

Rain Attenuation Modelling and Mitigation in The Tropics: Brief Review

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ABSTRACT

This paper is a brief review of Rain Attenuation Modelling and Mitigation in the Tropics. The fast depleting availability of the lower frequency bands like the Ku-band as a result of congestion by commercial satellite operations coupled with severe rain attenuations experienced at higher frequency bands (Ka and Q/V), particularly in the tropical regions which was caused by higher rainfall rates and bigger raindrop size, amongst others; it was pertinent that deliberate efforts be geared towards research along this direction. This became even more critical owing to a dearth database along the slant path in the tropical regions for use in rain propagation studies at microwave frequencies, especially at millimeter wave bands (where most signal depolarization and fading takes place). The results presented in this work are valuable for design and planning of the satellite link, particularly in the tropical regions. DAH, ITU-R and SAM model simulations along the slant-path were investigated using local rainfall data at 0.01% of the time, while making use of TRMM data from NigComSat-1 satellite to obtain the measured data for Lagos. Terrestrial attenuation data for 0.01% of the time for UTM were obtained from the UTM wireless communication center (WCC). The attenuation data were thereafter transformed to slant path using transformation technique proposed for Ku band by A. Y. Abdulrahman. The attenuation exceeded for other percentages of the average year was obtained using statistical interpolation extrapolation method. It was observed that the proposed model predicts creditably well for the ka down link frequency band, by producing the best performance when compared with SAM, DAH and ITU-R models

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1. INTRODUCTION

The weak point of satellite communication is the inability to guarantee communication during rainfall or when the line of sight (LOS) is obstructed [1]. The restrained use of millimeter bands for commercial operations in tropical countries is due to severe rain attenuation. Attenuation experienced in tropical areas is caused by considerably higher rainfall rates and bigger size of raindrops compared to other parts of the world [2]. Since the Ku frequency band (14/12GHz) has shown serious signs of depletion, research activity are now directed towards the full utilization of the Ka band (30/20 GHz), while the V band (50/40 GHz) is being considered for applications in the near future [3].

Rain fading channel is a function of frequency, elevation angle, polarization angle, rain intensity, raindrop size distribution and rain temperature. For temperate regions, the rain attenuation increases inversely with elevation angle due to large rain cell size while for tropical regions, attenuation is directly proportional to elevation angle for the same rain rate. This necessitates the need for modeling the propagation factors for tropical regions [4].

Attenuation increases with rain rate and frequency in the 10-40 GHz band in tropical regions and vertical polarization produces less attenuation than horizontal polarization at 15 (Ku), 21 (Ka) and 38 (Q/V) GHz bands [5].

According to ITU-R [6], linear polarization is better suited for atmospheric propagation effects because circular polarization is more affected by atmospheric conditions than linear polarization for high rainfall rates (greater than 12.5 mm/h) and low angles of arrival. Furthermore, the best performance of linear polarization is obtained when the signal is received vertically polarized.

However, this disadvantage of circular polarization may not be significant if compared with linear polarization transmission on or near a 45° plane [6].

The distribution of rain along the radio propagation path is inhomogeneous. Heavy rain is usually confined to a smaller area than lighter rain, and the rain cells, may in principle have any shape. If rainfall rate is measured only at a single point, it is difficult to know enough about the structure of a rain cell at some distance away from the observation point, the non-homogenous nature of rainfall may lead to incorrect estimates of the specific attenuation. The structure of rain cells can assume various shapes. For instance, it is admitted to be spherical for small size cells, while it is considered oblate spheroidal or oblate distorted for medium and large size rain cells respectively.

This is needed to indicate the best distribution model of rain falls within tropical climate which is a very important factor in the rain attenuation model simulation. Thus, the relation between the rainfall rate and the attenuation is a function of the effective path length.

