Progress In Electromagnetics Research B, Vol. 45, 37–56, 2012

A STUDY ON THE EFFECTS OF RAIN ATTENUATION FOR AN X-BAND SATELLITE SYSTEM OVER MALAYSIA

T. Siva Priya* **and T. Nizhanthi**

Faculty of Engineering, Multimedia University, Jalan Multimedia, Cyberjaya 63100, Selangor, Malaysia

Abstract—In this paper, the effect of rain attenuation on the FSS allocation in the 7250–7750 MHz in the Space-to-Earth direction is studied for a satellite at 78.5°E longitude. A simulation model based on the ITU-R P618-10 rain model is used to predict the rain attenuation in the C-, Ku- and X-bands in 15 different locations with varying rainfall intensities of between 145–300 mm/hr in East and West Malaysia. The simulations assume a 1.8 m receive antenna with 65% aperture efficiency, QPSK modulation and use of either vertical or horizontal polarization. The downlink centre frequencies used in this study are 4200 MHz, 7750 MHz and 11200 MHz for C-, X- and Ku-bands respectively. The average free-space path loss calculated for each band is used to estimate the signal attenuation due to rain and the corresponding E_b/N_o (dB) is computed at varying rain intensities. The results show that when using vertical receive polarization, all 15 locations of study with a rainfall intensity of up to 200 mm/hr could receive the X-band signal. At 200 mm/hr rain intensity in the horizontal receive, most of the X-band links could achieve the threshold E_b/N_o of 7.68 dB with a ULPC adjustment of approximately 1.5 dB where required. At 300 mm/hr rain intensity, video signals in the X-band were no longer receivable in both polarizations. At 145 mm/hr rain intensity, only one location with high satellite elevation and greater height above mean sea level maintained the Ku-band link in the horizontal receive. In the vertical receive, the Ku-band link was receivable at all locations at 145 mm/hr but were no longer receivable at 200 mm/hr. The study concluded that the elevation angle towards the satellite is a major factor in determining the quality of the signal in the X-band. The other factors that affected the receive E_b/N_o was the polarization, depth of rain and height of the earth station above

Received 31 August 2012, Accepted 15 October 2012, Scheduled 19 October 2012

* Corresponding author: Thiagarajah Siva Priya (sivapriya.thiagarajah@gmail.com).

mean sea level. In comparison to the Ku-band, the X-band was able to maintain a good quality satellite link in rain intensities of up to 200 mm/hr in the vertical receive. The results indicate that there is high potential for the use of X-band to provide for video transmission over Malaysia in spite of the high rain intensities.

1. INTRODUCTION

Malaysia is a tropical climate country where mean monthly rainfall accumulation in certain areas of East and West Malaysia reach up to 600 mm [1]. The intensities of the rainfall in Malaysia can reach up to 222 mm/hr [2]. In Malaysia, incumbent satellite operator MEASAT Satellite Systems Sdn. Bhd. uses the C- and Ku-bands to cater for data and video coverage. High capacity demand in satellite communications has caused congestion to the satellite frequency bands below 10 GHz, namely in the C-band. To cater for the high capacity demand, the 12/14 GHz Ku-band for Fixed Satellite Services (FSS) is being used for video transmission. Unfortunately, higher frequency bands are prone to high rain attenuation losses. At high frequencies, the wavelength becomes significantly shorter. These short wavelengths are easily absorbed and scattered as they pass through raindrops [3, 4]. In Malaysia, signals in the Ku-band are sometimes attenuated up to 7 dB in monsoon rainfall intensities. Due to this, video services often suffer a complete signal blackout during high rainfalls in spite of uplink power controls.

The Malaysia National Communications Satellite program aims to launch next generation satellite services into the orbital location of 78.5°E for satellite coverage over Malaysia with C-, Ku- and X-band capacity [5]. The X-band services is intended to be used for military applications such as maritime and air control, combat search and rescue and medium to long range UAV applications. The practice of using the X-band for military purposes only is more by practice than international rule, as the 8 GHz band is allocated by the International Telecommunications Union (ITU) for FSS usage regardless of what service it is actually used for [6]. Therefore, there is a possibility of using the X-band spectrum for Very Large Satellite Aperture (VSAT) or Direct-to-Home (DTH) services.

It is important to include rain fade margin when designing the satellite link budget. The rain fade margin is a component of the link margin and it is a calculation based on the expected rain attenuation over one year. The rain fade calculation takes into consideration the rainfall data, elevation angle, rain attenuation, gaseous attenuation, free space path loss, system noise, interference, depolarization, scintillation and slant range of an earth station from the satellite.

This paper will conduct a feasibility study on rain attenuation effects on X-band and analyze the feasibility of the usage of X-band for DTH services over Malaysia. Rain fade is calculated using ITU-R P.618-10 [7]. The performance of the X-band is compared to the C- and Ku-bands by choosing 15 locations across East and West Malaysia with mean monthly rainfall rates of between 200 mm–400 mm with varying heights above sea mean level. The locations are selected because these locations have rain monitoring stations set up by the Malaysian Meteorological Department (MMD). The study is focused on the downlink budget of the system and an analysis on E_b/N_o (dB) degradation during rain is performed to evaluate the system performance.

2. CALCULATION OF RAIN FADE MODEL PARAMETERS

Rain modeling and prediction techniques are developed after extensive study on rainfall patterns. The ITU-R P618-10 prediction model is used in this study because the model is well adopted for the Malaysian climate. Furthermore, this model is updated regularly using data from worldwide remote rain databases.

2.1. Path Loss and Gaseous Attenuation Calculations

The elevation angle of the earth station depends on the longitude of the satellite. In geostationary satellites, the angle of elevation will reduce with the increase in difference between the latitude or longitude of the earth station and the satellite [8]. Satellite signal coverage is usually reduced at low elevation angles.

Free space path loss (FSPL) contributes to large signal energy attenuation because of the spreading of the wavefront as it propagates from its source [9]. Free space path loss is given in Eq. (1) [9]

$$FSPL = 20\log_{10} S + 20\log_{10} f + 92.45 \tag{1}$$

where S is the slant path distance in km from satellite to the earth station and f is the operating frequency in GHz.

