Estimation of satellite link's fade margin using non-meteorological technique and worst month analysis

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ABSTRACT

Satellite technology is shifting to higher frequencies such as Q or V-band to cater to greater bandwidth and higher data rates applications such as videoconferencing, internet of things (IoT) and telemedicine. The main challenge in deploying high-frequency bands in heavy precipitation areas is severe rain attenuation. In this paper, a frequency scaling technique was developed to estimate the fade margin at a higher frequency. The worst month analysis was also conducted since the analysis is also important in determining dependable fade margin. The result was evaluated and analyzed using root mean square error (RMSE) and percentage error. The proposed model offers the smallest RMSE and lowest percentage error when compared to all existing prediction models. A dependable fade margin acquired from high-accuracy rain attenuation estimation is very important. This is to apply the best mitigation technique in overcoming rain attenuation in the satellite-Earth link so that, the best system performance can be delivered.

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1. INTRODUCTION

In recent years, an application that utilizes the internet and data-driven technology leads to the invention of high throughput satellites (HTS). HTS offers a high throughput and greater capacity which can reduce cost-per-bit whereas, in Malaysia, high-speed broadband is provided by MEASAT 5 [1]. Currently, most of the HTS works in Ka-band as Ka-band has larger bandwidth compared to C and Ku-band. No doubt, the satellite service provider will shift to higher frequencies such as Q or V-band in the future as greater bandwidth and larger capacity demand increase [2]–[6]. However, higher frequencies such as millimeter-wave frequencies are very vulnerable and susceptible to the scintillation effect, especially in rain [7], [8]. The rain will absorb and scatter the signal due to its shorter wavelength characteristics [9]–[12]. Since Malaysia is located in a tropical region which experiences severe rain and has a high-humidity environment, rain attenuation is the main challenge in applying higher frequencies technology [13]. Rain attenuation caused signal degradation that decreases the quality of service (QoS) [14], [15]. To attain a good QoS and reliable signal availability for satellite link transmission, proper planning is required to mitigate the attenuation due to rain effects at higher frequency bands.

Frequency scaling is a non-meteorological technique that can predict rain attenuation concerning frequency. The attenuation at desired frequencies can be predicted if rain attenuation at one reference frequency at a particular area is known [7], [16]–[18]. The frequency scaling method is an alternative method to predict rain attenuation models, where rainfall data is not available. Reliable long-term rain attenuation data in tropical regions is limited. This leads to the derivation of the frequency scaling technique [9]. The frequency scaling technique is one scaling technique that also can be extended to other scaling techniques which are polarization scaling, elevation angle scaling, and pathlength scaling as the attenuation is a function of the path length, elevation angle, and frequency [19]. In the frequency scaling technique, f_1 is referring to known frequencies and is usually lower than desired frequency which is f_2 [20]. Two approaches are available in deploying frequency scaling techniques which are long-term frequency scaling and short-term frequency scaling. Long-term frequency scaling or statistical frequency scaling highlights the relationship of attenuations at identical probability levels [16], [18]. It helps to define attenuation in a high-frequency band using measurements performed in a lower-frequency band. Power control also can be estimated by using this approach to compensate for uplink attenuation by using measured downlink attenuation. Short-term frequency scaling, well known as instantaneous frequency scaling, defines the relationship between simultaneous attenuation at different frequencies [18]. This approach can be used to generate attenuation time series at a high frequency by using attenuation time series measured at a lower frequency. This method can improve uplink power control in terms of real-time estimations.

