

Experimental Studies of Slant-Path Rain Attenuation Over Tropical and Equatorial Regions



A brief review.

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Propagation impairment due to rain is one of the most critical considerations for satellite communication (Satcom) links above 10 GHz. The existing studies at tropical and equatorial regions are mostly focused on rain attenuation characteristics derived from rainfall characteristics, which may not be adequate to represent actual rain attenuation characteristics. The experimental studies on the same topic are very scattered and limited over these regions. Consolidating experimental results can provide a good background for rain attenuation studies over these regions and will be helpful to validate new models as well as devise new strategies to combat high fade condition. In this article, we attempt to review and summarize the performance of different rain attenuation models validated against satellite signal measurements at tropical and equatorial locations. This will serve as a benchmark for understanding the rain attenuation characteristics over this part of the globe.

INTRODUCTION

As there is a steady push toward high-frequency bands to compensate for the quickly depleting availability of low frequencies and determine the requirements for miniaturizing device dimension using a high data rate, next-generation mobile and Satcom prefers to exploit millimeter-wave (mm-wave) frequency bands. Satcom can also efficiently provide high data capacity to digitally deprived, hilly, remote, and rural areas as well as in high-demanding urban areas. But, mm-wave transmission suffers heavily due to its inability to ensure reliable communication during heavy rainfall situations. Equatorial and tropical regions receive substantial rainfall throughout the year, and the propagation impairments are also very severe. Aggressive demands for high carrier frequencies motivate the need for a thorough, comprehensive survey of rain attenuation over this part of the globe.

Tropical climate is characterized by abundant rainfall throughout the year with a high probability of heavy rainfall due to convective rain and thunderstorms. In equatorial/tropical climates, the rainfall amount is likely to be within

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2,500–3,500 mm per year, with an average of 200 precipitation days per year. Heavy attenuation due to rain cannot be mitigated by conventional methods; therefore, novel fade-mitigation techniques are required. Designing an Earth Satcom link with assured link availability requires thorough insight about both static and dynamic rain attenuation characteristics. As rain is not spatially uniform throughout the region of interest, aggressive experimental measurements over a wide area of coverage are also required.

Link outage due to rain depends primarily on raindrop size distribution, rain rate, temperature, elevation angle, polarization angle, and frequency. The features of each of these parameters vary significantly over tropical regions as well as from features of temperate regions. The International Telecommunication Union Recommendations (ITU-R) provide globally accepted rain statistics [1] and the procedure to convert the meteorological factors to rain attenuation [2]. However, one of the reasons behind the inadequacy of ITU-R models for tropical regions is the large variability of rain characteristics [3]; this deviation becomes more significant with an increase in frequency. The ITU-Rs are based on experimental studies mostly over temperate regions and hence do not accurately represent tropical and equatorial regions.

To study the rain attenuation effect, two methods are globally used. First, if a satellite signal is available at the frequency of interest, then, by measuring the signal strength and rain simultaneously, one can model the rain attenuation characteristics of that location. This is the preferable and most direct way to study rain attenuation characteristics; however, it is very difficult due to the unavailability of long-term satellite signal measurements at these locations. Alternatively, rain attenuation is estimated with remote sensing instruments such as radar and radiometers, as well from in situ and model-estimated meteorological information like rain rate and raindrop size distribution using an analytical form of scattering theory. As an electromagnetic signal is scattered primarily by raindrops, raindrop size distribution provides a good estimation of the rain attenuation. These measurements are useful for modeling the spatiotemporal behavior of rain attenuation, provided all other necessary meteorological parameters, such as rain height, temperature, and so on, are measured/modeled accurately.

Other meteorological parameters such as gas, cloud, fog, ice, and so forth are also responsible for signal degradation. Rain also induces depolarization and scintillation on the signal; however, rain attenuation is the most dominant impairment among all of these. The primary focus of this article is on assessing the performances of existing rain attenuation models against the experimental satellite signal measurements over a tropical/equatorial region.

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SOME IMPORTANT RAIN ATTENUATION AND RAIN RATE PREDICTION MODELS

To date, a number of attempts have been made to model rain attenuation by taking into account different rain parameters. Rain rate prediction for rain attenuation study is another important part. The major issue with any model is that all of the input parameters are provided with a certain level of confidence; however, input parameters can be significantly different from the

actual characteristics of a location. For example, because specific attenuation depends on the drop size distribution, which varies widely for different locations, the coefficients also vary. Similarly, the vertical/horizontal reduction factors depend on the spatial structure of rainfall, which depends on local climatology and topography. Major rain attenuation prediction models are listed in Table 1, while Table 2, presents the rain rate prediction models. Brief discussions of these models are provided in the following sections. It is, however, to be noted that the following discussion on the models is not exhaustive.

