Fade Slope Analysis for Ku-band Earth-Space Communication Links in Malaysia

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Abstract: Heavy precipitation severely degrades the performance of satellite communication systems operating at frequencies higher than 10 GHz. For the implementation of effective countermeasures, rain attenuation statistics are needed, second order statistics in particular. In this paper, the characteristics of rain fade slope are extensively investigated, exploiting one year of Ku-band attenuation measurements collected in Malaysia.

1. Introduction

Operational frequency of modern satellite communication systems is gradually moving to Ku-band and beyond. Unfortunately, electromagnetic wave propagation at these frequency bands is severely affected by precipitation, especially in tropical and equatorial regions (temperate regions are affected less severely as compared to tropical and equatorial regions). According to [1], system performance degradation frequently occurs at tropical and equatorial regions where the convective events are frequent with a high rainfall rate. This is noticeably evidenced by the map showing 40 years of world mean annual rainfall from the European Centre for Medium-Range Weather Forecasts (ECMWF) databases [2] as shown in Figure 1. The location of this study, Johor Bahru (marked by a red circle), is located at the equatorial region, and the annual rainfall map shows that it has a high intensity of rain with more than 2500 mm of rain accumulated annually. This is verified by the cumulative distribution functions of rainfall rate for few climatic regions, as illustrated in Figure 2. Therefore, to guarantee the requested availability, Fade Mitigation Techniques (FMTs) must be used. For the correct design of FMTs, rain attenuation statistics are needed; first order statistics (such as the cumulative distribution function) are not sufficient, and second order statistics such as fade slope are requested. Information on fade slope is essential, for example, to improve the performance of uplink power control (ULPC) techniques. Several measurement campaigns have been carried out to investigate the statistical properties of fade slope in temperate regions [3-5], while only a few were conducted in heavy rain regions [6]. In this work we investigate fade slope statistics, particularly in terms of seasonal analysis and fade rate by exploiting one year (15 Jan 2013 to 14 Jan 2014) of Ku-band measurement results gathered in Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia. This paper is structured as follows. In Section 2, a brief explanation of the experimental setup and its link characteristics is given. Section 3 presents the dataset collected in UTM and gives details about data quality and

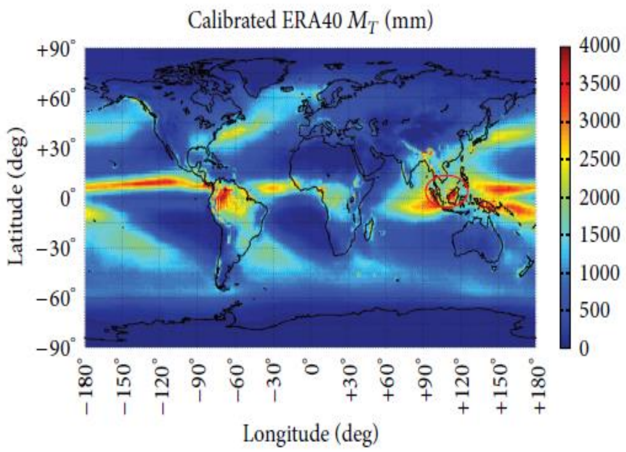


Fig. 1 *Map of 40 years of world mean annual rainfall from ECMWF databases [2].*

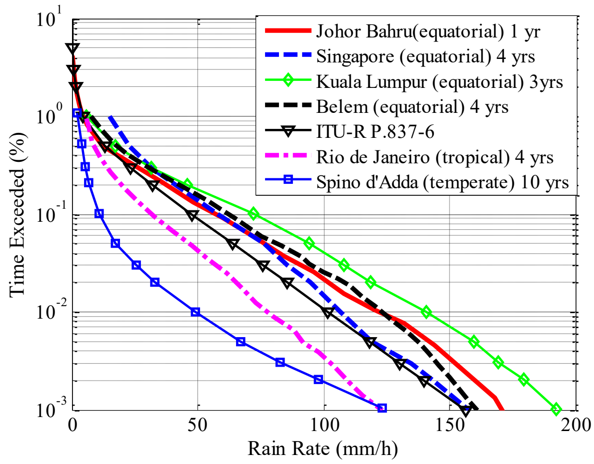


Fig. 2 *Cumulative distribution functions of precipitation rate for three climatic regions: equatorial (Johor Bahru, Singapore, Kuala Lumpur and Belém), tropical (Rio de Janeiro) and temperate (Spino d'Adda) [7].*

availability. Section 4 describes the process of scintillation filtering. Afterward, the fade slope calculation is presented in Section 5. The core of the paper is in Section 6, which analyses the fade slope distributions for different attenuation thresholds and their comparison with temperate regions and an ITU-R prediction model. In addition, analysis on standard deviation of fade slope for different time intervals, seasonal analysis as well as fade rise and fade fall rates are included. Finally, Section 7 draws some conclusions.

