Characterization of rain fade dynamics for Ku band satellite communication systems in a tropical location

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Abstract. Rain fade has always been regarded as the main obstacle to the terrestrial and satellite communication links operating at higher frequencies, particularly in the tropics. The dynamic features of rain fade such as duration and slope of fade are important parameters for system engineers to design and plan attenuation techniques for high reliability Ku-band services and other higher frequency bands. Twenty-four (24) consecutive months (January 2017 – December 2018) received signal strength data at 12.245 GHz (Ku-band) from EUTELSAT-W4 (geostationary at 36°E) is collected concurrently with rain intensity data at The Federal University of Technology, Akure (7.17°N, 5.18°E) Nigeria. Measured fade duration is compared with ITU-R P. 1623 model and the Cheffena-Amaya prediction model. The results show that the ITU-R model is close to the data measured, while the Cheffena-Amaya model overestimates the measurement for all timeframes taken into account. A modification of the ITU-R fade duration model is suggested according to the data measured. The proposed modified ITU-R prediction model is a recommended model to be adopted for Nigeria climate. These results can be used in the planning and design of fade mitigation techniques to overcome the effects of intense rain on terrestrial-satellite microwave links operating in the Ku-band in tropical regions.

1. Introduction

Fade due to rain is considered a dominant alteration in satellite communication links, particularly at a frequency exceeding 10 GHz and especially in tropical and equatorial regions with Nigeria inclusive. The fading of rain provides further insights on understanding the rainfall-induced degradations characteristics [1].

Rain fade is the dynamic fluctuation of received signals, ranging from a few seconds to a few minutes due to inhomogeneity of the signal trajectory. Consequently, for the Ku band system and higher band frequencies, the effect of rainfall is noticed to be more intense in the tropical areas which are characterized by heavy rainfall intensity and the presence of large raindrops [2, 3]. The probable duration of rain fade, the time of the day at which it is likely to happen, and how frequently it occurs are the most significant aspects to be considered when designing satellite communication system links. [4].

This problem can be reduced by deploying Fade Mitigation Techniques (FMGTs) such as the appropriate link budget strategy when designing the satellite network, the adaptive modulation scheme and the allocation of higher energy consumption to offset fade loss due to rain.

However, the fitting plan and execution of FMGTs require information on the first and second -
order measurements of rain attenuation. First-order measurement alludes to the total dissemination of rain fall attenuation and rainfall rate, while second-order measurement depict the dynamic characteristics of rain attenuation for example fade duration and fade slope [5].

The second-order measurements are important for aiding service providers to indicate the type of modulation, and error correction scheme, range of uplink, power control, and tracking speed of FMGTs that need to be used during intense periods of rainfall to reduce the probability of link outage [5]. Fade duration is a significant key to decide the exhibition, accessibility and Quality of Service (QoS) for microwave communication at high-frequency bands [6].

In addition, the fade duration estimation of the satellite signal variations are carefully determined and thus compared with the ITU-R recommendation model and other existing models. Such data is valuable for the system administrator and radio correspondence engineer for the plan of suitable FMGTs also as QoS that could be offered to the end-client (as per the time span for a regular day).

2. Experimental set-up

The experimental site is situated at the Department of Physics, the Federal University of Technology, Akure, Nigeria. Estimation of radio beacons on EUTELSAT-W4 (geostationary at 36°E) at 12.245 GHz frequency (Ku-Band), with 90 cm parabolic receiving antenna utilizing Tektronix Y400 NetTek spectrum analyzer was employed. The received signal level is collected for 24 months (Jan 2017 to Dec 2018) is utilized in this paper. In addition, rainfall rate is concurrently measured using a Vantage Vue automatic weather station. Table 1 shows the description of the estimation site and system parameters.

| Parameter                  | Value                |
|----------------------------|----------------------|
| Longitude (°E)             | 5.18                 |
| Latitude (°N)              | 7.17                 |
| Beacon Frequency (GHz)     | 12.245               |
| Satellite Position         | 36.0° E (EUTELSAT W4) |
| Polarization               | Vertical             |
| Azimuth (degree)           | 102.01               |
| Elevation Angle (degree)   | 53.2                 |
| Skew of LNB (degree)       | -76                  |

3. Fade duration assumption models and modification

Estimating the duration of fade is fundamental for the power control and error correction schemes for example the forward error correction techniques which decrease the effect of link failure. The selected fade duration thresholds presented are 1, 5, 10, and 15 dB. The duration of fade is estimated for 1 sec and above. Data points of 1, 10, 40, 70, 180, 300, 1600, 2400, and 3600 s, have been utilized to analyzed data distribution of fade duration measurement, and comparing between data measured to the model suggested by ITU-R and Cheffena-Amaya model.

