Slant Path Rain Attenuation Models Evaluation for Lagos at Ka Band

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ABSTRACT

This paper presented the results of evaluation of some selected rain attenuation prediction models for satellite communication links at Ka band at Ikeja, Lagos-Nigeria. These are ITU-R P. 618-12, which is the globally adopted prediction model, Simple Attenuation Model (SAM) and Bryant model. Rainfall data spanning a period of three years (January 2010 to December 2012) were sourced from Nigerian Meteorological Agency (NIMET). The ITU-R prediction model showed reliability at $p > 0.01\%$ of time exceeded, while Bryant proposed rain attenuation model exhibited good performances at $p \leq 0.01\%$ exceedances. This is quite significant because it is the range specified for commercial ($p = 0.01\%$) and military ($p = 0.001\%$) applications. Hence, Bryant model presented the overall best performances while SAM exhibited the worst performances. The results from this work will be suitable for use by satellite communication equipment designers and engineers in order to significantly mitigate against signal outages resulting from rain events.

Keywords: Attenuation, ITU-R, Rain rate, Slant path, Tropical region

1. INTRODUCTION

Rain attenuation (absorption, scattering and depolarisations) coupled with abrupt amplitude fluctuations resulting from atmospheric turbulences and rain scattering has been reported to be key factors in signal impairment; with consequence attendances in telecommunication system links' reliability, availability, and performance. This signal degradation is most apparent at frequencies above 10 GHz [1]. The slant path attenuation due to heavy rainfall had been observed to, sometimes, lead to the difficulty of separating the transmitted data from the noise signal of the receiver antenna. The intersection between rain cell(s) and the radio waves' propagation path resulting in absorption and/or scattering the transmitted signal subsequently manifests in attenuation [2]. The advancement in microwave communication technologies especially in telecommunication and broadcasting has resulted in congestion for frequencies below 10 GHz; thereby forcing microwave equipment designers to migrate to higher frequencies [3]. Although utilization of higher frequency bands for communication links provides certain benefits such as larger available bandwidths, high-speed service delivery and higher download/upload speeds, even at reduced costs [4].

Rainfalls are generally classified into convective and stratiform rain types. This classification is based on the mechanisms which prompt cooling, condensation and associated rain. Precipitation occurs in clouds not cooled down to the freezing point, through the process of coalescence while convective rains, including local storms and strong showers, occur when updrafts of hot and moist air acquire enough power; hence coalesced to produce cumulo-nimbus clouds. The raindrops which form about the same time at the bottom of the cloud are transported by the updrafts up to an altitude where their concentration increases relatively quickly and then fall back to the ground due to violent downdraft. As a result of atmospheric instability due to heat and moisture, thunderstorms are more frequent in equatorial and tropical regions [5]. Convective precipitation is associated with clouds that are formed below the 0°C isotherm and are inspired by the strong movement of air masses caused by differences in tropospheric pressure. In this process, water drops are created and grow in size, until they fall to the earth surface. The horizontal scale is of several km for durations of tens of minutes. In stratiform rains, the updrafts that maintain clouds are so weak that rain particles which form at the cloud top slowly gather and descend while increasing in size. The concept of stratiform precipitation is often used to describe rains in temperate regions. Stratiform precipitation results from formation of small ice particles aggregating to form bigger nuclei. The growing nuclei become unstable and as they pass through the melting layer, they morphed

into raindrops. Stratiform rain has a horizontal extent of hundreds of km for durations exceeding an hour. The vertical extent is up to the height of the bright band [6].

Furthermore, there is a dearth of data on direct attenuation measurement due to rainfall along with appropriate precipitation data for estimating attenuation due to rainfall in the tropical regions of the world [7]. This is because 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 augment this meager available data in view of the importance accorded it in the classical picture of global electrification [8].

