Journal of Atmospheric and Solar-Terrestrial Physics 73 (2011) 601–610

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Rain induced attenuation studies for V-band satellite communication in tropical region

Khairayu Badron [a,*], Ahmad Fadzil Ismail [a], Jafri Din [b], Abd.Rahman Tharek [b]

[a] Department of Electrical and Computer Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Jalan Gombak, 53100 Kuala Lumpur, Malaysia
[b] Faculty of Electrical Engineering, Universiti Teknologi Malaysia, Malaysia

ARTICLE INFO

Article history:
Received 4 May 2010
Received in revised form
2 December 2010
Accepted 2 December 2010
Available online 19 December 2010

Keywords:
Rain attenuation
V-band satellite communication system
Fade duration
Inter-fade interval
Tropical region

ABSTRACT

Satellite communications operating at 10 GHz and above in the tropics suffer severe signal degradation due to rain. Attenuation due to rain at 38 GHz had been measured for a period of 20 months in Malaysia. Analyses carried out include seasonal variations, diurnal effects and the annual cumulative distributions. Obtained results were compared with several established prediction models including the ITU-R. The rain fade characteristics were also investigated in determining the levels of signal loss and fading. In addition, the studies highlight several potential fade mitigation techniques that can be embarked. These fundamental aprehensions are very critical for future earth space communication link design and can be exploited as preliminary groundwork plan for the researchers as well as engineers.

1. Introduction

There have been restrained usages of 10 GHz and above satellite links for commercial operations in tropical countries. This is mainly due to severe rain attenuation. Attenuation experienced in these areas is caused by considerably higher rainfall rates and bigger size of raindrops compared to other parts of the world (Maki et al., 2001). Future and existing satellite operators in the tropics may soon have no other alternative but to use frequencies even as high as the V-band due to limited frequency spectrums (Ippolito, 2008). The effects of rainfall on satellite signals at these high frequencies in the tropical regions have not yet been fully detailed. Additional measured data, experiments, analyses and investigations are considered very crucial in order to obtain more insights in these areas. The databases from a measurement campaign in Johor Bahru, Malaysia, provide invaluable opportunities to examine the V-band propagation characteristics. The established microwave link should be able to provide some preliminary critical thoughts of a V-band link's characteristics in the absence of an actual satellite–Earth link. The information is considered very pertinent for the design of future earth space communication link. In tropical region like Malaysia, excessive rainfall is a frequent phenomenon throughout the year. The awareness of the rain fade at the desired frequency of operation is a critical necessity for the design of a reliable terrestrial and/or earth space communication links. It is of utmost important to be able to predict accurately the possible impairment that to be encountered on a given link. This will enable operators to cost-effectively plan their services. It is significant that such data as these should be used in determining the expected user acceptance of the new Digital to Home (DTH) and the Very Small Aperture Terminals (VSAT) services. Early appreciation for the variations in service quality over monthly and hourly phase may also allow the service provider to adjust the dimensioning of the link with the month and/or hour.

The measured and predicted values of signal loss can be used as parameters in the fade mitigation design. The implementations of fade mitigation techniques such as diversity, power control, coding and resource sharing should be taken into concern. Power adjustments are based on either a satellite beacon or a pilot carrier transmitted from the Earth station (Thomas, 1977). The transmit power modification can be done to compensate the differences between the beacon or pilot carrier and the uplink carrier. Incorporated carrier monitor verifies and refines the power adjustments for 'loopback' carriers. The downlink carriers that are visible at the uplink Earth station can be demonstrated in Fig. 1. New link adaptation techniques include the ability to adapt the appropriate modulation scheme and coding, according to the quality of the radio link. The performance of a special Adaptive Modulation and Coding (AMC) (Abdullah et al., 2008) scheme depends on how accurate the prediction of the channel condition. Obtained information i.e. the fade duration experienced within an established link can be a possible foundation of a wireless channel behaves in the tropics. Fig. 2 below shows the block diagram portraying the idea of

* Corresponding author. Tel.: +603 61963319, 60132167553; fax: +60361964488.
E-mail addresses: khairayu@iiu.edu.my, khairayu@gmail.com (K. Badron).

1364-6826/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jastp.2010.12.006

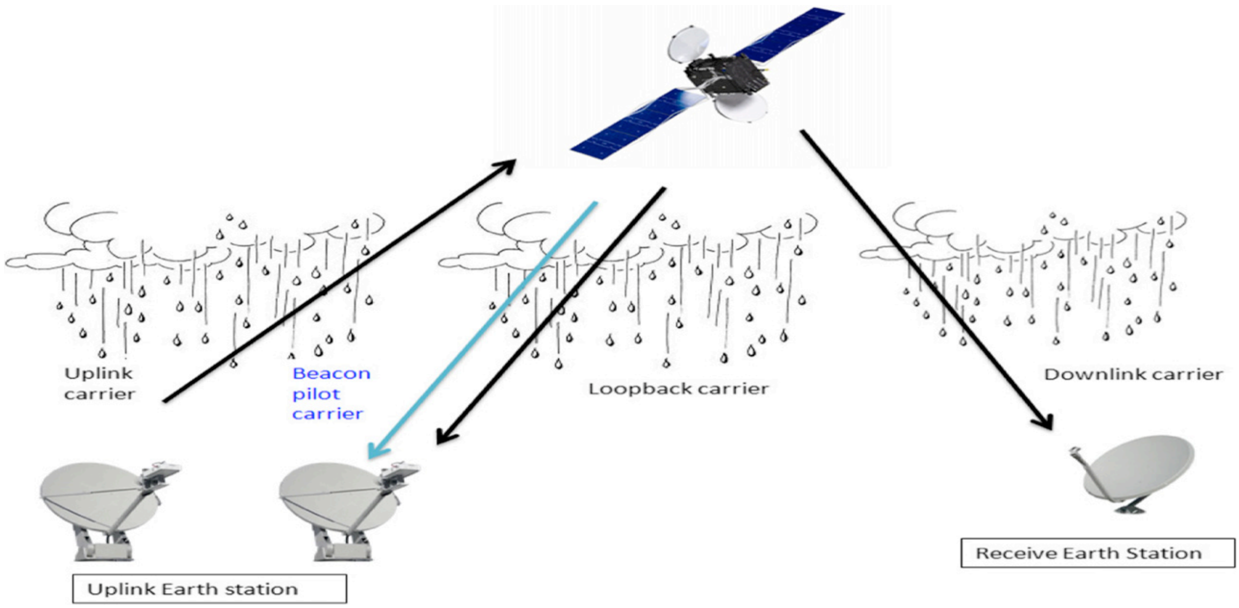

Fig. 1. Schematic of a satellite uplink power control (Thomas and Baltimore, 1977).