Different location of earth stations will contribute to different slant path ranges according to its longitude and latitude. The formula to obtain the slant range is given as [8]

$$S = 42,643.7 \times 10^3 \times \sqrt{1 - 0.29577 \times (\cos\theta\cos\delta)} \quad \text{(km)} \tag{2}$$

Table 1. Free space path loss for C, Ku and X-bands.

Earth Station Longitude (°E)	Satellite longitude (°E)	Slant Range (km)	C-band FSPL (dB) (4.2 GHz)	X-band FSPL (dB) (7.75 GHz)	Ku-band FSPL (dB) (11.2 GHz)
100.24°	78.5°	48304.48	198.59	203.92	207.11
101.22°		48271.49	198.59	203.91	207.11
101.39°		46578.06	198.28	203.60	206.80
103.45°		48401.00	198.61	203.93	207.13
101.06°		47774.92	198.50	203.82	207.02
102.15°		42946.48	197.57	202.89	206.09
101.70°		45040.43	197.99	203.31	206.51
102.23°		43442.09	197.67	202.99	206.19
103.05°		47487.74	198.45	203.77	206.97
118.04°		44058.49	197.80	203.12	206.31
111.27°		44213.67	197.83	203.15	206.35
102.46°		44798.67	197.94	203.26	206.46
118.00°		43819.27	197.75	203.07	206.27
116.5°		48349.78	198.60	203.92	207.12
103.19°		47901.40	198.52	203.84	207.04
Average Path Loss			198.179	203.500	206.699

where θ is the earth station latitude and δ is the angle difference between the satellite longitude and the Earth station longitude.

Based on a satellite longitude of $78.5°E$ and the earth station longitudes, the average free space path loss at different frequencies is summarized in Table 1. These values were subsequently used in the simulations for this study.

Gaseous components along a transmission path will cause attenuation to the radiowaves through absorption. This gaseous attenuation is dependent on the frequency, elevation angle, water vapor density and height above sea level [10].

Although the atmospheric attenuation in satellite communications is small, including the atmospheric attenuation into the analysis allows providing a better result. Attenuation of the atmospheric gases on slant path is estimated using Recommendation ITU-R P.676-9 [11].

2.2. Determination of Rain Attenuation

To determine the rain attenuation, the depth of rain and height of rain must be determined. Different frequency, location, polarization and

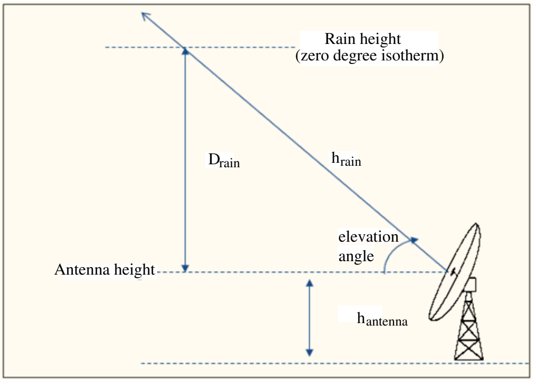


Figure 1. Illustration of depth of rain and height of rain [12].

rainfall rate varies the rain fade. The rain attenuation is calculated using Eq. (3) [11, 12]:

$$L_{\min} = \gamma_R D_{\text{rain}} \tag{3}$$

where D_{rain} is the depth of rain, L_{rain} is the rain loss in dB and γ_R is the specific rain attenuation in (dB/km).

Depth of rain is the path length through the troposphere in kilometers and is illustrated in Figure 1. The troposphere is the nearest layer of the atmosphere to the earth and is the layer in which majority of the rain clouds form. In the tropics, the depth of the troposphere can reach up to 20 km [13]. To determine the depth of rain, the information of the mean height of rain above mean sea level, h_{rain}, as illustrated also in Figure 1 is obtained from ITU-R P.839-3 [14] and calculated to be 4.86 km. The relationship between D_{rain} and h_{rain} is shown in Eq. (4) [7]

$$D_{\text{rain}} = \frac{h_{\text{rain}} - h_s}{\sin\theta} \tag{4}$$

where h_s is the height of the earth station above mean sea level in km and θ is the antenna elevation angle towards the satellite in degrees.

The ITU has specified Malaysia under the rain region P, which means at a rain intensity of 145 mm/hr, a satellite link will suffer a link disruption for 0.01% or 54 minutes per year [15, 16]. In this study, the rain fall data collected from the Malaysian Meteorological Department (MMD) for a period of one year between June 2011 and June 2012 is used [1]. Given that historical data [2] has shown that the intensities of rain over Malaysia can reach 222 mm/hr, it is useful to conduct an analysis in rain intensities which exceed 145 mm/hr. Therefore, this

Table 2. Values of the k and α coefficient used to determine specific rain attenuation, γ_R.

Rain fall rate, R	Frequency (GHz)	Vertical Polarization			Horizontal Polarization		
		k	α	γ_R (db/km)	k	α	γ_R (db/km)
0.01	4.2	0.000648	1.095	0.00000418384	0.000724	1.2634	0.00000215248
0.01	7.75	0.00358	1.315	0.00000839234	0.00409	1.331	0.00000890683
0.01	11.2	0.01333	1.224	0.0000474080	0.01494	1.239	0.0000496993

study includes the performance of X-band links under rain intensities of 200 m/hr and 300 mm/hr.

The specific rain attenuation, γ_R is determined by first finding the values of the k and α coefficients found using Eq. (5) and Eq. (6) [17]

$$\log_{10} k = \sum_{j-1}^{4} \left(a_j \exp\left[-\left(\frac{\log_{10} f - b_j}{c_j} \right)^2 \right] \right) + m_k \log_{10} f + c_k \quad (5)$$

$$\alpha = \sum_{j-1}^{5} \left(a_j \exp\left[-\left(\frac{\log_{10} f - b_j}{c_j} \right)^2 \right] \right) + m_\alpha \log_{10} f + c_\alpha \quad (6)$$

where f is the frequency expressed in GHz and a_j, b_j and c_j are defined in ITU-R P.838-2 [17]. The value of γ_R in dB/km is then determined using Eq. (7) [17]

$$\gamma_R =^{kR^\alpha} \quad (7)$$

where the values of the k and α coefficients which differ according to polarization. Table 2 summarizes the values of k and α and the corresponding specific attenuation, γ_R.