RAIN ATTENUATION PREDICTION MODELS

The most widely accepted model for worldwide use comes from the ITU. The ITU communicates its recommendation through a publicly accessible website (www.itu.int). Large databases resulting from several propagation measurements that maintain a minimum standard at different sites across the globe are used to develop these models.

According to Recommendation (Rec.) ITU-R P.618-13 [2], the long-term rain attenuation at a location is estimated using point rainfall rate probability at 0.01% of an average year (mm/h), frequency (GHz), Earth station height, elevation angle (degrees), latitude of the Earth station (degrees), and rain height (km). Using bilinear interpolation, the mean annual 0 °C isotherm height is calculated as per Rec. ITU-R P.839-4 [4], which is related to the rain height of that location. Slant path length under rain is estimated using the elevation angle, which is further adjusted using vertical and horizontal adjustment factors. The estimation of point rainfall rate for any location is provided by Rec. ITU-R P.837-7 [1]. Rec. ITU-R P.838-3 [5] provides frequency-dependent coefficients of specific attenuation. From effective path length and specific attenuation, the attenuation exceeding 0.01% of an average year is predicted. This can further provide the attenuation exceeded for any percentage of time through the procedure mentioned in Rec. ITU-R P.618-13 [2].

Although ITU-R recommendations are accepted worldwide, at this juncture, it is appropriate to briefly discuss the other models mentioned in Table 1. The Bodtmann and Ruthroff model [6] was developed primarily to understand the signal outage when it rains on short radio paths. The model relates the distribution of point rain rate and path attenuation distribution based on U.S. weather data. The Flavin model [7] was developed

TABLE 1. RAIN ATTENUATION PREDICTION MODELS.

Model	Year	Frequency Range (f) (GHz)	Elevation Angle (θ)	Inputs	Remarks
SST [24]	1973	10–50	—	Path length, rain cell velocity, time series of rain rate, signal frequency, and polarization	The rain and melting layers are considered separately.
Bodtmann and Ruthroff [6]	1974	—	—	Frequency, fade margin, polarization, and rain rate distribution	An emphasis is placed on rain rate integration time.
Lin [11]	1977	—	—	A 5-min point rain rate, path length, and elevation angle	Originally, it was thought to be valid for long-term statistics. But it does give satisfactory results for point-to-point/short-term conversion.
Crane global [10]	1980	1–100	$\theta \geq 10^\circ$ $\theta < 10^\circ$	Rain rate, horizontal profile of rain, temperature profile, and projected path length	It helps to estimate space diversity improvement, interference due to scatter of rain, and attenuation event duration.
Maseng–Bakken (M–B) [25]	1981	—	—	Rain attenuation and point rain intensity	Only one parameter can represent the dynamic nature of rain attenuation, but it does not include spatial variability.
SAM [16]	1982	10–35	$\theta \geq 10^\circ$	Frequency, latitude, altitude, elevation angle, and rain rate	This assumes a uniform horizontal distribution for a low rain rate and an exponential distribution for a high rain rate.
Leitao–Watson [12]	1986	11–30	$\theta \geq 5^\circ$ $\theta < 5^\circ$	Point-to-path conversion factor, rain rate, and slant path length	A dual-polarized radar-observed structure of storms is used with a scattering theory.
Yamada [22]	1987	10–20	$\theta \geq 10^\circ$	A 1-min rain rate for 0.01% of time, elevation angle, and the altitude and latitude of a specific site	For 0.01% of time, it calculates rain attenuation based on characteristic length of rain size.
EXCELL [13]	1987	>20	—	Peak rain intensity, cell radius, and spatial density of rain cell	The individual rain cell and constant vertical profile of rain intensity are considered.
Garcia–Lopez [15]	1988	—	$\theta \geq 5^\circ$ Most suitable for 10–40°	Frequency, elevation angle, point rainfall intensity, latitude of the Earth station, and polarization	This introduced four coefficients (different for various regions/countries). The model shows limitation at low-elevation angles.
Karasawa [23]	1989	12–18	—	Point rain rate, frequency, elevation angle, mean temperature and relative humidity of worst month, antenna diameter, and polarization	This model is mainly proposed for propagation system having low-elevation angles.
Flavin [7]	1996	5–60	5–90°	Frequency, latitude, rain height, elevation angle, dry air equivalent height, and rain intensity	This model is applicable when the signal outage is within the range of 0.001–1%.
DAH [18]	1997	4–35	$\theta < 10^\circ$ $10^\circ < \theta < 30^\circ$ $\theta > 30^\circ$	Latitude, altitude, and point rainfall rate for 0.01%, percentage-exceedance probability value, elevation and polarization angle, and frequency	It is a very good prediction model for temperate regions, but the underestimation of attenuation predictions is observed for tropical regions.

