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IMPROVING RAIN ATTENUATION ESTIMATION: MODELLING OF EFFECTIVE PATH LENGTH USING KU-BAND MEASUREMENTS AT A TROPICAL LOCATION

A. Adhikari[1], S. Das[2], A. Bhattacharya[1], and A. Maitra[1,*]

[1]S. K. Mitra Centre for Research in Space Environment, Institute of Radio Physics and Electronics, University of Calcutta, Calcutta, India

[2]Institute of Radio Physics and Electronics, University of Calcutta, Calcutta, India

Abstract—Rain attenuation is an important aspect of signal propagation above 10 GHz frequency. The attenuation time series generation from point rain rate measurement is crucial due to unavailability of actual signal measurements. In this paper, a simple and realistic approach has been demonstrated for better estimation of rain attenuation using Ku-band signal propagation data and ground rain rate measurements at Kolkata, India. The ITU-R model of rain attenuation has been modified by incorporating an effective slant path model. The effective slant path has been estimated and modelled in terms of a power-law relationship of rain rate data of 2007–2008. The methodology has been validated with the measured data of 2006. Comparison with ITU-R and SAM clearly demonstrates the improved predictability of the proposed model at the present tropical location.

1. INTRODUCTION

With the requirement of large bandwidths in modern satellite communication technology, it has become utmost important to move-up along the frequency bands above 10 GHz. Consequently, at Ku-band and above, satellite communication is becoming increasingly popular now-a-days for its own advantages like reduced equipment size and interference avoidance with terrestrial microwave communication

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* Corresponding author: Animesh Maitra (animesh.maitra@gmail.com).

systems. However, propagation impairments like rain attenuation is a serious concern in the design of high frequency (above 10 GHz) earth-space links as it increases severely with both rain rate and frequency [1, 2]. This situation is more critical in tropical regions where large convective rain is encountered [3]. Thus the possibility of efficient use of satellite communication in tropics demands characterization of rain attenuation and identification of suitable fade mitigation technique [3–5]. Further this type of study is also significant in modern satellite-based remote sensing of rain parameters utilizing high frequency bands [6].

Satellite signal strength measurements can provide an excellent opportunity of study and identification of suitable rain attenuation model [7] as well as fade mitigation technique. But unfortunately, actual signal measurements in tropical environment are very limited [3]. In absence of actual signal measurements, modelling of rain attenuation normally performed with the meteorological information [8]. Devising an optimum mitigation technique for earth-space links requires detailed study of different rain parameters among which rain rate, drop size distribution are the most common ones [9]. An appropriate estimation of the amount of signal degradation due to rain also demands more insight to the rain characteristics. The vertical and horizontal extents of the rain cell are two such parameters which control the amount of attenuation over terrestrial and satellite links [10]. Furthermore, rain characteristics vary with the type of rain (namely, stratiform and convective) and with the climatic zones (namely, tropical and temperate) of the globe [11, 12]. Presently available attenuation prediction models like ITU-R, SAM (Simple Attenuation Model), Global Crane Model, DAH (Dissanayake, Allnutt, Haidara) Model — all were established by utilizing the rain attenuation data from mostly different temperate climatic zones. These available prediction models exhibit significant deviation while estimating rain degradation in the tropical regions [13]. Thus the existing models are needed to be modified according to the tropical rain characteristics.

The objective of the present paper is to identify a simple approach to generate rain attenuation time series for tropical locations. In this paper we attempt to obtain the distribution of rain cell dimensional parameters (effective slant path length and effective horizontal extent) with respect to rain rates and, accordingly modify the existing attenuation prediction model for the present location by incorporating a power-law relationship between the rain cell parameters and the rain rate. Finally, the proposed model is compared with the attenuation values obtained from ITU-R and SAM model to understand its relative performance with respect to other popular attenuation models.