2.3. Earth Station Parameters

Table 3 shows the earth station parameters and the calculated D_{rain}. The elevation angles were calculated using Eq. (8) [18]

$$\phi_{\text{elevation}} = \cos^{-1}(R+h)/D\sqrt{1 - [\cos^2(\alpha_{ES})\cos^2(\theta_{SAT} - \theta_{ES})]} \quad (8)$$

where $\Phi_{\text{elevation}}$ is the angle of elevation, R and h are 35786 km and 6378.1 km and are the distances of the geosynchronous orbit and the radius of the Earth respectively, α_{ES} is the latitude of the earth station, θ_{ES} is the longitude of the earth station and θ_{SAT} is the longitude of the satellite. D is calculated using Eq. (9) [18].

$$D = \sqrt{h^2 - 2R(h+R)[1 - \cos(\alpha_{ES})\cos(\theta_{SAT} - \theta_{ES})]} \quad (9)$$

Table 3. Latitude, longitude and antenna elevation angle for the selected locations of earth stations representing malaysia.

Earth Station	Maximum mean monthly rainfall rate (mm)	Height above mean sea level, H_S (km)	Latitude North	Longitude East	Elevation angle, (towards 78.5°E)	D_{rain}
Alor Setar	225	0.004	6.12°	100.24°	77.46°	5.51
Cameron Highlands	300	1.545	4.28°	101.22°	77.51°	3.87
Petaling Jaya	225	0.046	3.06°	101.39°	77.82°	7.37
Senai	225	0.037	1.28°	103.45°	75.53°	36.71
Ipoh	250	0.039	4.35°	101.06°	77.65°	6.21
Melaka	200	0.009	2.16°	102.15°	77.22°	5.01
Subang	275	0.087	3.15°	101.70°	77.45°	5.38
Kota Bharu	600	0.005	6.13°	102.23°	75.49°	52.97
Muadzam Shah	200	0.033	3.03°	103.05°	75.96°	9.06
Sandakan	450	0.012	5.54°	118.04°	58.38°	5.02
Sri Aman	350	0.010	1.13°	111.27°	66.78°	6.72
Batu Embun	200	0.059	3.35°	102.46°	76.53	5.30
Temerloh	200	0.049	5.55°	118.00°	58.42	5.04
Kudat	400	0.010	6.31°	116.5°	59.92	21.3
Kluang	200	0.0881	2.01°	103.19°	76.05	7.87

2.4. Calculation of C/N

A power link budget is used to evaluate the performance of the satellite link in this study. The parameter to study the performance of the satellite system is the Carrier-to-Noise Ratio (C/N) and is given in Eq. (10) and Eq. (11) [8] for fair and rainy weather respectively.

$$\left(\frac{C}{N}\right)_{clear} = 10\log_{10}\left(\frac{EIRP_{sat}}{ESPL * a_{gd} * l_{ad}} \times \frac{gain_{rcv}}{k(T_{clear} * T_{other} * T_{rcv})B}\right) \text{dB} \tag{10}$$

$$\left(\frac{C}{N}\right)_{rain} = 10\log_{10}\left(\frac{EIRP_{sat}}{ESPL * a_{rd} * a_{gd} * l_{ad}} \times \frac{gain_{rcv}}{k(T_{rain} * T_{other} * T_{rcv})B}\right) \text{dB} \tag{11}$$

where $EIRP_{sat}$ is the satellite Equivalent Isotropic Radiated Power (EIRP) in the Space-to-Earth direction, $gain_{rcv}$ is the receiving

Table 4. Summary of verified satellite modem specification.

Modulation (Receive)	QPSK 1/2
Bit Rates	C-band — 512 kbps X-band — 4 Mbps Ku-band — 1 Mbps
Minimum E_b/N_o to guarantee a good transmission's quality	7.68 dB (V/H)
Bit error rate to guarantee a good transmission's quality	Better than 1×10^{-7}
Transponder Bandwidth per Channel	36 MHz

antenna gain, $FSPL$ is the free space path loss, l_{ad} is the downlink additional loss and is taken at a value of 1.174 dB, k is the Boltzman constant $k = 1.38 \times 10^{-23} JK^{-1}$ and B is the bandwidth (Hz). The a_{gd} and a_{rd} are the downlink gas attenuation and rain attenuation respectively expressed in dB and is obtained from Annex 2 of ITU-R P.676-9 [19].

It is assumed that for video transmission for DTH purposes, a Bit-Error-Rate (BER) of better than 10^{-7} is acceptable. The minimum required E_b/N_o to maintain a BER of 10^{-7} is calculated to be approximately 7.68 dB. The value is comparative to the value of required 6.4 dB E_b/N_o for a 0.6 m antenna used in past studies [20]. An antenna aperture efficiency of 65% and a modulation scheme using Quadrature Phase-Shift Keying (QPSK) with 1/2 code rate is assumed. Table 4 summarizes the satellite modem parameters.

2.5. Conversion of C/N to E_b/N_o

C/N is a measure of the analogue performance of the satellite link. To determine the digital performance of the link, the C/N must first be converted to Carrier-to-Noise-Density ratio, C/N_o(dB/Hz) using Eq. (12) [20]

$$\frac{C}{N} = \frac{C}{N_o}/B \tag{12}$$

The C/N_o value is then converted to Energy-per-Bit-Ratio, E_b/N_o, using Eq. (13)

$$\frac{E_b}{N_o} = \frac{C}{N_o} - 10\log_{10} R \tag{13}$$

where R is bit rate in bit/s and B is the transponder bandwidth in Hertz.