2. Experiment Setup and Link Characteristics

Ku-band measurement setup consisted of two pieces of equipment, a direct broadcast receiver and a weather station. The receiver was installed on the rooftop of Radio Communication Laboratory in the campus of UTM, Johor Bahru, situated at 103.64º E and 1.55º N, with a height above mean sea level of 50 m. The direct broadcast receiver was equipped with a 90 cm dish antenna pointed towards the Measat-3 (91.5º E) broadcast satellite, with an elevation angle of 75.61º and 262º of azimuth angle. The block diagram of the measurement setup was described in [8]. Another piece of equipment was the weather station, located at a distance of about 10 m from the receiver in order to obtain simultaneous measurements (which is useful for identification of a rain event). The weather station consisted of a tipping bucket rain gauge and sensors for wind direction, wind speed, temperature and relative humidity. The rain gauge resolution was 0.2 mm/tip with an integration time of 1 minute. The details of rain rate data processing were explained in [9].

The rain in temperate regions is characterized by low intensity and long duration except for some convective rainstorms occurring in summer and autumn. This is completely different from the weather in equatorial regions like Malaysia, where weather is wet and humid all year long. According to the recorded data in 2013, out of 256 rain events, about 63% of them were of the convective type. Convective events are characterised by high-intensity rain and short duration, whereas stratiform rain events are characterized by widespread and low-intensity rain. Monthly classification of rain is shown in Figure 3. This is very similar to the findings in Lam et al. [10] and Tokay and Short [11] in which the percentage of convective rain in equatorial climates is 64% and 68%, respectively. Yearly accumulated rain is 2889.8 mm, and the highest monthly accumulated rain amount that has been recorded is 420 mm during the month of December as depicted in Figure 4. The trend of monthly statistics agrees with the 47 years (1947-1996, excluding 1956 and 1994) of data collected at Kulai, obtained from the Department of Irrigation and Drainage (DID) Malaysia, which is about 15 km from Johor Bahru. This indicates that both locations are within the same climatic characteristics. In addition, the complementary cumulative distribution function of rain rate at 0.01% of time is 121.7 mm/h. Since convective rains are the major rain events in equatorial regions, electromagnetic waves are heavily attenuated (due to scattering and absorption), and this leads to signal degradation or even outage. As far as Quality of Service is concerned, first order statistics of rain attenuation have been reported in [8]. Second order statistics, and in particular the rate of change of attenuation, crucial for the implementation of appropriate fade mitigation techniques, are discussed in Section 6.

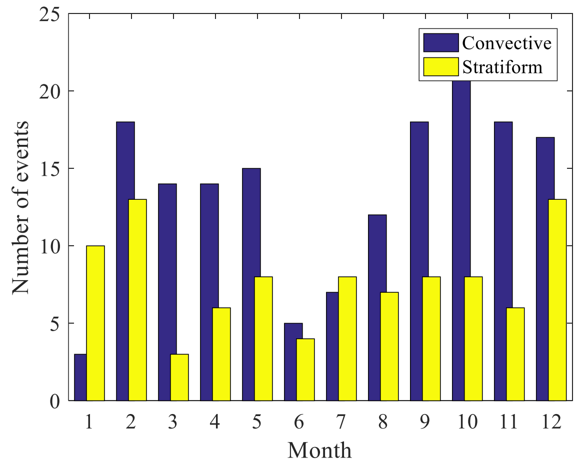


Fig. 3 *Monthly distributions of stratiform and convective rains in Johor Bahru.*

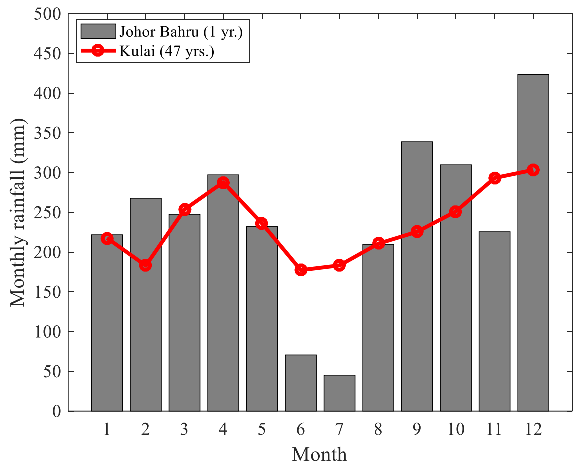


Fig. 4 *Monthly statistics of rainfall rate in Johor Bahru and Kulai spanning over 1 year and 47 years, respectively.*

