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Rain fade duration prediction models for A high elevation angle based on measured data in tropical climate

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Abstract

Rain fade duration is one of the essential components for engineers to design and plan satellite communication systems at high frequency bands. In this paper, rain fade duration was obtained for twelve consecutive months at Ku-band with 77.4° elevation angle from MEASAT3 in Kuala Lumpur, Malaysia. Empirically, the fade duration was found discrepant to the results predicted by models. Therefore, a modification of fade duration model is proposed based on measured data for this tropical climate and high elevation angle.

Keywords: Satellites; Rain attenuation; Fade duration; Fade mitigation techniques; Predictive models; Tropical climate

1. Introduction

Attenuation due to rain is the major cause that degrades signal on satellite communication above 10 GHz (Dao et al., 2012). As such, a reliable system design is necessary to ensure optimum services offered via satellite communication. Therefore, a service provider must deploy suitable fade countermeasure techniques to achieve a reliable system during severe periods, particularly due to rain (Dao et al., 2012). Several mitigation techniques employ first-order and second-order statistics of rain attenuation for the design and implementation of satellite and wireless communication (Cheffena and Amaya, 2008). The statistics of rain attenuation can provide valuable insights to the fade mitigation techniques (FMT) during rain events.

Fade duration is important to estimate performance, availability and Quality of Service (QoS) for a microwave communication at high frequency bands (Amarjit and Gangwar, 2014). Statistics of fade duration can indicate frequency of rain attenuation occurrence, time duration, and anticipate when it may occur. ITU-R P.1623-1 (2015) described fade duration statistics by two cumulative distribution functions (CDF): number of fade events d longer than a given duration D (s), and total time of fade exceeding for a certain duration D, a given attenuation threshold A (dB).

Several fade duration measurements have been carried out on low and moderate elevation angles whereas few works have been done on high elevation angles. In addition, prediction models are also limited up to 60 degrees of elevation angles which may lead to disparate predictions for high elevation angles (Cheffena et al., 2008, Mandeep, 2013).

This paper presents the fade duration statistics based on data measured in Kuala Lumpur, Malaysia. The cumulative distribution function of rain fade duration is calculated from the measured attenuation time series. Rain fade durations from three prediction models are compared and a modification model is also proposed based on the empirical result.

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2. Measurement of data

Attenuation time series at Ku-band signal were collected from MEASAT 3 (geostationary at 91.5°E) at Kuala Lumpur, Malaysia (3.25°N and 101.7°E). The measured signal was sampled and recorded at 1 s interval. Rain rate was measured by using 0.2 mm tipping bucket rain gauge which was synchronized with the measurement of satellite signal (Dao et al., 2013). In this study, the experimental data obtained from 2011 to 2012 is utilized to statistically characterize and test the models.

3. Fade duration statistics

The fade duration characteristics differ from fade slope which requires the separation of the low and rapid fluctuation components from the received signal time series (*ITU-R P.1623-1, 2015*). Identification of the fade durations due to different phenomena on a slant path is of prime importance. Short fade duration is mainly identified by scintillation while long fade duration is mainly related by precipitation and clouds. Fade event identification of short and long durations are usually between 10 s and 30 s (Garcia-del-Pino et al., 2011). A duration threshold of 30 s was effectively proven for the measurement (Dao et al., 2012; Dao, 2013).

Fade duration statistics are usually presented in terms of probability of occurrence P (d > D|a > A) of fade duration *d* (s) longer than a given duration *D* (s), given attenuation *a* (dB) above given attenuation threshold *A* (dB), (Dao, 2013). The probability of occurrence is expressed by Eq. (1).

$$P(d > D|a > A) = \frac{N(d > D|a > A)}{N_{tot}(A)} \quad (1)$$

where

N(d > D|a > A) is number of fade events distribution.

$N_{tot}(A)$ is the total number of fade events of attenuation exceeding a at a given attenuation A.