The probability of events \( P(d > D | a > A) \) which can be assessed by the proportion of the number of fades of duration longer than \( D \), \( N(d > D | a > A) \) to the absolute number of fades noticed, \( N_{tot} (A) \) given that the cut-off \( A \) is exceeded giving as [7, 8]

\[
P(d > D | a > A) = \frac{N(d > D | a > A)}{N_{tot}}
\]  

Finally, a comparison among measured data and available rain models has been employed in order to
determine the best model that suits locally measured data to be adopted as a prediction model in Nigeria.

3.1 ITU-R model. The probability of event $P(d>D | a>A)$ between the ITU-R P. 1623 [9] and the statistics of data measured for a given mitigation threshold is compared in this study. Calculation of the probability of event $P(d>D | a>A)$ of duration $d$ longer than $D$ given that attenuation $a$ is greater than $A$ is presented in [9].

As presented in Figures 1 and 2, the ITU-R rain model obviously has a wide range of validity and is close to the data measured. The ITU-R model forecasts the statistical data measured for 2017 fairly well for a short duration and long duration (except for 1 dB attenuation for long duration mainly caused by rain). The ITU-R model also overestimates the short and long-duration of the statistical data measured for 2018, except for the attenuation of 1 dB for a long duration.

![Figure 1](image-url)

**Figure 1**: Assessment of probability of event $P(d>D | a>A)$ between ITU-R model and data measured (MED) for given attenuation cut-off for 2017
Figure 2: Assessment of probability of event $P(d > D | a > A)$ between ITU-R model and data measured (MED) for given attenuation cut-off for 2018

3.2 Cheffena - Amaya Model-The model was created as a prediction model of a cumulative distribution function (CDF) of the probability of event of duration of fade. It contains the sum of two lognormal functions which associate with the path and climate parameters as seen in [5]. The input boundaries are the operating frequency in GHz, attenuation in dB, elevation angle in degree, and the rain convectivity factor $\beta(0.573)$. The probability distribution of fade is given by:

$$P(d > D | a > A) = \alpha \frac{Q\left(\frac{\ln(D/m_\tau)}{\sigma_\tau}\right)}{Q\left(\frac{\ln(D/m_\tau)}{\sigma_\tau}\right)} + (1 - \alpha) \frac{Q\left(\frac{\ln(D/m_s)}{\sigma_s}\right)}{Q\left(\frac{\ln(D/m_s)}{\sigma_s}\right)}$$

where $Q$ is the CDF for a normally distributed variable as represented in [9]. The essential parameters that considerably influence the model and accordingly should be determined are mean $m_s$ and standard deviation $\sigma_s$ of the lognormal distribution that can best portray the short durations due to scintillation. The $m_\tau$ and standard deviation $\sigma_\tau$ of the lognormal portrays long durations caused by rain and the small amount of fade associated with each lognormal $\alpha$.

Based on Figures 3 and 4, the Cheffena – Amaya model anticipated a comparable pattern to the statistics of data measured for specific attenuation cut-off for the year 2017 and 2018. However, the model has a relative overestimation of the data measured for all attenuation cut-off. The overestimation was a lot higher than the ITU-R model.
3.3 **Modification of ITU-R Model.** The analysis shows that the ITU-R and the Cheffena- Amaya forecast models cannot precisely estimate the fade duration distribution of the data measured. Therefore, a modification is proposed to the existing model to match the data measured. As earlier shown in Figures 1 and 2, even though the ITU-R underestimates the probability of event of the data measured, however, the model has close proximity with the data measured compared to the
Cheffena-Amaya model. Consequently, the ITU-R model is modified to guarantee that it fits the data measured.

The critical parameter of the ITU-R model which is the, average, and standard deviation due to long-duration of fades is recalculated. Derivation of parameters and equation in [9] respectively is analyzed using two-year measured data. To fit the parameters for the modification of the ITU-R model, the Levenberg-Marquardt Method (LMM) has been adopted in Figures 5 and 6. LMM fills in as an alternative technique to the Gauss-Newton method for deriving the minimum of a function, that is, an expansion of squares of nonlinear functions. For this situation, \( R \) is the amount of the square residual error of the regression. In view of the LMM, the experimental results determine the values of the parameters that minimize the sum of the squared leftover values for the arrangement of observations-least squares regression fit [10]. Equations (3) and (4) are best suited for the measurement data based on LMM.

\[
D_0 = 80\varphi^{0.647} f^{0.944} A^{-0.39} \quad (3)
\]

\[
\sigma = 1.9623 f^{-0.0341} A^{-0.027} \quad (4)
\]

where \( \varphi \) is the elevation angle, \( f \) is functional frequency in GHz, and \( A \) is attenuation cut-off in dB.

The assessment of the probability of event \( P(d > D | a > A) \) distribution between the modified ITU-R model and the data measured for given attenuation cut-off is shown in Figures 5 and 6 for 2017 and 2018 respectively. The curve provided by the modified model exhibits a similar pattern with the data measured for both short and long-duration.