2.6. Determination of Noise Temperature

The system temperature, T_{sys}, consists of three components T_{sky}, T_{rcv} and T_{other} [21]. Depending on either fair or rainy weather, T_{sky} is then expressed as either T_{clear} or T_{rain} using Eq. (14) and Eq. (15) respectively.

$$T_{clear} = \frac{T_{cb}}{a_{gd}} + T_{atm}\left(1 - \frac{1}{a_{gd}}\right) \text{ (K)} \tag{14}$$

$$T_{rain} = \frac{T_{cb}}{a_{rd}a_{gd}} + T_{atm}\left(1 - \frac{1}{a_{gd}a_{rd}}\right) \text{ (K)} \tag{15}$$

where T_{cb} is the contribution of cosmic background noise and is taken as 3 K in fair weather [22]. During rainy weather, the cosmic noise increases to approximately 3.8 K, 10 K and 18 K for C-, X- and Ku-bands respectively after taking into consideration the different cloud heights, thickness of cloud and liquid water densities of the clouds [23]. The atmospheric temperature, T_{atm} is taken as 280 K for use over Malaysia [24]. a_{gd} and a_{rd} are the downlink gas attenuation and downlink rain attenuation obtained from ITU-R P 676-9 [19] respectively. T_{other} consists of noises contributed by internal loss, radiation from the ground and surrounding environment of the receiver antenna. A value of 30 K is assumed for T_{other} in this study. Table 5 summarizes the system temperature values and the antenna characteristics of the earth stations.

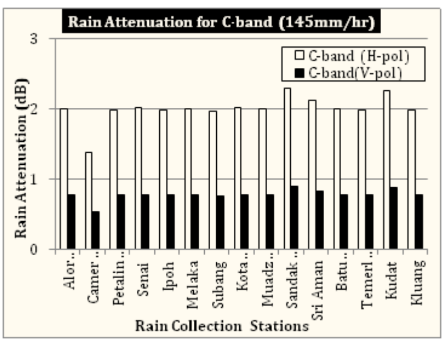
Table 5. Earth station antenna characteristics and downlink system temperature values.

Earth Station (Receiver parameters)	**C-band**	**X-band**	**Ku-band**
Polarization	Vertical/ Horizontal	Vertical/ Horizontal	Vertical/ Horizontal
Antenna diameter	1.8 m	1.8 m	1.8 m
Antenna aperture efficiency	65%	65%	65%
Antenna gain, G_{rcv}	36.1 dBi	41.4 dBi	44.6 dBi
Receiver noise temperature, T_{rcv}	60 K	70 K*	80 K
Clear sky-noise temperature, T_{clear}	5.2423 K	5.6216 K	6.1916 K
Sky-noise temperature during rain, T_{rain}	51.4665 K	266.2485 K	279.7261 K
T_{other}	30 K	30 K	30 K

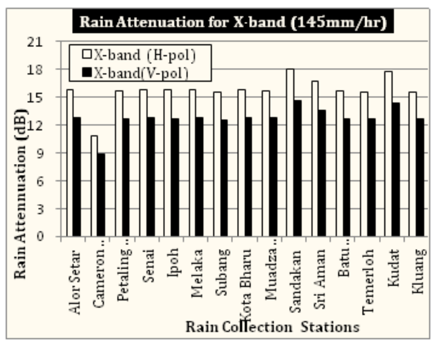
3. RESULTS AND DISCUSSIONS

The simulation was done using MATLAB and the average rain attenuation experienced by the signals in the vertical and horizontal polarization at the 15 locations of study predicted by the ITU-R 618-10 with R0.01 with rain intensities of 145 mm/hr, 200 mm/hr and 300 mm/hr is shown in Figures 2, 3 and 4 respectively.

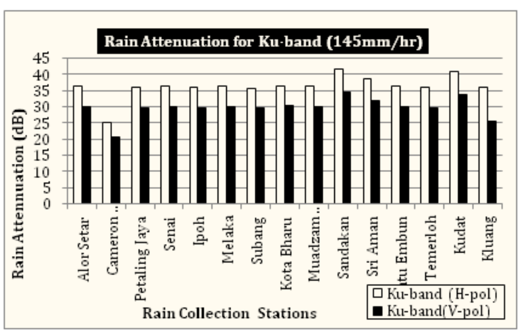
For the C-band, the simulation was only performed up to a rain intensity of 200 mm/hr as the simulated E_b/N_o value at 200 mm/hr was well above the threshold value and is estimated to be above the threshold E_b/N_o even at 300 mm/hr. Figure 2(b) shows that in the X-band, the highest rain attenuation was suffered in Sandakan with a rain attenuation of 18.04 dB and 14.6 dB in the horizontal and vertical polarizations respectively. The lowest rain attenuation was experienced in Cameron Highlands with 8.81 dB and 10.9 dB in the vertical and



(a)



(b)



(c)

Figure 2. Rain attenuation (dB) in 145 mm/hr. (a) C-band, (b) X-band, (c) Ku-band.

horizontal polarization respectively. Figure 2(c) shows that in the Ku-band, Sandakan suffered the highest rain attenuation with a rain attenuation of 34.4 dB and 41.69 dB in the vertical and horizontal polarization respectively. Cameron Highlands again experienced the lowest rain attenuation with 20.8 dB and 25.19 dB in the vertical and horizontal polarizations respectively.

Comparison of Figures 3(a)–(c) with Figures 2(a)–(c) show that as the rain intensity increases from 145 mm/hr to 200 mm/hr, the rain attenuation in the worst case location (Sandakan) increased by 0.3 dB, 7.5 dB and 15.56 dB for the C-, X- and Ku-bands respectively in the vertical polarization. In the horizontal polarization, this increase was 1 dB, 9 dB and 20 dB in the C-, X- and Ku-bands respectively.