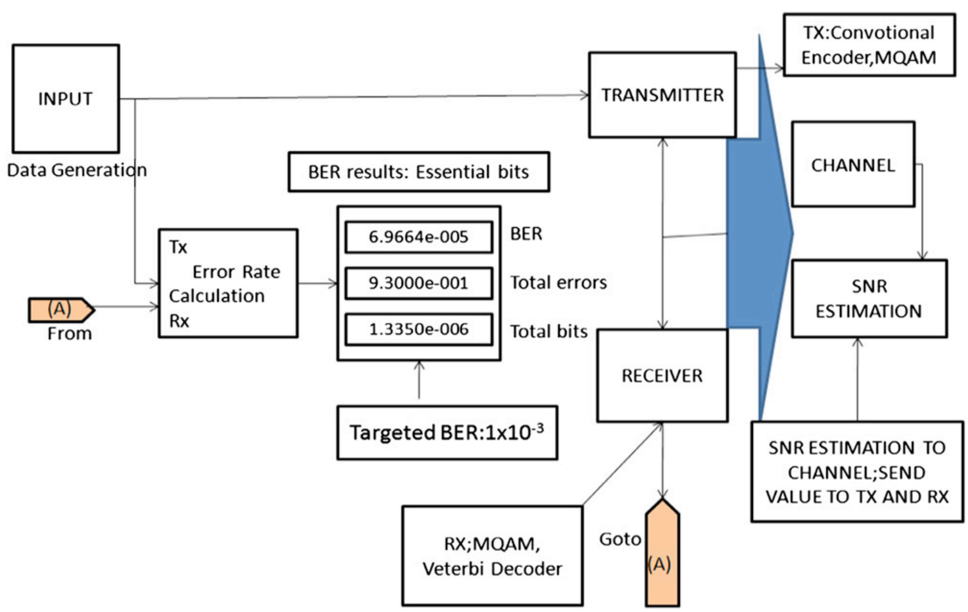

Fig. 2. Block diagram of a adaptive modulation coding (AMC) (Abdullah et al., 2008).

how to apply the analysed fade duration values in fulfilling the appropriate AMC codes depending on how much attenuation is detected at a certain point.

2. Experimental set-up

A 38 GHz experimental Ericsson MINI-LINKS was installed in 1998 at Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia. Two 0.6 m diameter antennas with horizontal polarisation covered by radomes were installed. The antennas were placed 300 m apart from one another. The transmitter was mounted on a tower situated at 103° 38′ 49″E and 1° 33′ 34″N. The receiver was situated on a building roof-top at 103° 38′ 54″E and 1° 33′ 34″N. The line of sight of the link was at approximately 18 m above sea level (ASL). A computer equipped with a data acquisition card was interfaced to the automatic gain control (AGC) output level of the RF unit. Data were sampled at every 10 min during clear sky condition. During rainy state, they were sampled at every second. Fig. 3 below illustrates the measurement set-up. Fig. 4 portrays a recorded rain attenuation event on July, 5 1999. From January 1999 to September 2000, 20 months of good quality data were recorded in total. Maximum recorded attenuation was measured at 40 dB within the period of measurements. The data allow the study of annual, diurnal, seasonal effects, fade characteristics as well as evaluation of prediction models applicability.

3. Analysis and result

3.1. Seasonal effects observed in Malaysia

The concept of four seasons such as Spring, Summer, Autumn and Winter is not applicable in a tropical country such as Malaysia. It is

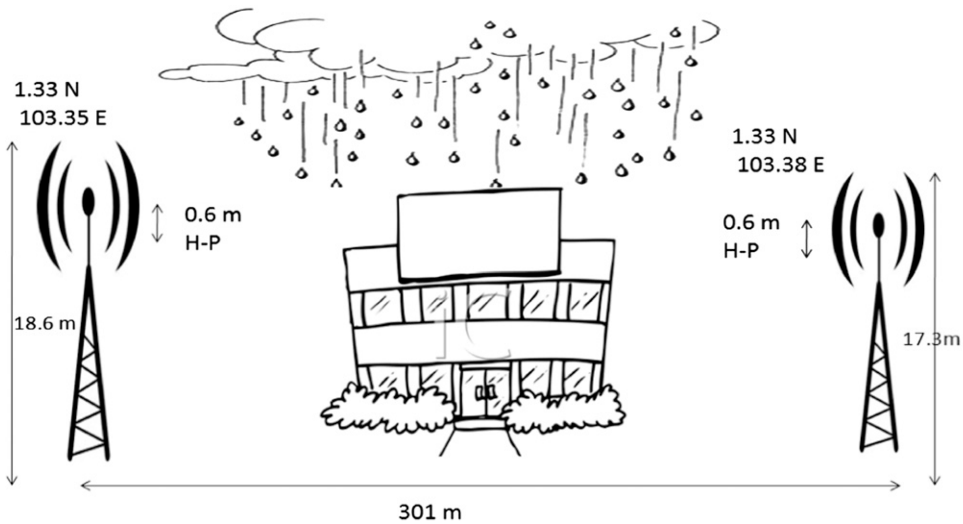

Fig. 3. Experimental set-up for 38 GHz frequency at Malaysia.