The total number of measured fade events as a function of attenuation, $N_{tot}(A)$ shown in Fig. 1 is discernibly declines with attenuation. The number of measured fade events exceeding a given duration for different attenuation thresholds is also illustrated in Fig. 2. The distributions evidently show similar trend and almost parallel to one another. The fade duration for attenuations of 10 and 13 dB are within 10 and 3 min, respectively. It is observed that data points for number of events and time exceeding of fade duration distribution complies with ITU-R P.311 (2017) for the time between 1 s and 3600 s

The probability of occurrences $P(d > D|a > A)$ as depicted in Fig. 3 is obtained by employing the ratio of number of fade events exceeding N($d > D|a > A$) in Fig. 2 to $N_{tot}(A)$ in Fig. 1. As shown by Fig. 3, the 1 dB curve is discernibly lower than the other curves that may be

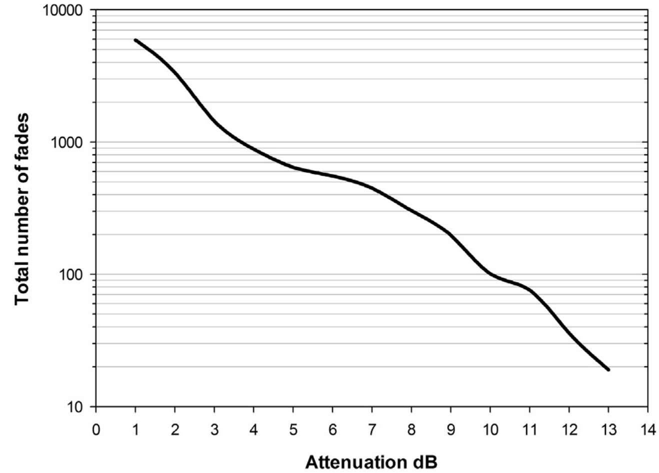

Fig. 1. Total number of fade events measured for a given attenuation threshold.

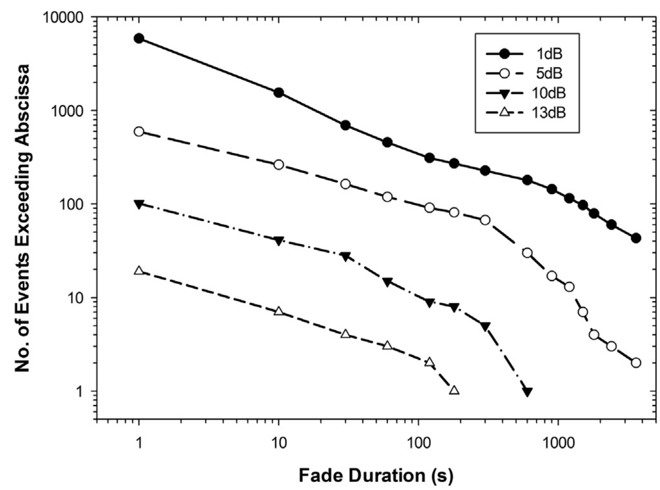

Fig. 2. Number of measured fade events exceeding for given durations, N (d > D|a > A).

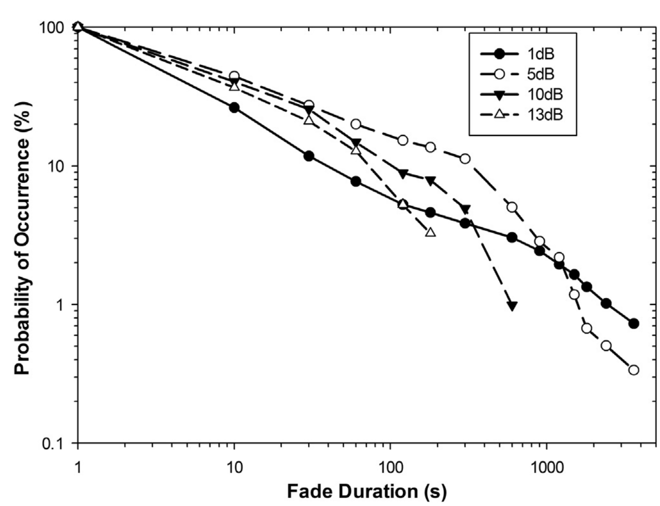

Fig. 3. Probability of occurrence from measured fade events, P(d > D|a > A).

impacted by a significant number of non-precipitation fades such as cloud events that is long-lasting occur compared to rain events (Al-Ansafi et al., 2003) while 10 dB and 13 dB are in the middle. Moreover, each curve has similar trends of short and long durations at the point of 30 s as proven by Dao et al. (2012).

4. Prediction models and modification

Generally, the cumulative distribution of fade duration is developed from power law and lognormal distributions (Castanet and Kamp, 2003). In this section, fade duration statistics, are computed and presented in terms of probability of occurrence, $P(d > D|a > A)$ and compared to three probability prediction models, namely ITU-R (*ITU-R P.1623-1, 2015*), Timothy (Timothy et al. 2000) and Cheffena-Amaya models (Cheffena et al., 2008, Dao, 2013, and ITU-R-P.311-17, 2017). The testing method for comparing fade duration predictions is calculated for the given attenuation thresholds of 1, 5, 10 and 13 dB respectively and complied with ITU-R P.311 (*2017*).