By comparing Figures 4(a)–(b) and Figures 2(b)–(c), Sandakan (worst case scenario) suffered a total of approximately 29.44 dB increase in rain attenuation in the horizontal receive and 23.3 dB in

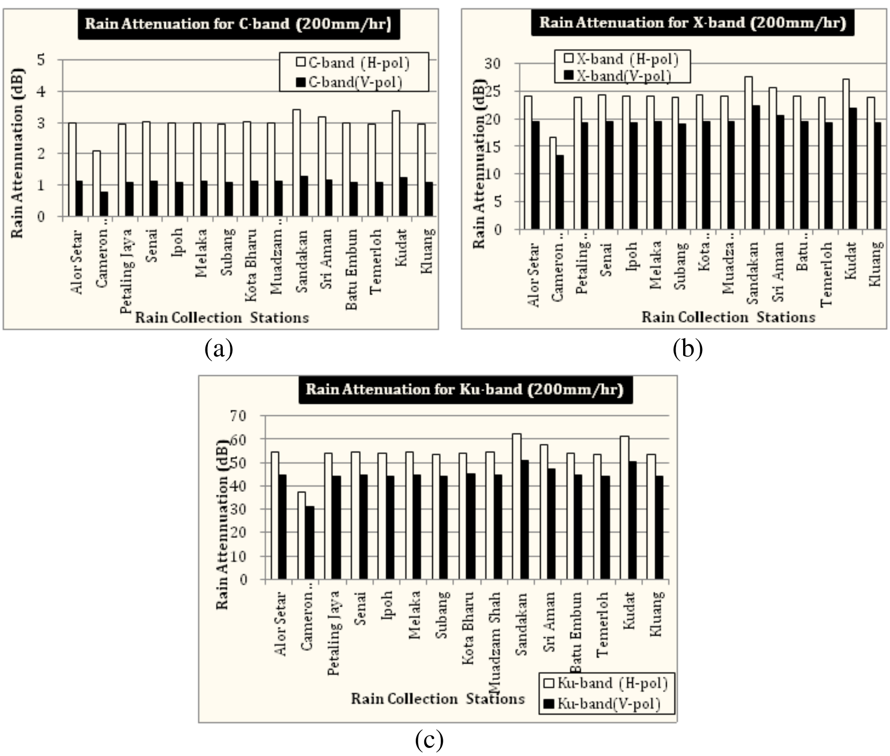


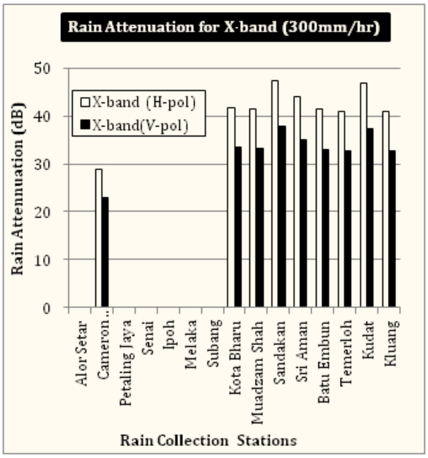
Figure 3. Rain attenuation (dB) in 200 mm/hr. (a) C-band, (b) X-band, (c) Ku-band.

the vertical receive in the X-band when rain intensity was increased from 145 mm/hr to 300 mm/hr. As for the Ku-band, the total rain attenuation suffered as rain intensity increased from 145 mm/hr to 300 mm/hr is 60.9 dB in the horizontal receive and 48.5 dB in the vertical receive.

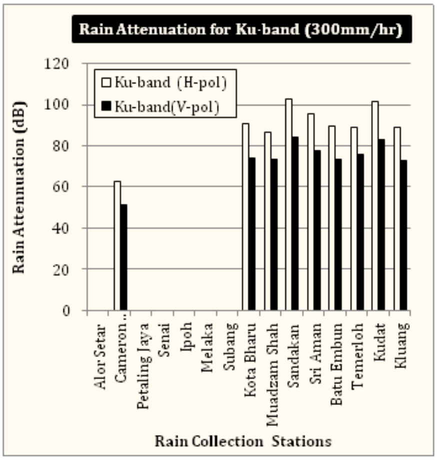
Figure 5 shows that in general, the signals in the vertical polarization suffer less rain degradation than the signals in the horizontal polarization. This result is consistent with past studies that show that vertically polarized antennas are less likely to be affected by rain attenuation. Table 6 summarizes the minimum and maximum rain attenuation values suffered by the signals at the various locations used in this study.

Figures 6(a) & (b) show that the C-band link in rainy sky was well above the E_b/N_o threshold of 7.68 dB at the rain intensities of 145 mm/hr and 200 mm/hr for both receive polarizations. The links suffered about 1.5 dB of loss in general as a rain intensity increased from 145 mm/hr to 200 mm/hr. The links in the horizontal receive suffered about 3 dB more attenuation that the links in the vertical receive.

For Figures 6 through 8, the grey bar indicates the clear sky E_b/N_o, the black bar indicates the rainy condition E_b/N_o in the vertical polarization, the white bar with a solid border indicates the rainy condition E_b/N_o in the horizontal polarization and the white bar with a dotted border indicates threshold E_b/N_o to maintain a link.



(a)



(b)

Figure 4. Rain attenuation (dB) in 300 mm/hr. (a) X-band, (b) Ku-band.

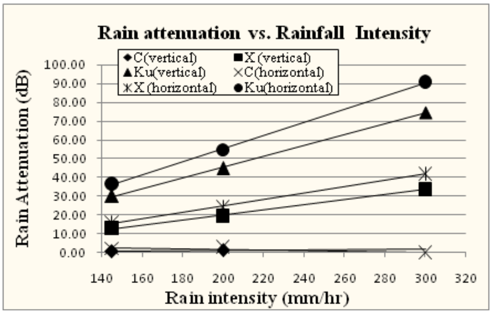
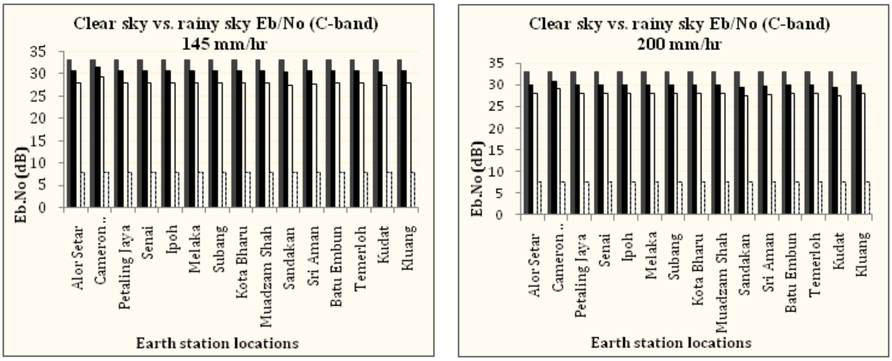


Figure 5. Rain attenuation (dB) versus rainfall density (mm/hr) in the C-, Ku- and X-bands.