Rain attenuation is defined as the product of specific attenuation (dB/km) and the effective propagation path length (km). The product of path reduction factor and the physical path length, which is defined as the ratio of rain attenuation to specific attenuation corresponding to the point rain rate. The concept of effective path length is a way of averaging out the spatial inhomogeneity of rain rate, and by extension, the specific attenuation. Since the degree of spatial inhomogeneity in rain rate generally varies with rain intensity, the variation of path length reduction factor can be expressed as a function of rain rate or the corresponding time exceedance. Hence, attenuation can be obtained from direct measurements or predicted from the knowledge of long-term rainfall rate. $A_{\%p}$ exceeded at $\%p$ of time is calculated as follow [9]:

$$A_{\%p}[\gamma(R_{\%p}), d_{eff}(R_{\%p}, d)] = \gamma_{\%p} d_{eff} \quad (1)$$

$$\gamma_{\%p} = k R_{\%p}^\alpha \quad (2)$$

$$d_{eff} = d r_{\%p} \quad (3)$$

Where $R_{\%p}$ (mm/hr) is the rain rate exceeded at $\%p$ of the time, $r_{\%p}$ is the path reduction factor at the same time percentage, d (km) is the radio path length. Parameters k and α depend on frequency, elevation angle, rain temperature and polarization and are obtained from ITU-R. Rec. P. 838-3 [10] using the following equations:

$$k = [k_H + k_V + (k_H - k_V) \cos^2 \theta \cos 2 \tau] / 2 \quad (4)$$

$$\alpha = [k_H \alpha_H + k_V \alpha_V + (k_H \alpha_H - k_V \alpha_V) \cos^2 \theta \cos 2 \tau] / 2k \quad (5)$$

1.1 Simple Attenuation Model (SAM)

The simple attenuation model [11] is one of the most widely used slant path rain attenuation prediction models; with the incorporation of individual characteristics of the stratiform and convective rain type. It employs the point rainfall rate of the location of interest to compute the attenuation time series. The major procedures are;

The attenuation:

$$A = \gamma L_S; R_{\%p} \leq 10 \text{ (mm/hr)} \quad (6)$$

Where L_S is the slant path length of the satellite's line of sight (LOS) from the ground station. Also,

$$L_S = \frac{H_R - H_S}{\sin \theta} \text{ (km)} \quad (7)$$

Where, in convective rainstorms, when $R > 10 \text{ mm/hr}$, the effective rain height, H_R depends on the rain rate. This is because strong storms push rain higher into the atmosphere, and thereby lengthening the slant path [12]. H_S is station's height above the sea level.

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

$$A = \gamma \frac{1 - \exp\left[-\gamma b \ln\left(\frac{R_{\%p}}{10}\right)\right] L_S \cos \theta}{\gamma b \ln\left(\frac{R_{\%p}}{10}\right) \cos \theta}; R_{\%p} > 10 \text{ mm/hr} \quad (8)$$

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

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

$$H_R = \begin{cases} H_0 ; R \leq 10 \text{ mm/hr} \\ H_0 + \log \left(\frac{R}{10} \right) ; R > 10 \text{ mm/hr} \end{cases} \quad (9)$$

H_R (km) is the rain height, L_S (km) is the slant path up to rain height, H_0 (km) is the 0°C isotherm height above mean sea level and its value can be obtained from the isotherm charts of ITUR. P.839-4 [13].

1.2 ITU-R. P. 618-12 Model

The ITU-R Recommendation P.618-12 [14] rain attenuation prediction model is the universally accepted method for the prediction of rain effects on satellite communication systems. Rainfall rate at 0.01% of the time ($A_{0.01}$) is the major input to this model, and the subsequent resulting attenuation at 0.01% ($A_{0.01}$) was used as the basis for estimating the attenuation exceeded at other percentages ($A_{\%p}$). However, the ITU-R model assumes a constant rain height and a fixed reduction factor in calculating the slant path. This is not a good choice for the tropical and equatorial locations, because effective rain height, H_R is known to vary with rain intensity [15]. The step-by-step procedures for calculating rain attenuation cumulative distribution function over the satellite link are as follow can be found at the ITU website and in the open literature. The effective path length L_{eff} (km) through rain is obtained by multiplying the horizontally adjusted slant path by the vertical reduction factor, and is expressed as

$$L_{eff} = L_{h0.01} r_{v0.01} \text{ (km)} \quad (10)$$

The predicted slant path attenuation exceeded for 0.01% of an average year is

$$A_{0.01} = \gamma_{0.01} L_{eff} \text{ (dB/km)} \quad (11)$$

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

$$A_{\%p} = A_{0.01} \left(\frac{p}{0.01} \right)^{-[0.655 + 0.033 \ln p - 0.045 \ln A_{0.01} - z \sin \theta (1-p)]} \text{ (dB)} \quad (12)$$