2. EXPERIMENTAL SETUP

Since June 2004, at the University of Calcutta, Kolkata (22°34′ N, 88°29′ E), Ku-band satellite signal of frequency 11.172 GHz has been continuously monitored from NSS-6 (geostationary at longitude 95°E) with an elevation angle of 62.5° [14–17]. The satellite signal is received with an offset parabolic antenna of 60 cm diameter. The horizontally polarized Ku-band satellite signal is down-converted to an L-band signal by using an LNBC having a noise figure of 0.5 dB. The down-converted signal is subsequently fed into a spectrum analyzer having a post-detection bandwidth of 10 Hz. The video filter output of the spectrum analyzer is recorded and stored in a computer at a sampling rate of 1 Hz by using a data logger.

To measure the ground-based rain rate, an optical raingauge, collocated with the Ku-band receiving system, have also been operated. The present study utilizes the Ku-band propagation data and the rain rate data of the period 2006–2008.

3. METHODOLOGY

Convective type of rain, often encountered in the tropical region, is a much localized phenomena in both time and space, contrary to the stratiform rain which is normally dominating in the temperate regions. In the rain attenuation prediction models like ITU-R model, a constant rain height with fixed reduction factor is assumed to calculate the slant path for attenuation calculation. The fixed slant path obtained in this way is not a good choice for the tropical region due to the presence of convective rain cells [17].

3.1. ITU-R Model

The total rain attenuation calculation based on ITU-R model utilizes a horizontal and a vertical reduction factor. The actual path length within the rain region can be different due to the presence of rain cells. Therefore, a reduction factor is introduced in ITU-R models to accommodate the variability of these rain parameters. The rain cell diameter varies due the spatial variability of rainfall. The rain height also has strong seasonal dependence. The horizontal and vertical reduction factors actually indicate the temporal variability of rain cell dimension and rain height, respectively. Therefore, the calculation of the reduction factors in ITU-R model is based on 0.01% rain exceedance probability level [18].

In ITU-R model, the horizontal reduction factor, $r_{0.01}$, for 0.01% of the time:

$$r_{0.01} = \frac{1}{1 + 0.78\sqrt{\frac{L_G\,\gamma_R}{f}} - 0.38\ \left(1 - e^{-2L_G}\right)} \tag{1}$$

where, L_G is the horizontal projection of slant path, γ_R is the specific attenuation and f is the frequency of the propagated signal in GHz. The vertical adjustment factor, $v_{0.01}$, for 0.01% of the time is calculated by,

$$\zeta = \tan^{-1}\left(\frac{h_R - h_s}{L_G\ r_{0.01}}\right) \text{ degrees} \tag{2}$$

h_R and h_S being respectively, the rain height and the height of the earth station above mean sea level in km.

$$\text{For } \zeta > \theta, \qquad L_R = \frac{L_G r_{0.01}}{\cos\theta} \text{ km} \tag{3a}$$

$$\text{Else,} \qquad L_R = \frac{(h_R - h_s)}{\sin\theta} \text{ km} \tag{3b}$$

Here θ is the elevation angle of the earth-space path in degrees.

$$\text{If } |\varphi\,| < 36^\circ\ , \qquad \chi = 36 - |\varphi\,| \text{ degrees}$$

$$\text{Else,} \qquad \chi = 0 \ \text{ degrees}$$

where, φ is the latitude of the earth station in degrees

$$\nu_{0.01} = \frac{1}{1 + \sqrt{\sin\theta}\left(31\left(1 - e^{-(\theta/(1+\chi))}\right)\frac{\sqrt{L_R\gamma_R}}{f^2} - 0.45\right)} \tag{4}$$

Therefore, the effective path length is:

$$L_E = L_R \nu_{0.01} \text{ km} \tag{5}$$

3.2. SAM Model

The simple attenuation model (SAM) [19], another popular model for attenuation prediction, incorporates the individual characteristics of stratiform and convective type of rainfall and utilizes the point rainfall rate at the ground to calculate the attenuation time series as:

$$A = \gamma L_E, \qquad R \leq 10\,\text{mm/h} \tag{6}$$

$$A = \gamma\frac{1 - \exp[-\gamma b \ln(R/10) L_E \cos\theta]}{\gamma b \ln(R/10)\cos\theta}, \qquad R > 10\,\text{mm/h} \tag{7}$$

Unlike ITU-R model, this model was initially proposed to predict rain attenuation from point rain rate measurements and thus did not require any long-term statistics of rain rate.