**Figure 5:** Assessment of probability of event \( P(d > D | a > A) \) between Modified ITU-R (MDFY) and data measured (MED) for given attenuation cut-off for 2017.
4. Statistical model testing

The techniques for statistical model testing of the probability of event $P(d>D \mid a>A)$ is characterized as the natural log of the relationship of the predicted probability $P_p(d>D \mid a>A)$ to the estimated probability $P_m(d>D \mid a>A)$, for each attenuation $A$ and duration $D$ [11]. The test variables, which are the mean, standard deviation (STD), and square of the quadratic mean (RMS), are computed according to the attenuation threshold $A$ and duration $D$. The smallest values of the measurement parameters are the best forecast.

Three prediction models for the duration of fade distribution were introduced and compared to the data measured. Results of the probability of event test factors $P(d>D \mid a>A)$ per mean, STD, and RMS for the three models with various attenuations are presented in Tables 2 and 3. The modified ITU-R model generally predicts better than the ITU-R and Cheffena-Amaya models.

The average prediction error of $P(d>D \mid a>A)$ of Mean, STD, and RMS for the three models are presented in Table 4. Benchmarking shows that the modified ITU-R model has minimal measurable values (mean, STD, and RMS) for both years. As a result, the modified ITU-R model provides the best forecast for $P(d>D \mid a>A)$. Therefore, the modified ITU-R model is the appropriate model to be adopted in Nigeria as a model for forecasting the rain fade prediction.

Table 2: Assumption test factors of $P(d>D \mid a>A)$ with various models for given attenuations ($A$) for the year 2017

| Models        | A(dB)s | 1      | 5      | 10     | 15     |
|---------------|--------|--------|--------|--------|--------|
| ITU-R         | Mean   | 0.881088 | 0.78143 | 0.756233 | 0.807369 |
|               | Std    | 0.579928 | 0.590481 | 0.711997 | 1.157501 |
|               | RMS    | 1.036949 | 0.959458 | 1.011188 | 1.357493 |
| Cheffena-Amaya| Mean   | 1.926654 | 1.465443 | 1.285843 | 1.151375 |
|               | Std    | 1.469293 | 1.354417 | 1.33582 | 1.635876 |
|               | RMS    | 2.372962 | 1.943744 | 1.799872 | 1.924685 |
| Modified-ITU-R| Mean  | -1.16534 | -0.50524 | -0.26799 | -0.11127 |
|               | Std    | 1.379041 | 0.793443 | 0.50171 | 0.470377 |
Table 3: Assumption test factors of $P(d>D \mid a>A)$ with various models for given attenuations (A) for the year 2018.

| Models          | A(dB)s | 1     | 5     | 10    | 15    |
|-----------------|--------|-------|-------|-------|-------|
| ITU-R           | Mean   | 1.664156 | 0.989225 | 1.01829 | 0.863327 |
|                 | Std    | 0.802775 | 0.972483 | 1.352063 | 1.064029 |
|                 | RMS    | 1.828184 | 1.348781 | 1.631524 | 1.323517 |
| Cheffena-Amaya  | Mean   | 2.709722 | 1.40841  | 1.329242 | 1.207332 |
|                 | Std    | 1.653804 | 1.402727 | 1.812412 | 1.540154 |
|                 | RMS    | 3.126302 | 1.932003 | 2.164888 | 1.884829 |
| Modified-ITU-R  | Mean   | -0.38227 | -0.12892 | 0.145667 | -0.05532 |
|                 | Std    | 1.150517 | 0.500856 | 0.266461 | 0.236077 |
|                 | RMS    | 1.150105 | 0.489493 | 0.290398 | 0.229346 |

5. Conclusion

The experimental data of two years (January 2017 – December 2018) of attenuation time series obtained from EUTELSAT- W4 downlink at Ku-band signal of frequency 12.245 GHz in a tropical weather FUTA (Akure) has been analyzed to observe the statistical characteristics. The probability distribution variation of duration of fade event is almost identical for the given attenuation cut-off. Two distribution assumption models of fade duration are introduced and compared with data measured. The ITU-R model underestimates the measured data statistics for a short duration and long duration in 2017. In 2018, the model overestimates the data measured except for 1 dB attenuation of the measured data for long-duration. Besides, the Cheffena-Amaya model overestimates the measured data for all durations considered. The results prove that the ITU-R model is close to the measured data compared to the Cheffena-Amaya model. Significant parameters of the ITU-R model are modified and the result shows that the curves are in proximity to the data measured. Hence, the modified ITU-R forecast model is the best model that can be received for Nigeria’s climate. This can be demonstrated from perception and correlation that has been made. This prediction model is important in system design especially to have a flexible and broadband feeder network. It will also assure telecommunication service providers to provide the best service during intense rainy days.

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