Table 6. Summary of rain attenuation suffered by satellite signals.

Band	Rain intensity (mm/hr)	Minimum rain attenuation (dB) (V pol)	Maximum rain attenuation (dB) (V pol)	Minimum rain attenuation (dB) (H pol)	Maximum rain attenuation (dB) (H pol)
C	145	0.53	0.88	1.38	2.25
	200	0.76	1.26	2.07	3.42
X	145	8.81	14.58	10.9	18.04
	200	13.45	22.26	16.72	27.68
	300	23.11	37.93	28.92	47.48
Ku	145	20.81	34.93	25.19	41.69
	200	30.84	50.29	37.51	62.10
	300	51.09	83.87	62.52	102.62

Figures 7(a), (b) & (c) show the effects of rain attenuation on the X-band satellite link. At a rain intensity of 145 mm/hr, the X-band was able to provide a satellite link with a E_b/N_o of at least 13.15 dB for both polarizations at each location of study. At 200 mm/hr, the X-band links in the vertical receive polarization had an E_b/N_o of at least 8.9 dB in all locations. In the horizontal receive, 6 locations had an E_b/N_o of more than 7 dB and may still be able to achieve the desired E_b/N_o of 7.68 dB with approximately 1 dB of Uplink Power Control (ULPC) adjustment at the transmitter side. The ULPC is a form of manual transmitter power control used in satellite communications to compensate for rain fade. If the ULPC is increased by 1 dB, an extra 1 dB of power margin is present in the overall link budget to compensate for rain losses be it in the uplink or downlink path. The ULPC requires manual intervention as it should be deactivated when



(a) (b)

Figure 6. C-band clear sky vs rainy sky E_b/N_o: (a) 145 mm/hr, (b) 200 mm/hr.

there is no rain to avoid transponder saturation on the satellite. Since not all locations suffered rain intensities of higher than 200 mm/hr, only the selected earth stations at 6 locations were simulated for effects on the X-band link at a rain intensity of 300 mm/hr. It was found that at this intensity, the X-band links were no longer available at the desired E_b/N_o threshold. The links in the horizontal receive suffered about 3 dB more attenuation that the links in the vertical receive.

Figures 8(a) & (b) show that in a rain intensity of 145 mm/hr, the Ku-band links have an E_b/N_o above the desired threshold only in the vertical downlink polarization. In the horizontal receive polarization, only Cameron Highlands had an E_b/N_o that is above the threshold. In the rain intensity of 200 mm/hr, it was observed that the Ku-band links degraded to below the required E_b/N_o for all locations in both polarizations except for Cameron Highlands. Although the results are not shown here, the Ku-band links were no longer available at all locations at a rain intensity of 300 mm/hr.

3.1. Effects of Antenna Height and Satellite Elevation Angle

Due to the significantly higher height above mean sea level in comparison with the other locations, it should be noted that the earth station E_b/N_o for Cameron Highlands differed significantly with other locations. At a rain intensity of 145 mm/hr over Cameron Highlands, the E_b/N_o of the X- and Ku-band satellite links in both polarizations were above the required E_b/N_o threshold by at least 7.52 dB. At a rain intensity of 200 mm/hr over Cameron Highlands, the E_b/N_o of the X-band satellite links in both polarizations were above the required E_b/N_o

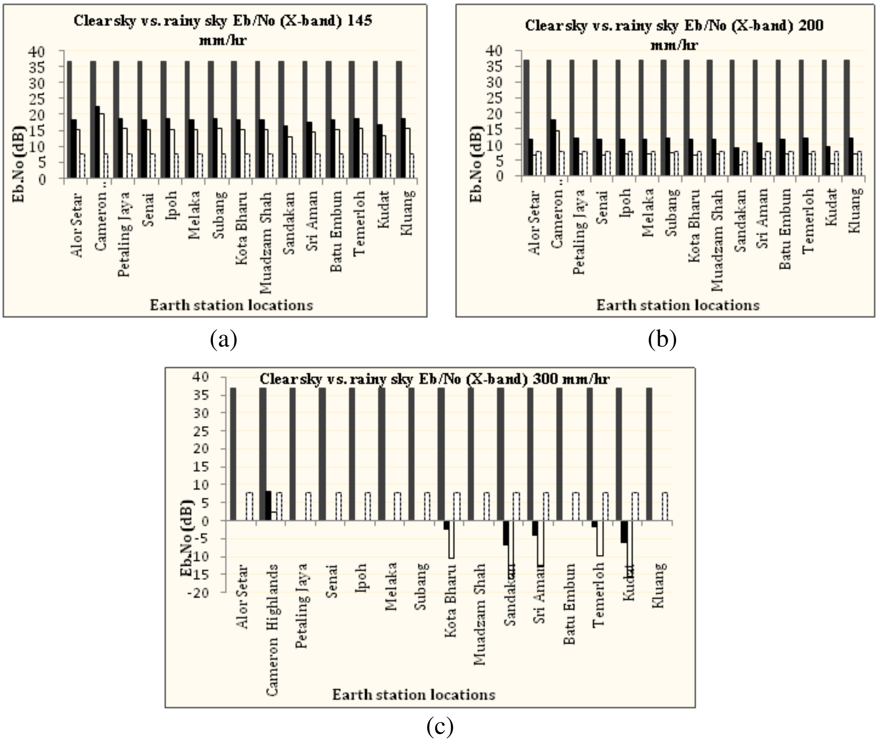
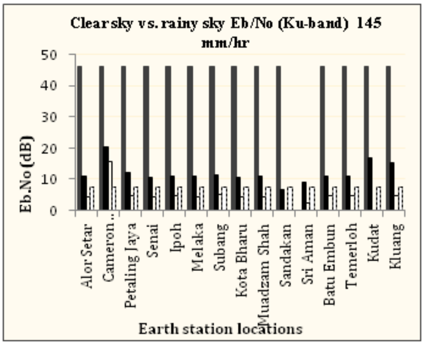


Figure 7. X-band clear sky vs rainy sky E_b/N_o: (a) 145 mm/hr, (b) 200 mm/hr, (c) 300 mm/hr.