3.3. Proposed Rain Attenuation Model

The present location, Kolkata, being a tropical location, the nature of rain prevailing here is mostly convective. Figure 1 illustrates the earth-space communication system at the present location in presence of convective rain.

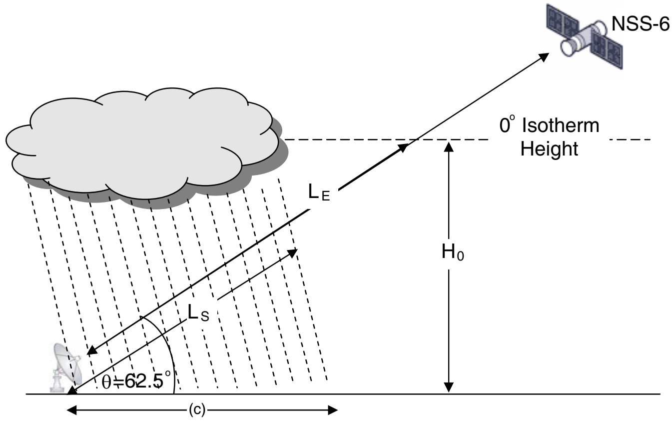

Figure 1. Schematic diagram of earth-space communication affected by convective rain.

Let L_E and X be respectively the effective slant length of the raining medium and the effective horizontal extent of the rain cell in Figure 1. The total slant path up to rain height according to the standard ITU-R model is L_s, which is obviously greater than the effective slant path through the raining medium. In ITU-R model, the effective slant path is estimated assuming a constant reduction factor which depends upon the 0.01% rain probability of the location [18]. This ITU-R model is applicable only for the calculation of annual rain attenuation characteristics. To generate a reliable rain attenuation time series, a rain rate dependent path length estimation technique is needed to be incorporated in the rain attenuation model.

Now, theoretically, the specific attenuation (γ) is expressed in dB/km and can be evaluated by using the relation [20]:

$$\gamma = aR^b \tag{8}$$

where a and b are the parameter of the power-law relation and R is the rain rate on the ground. For the present location the values of the two parameters at frequency 11.172 GHz are taken as $a = 0.01772$ and $b = 1.2140$ [8]. Consequently, the total attenuation along the path can be determined by the following relation:

$$A = \gamma L_E \tag{9}$$

Therefore, the effective slant path length (L_E) can be obtained as:

$$L_E = \frac{A}{\gamma} \tag{10}$$

Now, the effective horizontal extent of the rain cell (X) can be calculated from the horizontal projection of the effective slant path length as:

$$X = L_E \cos\theta \tag{11}$$

where θ is the elevation of the earth-space satellite signal propagation path.

In this methodology, we assume that the rain cell extensions are in the direction of the signal propagation, which is strictly not always the case. But, the rain cells will be distributed evenly if a large number of cases are considered and accordingly the effective slant path length will be varying. Since our purpose is to predict the rain attenuation based on the distribution of rain cells, a curve will be fitted with the observed values to obtain a relationship between the effective path length and the rain rate. Similarly, it is also assumed that the rain cell extents are limited within the actual slant path. This is also not very unrealistic since normally cell diameters are within a few km. Thus the result of the analysis will be realistic statistically.

Further, the rainfall is not uniform throughout the rain cell. There exists a horizontal as well as vertical variability of rainfall within the rain cell due to the presence of micro scale structures [21] and inhomogeneity of rain drop size distribution over the height range [22–24]. This type of spatial variability of rain within the rain cell is not explicitly taken into account in our calculation of the effective path lengths using Equations (10) and (11). However, when we model the effective path length as a function of the rain rate, the variability is automatically included in the formulation.

