

Analysis of Rain Fade Durations on Communication Links at Ka Band in Nigeria

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

Abstract—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. This study investigates the number of fade events per fade duration interval exceeding attenuation thresholds ranging from 1 dB to 18 dB at 40 GHz. 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 stations, under the Centre for Atmospheric research (CAR), an activity Centre of the National Space Research and Development Agency (NASRDA) in Nigeria, 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). The results show that fade duration decreases as attenuation increases across all the locations. The implication is that heavy rains, causing higher attenuation, occur for shorter time duration. Similarly, higher attenuation depends on raindrops size and rain intensity. Consequently, the frequency of fade events exceeding 1 dB threshold is higher than other thresholds with respect to the fade duration.

Index Terms—Fade durations, rain fade, radio propagation, rain attenuation, tropical regions, satellite communications, communication links, sub-Saharan Climate.

I. INTRODUCTION

The demands on communication networks around the world are increasing rapidly. With the increasing volume of information comes the need for faster and higher quality communication links [1]. Radiowave propagation prediction assumes a very significant part in links design and eventually determines performance of space communication systems [2]. The most troublesome and frustrating impairment in receiving radio signals is variations in signal strength, commonly known as fading. Microwave signals propagating through the atmosphere are attenuated by vapour, fog, oxygen, rain, and several other gases. In particular, rain attenuation can degrade higher frequency satellite signals [1]. Tropical areas with high volumes of rainfall will be unable to use Ka-band satellite communications without mitigation technology [3], [4]. Being mindful of rain fade at the desired frequency of operation cannot be overemphasised in the design of a reliable communication links. Evidently, it is crucial for the accurate prediction of possible impairments to be encountered

on a given propagation link. [5]

The characterisation of the duration of a fade is defined as the time interval between two consecutive crossings of the same attenuation threshold [6]. It indicates the time length of how long the attenuation will exceed a certain threshold value [7]. In particular, it estimates the performance, availability and Quality of Service (QoS) for high frequency microwave links [8]. According to ITU-R P.1623-1 [9], it is an important parameter to be taken into account in system design and link budget for several reasons:

- 1) System outage and unavailability: Fade duration statistics provides information on the number of outages and the probability of the system being unavailable for a time period of a given duration [10], [11].
- 2) Fade mitigation techniques (FMT): The implementation of FMT, namely site diversity, power control, coding and resource sharing should be considered. Depending on the link margin, fade duration statistics provide statistical information on the time durations the system stays in a compensation configuration mode. [5], [12]
- 3) Coding and modulation: Fade duration is a key element in the process of choosing forward error correction codes and best modulation schemes.

Of particular interest in the context of availability criteria is the distinction between fades of shorter and longer duration than 10 s. Knowledge of the distribution of fade duration as a function of fade depth is also a prerequisite for the application of risk concepts in the provision of telecommunication services [13].

The fade duration statistics are usually presented as conditional distributions of the number of fade events exceeding certain durations, given that a specified fade threshold has been exceeded. This representation provides information on the number of outages and system availability due to propagation on a link, given a fade margin and an availability specification [9], [18]. All models on fade duration statistics of both satellite and terrestrial path links adopted a cumulative distribution based on power law, lognormal and two lognormal distributions [14], [15].

Studies have shown that duration statistics such as probability of duration for rain fades at a given attenuation, what time and how frequent it occurs, and when it may happen next are vital to getting insight into the performance, availability and quality of service [16]. Therefore, service providers must consider these aspects to implement an appropriate forward error correction (FEC), choice of modulations and the range of adaptive power control (APC) during severe rain fade events

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Manuscript received July 20, 2019.

in the overall design of their satellite communication systems, especially for the low-margin, Ku-band and higher frequencies systems [17]. Hence, there is a need to analyse the distribution of rain fade durations on communication links at Ka band in Nigeria with respect to given fade depth thresholds.

II. FADE DURATION DISTRIBUTION MODELS

- 1) **ITU-R model** calculates fade duration statistics including effect of gases, clouds, rain and scintillation for earth-satellite path links. The model presents that the long-term of fade duration follows a lognormal distribution while short-term of fade duration follows a power-law distribution. According to ITU-R, the duration statistics is defined by two different types of conditional cumulative distribution function (CDF) [13]. The probability of occurrence of fades of duration d longer than D (s), given that the attenuation a is greater than A (dB). Calculation of $P(d > D | a > A)$ of duration d longer than D given that attenuation a is greater than A is given in Equations (1-2).