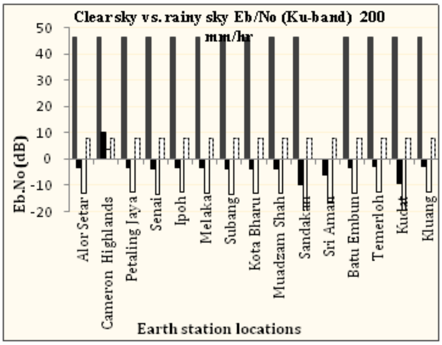
threshold by at least 6.81 dB. However, the E_b/N_o for the Ku-band satellite links were above the required E_b/N_o threshold by 2.51 dB for the vertical receive polarization only. At a rain intensity of 300 mm/hr, the X-band satellite link in the vertical receive could still maintain the link with a E_b/N_o of 8.09 dB. The links for the Ku-band in both polarizations were no longer available at this intensity over Cameron Highlands.

Due to its low height above mean sea level and a low elevation angle of 58.38°, the Earth station at Sandakan was unable to receive sufficient E_b/N_o to maintain a link in the Ku-band even a rain intensity of 145 mm/hr.

In general, the X-band link suffered an average degradation of 6.5 dB in the vertical polarization and 8.5 dB in the horizontal receive polarization when rain intensity increased from 145 mm/hr to 200 mm/hr. The degradation value was lesser for places with



(a)



(b)

Figure 8. Ku-band clear sky vs rainy sky E_b/N_o at: (a) 145 mm/hr, (b) 200 mm/hr.

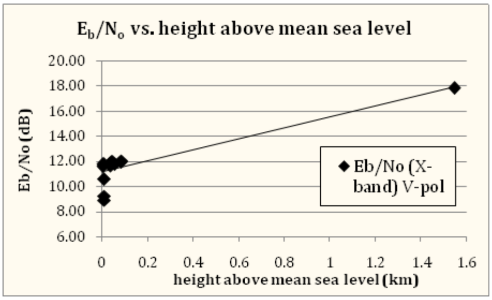


Figure 9. Relationship between E_b/N_o (dB) and height above mean sea level (km).

high height above mean sea level and greater for places with low height above sea mean level namely Sandakan, Kudat and Sri Aman. Although Melaka and Kota Bharu had much lower height above mean sea level than Sandakan, Kudat and Sri Aman, the received E_b/N_o levels at these locations were better due to their high elevation angles towards the satellite.

Figure 9 shows the relationship between the E_b/N_o and the height above mean sea level. In general, the results show a linear relationship between the E_b/N_o and the height above mean sea level. However, this linear relationship is not applicable for the locations of Sandakan, Sri Aman and Kudat. This is because these locations also have low elevation angles. For locations with high depth of rain but with high elevation angles like Senai and Kota Bharu, it was found that the E_b/N_o receive levels in the X-band were still acceptable

Table 7. Relationship between location height, depth of rain and elevation angle with E_b/N_o received.

Location	Height above sea mean level (km)	Eb/No (X-band) V-pol	D_{rain} (km)	Elevation angle
Alor Setar	0.004	11.73	5.5065	77.46°
Cameron Highlands	1.545	17.84	3.8672	77.51°
Petaling Jaya	0.0457	11.92	7.3027	77.82°
Senai	0.037	11.61	36.7060	75.53°
Ipoh	0.039	11.88	6.2050	77.65°
Melaka	0.009	11.73	5.0079	77.22°
Subang	0.087	12.05	5.3838	77.45°
Kota Bharu	0.005	11.57	52.9747	75.49°
Muadzam Shah	0.033	11.76	9.0615	75.96°
Sandakan	0.012	8.90	5.0173	58.38°
Sri Aman	0.01	10.54	6.7183	66.78°
Batu Embun	0.059	11.78	5.3040	76.53°
Temerloh	0.049	11.93	5.0368	58.42°
Kudat	0.01	9.24	21.2977	59.92°
Kluang	0.088	11.95	7.8666	76.05°

up to 200 mm/hr of rain intensity in both polarizations, although an adjustment of approximately 1.5 dB in ULPC may be required if the receive is planned in the horizontal receive. The data from Figure 6 is tabulated is Table 7, which also shows the elevation angles and the depth of rain at the various locations.

Based on the explanations, it can be summarized that a combination of two or more factors of low elevation angle, low mean sea heights and high depth of rain can cause low receipt E_b/N_o. However, in spite of the low height above mean sea levels and a high depth of rain, sufficient E_b/N_o at rain intensities of up to 200 mm/hr can be obtained for an X-band satellite link in the X-band, using both polarizations, as long as the elevation angels towards the satellite is high enough.

4. RECOMMENDATION FOR FUTURE RESEARCH

This study provided a simulation study on the feasibility of using X-band spectrum to cater for the shortage of satellite services spectrum in Malaysia from an orbital location of 78.5°E. The study found that even earth stations at low height above mean sea level and high depth of rain could receive good E_b/N_o in the X-band at a rain intensity of 200 mm/hr, provided it had a high satellite elevation to the desired service satellite.