In our approach, the rain attenuation has been calculated using the ITU-R model by considering the instantaneous rain rates instead of $r_{0.01}$ and the effective path length is directly modified as a function of rain rate as discussed in the following section.

4. RESULTS AND DISCUSSIONS

In order to find out the role of L_E on the variation of rain attenuation, it is primarily necessary to examine the variation of L_E with rain attenuation. The distribution of the effective slant path length is

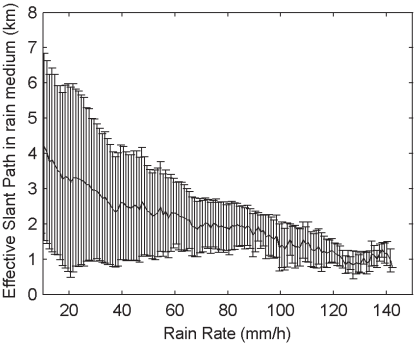

Figure 2. The variation of the effective path length in slant direction (L_E).

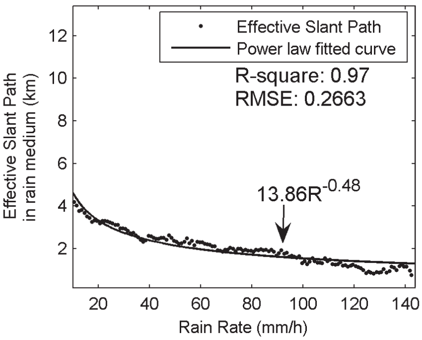

Figure 3. Power-law curve fitting of mean values of the effective slant path (L_E).

determined from the measurements of rain attenuation (A) and rain rate (R) using Equations (8) and (10). As the calculation of the effective slant path does not include the rain height information, it provides the actual extent of the rain which affects the signal.

Figure 2 depicts the distribution of L_E with R. The solid line shows the mean value variation of L_E and the vertical bars denote the ±1 standard deviation about the mean value. It is quite evident from Figure 2 that smaller rain rates are associated with greater effective slant path lengths in comparison to higher rain rates.

Figure 3 shows a power-law curve fitting corresponding to the mean values of L_E with minimum root mean square errors. The variation of L_E with the rain rate is modelled by a power-law relationship as follows:

$$L_E = 13.86R^{-0.48} \tag{12}$$

Figures 2 and 3 pertain to all the rain events of the monsoon (June to September) of the years 2007 and 2008. Similar variability as depicted in Figures 2 and 3 can be found in case of the horizontal extent of the rain cell (X) as it is linearly related to L_E by Equation (11).

5. VALIDATION

The attenuation prediction from the point rain rate is performed using the new slant path model. The performance of the new model is evaluated using the attenuation data of 2006 for the present location.

Using Equations (8) and (9), rain attenuation (A) can be estimated with the new path length model. Figure 4(a) demonstrates an event with measured and estimated (predicted) rain attenuation values for the year 2006. The deviations of the proposed attenuation model, ITU model and SAM estimated values from actually measured ones are indicated by the error plots as depicted in Figures 4(b) to 4(d) respectively. In order to provide some statistics of the errors, the standard deviations (STD) and mean of the errors have been estimated and accordingly depicted in the Figures 4(b) to 4(d). Overestimations and underestimations of the predicted values from the measured