This paper focuses on the first method which is when only attenuation information on known frequency is provided. Frequency scaling is derived from the empirical formula in terms of the attenuation ratio of desired and known frequency directly as a function of frequency and attenuation. The frequency scaling technique can be applied on the same path as the same path experience the same rainfall rate. Attenuation is directly proportional to the rainfall rate. Frequency scaling of attenuation is preferable deriving from long-term attenuation data instead long-term rain data [20]. Thorough studies on frequency scaling techniques in tropical regions are required since the ITU-R proposed frequency scaling that derives based on temperate region data. The temperate region experiences less precipitation compared to the tropical region, thus the frequency scaling proposed by ITU-R is less accurate to be used in Malaysia. Previous researchers have an effort in carrying out the frequency scaling using the empirical frequency scaling ratio but they are focusing on instantaneous frequency scaling instead of statistical frequency scaling.

In this paper, the existing frequency scaling models and the proposed method were compared with the measured data. The newly derived frequency scaling technique from empirical data on the rainy path was developed in this paper. Its performance was evaluated under a different year of data with different rain conditions within the same location in tropical regions. This paper also highlighted the worst month analysis. The satellite system planning often requires the attenuation value exceeded for a time percentage, *pw*, of the worst month. The procedure used to estimate the attenuation exceeded for a specified percentage of the worst month in tropical regions was elaborated in the next section.

2. METHOD

The beacon signal data from 12.201 GHz of Ku-band was retrieved from the MEASAT-3 satellite receiver and 20 GHz of Ka-band from the MEASAT-5 satellite receiver. The data was collected for one year which is from January 2016 to December 2016. Both receivers are located at Earth stations in Cyberjaya, Malaysia (N 2.9350°, E 101.6580°). The MEASAT-3 satellites are located in an orbit at 91.5° E and the MEASAT-5 is located in an orbit at 119.5° E. The rainfall data were retrieved from a rain sensor installed at ASTRO Broadcast Centre. The 8.1 m dual reflector Gregorian antenna was used to receive the Ka-band beacon signal and the Ku-band antenna was a Cassegrain type with a diameter of 13.1 m. The elevation angles are 77.5 degrees and 68.8 degrees for the MEASAT-3 and MEASAT-5 satellites respectively. The received beacons at the antenna were amplified by a low noise amplifier (LNA). Then, the beacons were down-converted to 1.5 GHz. The digital signal processing (DSP) based tracking receiver used a frequency of 1.5 GHz as input for satellite tracking and uplink power control. The received power signal of Ku and Ka-band during the non-rainy and rainy days were compared and analyzed to derive attenuation values.

The attenuation values were derived by deducting received power signals during rainy days with clear sky values. The clear sky value was determined from the average minimum received signal throughout the year. The monthly rain attenuation was accumulated and processed to obtain the cumulative distribution function (CDF). The CDF was represented in the time exceedance percentage graph. The time exceedance percentage graph is crucial for satellite engineers since it represents the percentage of link availability. The required fade margin can be determined from the annual CDF of each frequency. Figure 1 shows the annual CDF of Ku-band and Ka-band rain attenuation compared with the ITU-R P. 618-13 general prediction as well as ITU-R P. 618-13 frequency scaling method. From the Figure 1, at 0.01% of the time exceedance, rain attenuation of Ku and Ka-band predicted by the ITU-R have smaller values (15.7 and 42.5 dB) compared to the measured attenuation values which are 32 and 46.9 dB. When applying the frequency scaling model proposed by ITU-R, at 0.01% of time exceedance, rain attenuation for the Ka-band is 70.8 dB which is overestimating the measured rain attenuation.

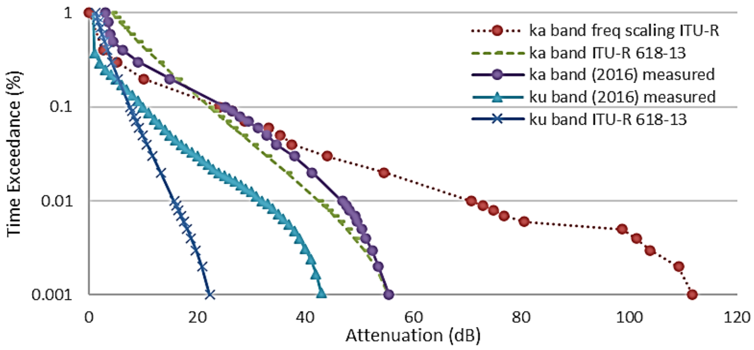


Figure 1. Comparison between empirical measured data and ITU-R P. 618-13 at Ku and Ka-band link