(continued)

TABLE 1. RAIN ATTENUATION PREDICTION MODELS. (CONTINUED)

Model	Year	Frequency Range (f) (GHz)	Elevation Angle (θ)	Inputs	Remarks
Bryant [8]	2001	$f > 15$	$\theta \leq 55^\circ$ $\theta > 55^\circ$	Rain rate, elevation angle, and rain height of the station	It is valid for both tropical and temperate regions as well for high-elevation angles.
van de Kamp [26]	2002	—	—	Attenuation at three consecutive times, time interval, average attenuation, and standard deviation	It is applicable for both short- and long-term rain attenuation prediction.
Ramachandran and Kumar [19]	2006	12–18	$40^\circ \leq \theta < 60^\circ$	Frequency, elevation angle, slant path length, rain height, and so on	It considers the intersection of rain cells in high rain rate. It introduces a correction factor to modify the ITU-R model for an elevation angle of $< 60^\circ$.
Hodges and Watson [27]	2006	10–50	—	Point rain rate, raindrop size, and rain height	It generates time-series attenuation that can predict future attenuation.
Heder and Bitó [28]	2008	13–38	—	Frequency, polarization, path length, temperature, and rain rate	This model is an N-state Markov model that generates attenuation time series.
Mandeep [17]	2010	—	—	Frequency, latitude, altitude, elevation angle, and rain rate	The proposed effective path length is a power function of rain rate.
Karagiannis [29]	2012	10–30	$5\text{--}60^\circ$	Rain rate in multiple links, elevation angle, frequency, and the distance between sites	This model is an advancement of the M–B model considering both the time and spatial variability of rain for multiple satellite links.
ITU-R P.1853-1 [30]	2012	4–55	$5\text{--}90^\circ$	Latitude, longitude, the probability of rain and the corresponding probability of rain attenuation, frequency, and elevation angle	A rain attenuation time-series synthesis method for spectral characteristics, fade duration, and fade slope statistics of rain attenuations.
Yeo [72]	2014	10–35	$10\text{--}90^\circ$	Rain rate, frequency, elevation angle, rain height, and station height	It is based on Singapore data and is applicable for tropical regions.
Parabolic equation model [31]	2014	35 94	—	Rain rate, temperature, raindrop size distribution and shape	It considers the irregular physical condition of rain on the propagation path.
ITU-R P. 618-13 [2]	2017	55	$\theta < 5^\circ$ $\theta \geq 5^\circ$	Frequency, rain rate at 0.01%, station height, elevation angle, and latitude	It is applicable for frequencies up to 55 GHz and is valid for the long-term rain attenuation prediction.
Lu [32]	2018	$f \leq 15$ $f > 15$	$\theta \leq 20^\circ$ $\theta > 20^\circ$	Slant path length, path-averaged rain rate, surface point rain rate, distance between the observation site and the maximum rain rate site, elevation angle, rain height, latitude and longitude, frequency, polarization tilt angle, and altitude	This model is more reliable than other existing models and can be used for low latitudes that are within 36° S and 36° N and elevation angles lower than 25° .

based on the Australian climate. It uses the entire rainfall rate distribution of a site and a vertical path-reduction factor dependent on that. The Bryant method [8] considers the rain cell characteristics and their vertical extension explicitly to calculate the rain attenuation. The Breakpoint model (or modified Bryant model [9]), consider stratiform and convective rain separately. It

also considers the breakpoint analysis of attenuation exceedances and multiple (intersecting) rain cells along the slant path. The Crane global attenuation model [10] was developed based on point rainfall rate, spatial rainfall structure, and vertical temperature structure; however, the prediction of slant path attenuation on vertically oriented radio waves is difficult to calculate using this

model. The Lin model [11] uses a 5-min rain rate distribution for path-averaged rain attenuation estimation.

The Leitao–Watson model [12] is based on a homogeneity assumption of rain in horizontal and vertical directions during both convective and widespread rains. An exponential rain structure was used to develop the EXCELL model [13] utilizing radar observations. The SC-EXCELL model [14] was developed on the foundation of the EXCELL model [13] by considering the effect of convective and stratiform rain separately.