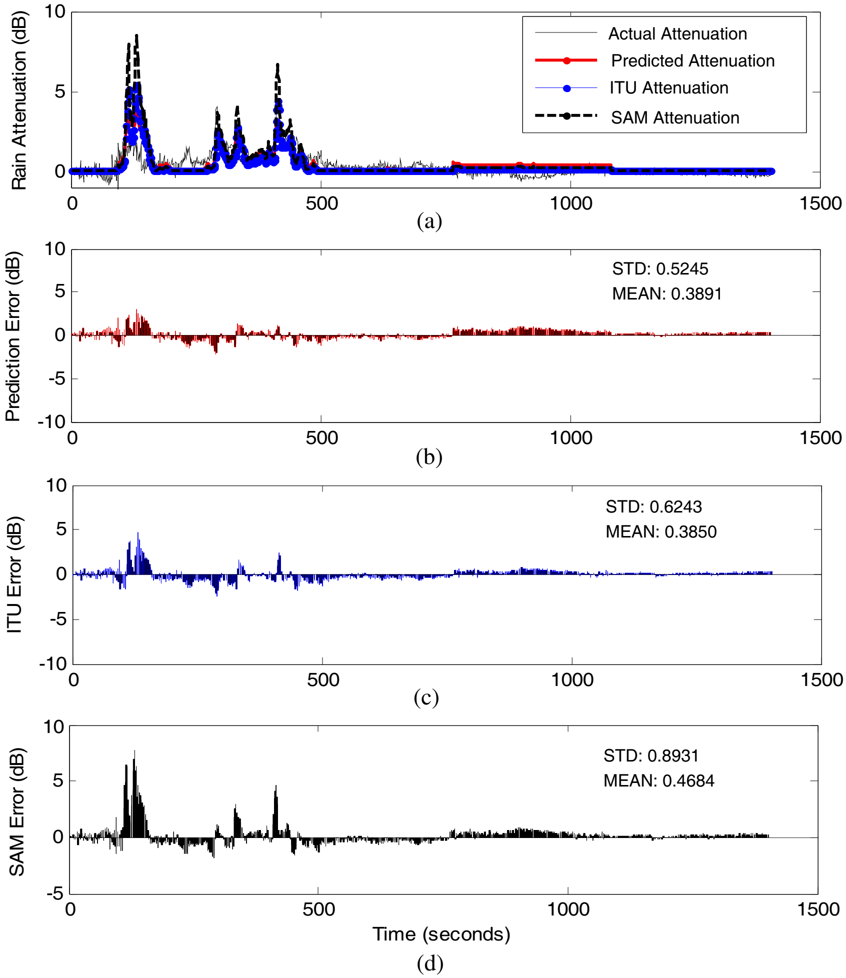

Figure 4. Example of estimated and actual attenuation for a rain event on 15 June 2006.

rain attenuation are indicated by positive and negative error bars respectively. Figures 5 and 6 demonstrate two more examples depicting the errors of the three considered rain attenuation estimation model.

Statistical investigation of the proposed rain attenuation model is pursued in three different ways. Firstly, we compared the percentage exceedances of rain attenuation derived from three different models, namely, ITU-R, SAM and proposed rain attenuation model as depicted