4.1. ITU-R model

ITU-R P.1623-1 (*2015*) proposed fade duration prediction model that considers the effects of gases, clouds, rain and scintillation for Earth-satellite links. In this model, the long-term fade duration follows the lognormal distribution and the short-term fade duration follows the power-law distribution.

Comparison of probability of occurrence $P(d > D|a > A)$ between ITU-R model and measured data statistics for given attenuation thresholds is depicted in Fig. 4. In general, the ITU-R model can effectively predict the measured statistics for short duration (<30 s) except for 1 dB attenuation. However, the model underestimates the measured data for long duration (>30 s) which is significantly affected by rain attenuations.

4.2. Timothy model

The model is developed by normalizing the lognormal distribution as expressed by Timothy et al. (2000). The model calculates the normalised fade duration $x = D/\bar{D}$, the average fade duration $\bar{D}$ for a specific threshold, the standard deviation σ of $\ln(x)$ which is equivalent to 2.331. $\overline{\ln x}$ is the mean of $\ln(x)$ which is equivalent to 1.206 and complementary of error function, *erfc*.

Fig. 5 depicts the probability of occurrences $P(d > D|a > A)$ and the comparison between Timothy model and measured data for given attenuation thresholds. The probability of occurrences clearly shows that the model overestimates both short and long durations for all attenuation thresholds. As such, the prediction proposed by the Timothy model is unable to fit for the short duration which is found close in ITU-R.

4.3. Cheffena-Amaya model

Cheffena-Amaya model is developed by sum of two lognormal functions which correlated with the path and climatic parameters as expressed in Cheffena et al. (2008). The input parameters are the operating frequency, attenuation, elevation angle and the rain convectivity factor β (0.573), obtained from ITU-R P.837-7 (2017). Crucial parameters that substantially affect the model and thus need to be calculated are mean *ms* and standard deviation *σs* of the lognormal distribution that can best describe the short durations due to scintillation. The mean *mr* and standard deviation *σr* of the lognormal describes long

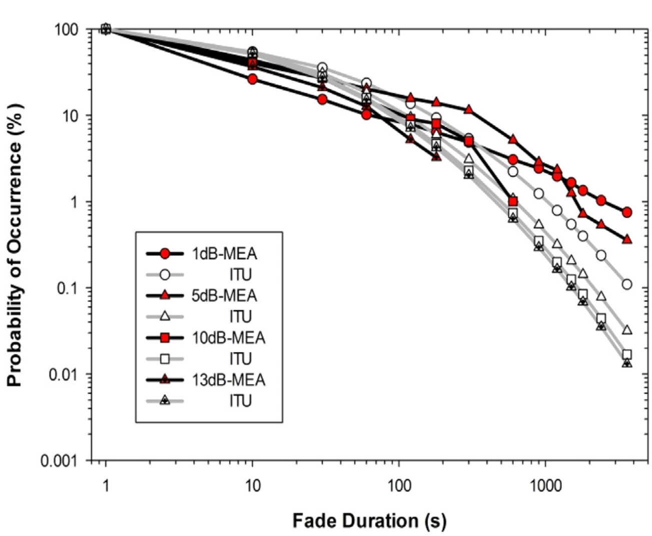

Fig. 4. Comparison of probability of occurrences P(d > D|a > A) between ITU-R model (ITU) and measured data (MEA) for given attenuation thresholds.

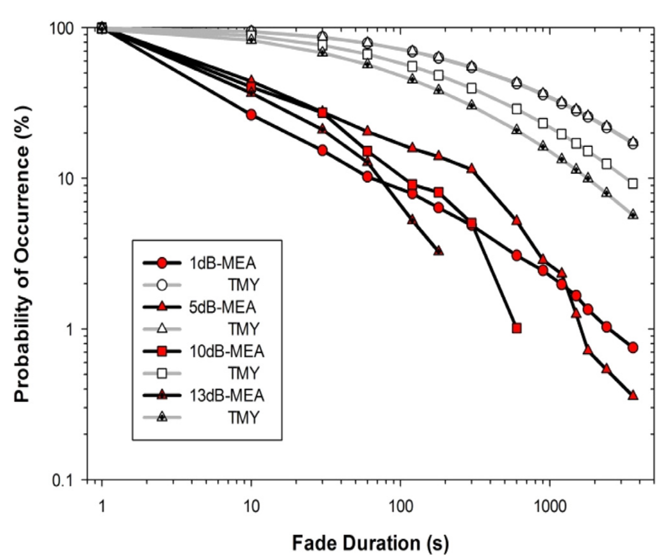

Fig. 5. Comparison of probability of occurrences P(d > D|a > A) between Timothy model (TMY) and measured data (MEA) for given attenuation thresholds.