Most of the studies reported in the literature have been carried out in temperate regions where solid precipitation is common, therefore there is need to supplement the meagre data available for the tropical regions in view of the importance accorded it in the classical picture of global electrification [7].

The results of data analysis carried out and reported by [9] suggests that the average fade duration might be inversely proportional to the fade depth, contrary to previous reported studies undertaken by [8], [9] and [10].

Some researchers have classified rainfalls into three as it relates to satellite communications [11]:

- i. *Stratiform Rain*, which is a widespread continuous precipitation produced by large-scale ascent due to frontal or topographic lifting or large scale horizontal air convergence caused by other means. This is when there exists the bright band.
- ii. *Convective rain*, which is a localized rapidly changing, showery precipitation produced by cumulus-scale convection in an unstable air. This is when the bright band does not exist, but any value of Z along the range exceeds a predetermined value.
- iii. *Others*, which comprise all the rain that is not included in the above categories. This is when the bright band does not exist and all values of Z along the range are less than the predetermined value.

Yet, others (in the tropics and sub-tropics) classified rain into four categories [12]:

- i. *The Stratiform rain*, characterized as a medium and low intensity of rainfall rate with longer duration and extended over a wide area.
- ii. *The Convective rainfall*, characterized as rainfall with high rain rates for short durations and extending over a small area.
- iii. *The Monsoon Precipitation rainfall*, a sequence of bands of intense convection type followed by intervals of stratiform precipitation.
- iv. *The Tropical Storm rainfall* covers large regions, larger than 100 km and may contain regions of intense convection.

1.1 Some Existing Rain Attenuation Mitigation Techniques

The key objective for implementing Fade Mitigation Technique (FMT) system should be the avoidance of static channel parameters and the design of adaptive systems that compensates for channel effects only when required, while at the same time providing the desired minimum QoS (quality of service) under clear-sky conditions.

Frequency diversity (FD) was employed Athanasios D. Panagopoulos et al (2004). He used frequency domain separation (in closed loop control) of propagation factors based on the fact that lower frequency components of the attenuation power spectrum are associated with gaseous absorption, mid-frequencies with clouds and rain, and higher frequencies with scintillations. This makes it possible to achieve the necessary separation through appropriate filtering. This is similar to one of the methods suggested by Gremont B. C. which he adjudged the most precise method in principle [13]. Frequency scaling and other methods for the detection or/and estimation of fades are usually incorporated in a control loop, similar to the one presented in Figure 3 obtained from [14].

Adaptive coding and modulation (ACM) could be used by the system by implementing, for instance, the most efficient coding rate (e.g. QPSK 9/10 with spectral efficiency of 1.788612 information bits

per symbol, ideal E_s/N_0 of 6.42dB and threshold E_s/N_0 of 7.42 dB)[15].When the link threshold is affected by rain events, the link would then switch to a less efficient but more robust coding rate; thereby adapting to the variations of the rain attenuation.

Site diversity (SD) FMT is based on the premise that the probability of attenuation being exceeded simultaneously at two sites is less than the probability of the same attenuation being exceeded at one of the sites by a factor which decreases with increasing distance between the sites and with increasing attenuation [6].Intense rain cells cause large attenuation values on an earth-space link and often have horizontal dimensions of no more than a few kilometers. SD systems can re-route traffic to alternate earth stations with consequent considerable improvements in the system reliability. A balanced SD system (with attenuation thresholds on the two links equal) uses a prediction method that computes the joint probability of exceeding attenuation thresholds and is considered the most accurate and is preferred by ITU [16].

Power control (PC) is the process of varying transmit power on a satellite link, in the presence of path attenuation, to maintain a desired power level at the receiver. Power control attempts to restore the link by increasing the transmit power during a fade event, and then reducing power after the event is back to its non-fade value [17].