Where p is the percentage probability of interest and z is given by

$$\text{For } p \geq 1.0\%, z = 0 \quad (13)$$

$$\text{For } p < 1.0\%, z = \begin{cases} 0; \text{ for } \phi / \geq 36^\circ \\ z = -0.005(\phi / - 36) \text{ for } \theta \geq 25^\circ \text{ and } \phi / < 36^\circ \\ z = -0.005(\phi / - 36) + 1.8 - 4.25 \sin \theta, \text{ for } \theta < 25^\circ \text{ and } \phi / < 36^\circ \end{cases} \quad (14)$$

1.3 Bryant Model

The Bryant proposed model [16] employs the concept of effective rain cell and variable rain height to compute the distribution of rain attenuation at a location of interest. It uses measured rain rate, R , the station height above mean sea level, H_S , and earth station's elevation angle, θ , as the inputs to compute the attenuation exceeded for the station of interest. The probability factor (PF) parameter is calculated using

$$PR = 1 + \frac{2}{\pi} \frac{L}{D} \quad (15)$$

Where D is the rain cell diameter defined as

$$D = 340 R_p^{-1.2} \quad (16)$$

And, the horizontal projection, L is

$$L = \frac{h_r}{\tan \theta} \quad (17)$$

Next the rain height h_r is calculated using

$$h_r = 4.5 + 0.0005R_p^{1.65} (km) \quad (18)$$

And finally, the attenuation, A_s along the slant path is calculated using the expression:

$$A_s = 1.57 D_m k_n \gamma_p \frac{L_s}{\xi L + D} (km) \quad (19)$$

Where L_s (the slant path length) and γ_p (the specific attenuation) are as previously defined in Equations (5) and (2) respectively and k_n is the number of rain cells involved. That is,

$$D_m = \left(\frac{2}{\pi}\right) D (km) \quad (20)$$

$$k_n = \exp(0.007 R_p) (km) \quad (21)$$

$$\xi = \begin{cases} \frac{1}{\sqrt{2}} \exp(\sin \theta) & \theta \leq 5^\circ \\ 1.1 \tan \theta & \theta > 5^\circ \end{cases} \quad (22)$$

2. RESEARCH METHOD

2.1 Experimental Setup

Satellite measured attenuation data for the Ka frequency band (19.45 GHz) at 0.1%, 0.01% of the time exceeded were retrieved from the contour maps in the work published by Ojo et al. [17]. Similarly, measured attenuation exceedances for other percentages of the time for the average year were obtained using statistical interpolation and extrapolation methods. These data were thereafter scaled up to 26 GHz by adopting the procedures provided in ITU-R. P.618-12 [14]. Furthermore, three-year (January 2010 to December 2012), monthly, hourly recorded rainfall data were sourced from the Nigerian Meteorological Services (NIMET) for Ikeja (6.35°N, 3.23°E), a coastal station in the rain forest area in the south-western tropical Nigeria with an altitude of 38 m above sea level and annual rainfall of 1425 mm. Measurement setup at the meteorological station consists of the buck-type rain gauge to record the rain rate. Figure 1 shows the Cumulative distributions (CDs) of rain rates for various percentages of outage time for each of the years under study.

Figure 1: CD of attenuation for respective years for Ikeja

Figure 2: Scatter plots for attenuation at 26 GHz for Ikeja

Again, the scatter plots for attenuation and rain rate exceeded for the rain attenuation prediction models under investigation (SAM, Bryant et al. and ITU-R) and the measurement is displayed in Figure 2.

3. RESULTS AND DISCUSSIONS

A closer look at the comparison of the CDs for attenuation exceedances for the three models under study with measurement data (Figures 3 and 4), along with Table 1 reveals that all the models generally exhibited poor performances. However, at $p = 0.001\%$ of time exceeded, SAM showed closest match to the measurement, which is significant because this value corresponds to a maximum allowed signal outage time of 5 minutes and 16 seconds per year. Again, $p = 0.001\%$ is the ITU-R recommended standard for military use, while $p = 0.1\%$ and $p = 0.01\%$ are recommended allowed annual outages for domestic and commercial use (with 8 hrs:46 minutes and 52 mins:34 secs), respectively. Still, at $0.001\% \leq p \leq 0.005\%$, SAM was followed by Bryant and ITU-R models respectively, albeit, not closely.