For $1 \leq D \leq D_t$,

$$P(d > D | a > A) = D^{-\gamma} \quad (1)$$

For $D > D_t$,

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

where γ is the exponent of the power-law distribution of the fraction of fading time due to fades of short duration and D_t is boundary between short and long fade durations. Details of the ITU-R model are available in the methodology.

- 2) **Timothy model** is developed by normalising a lognormal distribution that depends on the average fade duration $\bar{D}$ [19]. For fractions of fade events exceeding the normalised fade duration, the fade duration distribution approximation is given by

$$P(D_f \geq x) = \frac{1}{2} \operatorname{erfc} \left(\frac{\ln x - \ln \bar{x}}{\sigma \sqrt{2}} \right) \quad (3)$$

$$= \frac{1}{x \sigma \sqrt{2\pi}} \int_x^\infty \left[-\frac{1}{2} \frac{\ln x - \ln \bar{x}}{\sigma} \right] dx \quad (4)$$

where $x = D/\bar{D}$ is the normalised fade duration, $\bar{D}$ is the average fade duration for a particular threshold, 1 is the standard deviation of $\ln(D/\bar{D})$, erfc is the complementary of error function and $\ln \bar{x}$ is the mean of $\ln x$

III. EQUIPMENT

Data from Tropospheric Data Acquisition Network (TRODAN) stations, namely Mowe, Lagos (Geo. 6.5° N, 3.5° E), Port Harcourt (Geo. 8.99° N, 7.38° E), Minna, Nsukka, Akure, Yola (Geo. 9.35° N, 12.5° E) and Ayingba with observation periods: January - December 2011, October 2007 - November 2008, January 2009 - December 2009, January 2008 -

December 2009, January 2010 - September 2011, November 2009 - December 2010 and July 2010 - July 2011, respectively, were used for the analysis of rain fades duration. TRODAN is managed by the Centre for Atmospheric Research (CAR), an activity centre of the National Space Research and Development Agency (NASRDA), a Federal Government Agency that provides research facilities and services for the atmospheric and Earth sciences community in Nigeria.

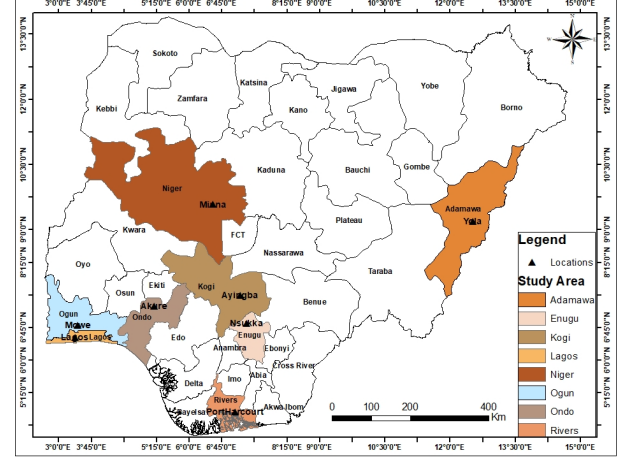


Fig. 1. Map of Nigeria showing study areas.

TABLE I
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)
Port Harcourt	4.82	123.47	55.9	7.52	2346.1
Lagos	6.52	110.72	51.5	10.75	1626.2
Mowe	6.82	74.83	50.5	19.00	430.5
Nsukka	6.84	106.52	56.1	414.40	1427.15
Akure	7.31	107.77	50.4	367.03	1485.6
Ayingba	7.49	70.11	55.5	377.42	349.6
Yola	9.08	94.33	60.7	282.63	948.5
Minna	9.58	90.15	54.2	273.3	814.33

IV. METHODOLOGY

The Fade duration model used in this study is the model recommended by the ITU-R P.1623-1 [9], regarded as the prediction method for fade dynamics on Earth-space path. Fade duration can be described by two different cumulative distribution functions:

- 1) $P(d > D | a > A)$, the probability of occurrence of fades of duration d longer than D (s), given that the attenuation a is greater than A (dB). This probability can be estimated from the ratio of the number of fades of duration longer than D to the total number of fades observed, given that the threshold A is exceeded.
- 2) $F(d > D | a > A)$, the cumulative exceedance probability, or, equivalently, the total fraction (between 0 and 1) of

fade time due to fades of duration d longer than D (s), given that the attenuation a is greater than A (dB). This probability can be estimated from the ratio of the total fading time due to fades of duration longer than D given that the threshold A is exceeded, to the total exceedance time of the threshold.