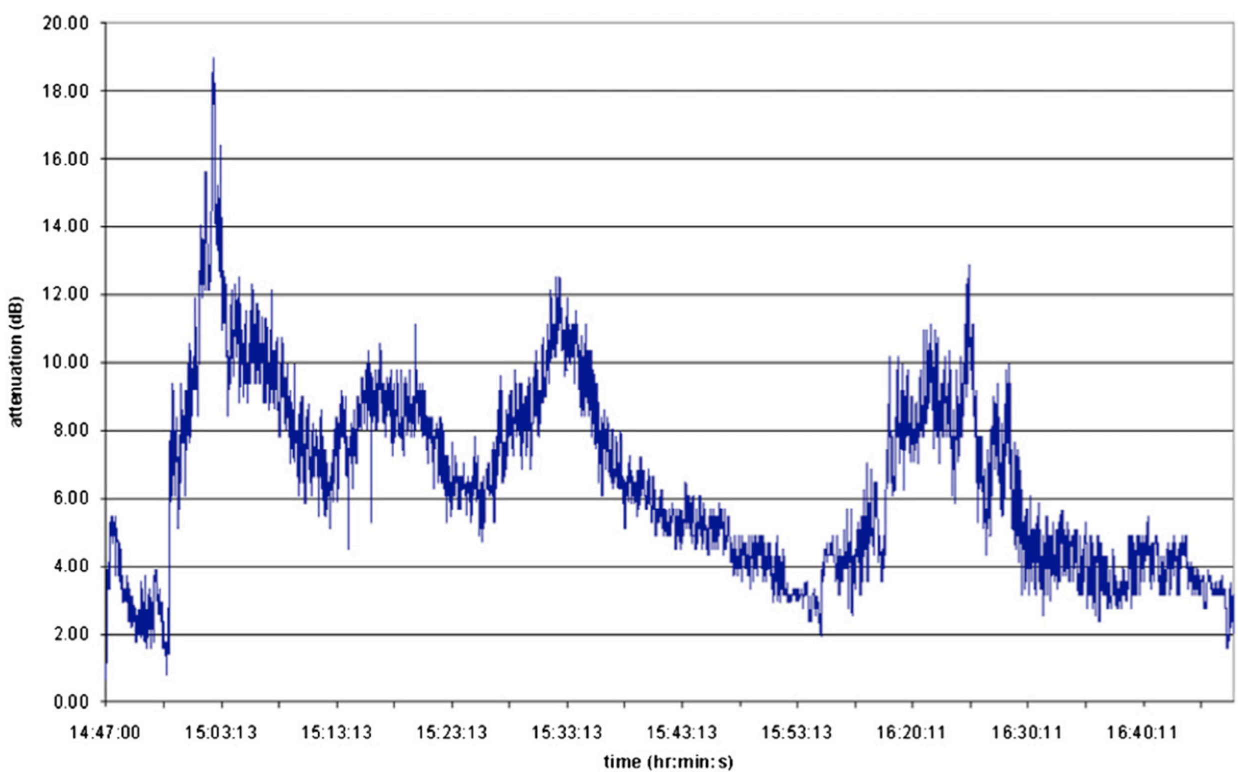

Fig. 4. Typical time series record of attenuation.

more common for a place in the tropics to be experiencing what is considered as 'wet' and 'dry' seasons. The long term seasonal effects perhaps cannot yet be concluded due to limited data. The monthly rain attenuation distributions are represented in Fig. 5. The attenuation distributions were calculated for each individual month. It was observed that the measured attenuation in October 1999 substantially exceeded measurements observed in most other months at all percentages of time within the period of the first twelve months. It can be concluded that the month of February 2000 was subjected to the most rain fade for most of the time fraction within the subsequent next twelve months. In principal, attenuation is very much depended on the intensities of the rainfall. Most locations in Malaysia should show some seasonality from the effects of the south west monsoon bringing higher rainfall intensities in months around March (Ismail and Watson, 2000). Similar nature of seasonal behaviour was also reported in Singapore (Ong and Zhu, 1999). Meteorology Department of Malaysia also reported that rainfall rates at the south-west coast of peninsula Malaysia; which is where UTM is located is normally affected by the Sumatran monsoon (Badron and Ismail, 2009).

3.2. Diurnal effect observed in Malaysia

Annual cumulative distributions of rain induced attenuation can generally suggest the required overall link margin for a satellite service. However, it does not offer any information into the potential variations of service degradations caused by propagation effects that present over smaller intervals of time. Details

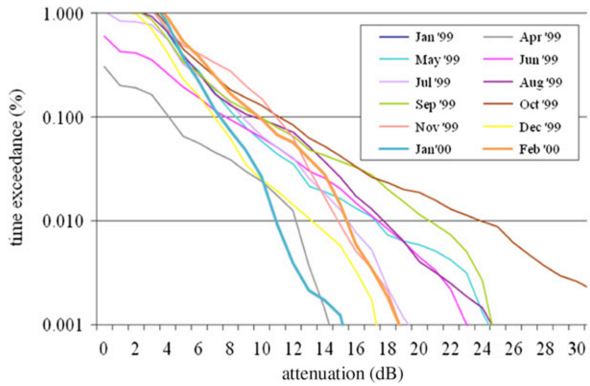

Fig. 5. Monthly CDF of rain attenuation at 38 GHz frequency for year I.

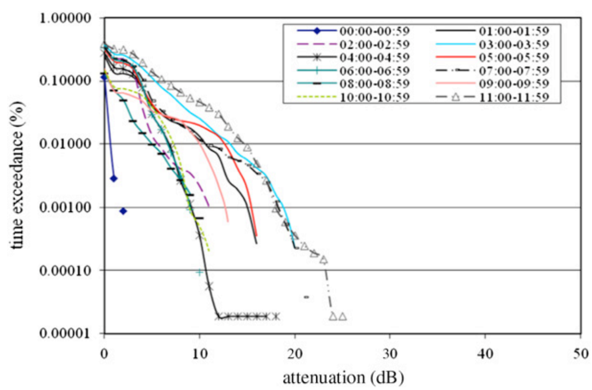

Fig. 6. Diurnal variations of rain attenuation at V-band frequency for first 12 h.

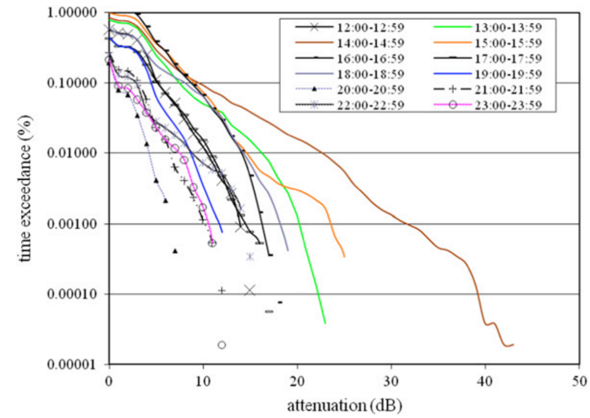

Fig. 7. Diurnal variations of rain attenuation at V-band frequency for next 12 h.

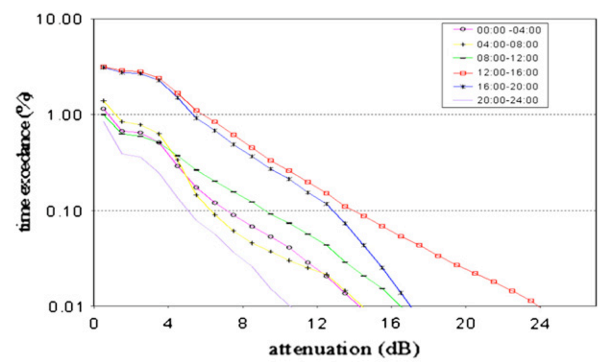

Fig. 8. Diurnal variation of beacon attenuation.

information is required about the likely impairments to be encountered on a link in designing an improved satellite–Earth system. Finer temporal details at the seasonal, monthly and diurnal levels had to be researched in such attempt. The cumulative distributions of attenuation for specific hours of day at every hour are shown in Figs. 6 and 7 below. From the evaluation carried out for every 1 h time interval, it can be seen that severe signal degradations are most likely to occur between 14:00 and 15:00. Substantial less attenuation was observed in the same figure during the early morning hours from 00:00 to 04:00.