3. Database Availability

The quality of the recorded data from the propagation measurement campaign was investigated to assess the reliability of the dataset. An index of data availability was computed through the ratio of the recorded data minutes to the total number of minutes during the observation period (the recorded-to-total time ratio, or RTT). In this work, the observation period was one year, and the system experienced very few equipment downtimes with a RTT ratio of 99.27%. Figures 5 and 6 show the monthly and hourly distributions of the RTT ratio, respectively. The availability on a monthly and hourly basis was always greater than 98%, except in February 2013, when the RTT ratio was 96.5%, due to power outage.

4. Scintillation Filtering

The most important tropospheric effects impacting the satellite communication system operating at Ku-band and above are scintillation and rain-induced fade. Since FMTs usually do not cope with scintillation, these two effects must be separated as much as possible before the fade slope analysis. In this work, scintillation was filtered out by using a fifth-order Butterworth low-pass filter. Since stronger scintillation (with larger spectral components at lower frequencies) can be found more frequently in convective events than in stratiform events, to identify the proper filter cut-off frequency, two convective rain events with different attenuation levels were chosen, as shown in Figure 7a (approximately 15 dB) and Figure 8a (about 5 dB). The cut-off frequency f_B of 0.02 Hz was fixed after the power spectral analysis. As can be inferred from Figure 7b and Figure 8b, the power spectral density decreases with a slope of 20 dB/decade up to 0.02 Hz (cut-off frequency); above this frequency, the typical scintillation plateau can be observed up to Nyquist frequency of 0.5 Hz. After filtering the received signal level, rain attenuation events were identified from concurrent time series of rain rate (collected from a tipping bucket rain gauge co-located with the receiver) and further confirmed by observing the Constant Altitude Plan Position Indicator (CAPPI) radar images. Once a rain event was confirmed, a 30-minute margin was taken at the beginning and at the end of the event. Then, five minutes of signal were averaged before the start and end of the event; these two levels are linearly interpolated, and the line became the zero reference level. Subsequently, time series of rain attenuation was calculated as the difference between the received signal level and zero reference level. Details of rain attenuation calculation were described in [12].