It is highly recommended that a field study on the rain attenuation suffered and the E_b/N_o received during high rainfall intensities of up to 200 mm/hr be conducted using an actual earth station dish that is pointed to an operational X-band satellite. The experiment should be done over a period of time to collect the samples of received signal strength. The data collected from this field experiment will provide a more actual prediction of the rain fade suffered by the X-band signals for coverage over Malaysia.

5. CONCLUSION

In this paper, the ITU-R P618-10 rain model is used to predict the rain attenuation in the C-, Ku- and X-bands in 15 different locations with varying rainfall rates of between 145–300 mm/hr in East and West Malaysia. The simulations assumed that customers use a 1.8 m receive antenna with 65% aperture efficiency, QPSK modulation and use either vertical or horizontal polarization. An E_b/N_o threshold of 7.68 dB was used in the study to receive a BER of 10^{-7}. The results show that at 200 mm/hr, all 15 locations of study was able to receive the X-band signal on the vertical receive polarization. The Ku-band links at 145 mm/hr were only receivable on the vertical downlink polarization. At 200 mm/hr, the satellite link in the Ku-band was receivable on the vertical polarization only at Cameron Highlands, which has a high mean height above sea level. At a rain intensity of 300 mm/hr, good quality video signals in the X-bands were no longer receivable in both receive polarizations. The study concluded that the elevation angle towards the satellite is a major factor in determining the quality of the signal in the X-band. The other factors that affected the receive E_b/N_o was the polarization, depth of rain and height above mean sea level. In comparison to the Ku-band, the X-band was able to maintain a good quality satellite link in rain intensities of up to 200 mm/hr. The X-band links that did not achieve the threshold E_b/N_o of 7.68 dB in 200 mm/hr rain intensity in the horizontal polarization could achieve the threshold E_b/N_o with approximately 1.5 dB adjustment of the ULPC at the transmitter side except for two locations which had a combination of low height above mean sea level and low elevation angles. It is therefore highly possible to utilize the X-band over Malaysia for future commercial video services.

REFERENCES

1. Malaysian Meteorological Department, "Monthly rainfall over Malaysia," http://www.met.gov.my/index.php?option=com_content&task=view&id=31&Itemid=156.

2. Desa, M., M. N. Munira, H. Akhmal, and A. W. Kamsiah, "Capturing extreme rainfall events in Kerayong catchment," *10th Int. Conf. on Urban Drainage, Copenhagen Denmark*, 21–26, August 2005.
3. Timothy, P., W. C. Bostian, and J. E. Allnutt, *Satellite Communication*, 2nd Edition, John Wiley & Sons, 2003.
4. Mandeep, J. S. and J. E. Allnutt, "Rain attenuation predictions at Ku-band in South East Asia countries," *Progress In Electromagnetics Research*, Vol. 76, 65–74, 2007.
5. ANGKASA and ATSB, "Malaysia national communications satellite," http://www.angkasa.gov.my.
6. International Telecommunications Union, Radiocommunications Bureau, *Article 5 Frequency Allocations*, Vol. 1, Edition of 2008, 2008.
7. International Telecommunications Union, Radiocommunications Bureau, *Recommendation ITU–R P.618-10 Propagation Data and Prediction Methods required for the design of Earth-space Telecommunication Systems*, October 2009.
8. Elbert, B. R., *Satellite Communications Applications Handbook*, 2nd Edition, Artech House, 2004.
9. Barclay, L. W., *Propagation of Radiowaves*, 2nd Edition, Institution of Engineering Technology, 2003.
10. Abdulrahman, A. Y., T. Abdul Rahman, S. K. Abdulrahim, and M. R. Islam, "Rain attenuation measurements over terrestrial microwave links operating at 15 GHz in Malaysia," *International Journal of Communication Systems*, August 12, 2011.
11. Crane, R. K., "Prediction of attenuation by rain," *IEEE Transactions on Communications*, Vol. 28, No. 9, September 1980.
12. Charlesworth, P., "Rain fade calculations," http://www.philsrockets.org.uk/Rain%20Fades.pdf.
13. Happ, E. and C. Wolk, "Climate change," climate-change1.wordpress.com.
14. International Telecommunications Union, Radiocommunications Bureau, *Recommendation ITU-R P.839-3 Rain Height Model for Prediction Methods*, February 2001.
15. Widodo, P. S., "It is time to use the Ku-band in Indonesia," *Online Journal of Space Communication*, No. 8, Fall 2005.
16. International Telecommunications Union, Radiocommunications Bureau, *Recommendation ITU-R P.838-2 Specific Attenuation Model for Rain for Use in Prediction Methods*, November 2004.
17. International Telecommunications Union, Radiocommunications

Bureau, *Recommendation ITU-R P.837-6 Characteristics of Precipitation for Propagation Modelling*, February 2012.

18. Kitano, T., "Elevation angle of quasi-zenith satellite to exceed limit of satellite visibility of space diversity which consisted of two geostationary satellites," *IEEE Transactions on Aerospace And Electronic Systems*, Vol. 48, No. 2, April 2012.
19. International Telecommunications Union, Radiocommunications Bureau, *Recommendation ITU-R P.676-9 Attenuation by Atmospheric Gases*, February 2012.
20. Abdul Rahim, K., M. Ismail, and M. Abdullah, "Satellite link margin prediction and performance of ASTRO Malaysia," *Proceeding of the 2009 International Conference in Space Science and Communication*, October 26–27, 2009.
21. Sakarellos, V. K., A. D. Panagopoulos, and J. D. Kanellopoulos, "Noise temperature increase effect on total outage analysis of an interfered satellite link," *International Journal on Infrared Milli Waves*, 99–111, 2008.
22. "Noise in satellite links," *Belgian Microwave Roundtable 2001*, 1–10, 2001.
23. Ho, C., S. Slobin, and K. Gritton, "Atmospheric noise temperature induced by clouds and other weather phenomena at SHF band (1–45 GHz)," 90, Jet Propulsion Lab, California Institute of Technology, August 2005.
24. International Telecommunications Union, Radiocommunications Bureau, *Recommendation ITU-R P.835-5, Reference Standard Atmosphere*, February 2012.