Table 1 presented the comparison of mean error, standard deviation and RMS (root mean square) for different prediction models. The standard deviation of the error distribution can be defined from:

$$\sigma_{ei} = \sqrt{\frac{1}{N} \sum_{i=1}^N e_i^2 - (\mu_{ei})^2} \quad (23)$$

Figure 3: CDs of attenuation for Lagos at 26 GHz

Figure 4: Equal probability plots of rain rate and slant path attenuation for Lagos at 26 GHz

Where e_{ei} is the percentage error and μ_{ei} is the mean square error for each exceedance of time percentage; and is given by:

$$\mu_{ei} = \frac{1}{N} \sum_{i=1}^N e_i \quad (24)$$

Where i is the individual test variable and N is the total number of test variables.

The mean square error μ_{ei} and standard deviation σ_{ei} are then used to calculate the Root Mean Square (RMS) D_{ei} ; which is defined as follows:

$$D_{ei} = \left[(\mu_{ei})^2 - (\sigma_{ei})^2 \right]^{1/2} \quad (25)$$

The percentage attenuation error was determined using the expression:

$$\% \text{ Attenuation error} = \left(\frac{\text{predicted} - \text{Measured}}{\text{Measured}} \right) * 100\% \quad (26)$$

Table1. Mean error, standard deviation and RMS for each percentage of time

Variables	Prediction	0.001	0.003	0.005	0.01	0.03	0.1	0.5	1.0
	model								
Mean error μ_{ei}	ITU-R	0.0262	0.0628	0.0784	0.0963	0.1135	0.1100	0.0520	0.0029
	SAM	0.0035	0.0447	0.0689	0.1076	0.1834	0.2737	0.3099	0.3005
	Bryant	-0.0202	0.0118	0.0307	0.0611	0.1216	0.1990	0.2692	0.2902
Standard deviation σ_{ei}	ITU-R	0.7870	0.7849	0.7835	0.7815	0.7792	0.7797	0.7857	0.7874
	SAM	1.8368	1.8363	1.8355	1.8337	1.8277	1.8163	1.8105	1.8121
	Bryant	1.4996	1.1996	1.4994	1.4984	1.4947	1.4864	1.4753	1.4714
Root mean square D_{ei}	ITU-R	0.7865	0.7824	0.7796	0.7756	0.7709	0.7719	0.7840	0.7874
	SAM	1.8368	1.8357	1.8342	1.8305	1.8184	1.7956	1.7838	1.7870
	Bryant	1.4994	1.4996	1.4991	1.4972	1.4898	1.4731	1.4506	1.4425

Again, from Table 1, the ITU-R model was observed to present the best performance at $0.01\% \leq p \leq 0.1\%$ and was closely followed by Bryant proposed model. However, SAM exhibited the worst performance at this % of time.

Furthermore, according to the evaluation procedures adopted by the ITU-R P.311-15 [18], the best prediction method is that which produces the smallest values of the statistical parameters. Therefore, ITU-R model exhibited the best performances at low percentages of time exceeded (domestic applications) as can be seen on Table 1, while the Bryant proposed model presented the best matches to the measured data for both commercial and military applications.

4. CONCLUSION

This paper presented the evaluation of some of the widely acknowledged rain attenuation prediction models designed for use in the tropics. The choice of this frequency band for study (26 GHz) is deliberate as this is where the impact of rain attenuation is more pronounced. The ITU-R prediction model showed reliability at $p > 0.01\%$ of time exceeded. This indication of good performance by the ITU-R model may be largely due to the assumption of uniformity of rainfall distribution along the slant path in the formulation of this model; which may not be entirely correct for stations with low elevation angles, (which is typical of tropical stations as it is under consideration in this work). Furthermore, this is because the slant paths are much more lengthened which may thus stretch beyond a rain cell. However, at $p \leq 0.01\%$ exceedances, Bryant proposed rain attenuation model exhibited the best performances. In conclusion, the Bryant model presented overall best performances for Ikeja, Lagos, for commercial and military uses as demonstrated in statistical parameters presented in Table 1.

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