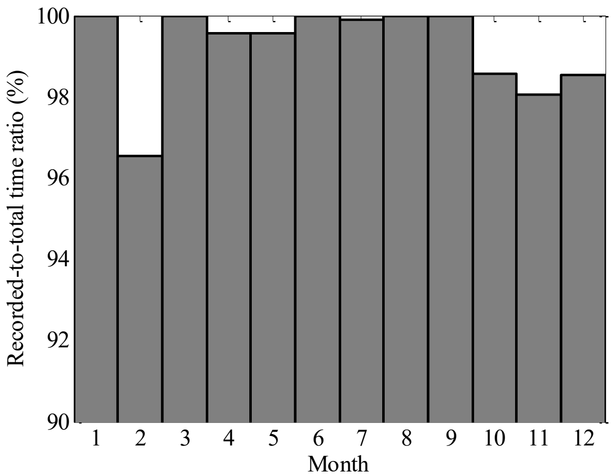


Fig. 5 *Data availability on a monthly basis.*

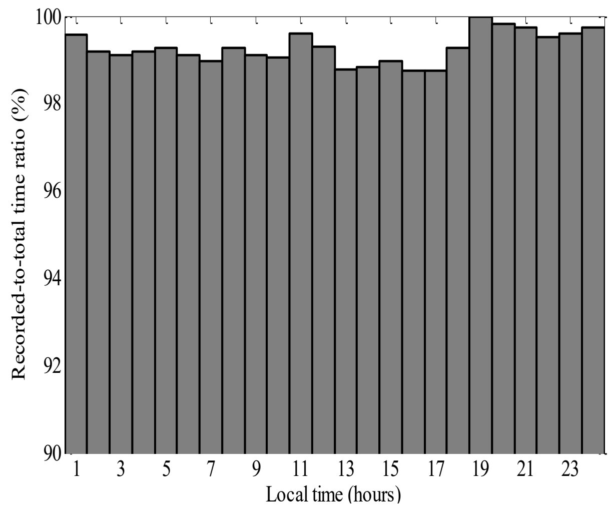
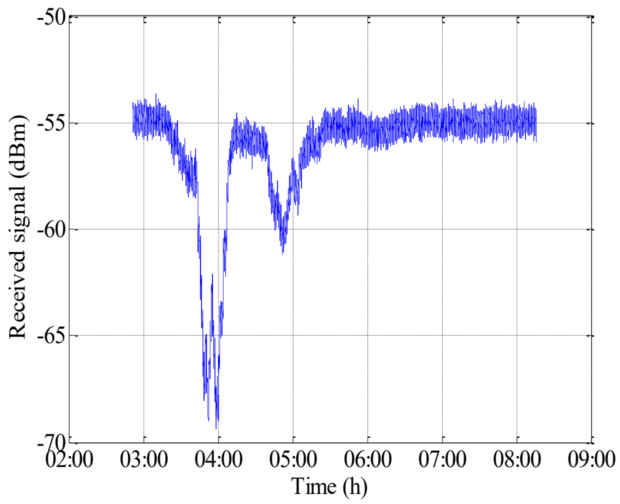


Fig. 6 *Data availability on an hourly basis.*



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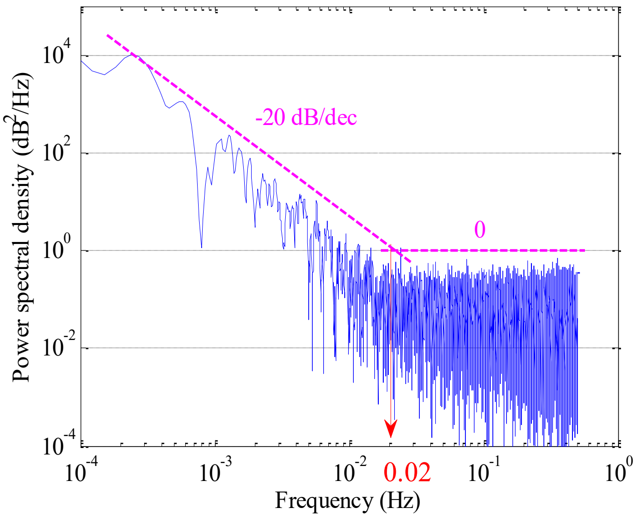

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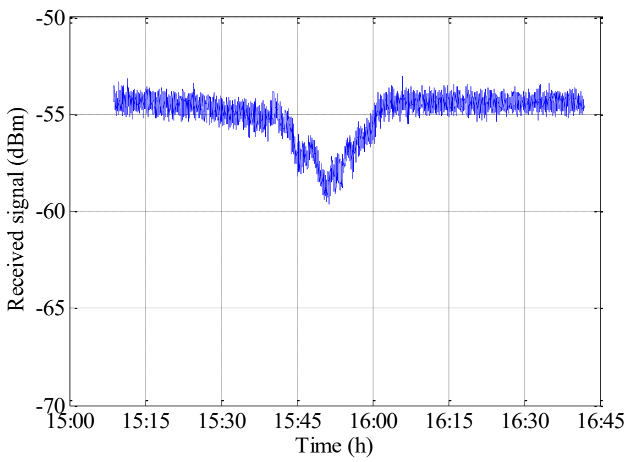
Fig. 7 *(a) Time series of received signal on 4 December 2013, (b) corresponding power spectral density*



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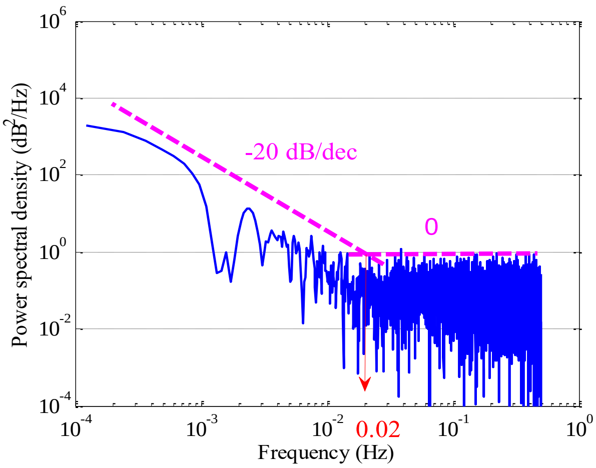

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Fig. 8 *(a) Time series of received signal on 22 March 2013, (b) corresponding power spectral density.*

5. Fade Slope Calculation

Once the attenuation data were extracted, fade slope $\zeta(t)$ (dB/s), was calculated as:

$$\zeta(t) = \frac{A(t+0.5\Delta t) - A(t-0.5\Delta t)}{\Delta t} \qquad (1)$$

where $A(t)$ is the attenuation level at time t, and Δt is the time interval considered to calculate the rate of change. The length of this interval directly influences the slope distribution; large values of Δt, in fact, "filter out" peaks of high attenuation, and this leads to errors in the estimation of fade slope [8], especially in tropical/equatorial regions where most of the rain events are extremely intense with short duration.