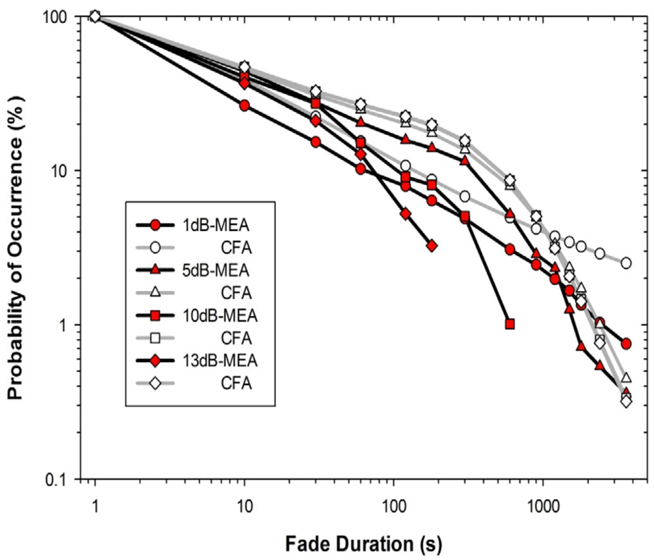

Fig. 6. Comparison of probability of occurrences P(d > D|a > A) between Cheffena-Amaya model (CFA) and measured data (MEA) for given attenuation thresholds.

durations caused by rain, and fraction of fade associated with each lognormal α.

Comparison of probability of occurrence P(d > D|a > A) between Cheffena-Amaya model and measured data statistics for given attenuation thresholds is shown in Fig. 6. In general, the model predicts similar trend to the measured data statistics for given attenuation thresholds. The model relatively overestimates the measured data for all attenuation thresholds. However, the overestimation is substantially lower than Timothy model shown in Fig. 5.

4.4. Modified Cheffena-Amaya model

Most prediction models for fade duration distribution are generally developed by two functions of statistics, e.g. power-law plus lognormal, exponential plus lognormal, and two lognormals. Basically, the functions are defined to cover the fade duration distributions for the short and long duration characteristics. Based on observation, it is found that all prediction models are unable to accurately estimate fade duration distribution of the measured data. Hence, modification to the existing model is recommended to ensure the model suits with the data measured in tropical country i.e. Malaysia.

Based on Fig. 6, although the Cheffena-Amaya model overestimates the probability of occurrence of the measured data, it is deemed to depict a trend comparable to the measured data. Therefore, this model is modified to ensure fit with the measured data. The crucial parameters of Cheffena-Amaya model which are the fraction of fades associated with each lognormal α, mean (*ms* and *mr*) and standard deviation (σs and σr) due to scintillation and rain are recomputed.

Derivation of the parameters α, σs and σr from equations in Cheffena et al. (2008), respectively are investigated by analytical method using one-year measured data. Eq. (2) through Eq. (4) are found to best fit with the measured statistical distribution.

$$\alpha = 0.88 - 0.0266\beta^3 + 0.173\exp(-A/2.61) \quad (2)$$

$$\sigma_s = 1.6462 + 19.8041\exp(-f/3.5) - 1.3671 \cdot 10^{-6}A^3 \quad (3)$$

$$\sigma_r = 0.501 + 2.31 \cdot 10^{-3}f^{1.5} + 3.3637A^{-2} \quad (4)$$

where

f is operational frequency in GHz.
A is attenuation threshold in dB.
β is the rain convectivity parameter obtained from ITU-R P. 837-7, equivalent to 0.573.

The comparison of probability of occurrence P(d > D|a > A) distribution between modified model and measured data for given attenuation thresholds is illustrated in Fig. 7. Curves provided by the modified model has similar trend with the measured data for both short duration (D < 30 s) and long duration. Since the curves of measured data for 10 and 13 dB between 60 and 600 s has lower number of events, no exact conclusion can be derived. However, it is obvious that the predicted curves for 10 and 13 dB follow the measurement trend.

