J. and Tharek, A., (2011) Rain induced attenuation studies for v-band satellite communication in tropical region, *Journal of Atmospheric and Solar-Terrestrial Physics*, **73**(5), pp. 601-610. doi:https://doi.org/10.1016/j.jastp.2010.12.006.
7. Cox, D. and Arnold, H., (1982) Results from the 19- and 28-GHz COMSTAR satellite propagation experiments at Crawford Hill, *Proc. IEEE*, **70**, pp. 458-488.
8. Fujita, M., Shinozuka, T., Ihara, T., Furuhama, Y., and Inuki, H., (1980) ETS-II experiments part IV: Characteristics of millimetre and centimetre wavelength propagation, *IEEE Trans*., **AES-16**, pp. 581-589.
9. Ajaz, H. and Safaai-Jazi, A., (1993) Fade and inter-fade duration in Ku- and Ka-band frequencies measured from the OLYMPUS satellite beacons, *SATCOM Rep. 93-17*, Virginia Tech, Blacksburg.
10. Amaya, C. and Nguyen, T., (2011) Fade duration and fade slope statistics derived from long-term anik-f2 satellite beacon measurements in Ottawa-Canada, *XXXth URSI General Assembly and Scientific Symposium, Communications Research Centre Canada*, doi:10.1109/URSIGASS.2011.6050812.
11. Dintelmann, F., (1981) Analysis of 11 GHz slant path fade duration and fade slope, *Electronics Letters,* **17**(7), pp. 267-268.
12. Robert, S., Heder, B., and Bito, D.J., (2005) Rain fade slope analysis, *Broad Band Europe*, Bordeaux, France, pp. 1-5.
13. Amarjit, and Gangwar, R.P.S., (2014) Implementation of artificial neural network for prediction of rain attenuation in microwave and millimeter wave frequencies, *IETE Journal of Research*, **54**(5), pp. 346-352.
14. ITU-R P.1623-1, Prediction Method of Fade Dynamics on Earthspace Paths, Tech. Rep. REC. 1623-1, International Telecommunications Union (ITU), Geneva, Switzerland (2015).
15. ITU-R P.530-17, Propagation data and prediction methods required for the design of terrestrial line-of-sight systems, Tech. Rep. REC. 530-17, International Telecommunication Union, Geneva, Switzerland (2017).
16. ITU-R P.530-9, Propagation data and prediction methods required for the design of terrestrial line-of-sight systems, Tech. Rep. REC. 530-9, ITU, Geneva, Switzerland (2001).

17. Abdullah, N.A., Adullah, R.S.A., and Noordin, N.K., (2008) Adaptive coding and modulation for 38 GHz rain fade countermeasure, *Spectrum Research Colloquium 2008 Proceedings*.
18. Cheffena, M. and Amaya, C., (2008) Prediction Model of Fade Duration Statistics for Satellite Links between 10-50 GHz, *IEEE Antennas and Wireless Propagation Letters*, **7**, pp. 260-263.
19. ITU-R P.1623, Prediction method of fade dynamics on Earth-space paths, Tech. Rep. REC. 1623, ITU, Geneva, Switzerland (2003).
20. Yunus, M.M., Din, J., Lam, H.Y., and Jong, S.L., (2016) Estimation of interface duration for ku- and ka-band satellite communication system in equatorial Malaysia, *URSI Asia-Pacific Radio Science Conference (URSI AP-RASC)*, pp. 1967-1970. doi:10.1109/URSIAP-RASC.2016.7601225.
21. Dao, H., Rafiqul, I.M. and Al-Khateeb, K., (2013) Rain fade slope model in satellite path based on data measured in heavy rain zone, *IEEE Antennas and Wireless Propagation Letters*, **12**, pp. 50-53.
22. Dao, H., Rafiqul, I.M., and Al-Khateeb, K.A.S.,(2013) Analysis of rain fade duration models for earth-to-satellite path based on data measured in Malaysia, *IOP Conf. Series: Materials Science and Engineering*, **53**.
23. Maitra, A., Das, S., and Shukla, A.K., (2009) Joint statistics of rain rate and event duration for a tropical location in India, *Indian Journal of Radio and Space Physics*, **38**, pp. 353-360.
24. Pan, Q.W. and Allnutt, J.E., (2004) 12-GHz Fade Durations and Intervals in the Tropics, *IEEE Transactions on Antennas and Propagation*, **52**(3), pp. 693-701.
25. Chebil, J. and Rahaman, T.A., (1999) Rain rate statistical conversion for the prediction of rain attenuation in Malaysia, *Electronics Letters*, **35**(12), pp. 1019-1021.
26. ITU-R P.618-12, Propagation data and prediction methods required for the design of Earth-space telecommunication systems, Tech. rep., ITU, Geneva, Switzerland (2015).
27. Govardhani, I., (2014) Experimental Studies on Ku Band Down Link Satellite Signal Propagation Impairments, *PhD thesis*, Department of Electronics and Communication Engineering, KL University.