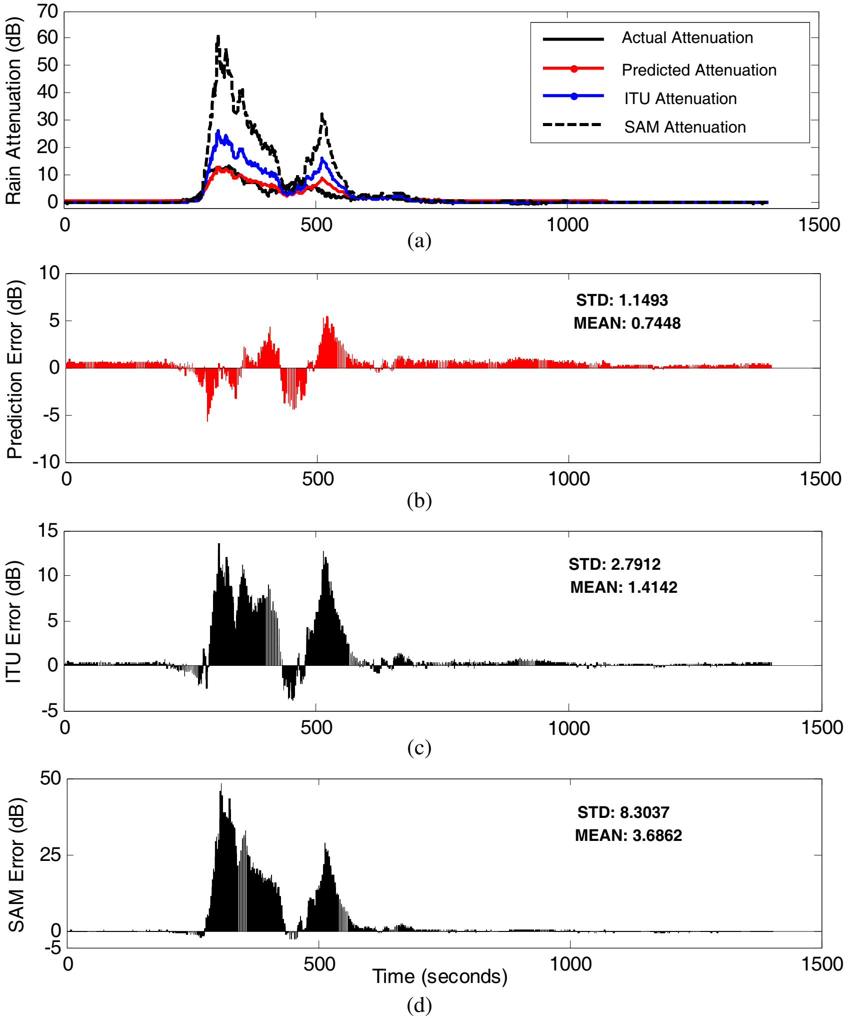

Figure 5. Example of estimated and actual attenuation for a rain event on 13 July 2006.

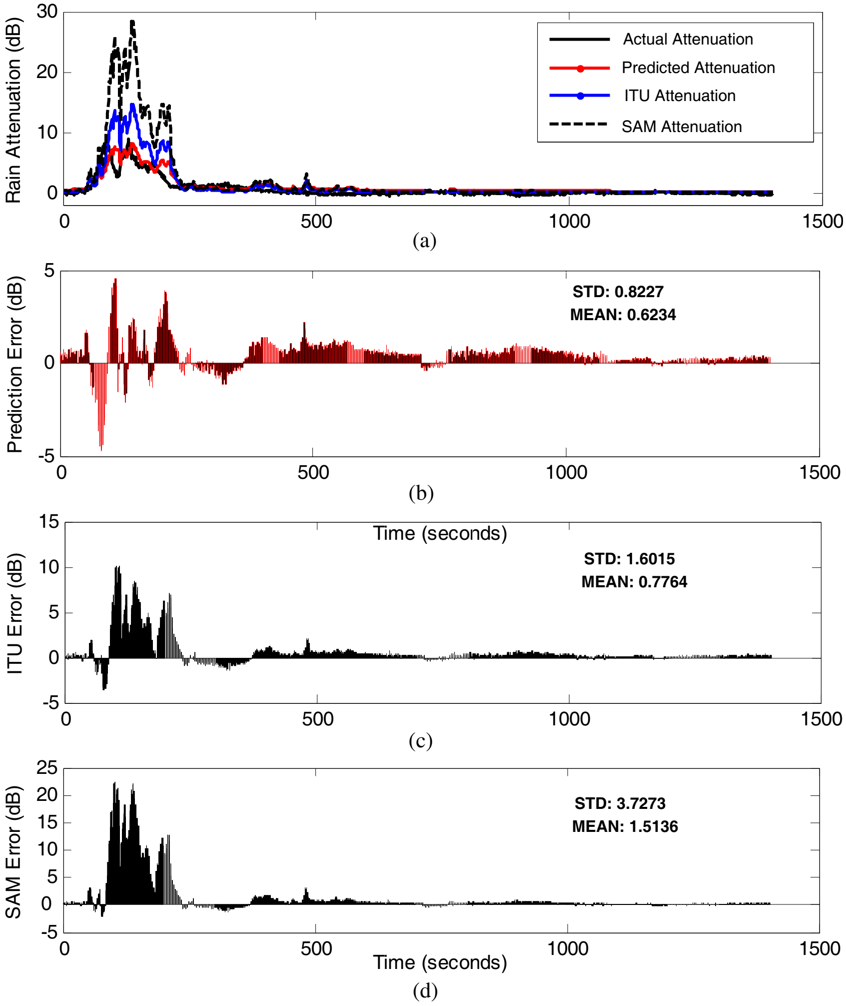

Figure 6. Example of estimated and actual attenuation for a rain event on 15 July 2006.