Time diversity (TD) can be considered as a FMT that aims to re-send the information when the state of the propagation channel allows to be received. Oftentimes, it is unnecessary to receive the data file in real time and it is acceptable from the user point of view to wait for the end of the propagation or for reduction in traffic. This technique benefits from the use of propagation mid-term prediction model in order to estimate the most appropriate time to re-send the message without repeating the request [18].

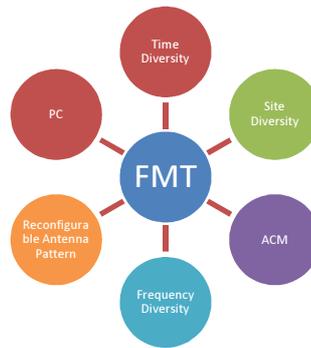


Figure 1. Some FMTs.

Table 1 Summary of some FMTs

PIMT	AVAILABILITY RANGE (% OF YEAR)	MAXIMUM ACHIEVABLE GAIN (dB)	LIMITING FACTOR
ULPC	0.01 - 10	5 (VSAT), 15 (hubs)	Earth station power range
DLPC	0.01 - 10	3 (satellite TWTA)	1. Satellite power range. 2. Does not compensate for down link fades
SBS	0.01 - 10	5 (satellite antenna)	Immature research
HC/HM	0.01 - 1	10 - 15 (E_b/N_0 range)	Simultaneous fading in many factors
DRR	0.01 - 10	3 to 9	Rate reduction intolerant applications
SD	0.001 - 0.1	10 - 30 (convective rain)	Cost
OD	0.001 - 1	3 to 10	Switching between satellites
FD	0.001 - 10	30 (between Ka and Ku)	Cost
TD	NA	NA	Not suitable for real-time applications
RAP	NA	NA	Cost, Space and complexity (antennas must be installed on-board)
ULPC: -Uplink power control		SD: -Site diversity	
DLPC: -Downlink power control		OD: -Orbit diversity	
SBS: -Spot beam shaping/On-board beam shaping		FD: -Frequency diversity	
HC/HM: -Hierar hierarchical coding/hierarchical modulation		TD: -Time diversity	
DRR: -Data rate reduction		RAP: -Reconfigurable antenna pattern	

Reconfigurable antenna pattern (RAP) is an emerging technology. It is envisaged to be implemented on the space end of the satellite communication link. It is intended to adaptively vary the-board antennas characteristic such as the gain when problems, such as signal fading, depolarization and co-channel polarization due to scattering were experienced along the satellite link. For instance, the antenna gain is expected to be increased momentarily during these events to compensate for the signal attenuation, and only

for the preset gain to be restored when the events no longer subsist. One design is a 2X2 MIMO antenna configuration. Figure 1 depicts some types of FMTs, while a summary of some their characteristics are provided in Table 1.

2. RESEARCH METHOD

There are as many as sixteen rain attenuation models in the literature [19]. The International Telecommunication Union – Radiocommunication Sector (ITU-R) model was adjudged the most widely accepted internationally for the prediction of rain effects on communication systems [12]. Hence, most emerging models are compared against it for conformity and reliability, especially for cases where measured data are not available. However, recent researches have shown that some ITU-R models are only suitably reliable in certain geographical areas [20], [21], and [22]. In view of these, we have made use of local rain rate data of 120 mm/h at $R_{0.01\%}$ obtained by [23] for Skudai campus.

DAH, ITU-R and SAM model simulations along the slant-path were investigated using local rainfall data at 0.01% of the time, while making use of TRMM data from NigComSat-1 satellite to obtain the measured data for Lagos. Terrestrial attenuation data for 0.01% of the time for UTM were obtained from the UTM wireless communication center (WCC). The attenuation data were thereafter transformed to slant path using transformation technique proposed for Ku band by [24]. For UTM data of Middle-East Asia Satellite (MEASAT) were used. The following parameters were used: -

Location 1: - Ikeja, Lagos; Satellite:- NigComSat-1; Azimuth (λ)=262.1⁰; Elevation (θ)=44.5⁰;

h_r = 4.76 km; Lat.=6.35⁰N; Long.=3.2⁰ E; $R_{0.01}$ =110 mm/h; H_s =0.038 km.