The model is expected to be valid for durations longer than 1 s. The following parameters are required as input to the model:

f : frequency (GHz) : 10 – 50 GHz

φ : elevation angle (degrees) : 5 – 60°

A : attenuation threshold (dB)

The step-by-step calculation of fade duration distribution is shown in (5)-(18):

Step 1: Calculate the mean duration D_0 of the log-normal distribution of the fraction of fading time due to fades of long duration, given that the attenuation is greater than A , as:

$$D_0 = 80 \varphi^{-0.4} f^{1.4} A^{-0.39} \quad s \quad (5)$$

Step 2: Calculate the standard deviation σ of the lognormal distribution of the fraction of fading time due to fades of long duration as:

$$\sigma = 1.85 f^{-0.05} A^{-0.027} \quad (6)$$

Step 3: Calculate the exponent γ of the power-law distribution of the fraction of fading time due to fades of short duration as:

$$\gamma = 0.055 f^{0.65} A^{-0.003} \quad (7)$$

Step 4: Calculate the boundary between short and long fade durations, D_t , as:

$$D_t = D_0 \exp^{p_1 \sigma^2 + p_2 \sigma - 0.39} \quad s \quad (8)$$

where:

$$p_1 = 0.885\gamma - 0.814 \quad (9)$$

$$p_2 = -1.05\gamma^2 + 2.23\gamma - 1.61 \quad (10)$$

Step 5: Calculate the mean duration D_2 of the log-normal distribution of the probability of occurrence of fading events of long duration as:

$$D_2 = D_0 \cdot \exp^{-\sigma^2} \quad s \quad (11)$$

where:

Step 6: Calculate the fraction of time k due to fades of duration less than D_t as:

$$k = \left[1 + \frac{\sqrt{D_0 D_2} (1 - \gamma) Q\left(\frac{\ln(D_t) - \ln(D_0)}{\sigma}\right)}{D_t \gamma Q\left(\frac{\ln(D_t) - \ln(D_2)}{\sigma}\right)} \right]^{-1} \quad (12)$$

where Q is the standard cumulative distribution function for a normally distributed variable:

$$Q(z) = \frac{1}{\sqrt{2\pi}} \int_z^\infty e^{-\frac{1}{2}x^2} dx \quad (13)$$

Step 7: Calculate the probability of occurrence of fade events of duration d longer than D given that attenuation a is greater than A as:

For $1 \leq D \leq D_t$,

$$P(d > D | a > A) = D^{-\gamma} \quad (14)$$

For $D > D_t$,

$$P(d > D | a > A) = D_t^{-\gamma} \cdot \frac{Q\left(\frac{\ln(D) - \ln(D_2)}{\sigma}\right)}{Q\left(\frac{\ln(D_t) - \ln(D_2)}{\sigma}\right)} \quad (15)$$

Step 8: Calculate the cumulative probability of exceedance, i.e., the total fraction of fade time due to fades of duration d longer than D :

For $1 \leq D \leq D_t$,

$$F(d > D | a > A) = \left[1 - k \left(\frac{D}{D_t} \right)^{1-\gamma} \right] \quad (16)$$

For $D > D_t$,

$$F(d > D | a > A) = (1 - k) \cdot \frac{Q\left(\frac{\ln(D) - \ln(D_0)}{\sigma}\right)}{Q\left(\frac{\ln(D_t) - \ln(D_0)}{\sigma}\right)} \quad (17)$$

Step 9: If required, the total number of fades of duration d longer than D for a given threshold A can be calculated from:

$$N(D, A) = P(d > D | a > A) \times N_{tot}(A) \quad (18)$$

V. RESULTS AND ANALYSIS

Figures 2 to 17 show the number of fade duration exceeding the thresholds at 1, 3, 6, 9, 12 and 18 dB levels. The average number of events per year of rain attenuation greater than the given thresholds were estimated.