2.1. Frequency scaling technique

Several frequency scaling approaches from previous studies were tested for the Ka-band along the same communication paths. The simple power-law model is one of the well-known frequency scaling models. The model applies statistical attenuation ratio (RAS) as in (1).

$$RASn = (A(f2))/(A(f1)) = (f2/f1)n \quad (1)$$

Various values of power n have been proposed by [21]: n=1.8 Dintelman, n=2 Owalabi and Ajayi, n=1.9 Olympus, and n=1.72 Drufuca. The model has been proposed by ITU-R [20] is

$$A_2 = (A_1(\varphi_2/\varphi_1)^{(1-H(\varphi(f1),\varphi(f2),A1))} \quad (2)$$

$$\varphi(f) = f_2/((1+10^{-4}) \times f^2) \quad (2a)$$

$$H(\varphi_1,\varphi_2,A_1) = 1.12x10^{-3} \times (\varphi_2/\varphi_1)^{0.5}(\varphi_1 \times A_1)^{0.55}. \quad (2b)$$

Boithias [21] proposed an improved frequency scaling model which is:

$$A2/A1 = (\varphi2/\varphi1)^{(1-H(\varphi(1),\varphi(2),A1))} \quad (3)$$

$$\varphi(f) = f^2/(1+10^{-4} \times f^2) \quad (3a)$$

$$H(\varphi_1,\varphi_2,A_1) = 1.12 \times 10^{-3} \times (\varphi_2/\varphi_1) \times (\varphi_2 \times A_1)^{0.55}. \quad (3b)$$

A simple model has been proposed by CCIR [17] is:

$$RAS_{CCIR} = A_{f2}/A_{f1} = \varphi(f_2)/\varphi(f_2) \quad (4)$$

$$\varphi(f) = f^{1.72}/(1+3 \times 10^{-7} \times f^{\,3.44}). \quad (4a)$$

The more complex models proposed by Hodge, Battesti, and Kheirallah are in (5) to (7), respectively [17].

$$A_2/A_1 = (a_2/a_1)(A_1/a_1 \times (\sqrt(b_1/\pi)))^{(b_2/b_1)-1)} \times (\sqrt(b_1/b_2)) \quad (5)$$

$$\text{If } f_1, f_2 \leq 20\ GHz, A_{f2}/A_{f1} = (f_2-6)/(f_1-6) \quad (6)$$

$$\text{If } f_1, f_2 \geq 20\ GHz, A_{f2}/A_{f1} = (f_2-10)/(f_1-10) \quad (6a)$$

$$\text{If } f_1 < 20\ GHz, f_2 > 20\ GHz, A_{f2}/A_{f1} = 1.4 \times (f_2-10)/(f_1-6) \quad (6b)$$

$$A_{f2}/A_{f1} = (A_{s2} \times L_2 \times r_2)/(A_{s1} \times L_1 \times r_1) = A_{s2}/A_{f1} \quad (7)$$

Zhou [22] has proposed a model that was tested in Singapore which is:

$$A_2 = 4.8 + 1.61 \times A_1. \quad (8)$$

2.2. Worst month analysis

The worst-month analysis is very useful to design satellite-to-Earth because the required fade margin must be contented in any given month throughout the year. Therefore, performing analysis for the worst month data is crucial for telecommunication system designers [23]–[26]. The worst month statistic is determined by choosing the worst at the occurrence level computed during 12 sequential months. Comparing each monthly CDF at a particular level is recognized as the worst month [5], [23], [24]. In this paper, at probability exceeding 0.1% and 0.01% of the time outage percentage, January and May 2016 are the worst months for the year 2016 of Ku-band fading and March 2016 is the worst month for the year 2016 of Ka-band fading. The relationship between worst-month and annual statistics is defined as (9):