Investigations were also carried out to determine the diurnal variability of signal losses due to precipitation experienced at the site for every four-hour interval. The following presented results can be the basis for both the determination of satellite link availability and the development of fade countermeasures in reducing communication link outages.

The cumulative distributions of attenuation for specific hours of day at interval hours [00:00, 04:00], [00:04, 08:00], [08:00, 12:00], [12:00, 16:00], [16:00, 18:00], [18:00, 24:00] are presented in Fig. 8 below. It can be observed that severe signal degradations are most likely to occur between 12:00 and 16:00 from the inspections carried out at every 4 h time interval. It can be assumed that this is due to the weather condition during the mentioned time period, similar to previous investigation in Malaysia by Watson et al. (1998). Considerable less attenuation can be seen in Fig. 8 during the [04:00, 08:00] and [20:00, 24:00] intervals. This complies to the low rainfall rates measured by the previous investigators (Watson et al., 1998) indicating that rain events are quite rare in the early morning time

The probability of specific threshold of attenuation is exceeded for specific hours of day at interval hours [00:00, 04:00], [00:04, 08:00], [08:00, 12:00], [12:00, 16:00], [16:00, 18:00], [18:00, 24:00] are presented as a line chart in Fig. 9 below. Considerable less attenuation is observed during [00:00, 08:00] and [20:00, 24:00] intervals compared to the [12:00, 16:00] and [16:00, 20:00] intervals. The information is critical because demands are normally very high for broadcasting services at peak hours i.e. 12:00–20:00.

3.3. Annual cumulative distributions of path attenuation

Cumulative distributions are one of the most appropriate presentation formats for link designers. Link availability or exceedance at a point can be recognised from the annual cumulative distribution. Thus, acquired rain induced attenuation values can be included into the system margin in the attempt to attain the desired link performance. The cumulative distributions of measured rain attenuation at 38 GHz transmission in the first year and the extrapolated two years had been obtained through analyses and research works. Fig. 10 shows the cumulative distributions of measured rain attenuation with different percentages of time for the year 1999, 2000 and average of the two years. For the two years average it can be viewed that as high as 16 dB attenuation is experienced at 0.01% exceedance. Baring in mind that the data shown is only for mere distance of 300 m and the attenuation would definitely be higher for a typical satellite–Earth path in tropical region which is at about 5.2 km link.

3.4. Comparison to other prediction models

Predicted statistics proposed by various investigators including the ITU-R are reproduced in Fig. 11. The latest ITU-R Recommendation P.618-9 (ITU-R P.618-9 2007) proposes that the estimated attenuation for the range 0.001–5%, time exceedance can be determined from the extrapolation of attenuation at 0.01% such

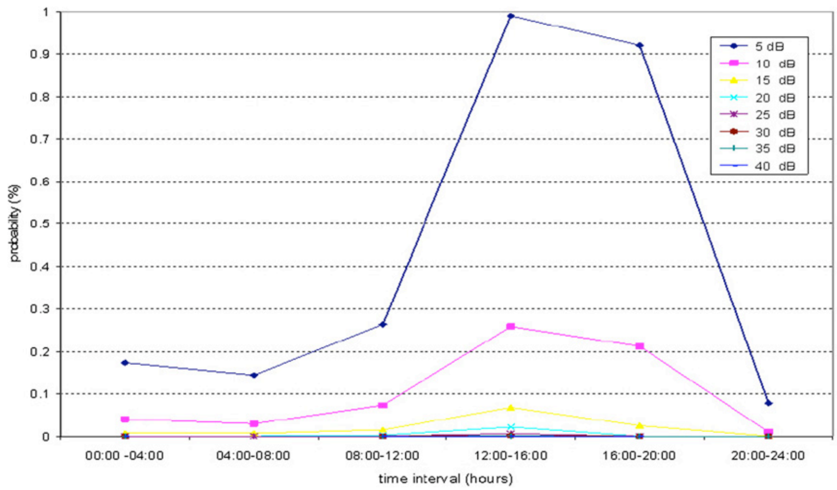

Fig. 9. Probability of specific threshold of attenuation is exceeded.

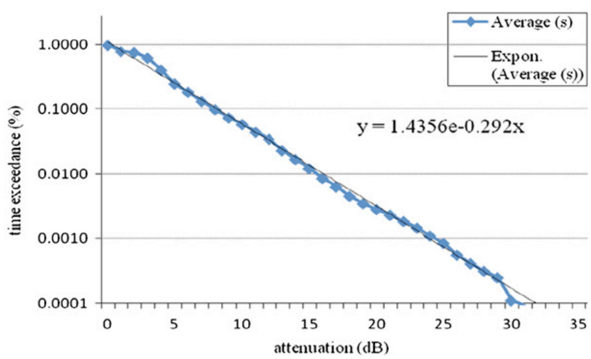

Fig. 10. Cumulative distribution of measured rain attenuation data.

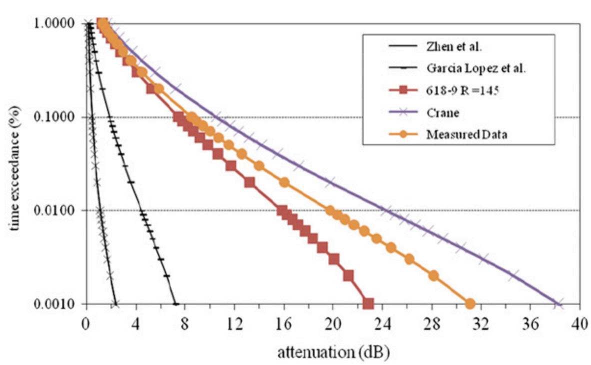

Fig. 11. Measured and predicted statistics of attenuation for extrapolated two year period using various methods of predictions.

listed below

$$A_p = A_{0.01}\left(\frac{p}{0.01}\right)^{-(0.655+0.033\ln(p)-0.045\ln(A_{0.01})-\beta(1-p)\sin\theta)}\ \text{dB} \tag{1}$$

For Malaysian environment, where $p<1\%$ and $|\varphi|<36^{\circ}$ and $\theta \geq 25^{\circ}$

$$\beta = -0.005(|\varphi|-36) \tag{2}$$

Comparisons are also made against a scaled-up 5.2 km V-band link (Badron et al., 2009) that is plotted in the same graph. The illustration offers basic indication of each prediction models' practicability as they are compared against the data collected in Malaysia. The figure indicates that most prediction models under estimate the measured attenuation except from Crane (1990). Crane had proposed a very high rain intensity of 209 mm/h to be used in his prediction model. The ITU-R 618-9 Recommendation seems to give good approximation values similar to those of measured for time exceedance greater than 0.01%. A deviation of 0.6 dB is observed between the measured data and ITU-R predicted value at 0.01% exceedance and the differences are even greater at lower percentages of time. Zhen et al. (2007) and Garcia Lopez et al. (1998) predictions underestimate the measured data. At 0.01% time exceedance, the differences are about 8 and 13 dB, respectively.