Location 2: - UTM, Skudai; Satellite:- MEASAT; Azimuth (λ)=227.56⁰; Elevation (θ)=76⁰; h_r = 4.5 km; Lat.=1.45⁰N; Long.=103.75⁰ E; $R_{0.01}$ =120 mm/h.

2.1 Simple Attenuation Model (SAM)

The SAM [25] is one of the most widely used slant-path attenuation prediction models, which incorporates the individual characteristics of the stratiform and convective types of rainfall. The model utilizes the point rainfall rate at the ground for the calculation of the attenuation time series, as follows:

$$A = \gamma L_s; R_{\%p} \leq 10 \text{ mm/h} \quad (1)$$

$$L_s = \frac{H_r - H_s}{\sin \theta} \quad (2)$$

In convective rainstorms, when $R > 10$ mm/h, the effective rain height, H_r depends on the rain rate because strong storms push rain higher into the atmosphere, and thereby lengthening the slant path [26].

To determine the slant path attenuation, a modified value of effective path length must be used, as follows:

$$A = \gamma \frac{1 - \exp \left[- \gamma b \ln \left(\frac{R_{\%p}}{10} \right) \right] L_s \cos \theta}{\gamma b \ln \left(\frac{R_{\%p}}{10} \right) \cos \theta}; R_{\%p} > 10 \text{ mm/h} \quad (3)$$

where the empirical constant $b = 1/22$;

Based on measurement data, the following empirical expressions for effective rain height H_r were derived:

$$H_r = \begin{cases} H_0; R \leq 10 \text{ mm/h} \\ H_0 + \log \left(\frac{R}{10} \right); R > 10 \text{ mm/h} \end{cases} \quad (4)$$

H_r (km) is the rain height, L_s (km) is the slant path up to rain height, H_0 (km) is the 0⁰ C isotherm height above mean sea level and its value can be obtained from the isotherm charts of the Recommendation ITU-R P.839-3 [27].

2.2 Dissanayake, Allnutt and Haidara (DAH)

Dissanayake et al. [28] model is based on log normal distribution of rain rate and rain attenuation. The model is approximately similar to the ITU-R model since the rain related input to the model is the rain

intensity at 0.01 % of the time. The model is applicable to both terrestrial and slant paths within the frequency range 4 - 35 GHz, and the percentage probability range of 0.001 – 10%.

The behaviour of the localized DAH model can be modelled by the expressions in equation (2.5), where $A_{p\%}$ and $A_{0.01}$ are attenuations for P% and 0.01% of time respectively.

$$A_{p\%} = A_{0.01} \left(\frac{p}{0.01} \right)^{-[0.655+0.033 \ln p - 0.045 \ln A_{0.001}]} \text{ dB} \quad (5)$$

2.3 International Telecommunication Union - Recommendation (ITU-R) P.618-10

The Recommendations ITU-R P.618-10 [16] was employed for comparing the measured rain attenuation with ITU-R predictions.

The step-by-step procedure for calculating rain attenuation CDF over the satellite link is as follows:

Step 1: Freezing height during rain H_R (km) is calculated from the absolute values of latitude and longitude of Earth station, as follows:

$$H_R = 0.36 + h_0 \quad (6)$$

where, h_0 (km) is the 0°C isotherm height above mean sea level and its value can be obtained from the isotherm chart of [29].

Step 2: Slant-path length L_s (km) below the rain height is given by:

$$L_s = \frac{H_R - H_s}{\sin \theta} \quad (7)$$

where H_s (km) is the altitude of Earth station above sea-level and θ (degree) is the elevation angle between the horizontal projection and slant path.