$$Q = X/Y \quad (9)$$

where X is the average worst-month probability and Y is the average annual probability for the same threshold. Regions with the same climatic categories will have alike values of Q. Least square method is one of the methods to obtain regression parameters Q_1 and β with the measured rainfall rate and rain attenuation data. ITU-R has proposed to relate the parameters Q_1 and β by a power law as in (10) and (11).

$$Q = Q_1\, Y^{-\beta} \quad (10)$$

$$X = Q_1\, Y^{1-\beta} \quad (11)$$

3. RESULTS AND DISCUSSION

3.1. Frequency scaling

All the existing frequency scaling models produce variations of attenuation values since the models were derived in different locations. Different regions have different geographical climates and rain statistics. Rain statistics also vary with drop size distribution, temperature, and rain height. All the estimation models are higher than the measured values. The previous models of frequency scaling were compared with the measured Ka-band rain attenuation as presented in Figure 2.

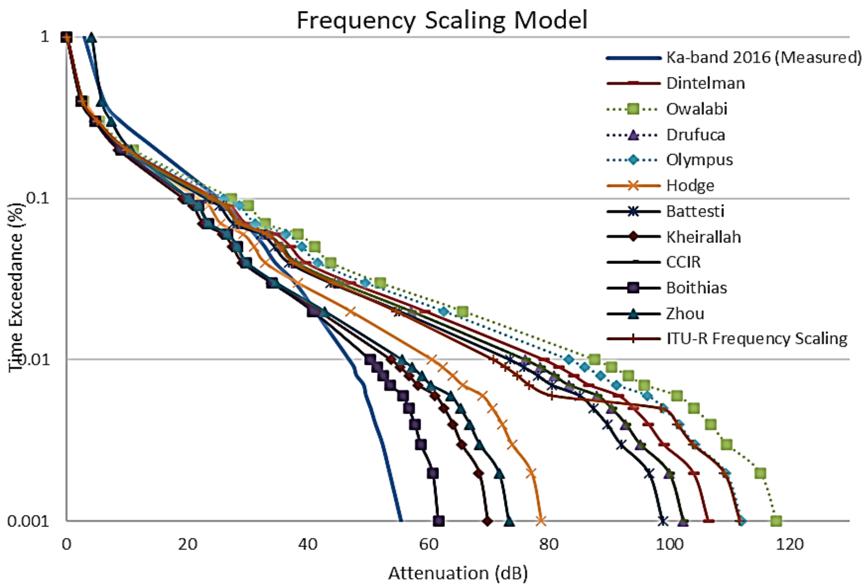


Figure 2. Comparing the previous model of frequency scaling with measured Ka-band rain attenuation value

From the Figure 2, it can be seen at 0.01% of time exceedance, the rain attenuation prediction from all available models including the ITU-R gives larger values compared to the measured value of Ka-band rain attenuation. This paper proposed a new model of frequency scaling that is useful for the tropical region. The model utilized Ku-band rain attenuation data at Cyberjaya as an attenuation at a base frequency to determine attenuation at the desired frequency at the Ka-band link. The proposed frequency scaling of rain attenuation for tropical regions is proposed by given in (9), (9a), and (9b).

$$A_2 = (\alpha \times A_1^{0.669}) - (1.425 \times ln(b) + (2 \times b)) \tag{9}$$

$$b = f_2/f_1 \tag{9a}$$

$$\alpha = (\sqrt{(f_2 - f_1)}) + 1.38 \tag{9b}$$

A_1 is Attenuation at the upper frequency, A_2 is Attenuation at the lower frequency, f_1 is the lower frequency, and f_2 is the upper frequency.