Tables II-IV show the typical number of events for which duration exceeds threshold at 1, 3, 6, 9, 12, 15 and 18 dB levels at Port Harcourt, Ayingba and Minna. From these tables, it is seen that when the attenuation is increased the time duration will decrease in all the locations. This is because heavy rains causing high attenuation level is at short duration. Consequently, higher attenuation depends on the raindrop size and also the rain intensity [20]. The lognormal distribution of Figures 2 to 17 show the number of events grouped by exceeding levels versus duration(s) for all the locations. The number of events of attenuation exceeding 1 dB level is higher than other levels, and also the duration of fade events is longer especially for Lagos and Port Harcourt. This is due to attenuation exceeding 18 dB level; it needs higher rain intensity and longer raining time compared to attenuation exceeding 1 dB level.

VI. CONCLUSION

This study has provided information on features of rain fade durations at eight locations across Nigeria. The ITU-R model predicts the measured data statistics well. The probability distributions of fade duration were found almost similar in short and long durations. The result of this study will assist

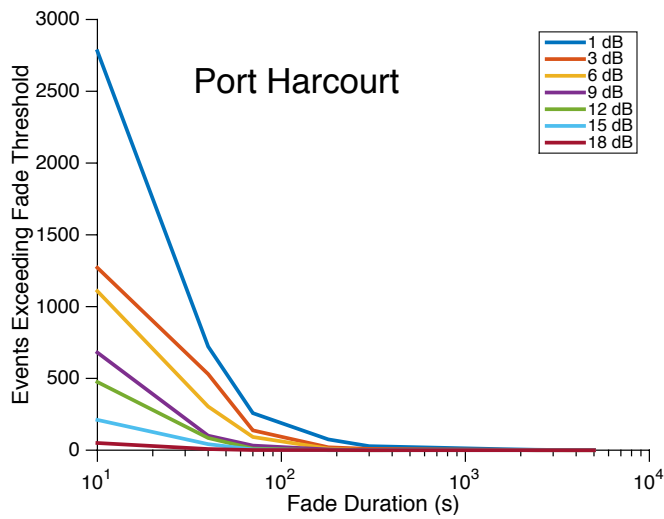


Fig. 2. Fade durations by attenuation levels in Port Harcourt

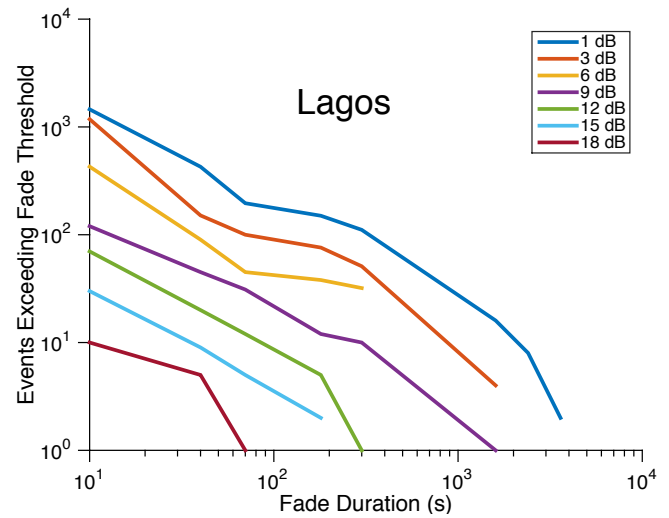


Fig. 5. The log-normal distribution plot of Fade durations in Lagos

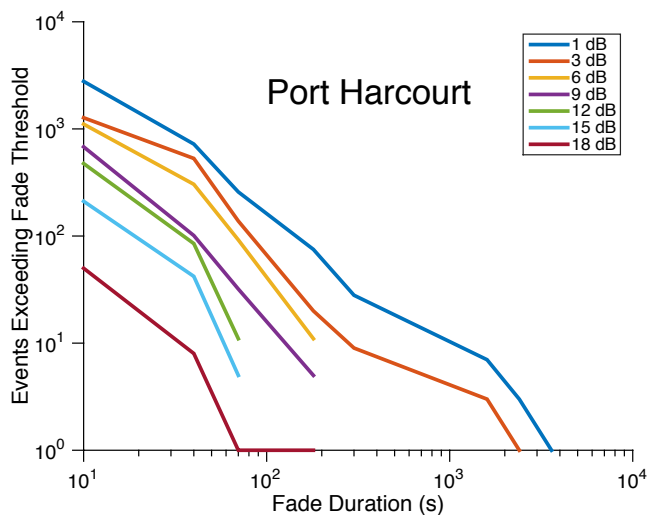


Fig. 3. The log-normal distribution plot of Fade durations in Port Harcourt

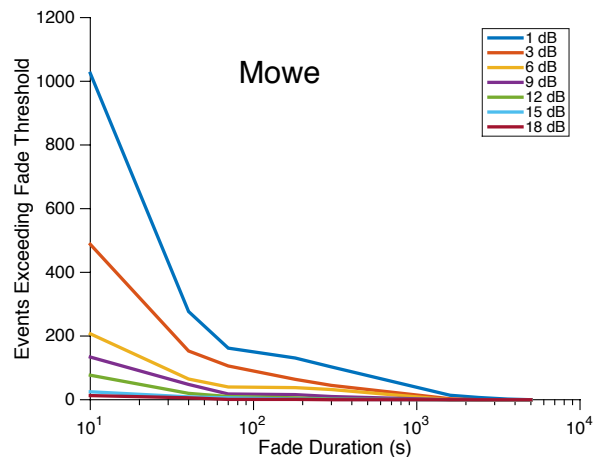