Step 3: The horizontal projection of slant-path length, L_G (km) is calculated as:

$$L_G = L_s \cos \theta \quad (8)$$

Step 4: Point rainfall rate $R_{0.01}$ (mm/h) exceeded for 0.01 % of an average year may be obtained from one-minute integration rain rate data.

Step 5: The specific attenuation $\gamma_{0.01}$ (dB/km) for 0.01 % of time is given by:

$$\gamma_{0.01} = k R_{0.01}^\alpha \quad (9)$$

Parameters k and α can also be obtained from ITU-R P.838-3 [30].

Step 6: The horizontally adjusted path reduction factor $r_{h0.01}$ for 0.01 % of the time is given by:

$$r_{h0.01} = \frac{1}{1 + 0.78 \sqrt{\left(\frac{L_G \gamma_{s0.01}}{f} \right) - 0.38 [1 - \exp(-2L_G)]}} \quad (10)$$

where f (GHz) is the operating frequency; so that the horizontally adjusted rainy slant path length is calculated from:

$$L_{h0.01} = L_G r_{h0.01} / \cos \theta, \text{ for } \rho > \theta \quad (11)$$

Otherwise,

$$L_{h0.01} = (H_R - H_s) / \sin \theta, \text{ for } \rho \leq \theta \quad (12)$$

where

$$\rho = \tan^{-1} \left(\frac{H_R - H_S}{L_G r_{h0.01}} \right) \tag{13}$$

Step 7: The vertical reduction factor $r_{v0.01}$ for 0.01% of the time is also given by:

$$r_{v0.01} = \frac{1}{1 + \sqrt{\sin \theta} \left[31(1 - \exp(-\theta/[1 + \sigma])) \frac{\sqrt{L_G \gamma_{0.01}}}{f^2} - 0.45 \right]} \tag{14}$$

And,

$$\sigma = 36 - |\phi|, \text{ for } |\phi| < 36^{\circ} \text{ or } \sigma = 0, \text{ for } |\phi| \geq 36^{\circ} \tag{15}$$

Step 8: Finally, the effective path length L_{eff} (km) through rain is obtained by multiplying the horizontally adjusted slant-path by the vertical reduction factor, as follows:

$$L_{eff} = L_{h0.01} r_{v0.01} \tag{16}$$

Therefore, the predicted slant-path attenuation exceeded for 0.01 % of an average year is:

$$A_{0.01} = \gamma_{0.01} L_{eff} \tag{17}$$

The predicted attenuation exceeded for other percentages % p of an average year may be obtained from the value of $A_{0.01}$ by using the following extrapolation [16]:

$$A_{p\%} = A_{0.01} \left(\frac{p}{0.01} \right)^{-[0.655 + 0.033 \ln p - 0.045 \ln A_{0.01} - z \sin \theta (1-p)]} \text{ dB} \tag{18}$$

where p is the percentage probability of interest and z is given by:

$$\text{For } p \geq 1.0\%, z = 0 \tag{19}$$

$$\text{For } p < 1.0\%, z = \begin{cases} 0; & \text{for } |\phi| \geq 36^{\circ} \\ z = -0.005(|\phi| - 36) & \text{for } \theta \geq 25^{\circ} \text{ and } |\phi| < 36^{\circ} \\ z = -0.005(|\phi| - 36) + 1.8 - 4.25 \sin \theta, & \text{for } \theta < 25^{\circ} \text{ and } |\phi| < 36^{\circ} \end{cases} \tag{20}$$

3. RESULTS AND ANALYSIS

A study which was carried out by K. Badron et al at 38 GHz at Universiti Teknologi Malaysia show that severe signal degradations are most likely to occur between 14:00 and 15:00 hours, while significantly less attenuation was observed from 00:00 and 04:00 hours [29]. Shown in figure 1 is the time-series plot of May 7, 2000 at 38 GHz for UTM, Malaysia; showing the highest signal degradations between 12:30 and 14:00 hours, with its peak at about 13:00 hours. This correlates the result obtained by [31].