Fade slope was calculated at attenuation levels ranging from 0 to 20 dB with 1 dB steps, while the width of the considered fade slope bins was 0.01 dB/s.

6. Results and Discussion

Fade slope distributions strongly depend on data processing and climatic parameters. In this sections, we analyze the measurements collected in Johor Bahru to extract the statistical properties of fade slope, as a function of the different parameters.

6.1. Dependence on Attenuation Threshold

Figure 9 depicts fade slope probability density function (PDF) for attenuation levels equal to 1, 2, 3 and 5 dB and for $\Delta t = 4$ s. It was found that the distributions were nearly (but not perfectly) symmetrical around zero dB/s; moreover, the slope distribution was broader for larger attenuation values. It is common knowledge that fade slope distribution is broader as the attenuation increases. However, the same attenuation value and the same operational frequency might not have the same fade slope distribution if the data are from different climatic regions. This is clearly seen in Figure 10: the slope distribution of Johor Bahru at 12.2 GHz is broader than that of Eidhoven (the Netherlands, temperate climate) at 12.5 GHz. This indicates that the rate of change of attenuation in an equatorial region is generally faster than that in a temperate region, mostly due to the presence of convective rain. This is further confirmed by the number of occurrences of rain events in Johor Bahru: convective rain is absolutely more frequent than stratiform rain as shown in Figure 3.

The main characteristics of the two data sets are given in Table 1. As can be seen, the considerable difference in elevation angle between the two links (75.6º for Johor Bahru and 26.8º for Eindhoven) can have an impact: lower elevation angles correspond to longer path length in the troposphere, and thus to larger averaging effect. In addition, the predictions of the ITU-R 1623-1 model [13] for 2 dB and 5 dB are also shown in Figure 10, for comparison purposes. The ITU-R model matches well with measurements collected in Eindhoven but underestimates the slope distributions collected in Johor Bahru. This might be due to the fact that ITU-R model was developed mainly using data collected in temperate regions and only some data from tropical regions. Therefore, the ITU-R model could be improved by taking into consideration tropical/equatorial data. In our opinion, the prediction of fade slope can be done based on the classification of rain and its attenuation level. Furthermore, the existing ITU-R model is suitable to predict rain attenuation for elevation angles between 5º and 60º, while the measured data in equatorial Malaysia is at an elevation angle of 75.6º. In our opinion, the ITU-R model could be improved to extend the elevation angle range.

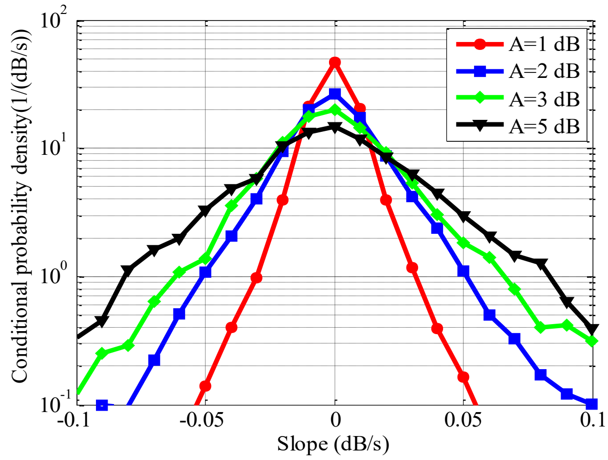


Fig. 9 *Fade slope distributions for different attenuation thresholds in Johor Bahru.*