Fig. 6. Fade durations by attenuation levels in Mowe

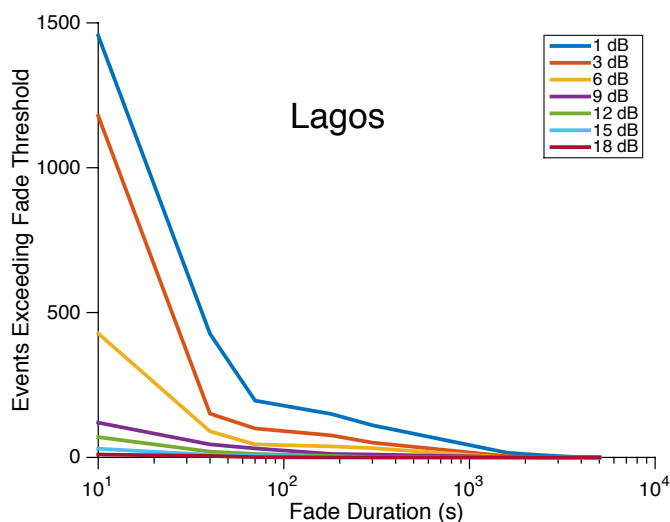


Fig. 4. Fade durations by attenuation levels in Lagos

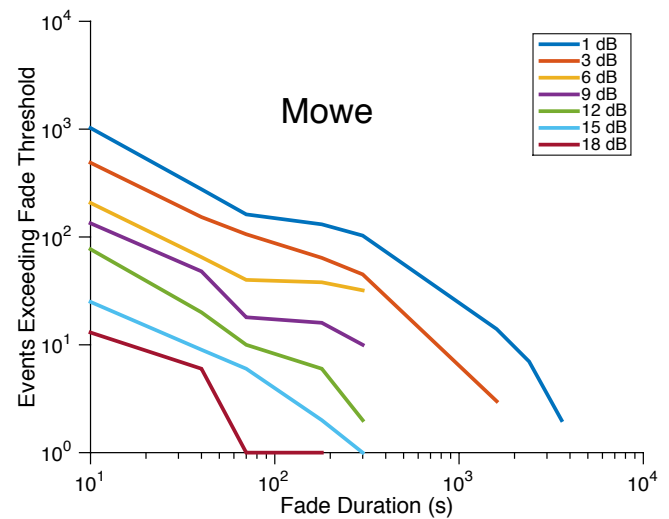


Fig. 7. The log-normal distribution plot of Fade durations in Mowe

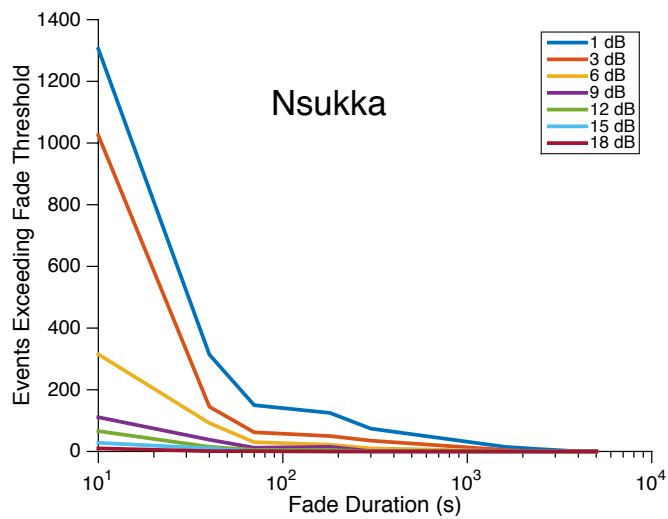


Fig. 8. Fade durations by attenuation levels in Nsukka

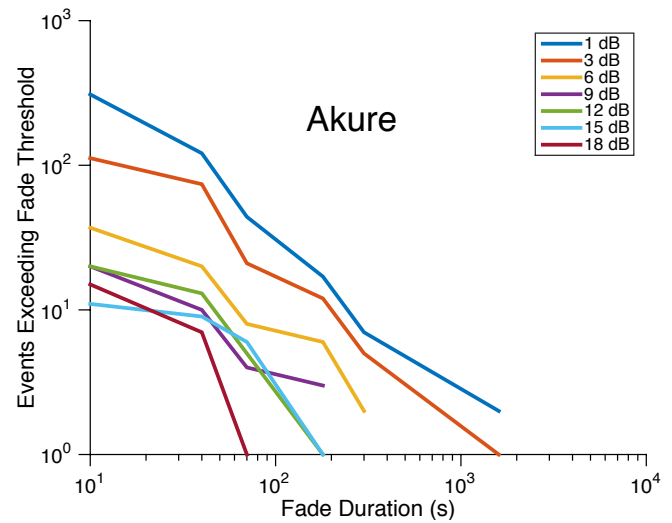


Fig. 11. The log-normal distribution plot of Fade durations in Akure

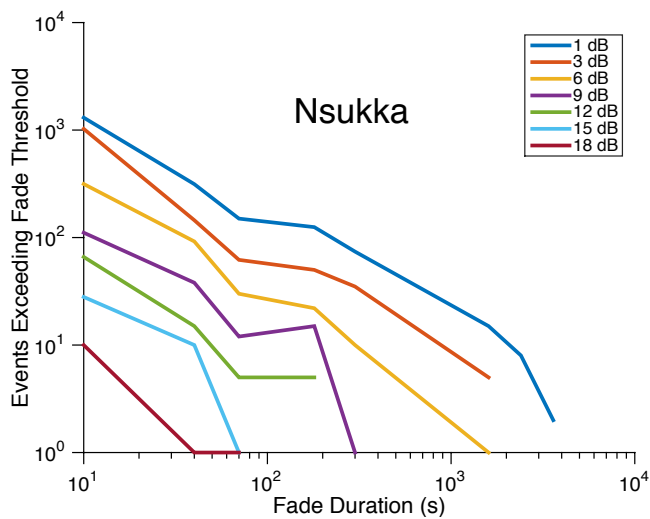


Fig. 9. The log-normal distribution plot of Fade durations in Nsukka

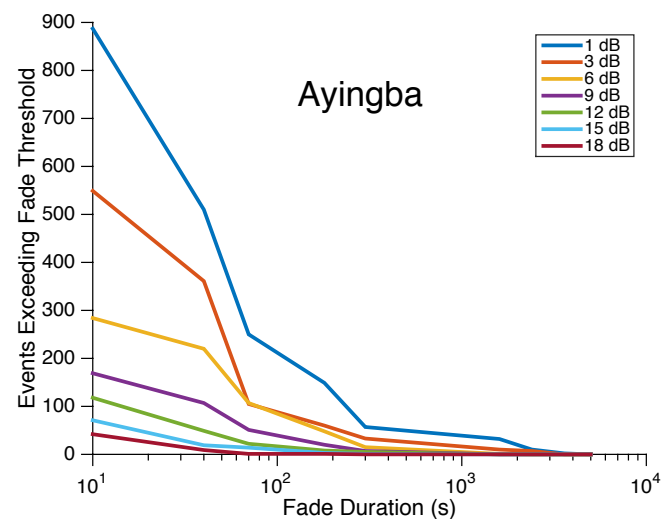


Fig. 12. Fade durations by attenuation levels in Ayingba

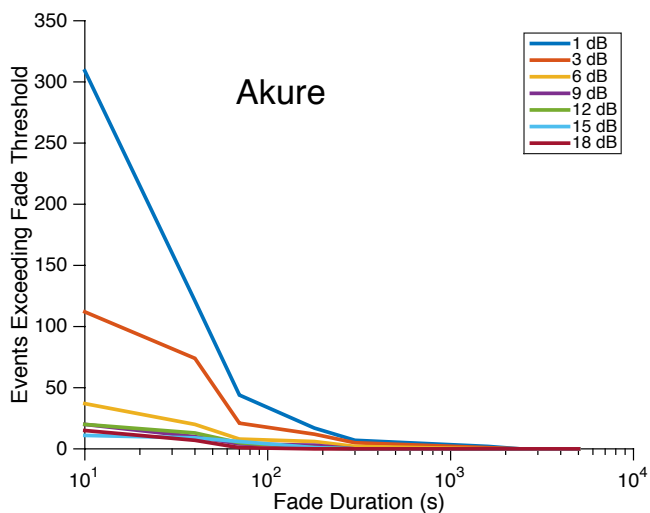


Fig. 10. Fade durations by attenuation levels in Akure

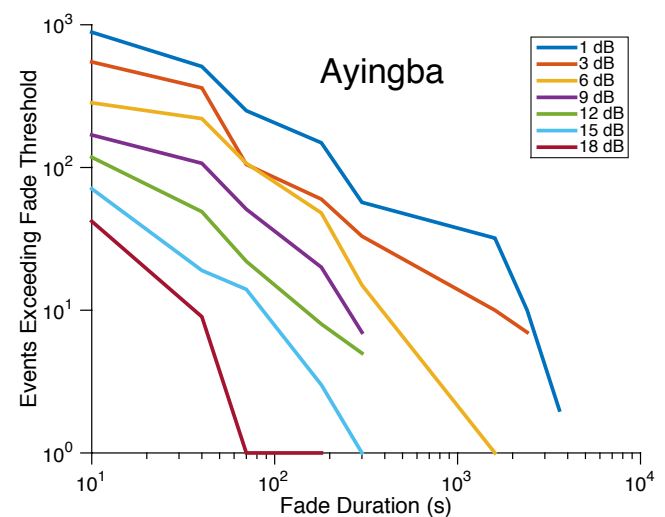