Rain attenuation prediction by applying the frequency scaling method such a best alternative way to determine rain attenuation at the desired frequency when the rainfall data is not available. A reliable fade margin is obtained from a rain attenuation prediction model that has high accuracy. The proposed frequency scaling model for year-wise estimation of rain attenuation for the Ka-band compared with the measured Ka-band rain attenuation is depicted in Figure 3. From the figure, it can be seen that the proposed model fits the measured rain attenuation of the Ka-band compared to other previous models. From the figure, fade margins at 0.1%, 0.3%, 0.01%, and 0.03% of time exceedance were determined. Table 1 shows the fade margin obtained from measured and predicted Ka-band rain attenuation in tropical regions. From the table, it is noted that the percentage error at all selected time exceedance was below 20% which has high accuracy. The fade margin obtained for the Ka-band rain attenuation prediction model at 0.01% of time exceedance is 51 dB.

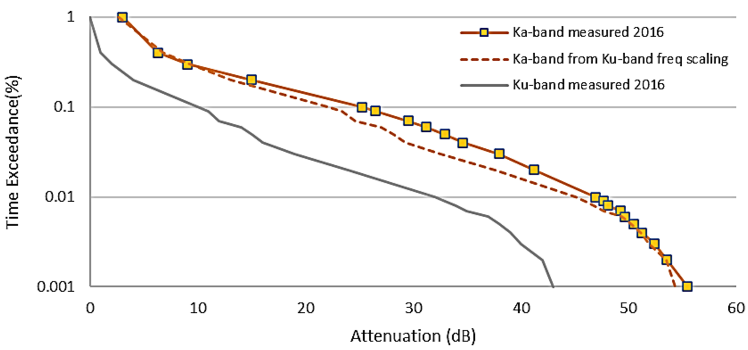


Figure 3. Comparing the proposed frequency scaling model with measured Ka-band rain attenuation

Table 1. Fade margin value of Ka-band rain attenuation at 0.1%, 0.3%, 0.01% and 0.03% of time exceedance

Time Exceedance (%)	Measured Value of Rain Attenuation (dB)	Predicted Value Using New Model (dB)	Percentage Error
0.3	9	9	0
0.1	25	22	12
0.03	37	32	13.5
0.01	52	51	1.9

All the previous models and the new models were analyzed and evaluated by using percentage error and root mean square error (RMSE). Table 2 shows the error matrix consisting of RMSE value and average relative percentage error comparing previous models and the proposed model with measured rain attenuation at the Ka-band link. At the same probability level, the percentage errors, ε, between measured rain attenuation data (*A%p*, measured) and the model's predictions (*A%p*, predicted) were evaluated within the percentage interval of 0.001%<P<1%. The percentage error was determined by using (10).

$$\text{Percentage error}, \varepsilon = (\text{A\% predicted} - \text{A\% measured}/(\text{A\% measured} \times 100\ [\%] \tag{10}$$

Table 2. Percentage error obtained after testing over the interval [0.001% to 1%]

No	Model	RMSE	ε
1	Dintelman	29.0	32.3
2	Owalabi	35.9	39.6
3	Drufuca	26.5	30.9
4	Olympus Data	32.4	35.7
5	Hodge	13.2	25.6
6	Battesti	24.5	30.1
7	Kheirallah	8.5	30.4
8	CCIR	26.5	30.9
9	Boithias	5.0	28.2
10	Zhou	9.9	17.3
11	FS ITU-R	28.3	28.0
12	Proposed FS	2.8	11.3

As presented in Table 2, the proposed frequency scaling model gives the smallest RMSE value and lowest average relative error percentage as compared to the previous models for 0.001%<P≤1% of time exceedance. The value of RMSE for the proposed model is 2.8 and the average relative error percentage of 11.3%. Lower the RMSE, the model better fits the measured data. Thus, this result proved that the model is more practical to be used in tropical regions such as Malaysia. The frequency scaling model proposed by ITU-R is inaccurate to be applied in the tropical region since it has a high RMSE value and huge percentage error which are 28.3 and 28% respectively.