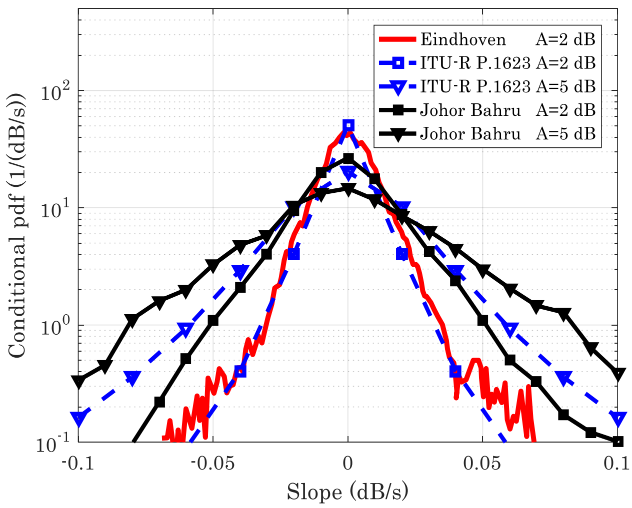


Fig. 10 *Fade slope distributions comparison between Johor Bahru, Malaysia (equatorial), Eindhoven, the Netherlands (temperate) and ITU-R prediction [13].*

Table 1 Parameters for measurement site.

Measurement	Eindhoven (the Netherlands)	Johor Bahru (Malaysia)
Frequency (GHz)	12.5	12.2
Elevation angle(∘)	26.8	75.61
Low Pass Filter	Moving average 20 mHz	Butterworth 20 mHz
Δt (s)	2	2
Sampling time (s)	0.3	1
Data collection period	18 months (Jan 1991–Jun 1992)	12 months (15 Jan 2013–14 Jan 2014)

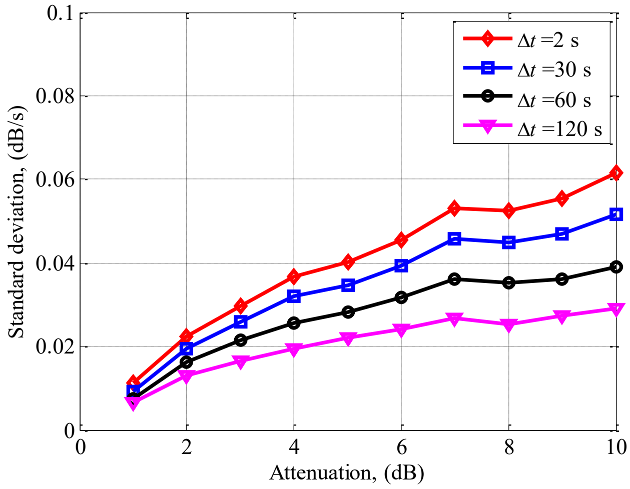


Fig. 11 *Standard deviation of fade slope for different Δt for Johor Bahru.*

In addition, Figure 11 shows the standard deviation of fade slope for different Δt. It can be observed that standard deviation increases with attenuation, since higher rain rates of convective events are associated with higher fade slopes. In addition, standard deviation decreases with the increasing time interval. The effect of time interval on fade slope distributions is stronger in heavy rain regions where precipitations are exceptionally intense with short duration.

6.2. Seasonal Analysis

In case of particular Quality of Service (QoS) system requirements, seasonal statistics could be quite useful [9]. Seasonal variation of rain attenuation in Malaysia depends essentially on wind direction, which, in Johor Bahru, can be classified according to four yearly intervals [10]: December–March, June–September, October–November and April–May with Northeast (NE), Southwest (SW), pre–Northeast and pre–Southwest direction, respectively. October–November and April–May periods are also called inter-monsoon seasons. Figure 12 shows that the standard deviation of fade slope (calculated for Δt = 2 *s*) is almost independent of the

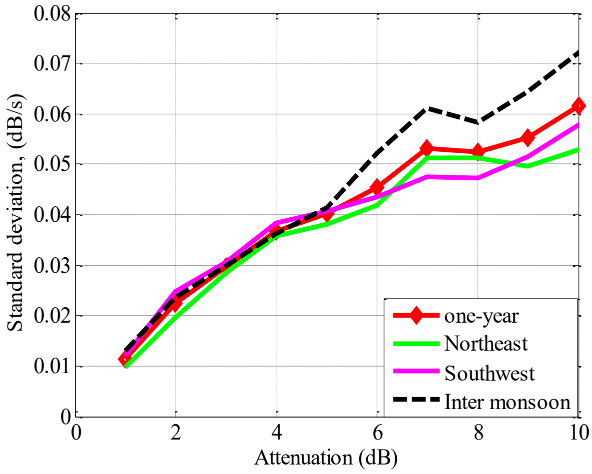


Fig. 12 *Standard deviation of fade slope for each season at Δt = 2s for Johor Bahru.*

Table 2 Type of rain event as collected in Johor Bahru.