Fig. 13. The log-normal distribution plot of Fade durations in Ayingba

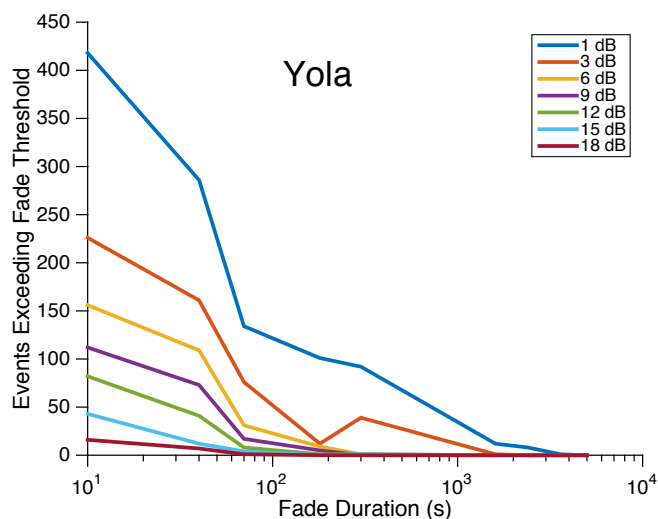


Fig. 14. Fade durations by attenuation levels in Yola

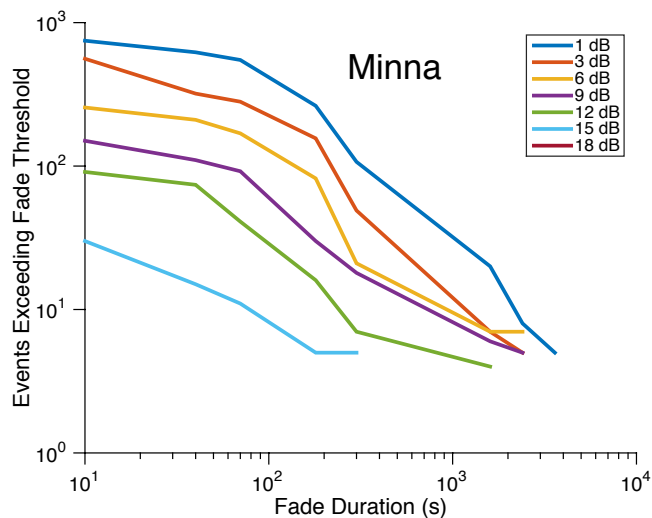


Fig. 17. The log-normal distribution plot of Fade durations in Minna

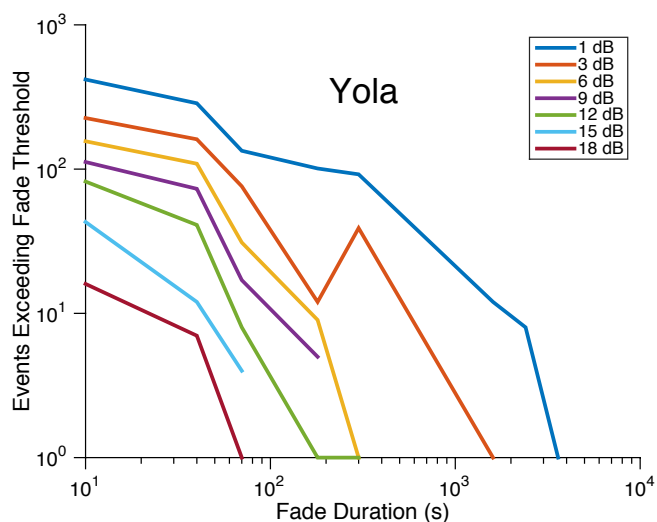


Fig. 15. The log-normal distribution plot of Fade durations in Yola

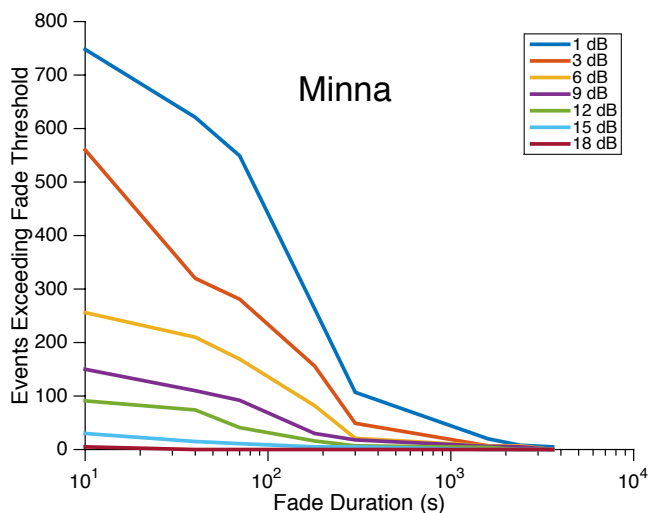


Fig. 16. Fade durations by attenuation levels in Minna

TABLE II
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 III
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 IV
TYPICAL FADE DURATION EVENTS IN MINNA

Duration (s)	1 dB	3 dB	6 dB	9 dB	12 dB	15 dB	18 dB
10	748	560	256	150	91	30	5
40	621	320	210	110	74	15	0
70	549	281	169	92	41	11	0
180	263	156	82	30	16	5	0
300	107	49	21	18	7	5	0
1600	20	7	7	6	4	0	0
2400	8	5	7	5	0	0	0
3600	5	0	0	0	0	0	0
5000	0	0	0	0	0	0	0

system designers in the employment of mitigation techniques for designing reliable broadband communication link. 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 service availability during rain events.

ACKNOWLEDGMENT

The authors would like to thank the activity Centres of the National Space Research and Development Agency (NAS-RDA) namely the Centre for Basic Space Science (CBSS), Nsukka and the Centre for Atmospheric Research (CAR), Anyigba, Prof. P. N. Okeke, Prof. A. B. Rabi, Director, CAR, and Dr. S. O. Mohammed, Director-General and Chief Executive Officer, NASRDA, for the data, support and approval to access the Tropospheric Data Acquisition Network (TRODAN).

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