3.5. Fade duration and inter-fade duration analysis

Fade duration statistics are usually regarded as conditional distributions of the number of fades exceeding certain durations, given that a specified fade threshold has been surpassed. Fig. 12 displays the statistics of fade duration of rain induced attenuation measured at 38 GHz transmission frequency for 20-month period. According to ITU-R P.1623-1 (2005) the mean duration, D_0 of the log-normal distribution of the fraction of fading times given the attenuation is greater than A is

$$D_0 = 80\varphi^{-0.4} f^{1.4} A^{-0.39} \tag{3}$$

where; f: frequency (GHz), φ: elevation angle (degrees), A: attenuation threshold (dB)

This representation offers information on the number of outages and system availability due to propagation on a link. The average fade duration for a given fade level can be calculated from the accumulated time at that fade level divided by the number of events that occurred at that fade level. Whereas, inter-fade interval is the duration between the fade threshold goes back to the same level of the thresholds. Since the interval between fades of a given level can be calculated as the inter-fade duration, that is the complement of the fade duration, the average inter-fade interval can also be configured. Fig. 13 below illustrates the features commonly used in characterizing precipitation events. The corresponding average fade duration and the inter-fade interval as the function of fade depth on a 38 GHz link are portrayed in Fig. 14. The analyses of the data suggest that the average fade duration might be inversely proportional to the fade depth. This is contrary to previous reported studies by Pan and Allnutt (2004), Ayama and Nguyen (2005) and Fukuchi et al. (2000) where there were no obvious relationships between these two parameters.

There seems to be no noticeable relation for higher fade thresholds. Fade duration and inter-fade interval of the link can be characterised

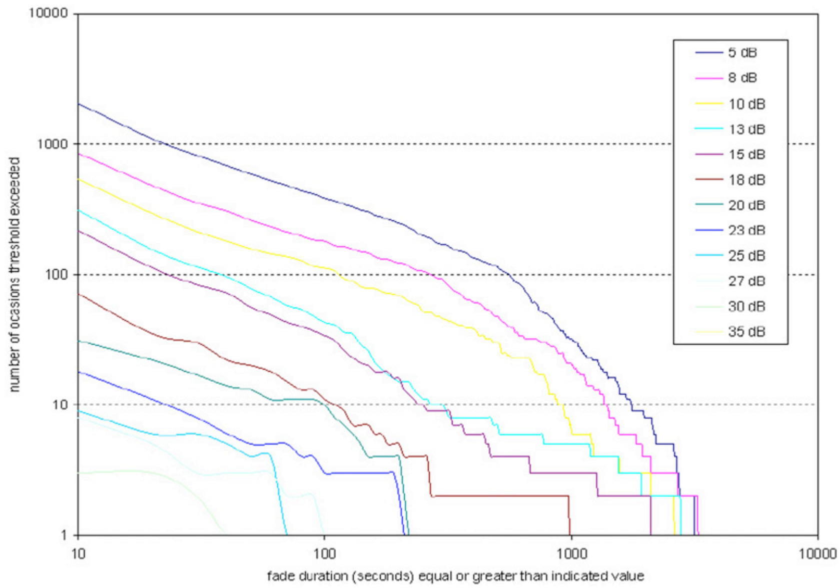

Fig. 12. Statistics of fade duration of rain induced attenuation measured for 01/99–10/2000.

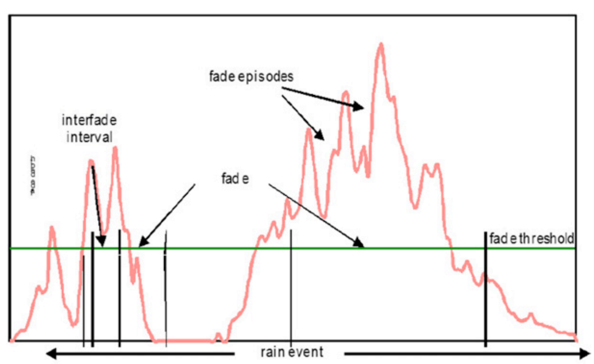

Fig. 13. Features commonly associated characterizing precipitation events.

in the below Eqs. (4) and (5)

$$t_{fd} = -0.11A + 4.0005 \quad (4)$$

$$t_{if} = -0.0263A + 2.3707 \quad (5)$$

where t_{fd} is the fade duration, t_{if} is the average inter-fade interval and A is the attenuation that varies during rain events.

The attenuations exceeded for 99.7%, 99.9% and 99.99% of the average year are reported in Table 1 and compared with data from other sites.

3.6. Daily concentration of events

Combining the knowledge of the fading duration, number of occasions when the threshold is exceeded and the time of occurrence, the daily diurnal distribution for any specific fade level have been produced. Fig. 15 shows the daily distribution of attenuation events exceeding 10 dB at Johor Bahru, Malaysia.

The events appear to be concentrated between late afternoon and early hour of the day at the earth station site with duration tending to be less than 1 min. The late afternoon diurnal distribution between 12:00 and 16:00 h in Johor Bahru, Malaysia has more than two fade duration modes as evidence of long lasting heavy rainfall events occurring evenly during the year. Fig. 15 is reproduced as Fig. 16 below for easier observation. This is a typical characteristic of equatorial climate as observed from similar results procured at another location in Brazil (Pontes et al., 2005). It is of particular interest to acquire detailed information concerning the conditions during which the satellite–Earth links are most impaired for the development of the fade countermeasures.