The testing method for comparing fade duration predictions is defined by the logarithm ratio of the predicted probability to the measured probability as proposed by ITU-R P.311–17 (2017). The measured data are tabulated for fixed individual duration D in the range of 1 s to 3600 s and for fixed attenuation threshold A of 1, 5, 10 and 13 dB. Testing variables, namely mean, standard deviation and root mean square (RMS) are calculated according to the attenuation threshold A and duration D. The smallest values of the statistical parameters represent the best prediction. Table 1 shows the results of probability of occurrence $P(d > D|a > A)$ by mean, standard

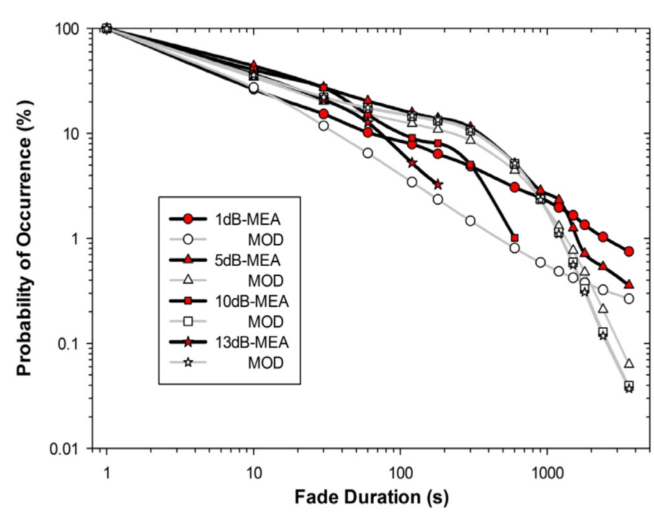

Fig. 7. Comparison of probability of occurrences P(d > D|a > A) between modified Cheffena-Amaya model (MOD) and measured data (MEA) for given attenuation thresholds.

Table 1
Prediction testing variables of $P(d > D|a > A)$ with different models for given attenuations.

Models	A (dB)s	1	5	10	13
ITU-R	Mean	−0.18	−1.07	−0.17	0.11
	Std	1.03	0.87	0.34	0.23
	RMS	1.01	1.36	0.36	0.23
Timothy	Mean	2.40	2.13	1.55	1.23
	Std	0.84	1.21	1.01	0.80
	RMS	2.53	2.43	1.81	1.43
Cheffena-Amaya	Mean	0.66	0.36	0.75	0.67
	Std	0.37	0.31	0.79	0.61
	RMS	0.72	0.45	1.00	0.86
Modified Cheffena-Amaya Model	Mean	−0.79	−0.41	0.40	0.35
	Std	0.51	0.41	0.60	0.50
	RMS	0.97	0.57	0.70	0.57

Table 2
Average prediction error of $P(d > D|a > A)$ for all models.

Model	ITU-R	Timothy	Cheffena-Amaya	Modified Cheffena-Amaya Model
Mean	−0.33	1.83	0.61	−0.11
Std	0.62	0.96	0.52	0.50
RMS	0.74	2.05	0.76	0.70

deviation (Std) and root mean square (RMS) for four models. Each model has different attenuations and average prediction error of $P(d > D|a > A)$ as presented in Table 2. The comparative analysis shows that the modified Cheffana-Amaya model has minimum statistical values (mean, standard deviation and RMS). Hence the modified Cheffana-Amaya model yields best prediction for $P(d > D|a > A)$.

5. Conclusion

Rain fade duration is derived and presented from one year measured data on Ku-band Earth-satellite link in Malaysia. The short duration is mainly caused by scintillation while long duration is consequences of rain. The probability distribution variation of fade duration is almost identical for the given attenuation thresholds. Three distribution prediction models of fade duration are presented and compared with measured data. The ITU-R model predicts the measured data statistics well for short duration except 1 dB attenuation whereas the models underestimated the measured data for long duration. Moreover, Timothy prediction model overestimates the measurement for all durations. On the contrary, the Cheffana-Amaya model predicts similar trend to the measured data statistics and overestimated for both short and long durations. However, the overestimation is significantly lower compared to the Timothy model. Hence crucial parameters of the Cheffana-Amaya are modified to predict the rain fade duration. The results prove that the modified model is in close proximity to the measured data.

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