3.2. Worst month

The ITU-R claims that standards value for parameters Q_1=2.85 and β=0.13 can be used for any planning globally and parameter values of Q_l=1.7 and β=0.22 are proposed for Indonesia [25]. The worst month analysis for Ku-band at Cyberjaya in the year 2016 was detected in May 2016 as shown in Figure 4. The value of Q_l=1.85 and β=0.18 for rain attenuation at the Ku-band link and of Q_l=1.67 and β=0.21 for rain rate as shown in Figure 5(a). Figure 5(b) presented four comparison graphs which are CDF of rain attenuation cumulative distributions for the year 2016, the proposed worst month envelope that was acquired, the measured worst month from annual CDF rain attenuation and the predicted average worst month proposed by ITU-R.

Table 3 summarizes the Q_1 and β parameter values at Cyberjaya with other tropical locations as well as compares to ITU-R proposed values. The measured value of Q_1 and β for Cyberjaya is close to the proposed value by ITU for Indonesia since Indonesia and Malaysia are located in tropical and equatorial regions. The Q factor is climatic dependent, thus different climate regions will have different Q factors. However, in this paper, a new value of parameters Q_1 and β has been proposed created on the Cyberjaya weather information since different places provide a different value of Q_1 and β. Besides that, for the worst month analysis for Ka-band rain attenuation, the monthly and yearly distributions only up to 0.1% of time outage since the attenuation or Ka-band is saturated at 33 dB. Therefore, accurate parameters Q_1 and β cannot be properly defined. Measured values of Q_1 and β for Ka-band rain attenuation are Q_l=2.19 and β=0.0007 is not close to the worst month proposed by ITU-R for the Indonesia region.