3.7. Worst-month rain statistics for tropical V-band fading

The worst month statistics information is also critical to the designers of wireless telecommunication systems. The ITU description of 'worst' month deals with the situation where accumulation of an outage in just one month has worse effect than the accumulation distributed throughout the year on a transmission link. ITU-R P.618-9 states the procedure that can be employed to estimate the attenuation exceeded for a specified percentage based on the average year probability p. This is applicable in situations when system planning involves the attenuation value exceeded for a time percentage p_w of the worst month. The 'worst month' can be recognised literarily by comparing individual monthly distributions. ITU (ITU-R P.581-2, 1990) proposed that the fraction of time during which a pre-selected threshold is exceeded in the worst month of a year is referred to as 'the annual worst-month time fraction of excess'. In other words, the probability distribution

P_{wm}=Probability that $s > s$ in the worst month period of the average year is the ITU-R definition of 'average annual worst month', where s is the random variable in question such as rain intensity or attenuation and s is a chosen threshold for exceedance measured (Watson, 1997). The concept of 'worst month' statistics was led by condition where it has always recognised by ITU that the average yearly exceedance of cumulative distribution may be irrelevant in illustrating the variability of attenuation from month to month, season to season or year to year. Hence, it is apparently worthwhile to take into account the occurrence of pronounced monthly or seasonality of a specific region.

This section reports the study of the worst month rain induced attenuation statistics for a tropical environment. It is a continuation from the monthly variability analyses discussed in Section 3.1 earlier. The measurements of attenuation recorded at every 1 second's integration time using the MINI-LINKS measurements set-up were utilised to derive the annual worst month statistics and its relationship with the average annual distribution. The relationship between

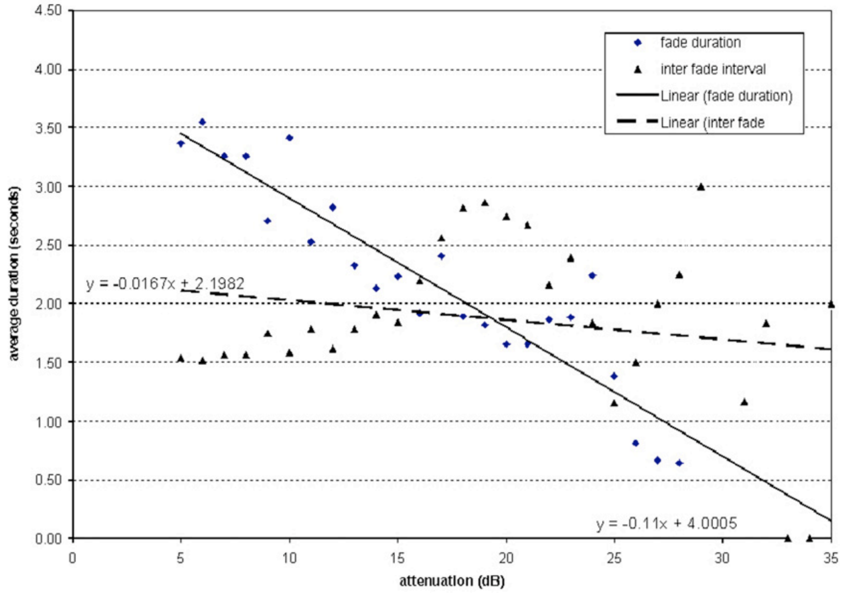

Fig. 14. Average fade duration and inter-fade duration for 38 GHz link.

Table 1
Comparison of measured annual cumulative statistics of slant path attenuation measured at V-band.

Site	Elevation (°)	Period of measurement (year)	Attenuation exceeded for specific % times (dB)		
			0.3%	0.1%	0.01%
Johor Bahru, Malaysia (Badron et al., 2009)	77.4	'96–'98	13	16	22
Nigeria, Abakaliki (Otomosho and Oluwafemi, 2009)	50.7	'91–'00	11	39	125
Rio De Jeneiro, Brazil (Pontes et al., 2005)	53.5	'87–'05	20.1	24.5	30.8
Milan,Italy (Fiebig and Riva, 2004)	4.8	'91–'01	11.5	20	42
Munich, Germany (Fiebig and Riva, 2004)	34.8	'91–'01	9	16	42
Athens, Greece (Panagopoulos et al., 2004)	30	'03	12	19	46

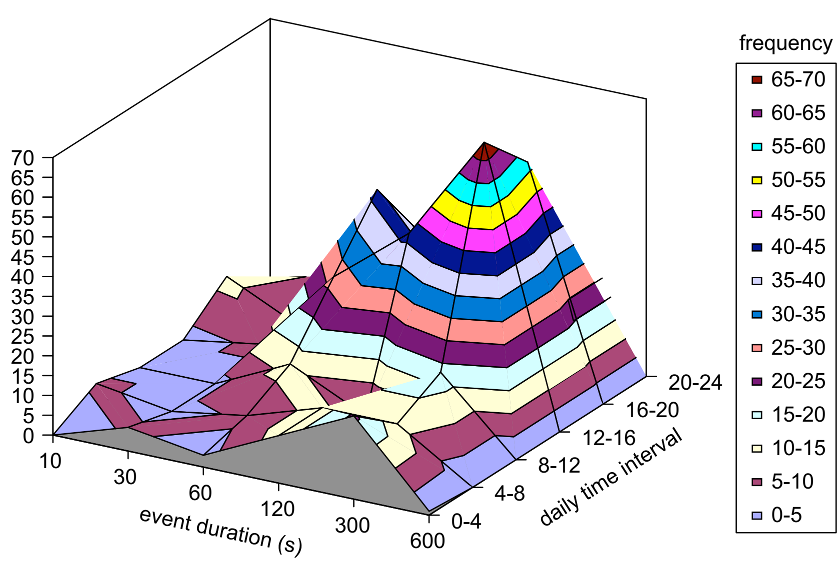

Fig. 15. Illustration of diurnal concentration at 10 dB threshold based on 20 months data (number of events).

the measured worst month and the yearly probabilities was studied and evaluation was made against the ITU-R model. New values for the parameters Q_1 and β were derived based on measurements in Johor Bahru, Malaysia.

The research emulates the recommendation of the ITU-R P581-2 (1990) where the definition for worst month statistics that applies to rain induced attenuation. The annual worst month for a pre-selected threshold is defined as the month with the highest

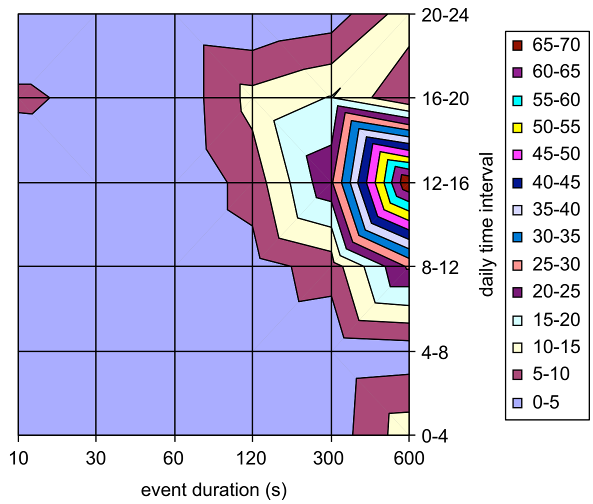

Fig. 16. Illustration of diurnal concentration at 10 dB threshold based on 20 months data in 2-D (number of events).

probability of exceeding that threshold within the period of 12 consecutive months. A worst month can therefore be recognised for each threshold level. It can be observed in Fig. 5 that at probabilities exceeding 0.1 and 0.01 time percentage, the month of October 1999 is the worst month for the period starting from January 1999 to December 1999. The envelope of the highest monthly probability values of all the monthly cumulative distributions from that year can be achieved using the highest detected attenuation at each time exceedance percentages.