Season	Number of rain events	
	Stratiform	Convective
NE monsoon	39	52
SW monsoon	27	42
Inter-monsoon	28	68

season up to about 5 dB of attenuation; afterwards, it is larger for the inter-monsoon season, characterized by a higher number of strong convective activities as shown by the seasonal occurrence of rain types (i.e. stratiform, low intensity and long duration; or convective, high intensity and of short duration) in Table 2.

6.3. Positive and Negative Fade Slopes

As shown in Figures 9 and 10, the fade slope distributions appear to be nearly symmetrical around 0 dB/s. However, Figure 13 evidences that fade rise (positive slope) is generally higher than fade fall (negative slope); this is clearly seen especially at higher attenuation values. This is most likely due to the structure of heavy convective events (high intensity and short duration) that frequently occur in equatorial regions. Unlike the finding in [14], Van de Kamp claimed that fade slope distribution is symmetrical with no sign of asymmetry. On the other hand, Andrew et al. [15], who analysed the rain fade slope for Ka- and V-band, found that the slope distribution is symmetrical only at a smaller slope as shown in Figure 14. However, data for higher slope are sparse and therefore less reliable than lower values of fade slope. Furthermore, both measurement campaigns were carried out in the Netherlands and Southern England, respectively, so they may not be representative of the climate in equatorial regions.

In order to further characterize the structure of convective events that influence the distributions of fade slope, Figure 15a shows the convective type of rain event for a period of about 80 minutes, occurring on 25 February 2013 during Northeast monsoon season. The stratiform and convective rain events are discriminated by the threshold of 10 mm/h of their peak rain rate [16]. The figure also shows that rain rate reached its maximum of 72 mm/h within 18

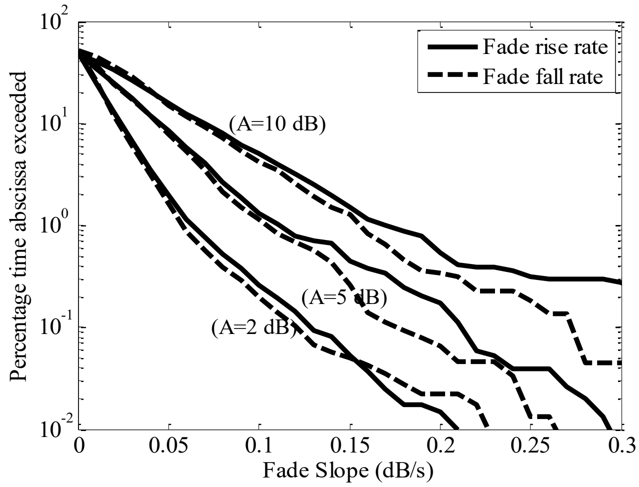


Fig. 13 *Fade rate at attenuation thresholds of 2, 5, and 10 dB for Johor Bahru.*

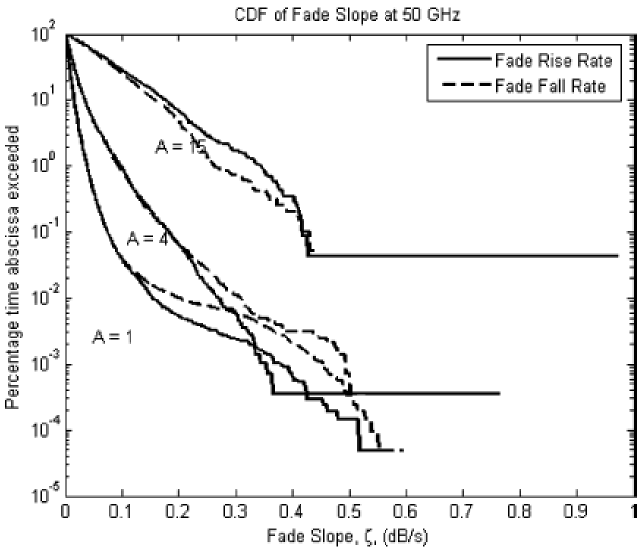


Fig. 14 *Cumulative distribution of fade rise and fade fall rate at 50 GHz [15].*