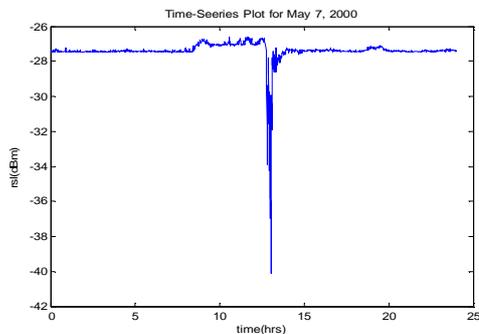


Figure 2. Time-Series plot for May7, 2000 at 38GHz for UTM, Malaysia

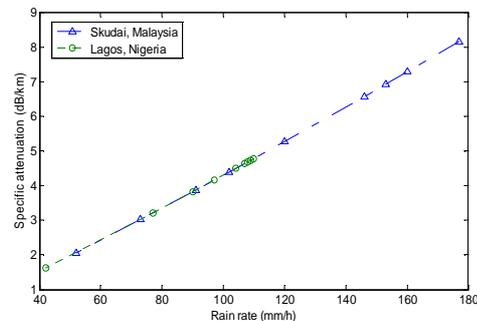


Figure 3. Comparison of plots of specific attenuation for Nigeria and Malaysia 12GHz in an average year.

The specific attenuation plots for Nigeria and Malaysia was observed to be highly and linearly correlated, despite having different rainfall rates as shown in figure 2.

Fig. 7 shows the comparison of 1-year Slant-Path equi-probable plots of attenuation CDFs for UTM at 12GHz. SAM was observed to show least performance by producing negative attenuation values (large under-estimations) for all frequencies at all percentages of time, using the same measurement data. Furthermore, it was observed that there is high degree of correlation between DAH and ITU-R models for all the frequency bands considered for slant-path attenuation for 0.01% percentages of time exceeded. This may be due the fact that the rain related input to both models is the rain intensity at 0.01 % of the time.

Additionally, the experimental model shows slight degree of correlation with the proposed model for both Lagos and UTM at 12 GHz. The poor result from the predicted model may be due to the fact that only the attenuation for 0.01% exceedance for the average year was actually obtained from measurement while attenuation exceeded for other percentages of the average year was obtained using statistical interpolation extrapolation method. The result of the simulation plots of local data for all the models under investigation (except for SAM- figure 8 (b)) shows that higher percentage unavailability translates to higher rainfall attenuation. It was further observed that slant path attenuation is linearly correlated with the down link frequency as seen in Figure 9.

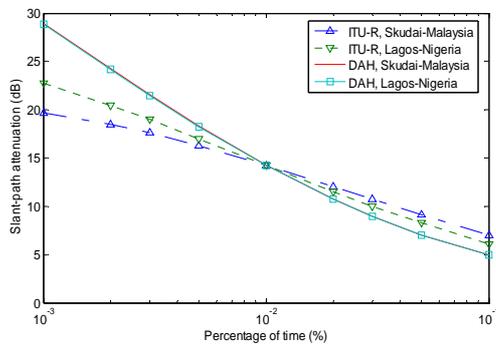


Fig.4 Slant-path Attenuation plot for Nigeria and for Malaysia at 12 GHz for 0.001% - 0.1% of the time in an average year.

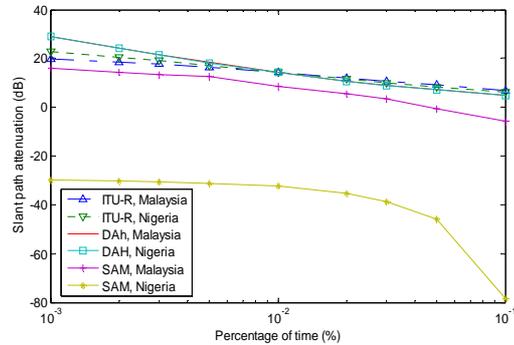


Fig.5 Comparison of slant-path attenuation plot at 12 GHz for UTM, Malaysia for 0.001- 0.1 % of the time in an average year.