Worst month statistics can be related to annual statistics by the parameter Q, which is the ratio between the worst-month and annual probability and is given by

$$Q = \frac{p_w}{p} \tag{6}$$

where as defined earlier p_w is the average worst-month probability and p is the average annual probability. Studies of the relationship between worst-month and annual statistics have been conducted at various locations for different frequencies. Different propagation effects and their associated Q_1 and β values are available in Table 1

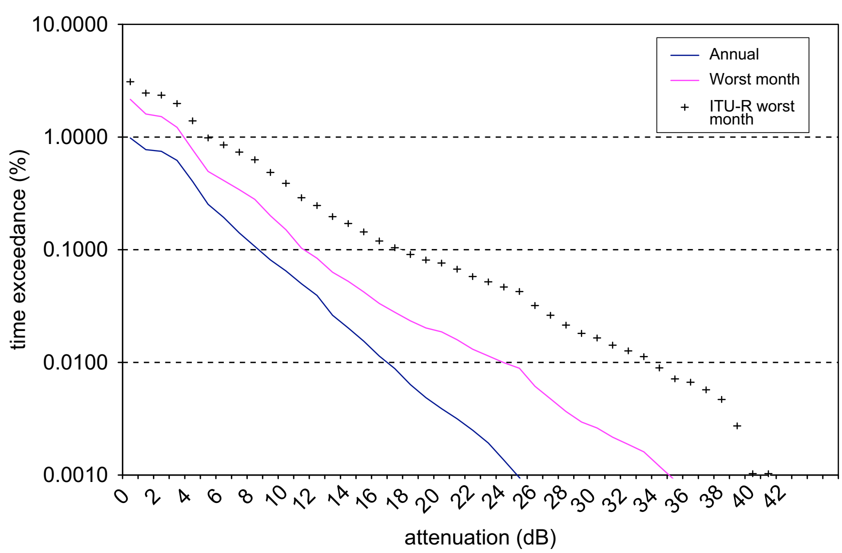

Fig. 17. Plots of annual and worst month attenuation cumulative distributions.

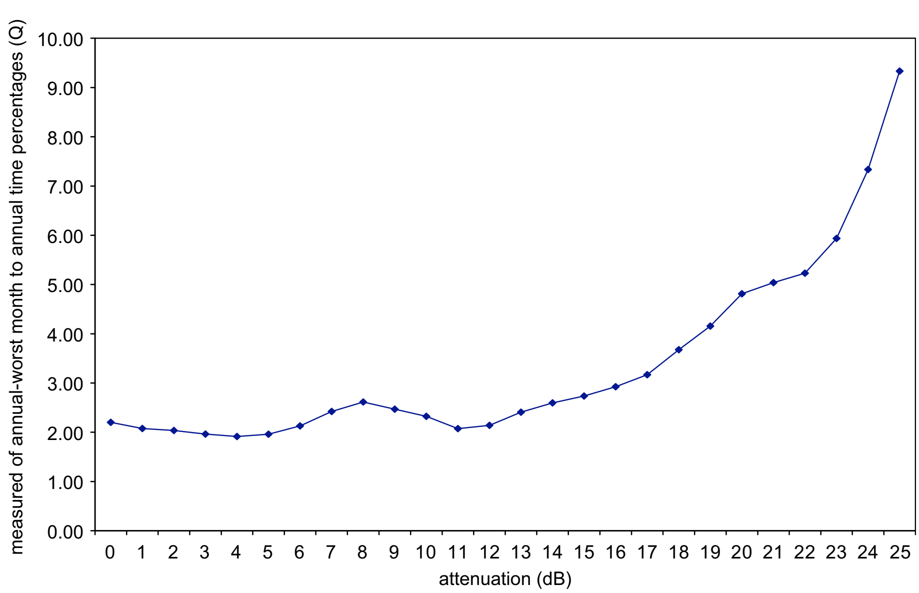

Fig. 18. Ratio of exceedances between average year and average worst month (Q) as a function of attenuation.

of the ITU database (ITU-R P.841-4, 2005). However no values for Q_1 and β have yet been quantified for rain effect slant path in the tropical region. It is suggested by ITU-R that the Q_1 and β could be approximated for $(Q_1/12)^{1/}\beta < p_w(\%) < Q_1 3^{(1-\beta)}$ by a power law relationship of the form of

$$Q = Q_1 p^{-\beta} \tag{7}$$

Substituting the above equation into Eq. (6), giving new expression

$$p_w = Q_1 p^{(1-\beta)} \tag{8}$$

The ITU-R recommends that values of Q_1=2.85 and β=0. 13 can be used for global planning purposes. For tropical region, the only values Q_1 and β available are from Indonesia that was determined from terrestrial microwave rain effect experiment. The rain induced attenuation cumulative distributions for the average year and the worst month envelope were obtained from measured data at UTM and plotted in Fig. 17. The predicted average worst month by ITU-R is included in the same figure for comparison purposes. The ratio of exceedance between the average year and the average worst month, Q was procured using the values taken from measurement data. The new Q values varying from 2 to 4.5 over the 6 to 25 dB attenuation ranges can be observed in Fig. 18.

Fading at 99% of the worst month is usually of greatest concern as proposed by ITU (ITU-R P.679-3, 2001) for satellite broadcast applications. The attenuation for time exceedance of 1% of the worst month is 6 dB as can be seen in Fig. 18. Should the margin be adopted for satellite link operating in the tropical region such as Malaysia, yearly average availability of just 99.5% can be achieved which is less than the operating standard 99.7%. Therefore conventional worst month criterion is considered not appropriate to be applied in equatorial climate link design based on these analyses.