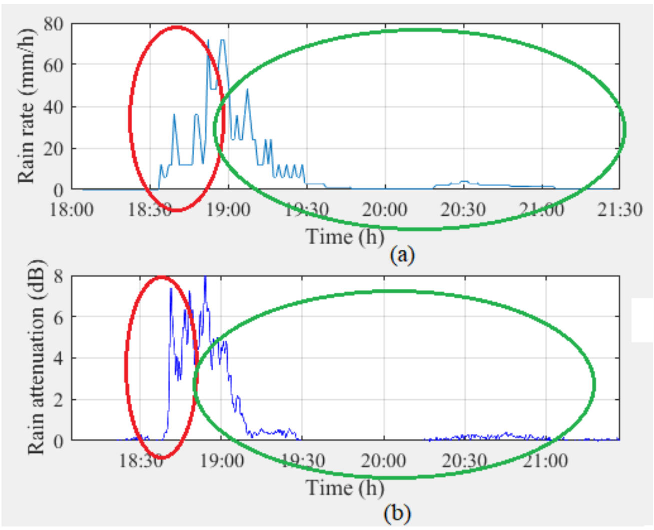
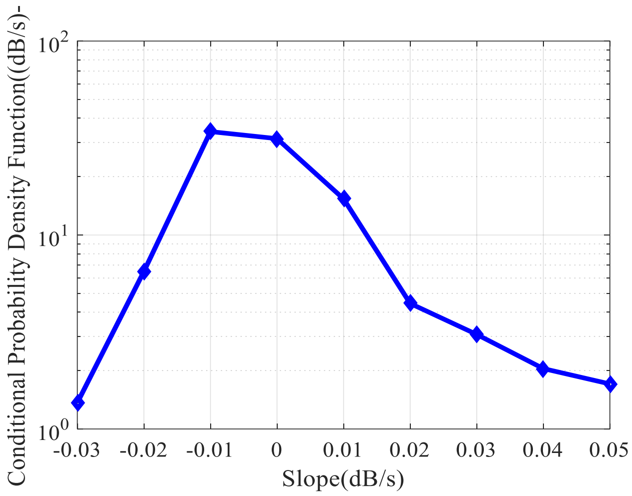


Fig. 15 *(a) Example of convective event in the evening on 25 Feb 2013, (b) the corresponding rain attenuation due to the rain event*



(c)

Fig. 15 (c) the corresponding fade slope distribution at attenuation threshold of 1 dB.

Table 3 Fade slope statistical descriptors for Johor Bahru.

Attenuation	1 dB	5 dB	10 dB
Mean (dB/s)	2×10^{-6}	18×10^{-6}	94×10^{-6}
Standard deviation (dB/s)	0.011	0.040	0.062
Skewness $(dB/s)^3$	-0.122	0.301	0.298
Kurtosis $(dB/s)^4$	27.563	7.693	7.119

minutes but it took three and a half hours for the rain to subside. Figure 15b clearly shows that attenuation rise rate (red circle) is faster than attenuation fall rate (green circle) and causes the asymmetry of fade slope distribution as illustrated in Figure 15c. This information is particularly useful for the response time of uplink power control systems [17].

In order to further characterize the fade slope distribution, we report in Table 3 mean value, standard deviation, skewness and kurtosis of the fade slope. The positive skewness indicates that the distribution is asymmetric towards positive value. On the other hand, as attenuation increases, the fade slope distribution tends to become flatter as indicated by the decreasing value of kurtosis.

7. Conclusion

This work investigated the characteristics of precipitation fade slope for Ku-band satellite communication systems in equatorial Malaysia. Yearly accumulated rain is 2889 mm and 63% of precipitation events are convective type, which are frequent during the inter-monsoon season. Prior to fade slope analysis, the scintillation effect was filtered out using 0.02 Hz of fifth-order low-pass filter. The PDF and standard deviation of fade slope have been analysed. The results show that broader slope distribution and high values of standard deviation are associated with higher attenuation levels, due to convective rain. However, this is quite different from temperate regions where the rate of change of attenuation is slower than in equatorial regions. The ITU-R model that was developed based on a temperate region dataset seems to underestimate the fade slope distributions in tropical regions. In our opinion, the model could be improved by adopting tropical and equatorial data and by extending the elevation angle range. Moreover, it is found that slope distribution is not symmetrical at 0 dB/s. Fade rise rate is usually higher than fade fall rate during heavy convective events. Such information is particularly essential to apply appropriate FMT during this critical season.

The authors are well aware that one year of data is the bare minimum to produce meaningful statistics; on the other hand, the authors are also convinced that conditioned statistics (e.g. fade slope conditioned to the attenuation threshold) are more stable for their own intrinsic nature (e.g. it is less probable that fade slope distribution conditioned to the same attenuation threshold changes a lot from one year to the other, even if the probability of such attenuation values can vary substantially). As a logical next step, future data that includes a few years of dataset and annual variability shall be published in the future, after duly processing and analysis that requires some time.

8. Acknowledgments

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