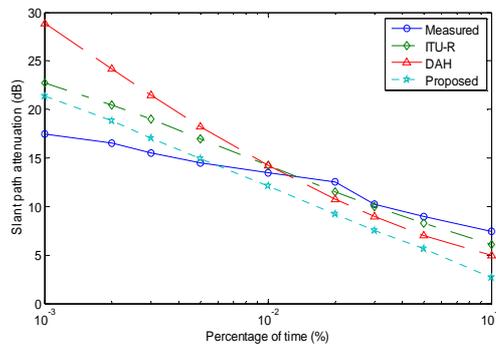


Fig. 6 Comparison of the Slant path attenuation exceedance at 12 GHz for Lagos, Nigeria.

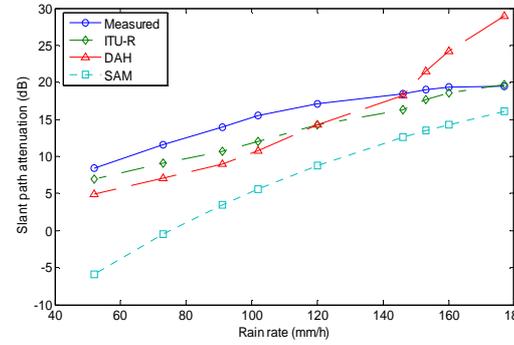


Fig. 7 Equal Probability plots of rain rate and slant path attenuation at 12 GHz for UTM, Malaysia.

Again, the experimental attenuation curve slightly under-estimated the the rain event at 20 and 40 GHz because of the experimental links used. The propagation path (the distance between the transmitting and receiving stations used in this experimental setup by UTM, Skudai, Wireless Communication Center (WCC) was 301.32 meters.

In conclusion, it was observed that the proposed model predicts creditably well for the ka down link frequency band, by producing the best performance when compared with SAM, DAH and ITU-R models as can be seen in Figure 8 (a).

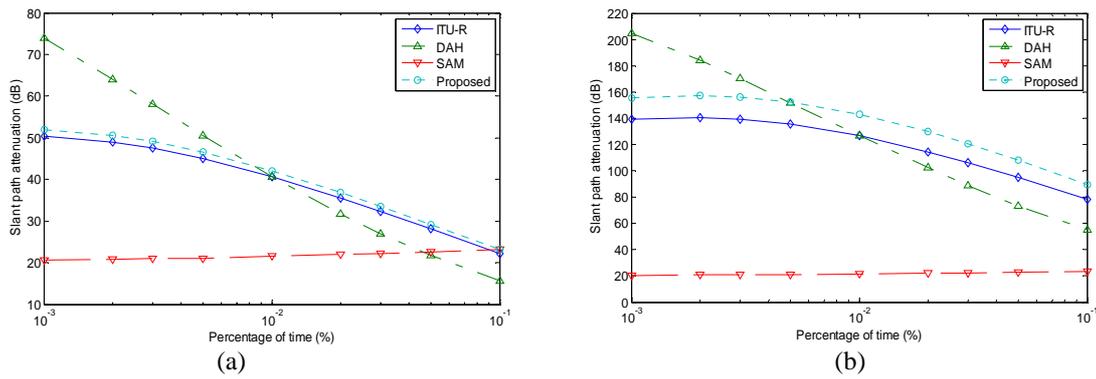


Fig. 8 Slant path exceedance for UTM at (a) 20 GHz, and (b) 40 GHz.