in Figure 7. The percentage exceedances of actual and three different model-derived rain attenuations are computed for the monsoon (June to September) of the year 2006 only. Figure 7 clearly shows that though the performance of ITU model is the best for the rain attenuation values up to about 8 dB, but at higher rain attenuations the proposed model is an improved one in comparison to ITU at the present location. However, the proposed model clearly outperforms SAM model for entire attenuation range.

Secondly, we computed the percentage occurrences of modelling errors for all the events pertaining to the year 2006 as shown in Figure 8. Here we first calculated the prediction errors for each instant using the three models. Then we estimated the frequency of errors within equal error ranges for three different models each with a bin size of 1 dB. To realize the distribution of errors, we further calculated the percentage occurrences of the errors in their respective bins. Figure 8 suggests that the proposed model is more efficient than both ITU-R and SAM which are commonly used attenuation prediction models.

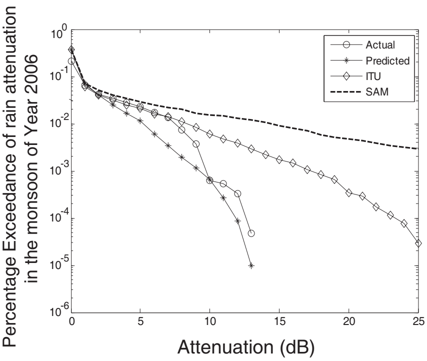

Figure 7. Comparison of percentage exceedance of rain attenuation between predicted and actual rain attenuation for all rain events of the monsoon of the year 2006.

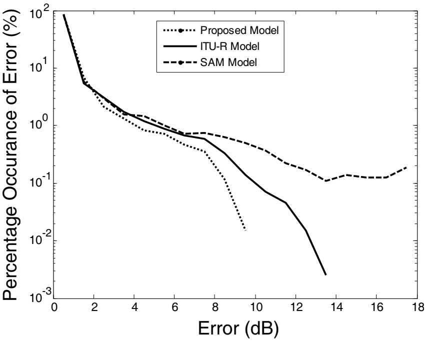

Figure 8. Comparison of percentage occurrence of errors between predicted and actual rain attenuation for all rain events of the monsoon of the year 2006.

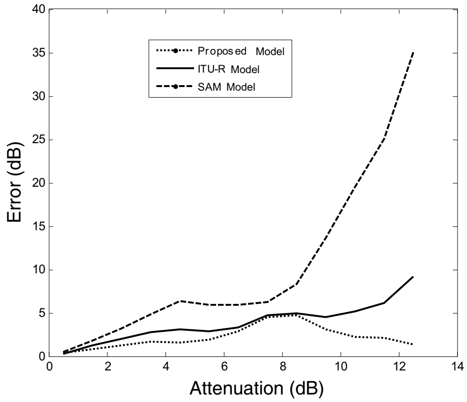

Figure 9. Comparison of average error of rain attenuation.

Finally, the mean errors of the three models have been calculated and plotted in Figure 9 for the same rain attenuation values incurred during the monsoon (June to September) of the year 2006. This figure also clearly depicts the improvement accomplished by the proposed model.

6. CONCLUSION

In this paper, a simplistic approach of rain attenuation time series generation has been demonstrated for a tropical location. The attenuation is generated incorporating the model of the effective slant path in the frame work of ITU-R attenuation prediction model. The effective slant path is modelled in power-law form. It is found that the performance of the new model is better than ITU-R and SAM for the present location as established from the percentage exceedances of rain attenuation, the percentage occurrences of the errors and the mean error corresponding to different rain attenuation values derived from three different models. Further validation of the proposed model requires satellite propagation data from other locations which we are presently lacking.

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