4. Conclusion

Monthly, diurnal and annual statistics of rain attenuation have been presented for a V-band link operating in Malaysia. The results suggest an overview of how 38 GHz satellite–Earth link might propagate. Equatorial climate such as in Malaysia experiences frequent severe fading observed at 38 GHz with typically up to 38 dB for 99.99% availability in a year. The worst month of each year explored is to some extent related to the monsoon experienced in Malaysia and its nearby countries. When comparing ITU-R prediction to the measured data, the mode model exhibits small deviation at 0.1–0.001% time exceedance; but tends to deviates severely afterwards. A projected 38 GHz rain attenuation emulating a typical satellite–Earth link was generated. Evaluations of available prediction models were made and the findings seemed to be very disapproving. Hence, further investigations to accurately predict the rain attenuation at V-band frequency are eminent.

Fade characteristics of V-band frequency link in a tropical country are also presented. These results are essential in developing the best fade mitigation technique for the future satellite to Earth link in the tropics. The diurnal variabilities of signal loss due to rain can be the source for both the determination of link availabilities and the development of novel fade countermeasures in reducing communication link outages. Fade mitigation techniques that integrate modulation selections or forward error correction coding for future satellite communications can be very much dependant on information relating to fade dynamics and long-term fade occurrence statistics. The worst month statistics of rainfall rate are very useful in designing high quality communication networks since the maximum occurrence of events that lead to the degradation of the network is expected to be higher in the worst month.

More researches have to be initiated and supported in the attempt to explore channel conditions at the millimetre wave frequencies.

Acknowledgements

The findings are part of deliverables to Malaysian Communication and Multimedia Commission (MCMC) of Malaysian Government on a spectrum research project entitled ‘‘Issues on Reliable Communications at Frequency Bands above 25 GHz in the Tropics’’. It is a collaboration project between International Islamic University (IIUM), Universiti Putra Malaysia (UPM), Universiti Teknologi Malaysia (UTM) and Universiti Sains Malaysia (USM).

References

Abdullah, N.A., Adullah, R.S.A., Noordin, N.K., 2008. Adaptive coding and modulation for 38 GHz rain fade countermeasure. In: Spectrum Research Colloquium 2008 Proceedings, Kuala Lumpur 18–19 December, ISBN 978-983-42563-2-6.

Ayama, C., Nguyen, T., 2005. Fade and interfade durations on earth–space links in temperate and tropical locations. In: International Union of Radio Science-URSI Proceeding GA06.

Badron, K., Ismail, A.F.. Constraint of high frequency military communications in tropical region. In: Proceedings of Asia Pacific Conferfence on Defence and Security Technology, no. 004, 6th–7th October 2009, K. Lumpur.

Badron, K., Ismail, A.F., Din, J., Tharek, A.R., Rain induced attenuation studies for V-band in tropical regions. In: Proceedings of Loughborough Antenna and Propagation Conference 2009, 689–692, 16th–17th November 2009.

Crane, R.K., 1990. Modeling attenuation by rain in tropical region. International Journal of Satellite Communication 8, 197–210.

Fiebig, U.C., Riva, C., 2004. Impact of seasonal and diurnal variations on satellite system design in V band. IEEE Transactions on Antennas and Propagation 52 (4), 923–932.

Fukuchi, H., Watson, P.A., Ismail, A.F., 2000. Proposed novel attenuation mitigation technologies for future millimetre wave satellite communications. In: Proceedings of IEE/EUREL International Conference on Antenna and Propagation, AP-2000.

Garcia Lopez, J.A., Hernando, J.M., SELGA, J.M., 1998. Simple rain attenuation prediction method for satellite radio links. IEEE Transaction of Antenna and Propagation 36 (3), 444–448.

Ippolito Jr., L.J., 2008. Satellite Communications Systems Engineering. John Wiley and Sons Ltd., UK.

Ismail, A.F., Watson, P.A., 2000. Characteristics of fading and fade countermeasures on a Satellite-Earth link operating in an equatorial climate, with reference to broadcast applications. IEE Proceedings on Antennas and Propagation 147 (5), 369–373.

ITU-Recommendations P.581-2, 1990. The Concept of Worst Month. ITU, Geneva.

ITU-R Recommendations P.618-9. 2007 Propagation data required for the design of Earth–space telecommunications system. ITU, Radio Communications Bureau, Geneva.

ITU-Recommendations P.679-3, 2001. Propagation data required for the design of broadcasting-satellite systems. ITU, Geneva.

ITU-Recommendations P.841-4, 2005. Conversion of annual statistics to worst-month statistics. ITU, Geneva.

ITU-Reccomendations P.1623-1, 2005. Prediction method of fade dynamics on Earth-space paths. ITU, Geneva.

Maki, M., Keenanm, T.D., Sasaki, Y.K., Nakamura, 2001. Characteristics of the raindrop size distribution in tropical contenental squall lines observed in Darwin, Australia. Journal of Applied Meterology 40, 1393–1412.

Ong, J.T., Zhu, C.N., 1999. Rain rate measurements by a rain gauge network in Singapore. Electronics Letters 33, 240–242.

Otomosho, T.V., Oluwafemi, C.O., 2009. Impairment of radio wave signal by rainfall on fixed satellite services on Earth–Space path at 37 stations in Nigeria. Journal of Atmospheric and Solar–Terrestrial Physics 71, 830–840.

Pan, Q.W., Allnutt, J.E., 3, March 2004. 12-GHz fade durations and intervals in the tropics. IEEE Transaction on Antennas and Propagation, 52.

Panagopoulus, A.D., Arapoglous, P.-D.M., Cotis, P.G., Third Quarter 2004. Satellite communications at Ku, Ka and V bands: propagation impairments and mitigation techniques. IEEE Communications Surveys and Tutorials 6 (3).

Pontes, M.S., da Silva Mello, L., de Souza, R.S.L., Miranda, E.C.B., 2005. Review of rain attenuation studies in tropical and equatorial regions in Brazil. In: Fifth International Conference on Information, Communications and Signal Processing, 2005, pp. 1097–1101.

Thomas, L.D., Baltimore, M.D., 1977. Power control on satellite uplinks. United States Westinghouse Electric Corporation Pittsburgh, PA, 4038600 ⟨http://www.freepatentsonline.com/4038600.html⟩.

Watson, P.A., 1997. Effect of rain on SHF/EHF terrestrial systems. Radio Propagation Prediction IDGS Lectures.
Watson, P.A., Ismail, A.F., Seng, P.K., Ja, Y.Y., Kamaruddin, H.S., Eastment, J., Thurai, M. 1998. Investigation on rain fading and possible countermeasures on satellite-earth links in tropical climates. In: Proceedings URSI Commission F Symposium Wave Propagation and Remote Sensing, Portugal, pp. 1.3–1.7.
Zhen, Z.W., Zhang, M.G. Zhu, W.S., 2007. An analytic model of specific attenuation due to rain. In: Proceedings of International Conference on Infrared and Millimeter Waves, pp. 471–472.