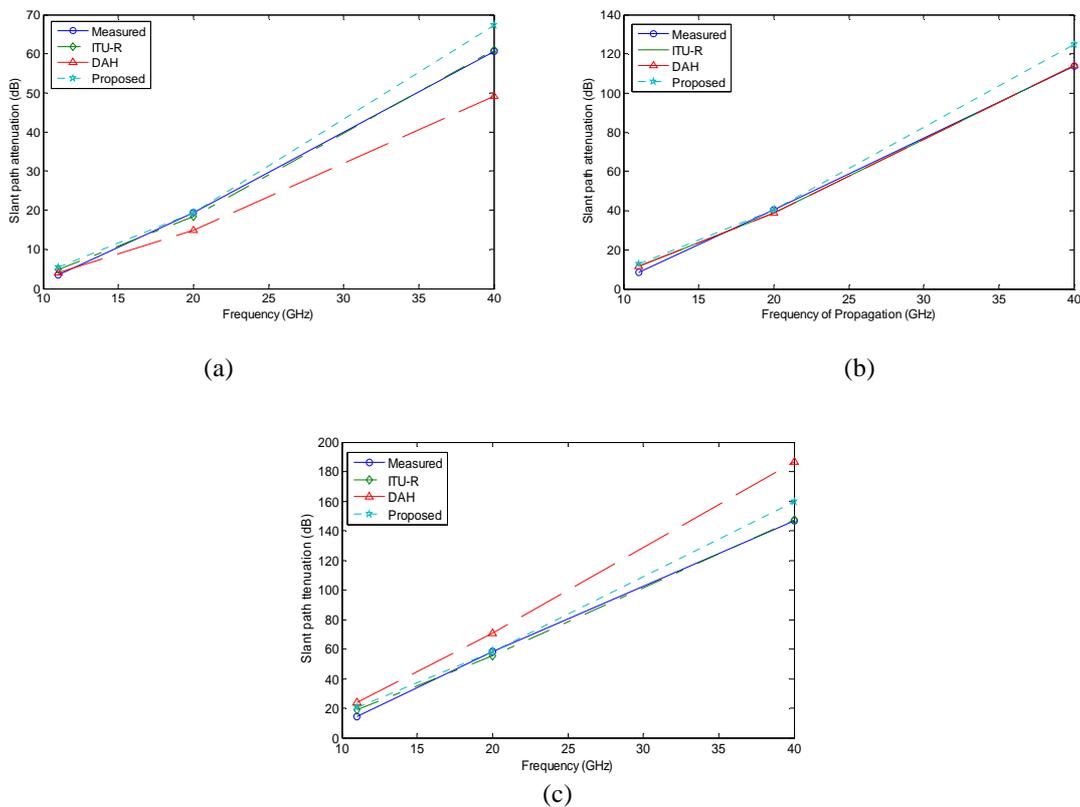


Fig. 9 Relationship between slant path attenuation and frequency for Lagos at (a) 0.1% (b) 0.01% and (c) 0.001% of time.

4. CONCLUSION

The slant path attenuation plots for both Nigeria and Malaysia exhibits lower attenuation rainfall rates and high attenuations at higher rainfall rates for 0.001%-0.1% of the time exceeded, as expected. That is, plots shows that higher percentage unavailability translates to higher rainfall attenuation. The good performance by ITU-R model may be largely due to the assumption of uniformity in the rainfall distribution along the slant path. It was observed that the DAH model produced approximately the same attenuation as the ITU-R model at 0.01% of time, because the rain related input to both models is the rain intensity at 0.01% of the time. Most of the available research studies on FMTs at high frequencies are for temperate regions, at the expense of tropical, leading to most research work being based on empirical approach. However, semi-empirical methods may have been widely accepted because it is easier to extrapolate the results to other sites, in contrast to direct measurement which is additionally inundated by high cost and time constraint required to collect statistically meaningful data.

To sum up, it was observed that the proposed model predicts creditably well for the ka down link frequency band, by producing the best performance when compared with SAM, DAH and ITU-R models.

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