The Garcia–Lopez attenuation model [15] proposes the concept of a path-reduction coefficient, depending on rain spatial structure and rain data of 1-min resolution. The simple attenuation model (SAM) [16] considers exponential-shaped rain cells. The Mandeep model [17] is based on the SAM, and a power law is used to relate rain rate and effective path length. In the Dissanayake, Allnut, and Haidara (DAH) model [18], the overall attenuation absorptive part is divided into clear air and precipitation. This model also takes care of contributions from several other meteorological factors for calculating rain attenuation.

The most widely accepted model for worldwide use comes from the ITU.

The Ramachandran and Kumar model [19] is basically a modification of Rec. ITU-R P.618-8. It introduces a correction factor for calculating path attenuation beyond breakpoint. The Korea model [20], [21], developed over Korea and Japan, is a modification of Rec. ITU-R P.618-5 and P.618-8. The Yamada model [22]

focuses on the reduction of prediction errors, while the Karasawa model [23] is only applicable for the Japanese environment.

The synthetic storm technique (SST) [24] was developed to convert rain rate time series into rain attenuation time series. The frozen flow of precipitation and two layers are assumed in this model. Several other short-term and time-series models were also developed assuming stochastic processes as well as fade-slope statistics [25]–[30]. A parabolic equation-based model [31] was proposed, considering the size and shape of both spherical and ellipsoidal raindrops. In [32], a rain attenuation model was developed based on exponential rain cells with an adjusted rain rate.

RAIN RATE PREDICTION MODELS

The Kitami model [33] is based on data from 84 locations spread over tropical, temperate, and frigid regions. The model

TABLE 2. RAIN RATE PREDICTION MODELS FOR RAIN ATTENUATION STUDIES.

Model	Year	Inputs	Remarks
R–H model [34]	1973	Annual rainfall, ratio of thunderstorm to total rainfall, average number of thunderstorm days, and highest monthly rain for consecutive 30 years	This model emphasizes considerations such as heavy rain and surface rainfall.
Matricciani [35]	1990	Rain rate, Earth station altitude, frequency, latitude, and elevation angle	As the model is based on stratiform rain, it performs poorly when the rain is convective in nature.
Moupfouma [37]	1995	Rain rate exceeded in 0.01% of time for an average year, and local climatological and geographical data	A good rain rate prediction model for temperate and tropical regions.
Kitami [33]	1999	Rain rate, average total annual rainfall, thunderstorm ratio, and average number of thunderstorm days	The model can be used worldwide to predict a 1-min rain rate distribution for any percentage of time.
Crane local rain rate model [38]	2003	Cell rain rate, rain cell probability of occurrence, rain rate, and peak value of rain rate	A two-component rain rate model for the monthly/yearly distribution of rain rate prediction uses a 30-year data set for 150 locations in the United States.
Jung [39]	2007	Rain rate distribution obtained from long-term measured rainfall rate data at any integration time	This model helps in the conversion of a 1-min rain rate from any other integration time rain rate data but was found to be reliable up to a 10-min integration time.
MORSE [40]	2013	Rainfall rate exceeded for a particular value of probability, convective and total rain amount, and mean value of probability of rain for continuous 6 h	It is a global model for the prediction of spatial rainfall rate on an hourly basis and temporal rainfall rate on a monthly, seasonal, and/or yearly basis.
ITU-R P.837-7 [1]	2017	Annual rainfall accumulation and monthly average temperature collected above 2 m from the ground.	This is basically a revision of ITU-R P.837-6, in which monthly rainfall rate data are used.

requires 1-min rain data for predicting rain rate. The Rice–Holemborg model [34] considers the ratio of thunderstorm rain to uniform rain for rain rate prediction, whereas the Matriciani model [35], [36] considers both the melting and rain layers for the same. An empirical relation is described by the Moupfouma model [37] to predict the cumulative distribution of rainfall rate where a lower rain rate distribution is explained by log-normal distribution, while a higher rain rate is explained by gamma distribution. The Crane local rain rate model [38] was developed for predicting monthly and yearly distribution, while the Jung model [39] was developed for finding the rain rate for a 1-min integration time from any other integration time data. The model for rainfall statistics estimation (MORSE) [40] can be used globally for predicting rain rate. Rec. ITU-R P. 837-7 [1] provides a gridded rain rate value for a 0.01% annual probability level globally.