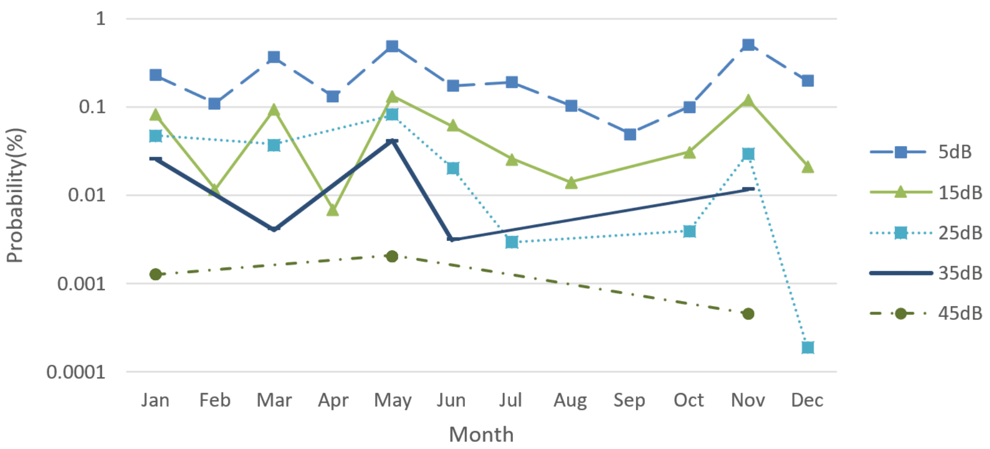
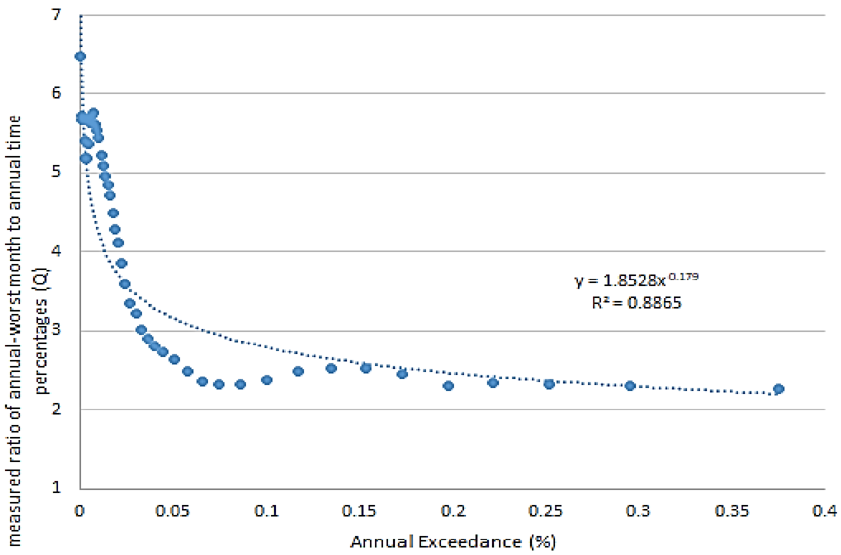
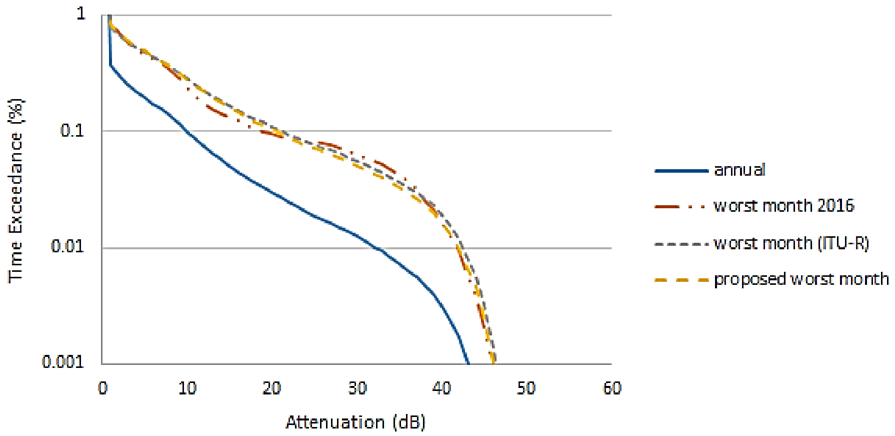


Figure 4. Specific threshold of rain attenuation at Ku-band for the year 2016 at Cyberjaya



(a)



(b)

Figure 5. The worst month of rain attenuation (a) a regression fit to determine Q_l and β of the worst month of Ku-band rain attenuation and (b) the worst month's model comparison

Table 3. Measured values and existing proposed values for Q_1 and β in the tropical region

	Q_1	β
Islam *et al.* [17]	1.32	0.27
Islam *et al.* [26]	0.92	0.3
Ting and Mandeep [2]	1.68	0.7
ITU-R for Indonesia [20]	1.7	0.22
ITU-R for a general purpose [20]	2.85	0.13
Cyberjaya (Ku-band attenuation)	1.85	0.18

4. CONCLUSION

Since Malaysia is located in a severe rainfall geographical country, an analysis of the frequency scaling technique of the satellite-Earth link as well as the worst month analysis has been conducted. The analysis is very important in determining a reliable fade margin for Ka-band rain attenuation. This paper has presented the results on the annual cumulative distribution of Ka-band rain attenuation compared to the ITU-R prediction model as well as the ITU-R frequency scaling model. The new frequency scaling formula was proposed and the ratio of exceedances between the average year and the average worst month, Q in the tropical region also was discussed. In a conclusion, the proposed frequency scaling model gives a small RMSE and low percentage error compared to the existing frequency scaling model. The fade margin of Ka-band rain attenuation obtained from the new model and measured values are 51 and 52 dB, respectively.

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