EXPERIMENTAL STUDIES

Signal measurement campaigns are mainly concentrated in a few countries, such as Malaysia, Singapore, India, Brazil, Thailand, and Nigeria. The locations of the studies are presented in Figure 1.

INDIA

Several efforts have been made to develop channel models in the Ku- and Ka-bands over India. The beacon data were measured from *GSAT-10* at a 11.6985-GHz frequency with a 90-cm diameter parabolic dish at KL University, Vaddeswaram, India (16°44' N, 80°60' E, 29.08 m) [41]. In this study, although the heavy rainfall was found to be short spanned, in all such instances, the signal was lost for at least 60–300 s.

Another study in Umiam, India (25°67' N, 91°55' E, 1498 m), at an elevation angle of 55°, was carried out with the help

of the *GSAT-14* satellite at 20.2 (horizontally polarized) and 30.5 GHz (vertically polarized), respectively [42]. It was found that, at the higher end of the probability distribution of attenuation, the experimental attenuation data pretty well matched the attenuation value estimated from Rec. ITU-R P. 837-5 but did not match that well at the lower end. It is concluded that only in the case of high rain rate is the attenuation mostly due to raindrop scattering. The attenuation cannot be solely attributed to raindrop scattering, it is also due to cloud absorption and depolarization effects during low rain rate.

Another experimental setup [43] was installed in Kharagpur, India (22°32' N, 88°31' E, 42 m), to receive a signal at a frequency of 11.6995 GHz from the satellite *INSAT 4CR*, and its results were compared with Rec. ITU-R P. 618-8 and the Crane global, Korea, DAH, SAM, and Garcia–Lopez models. It was concluded that, at a higher rain rate, the DAH and Korea models are more suitable for this location than the other models.

A few experiments were carried out from 2007 to 2008 in Kolkata, India (22°34' N, 88°29' E, 10 m), at the Ku-band (11.172 GHz) from the *NSS-6* satellite at an elevation angle of 62.5° with a dish antenna of 60 cm in diameter [44], [45]. It was found that Rec. ITU-R P. 618-10 was not giving acceptable results for Kolkata. Rec. ITU-R P. 618-10 was modified with a new, effective slant path calculation. The performance of the SAM model, modified ITU-R, and ITU-R were compared with actual observations, and the modified ITU-R was found to be better.

An experimental set up [46] was installed in Delhi, India (28°61' N, 77°18' E, 280 m), to receive the beacon signal in the Ka-band (20.199 GHz) from the *IPSTAR* satellite with an elevation angle of 33.3° and in the Ku-band (11.689 GHz) at an elevation angle of 55° from *GSAT-8* with a 4.6-m antenna. It is observed that the measured attenuation exceedance is



FIGURE 1. Red markers denote the locations where rain attenuation studies were carried out with satellite signal measurements.

significantly different from the Rec. ITU-R P. 618-9 predicted values in both frequencies. The slope of standard deviation variation with attenuation is also found to be different from the expected result of Rec. ITU-R P. 618-9.

BRAZIL

A satellite beacon-measurement campaign [47] was carried out at 11.452 GHz with clockwise circular polarization at four sites with different climatic conditions: Belem ($1^{\circ}27' \text{ S}$, $48^{\circ}69' \text{ W}$, 24 m); Rio de Janeiro ($22^{\circ}55' \text{ S}$, $43^{\circ}30' \text{ W}$, 30 m); Curitiba ($25^{\circ}25' \text{ S}$, $50^{\circ}43' \text{ W}$, 915 m); and Porto Alegre ($30^{\circ}03' \text{ S}$, $51^{\circ}1' \text{ W}$, 75 m). The signal was received from *INTELSAT 705*. Here, the Crane, Rec. ITU-R P. 618-7, and EXCELL models are compared on the basis of cumulative probability distribution functions. None of these models performed well for all the sites. An underestimation was found while comparing with Rec. ITU-R P. 618-7, and an acceptable result was found by the EXCELL model for Rio de Janeiro (tropical) and for Curitiba and Porto Alegre (subtropical) within a certain percentage of time (0.1–0.01%); however, an overestimation was found for Belem (equatorial). The Crane model overestimated the attenuation at the equatorial and tropical climates but approximated very well for the subtropical sites. In another study [48], rain attenuations were measured with the same satellite for the cities of Belem, Recife ($8^{\circ}04' \text{ S}$, $34^{\circ}87' \text{ W}$), and Rio de Janeiro. The results were compared considering the fade slope characteristics. The mean values were positive for all the sites and all the threshold attenuation values.

If events were separated by a threshold value of fade slope, the characteristics deviated from the Gaussian distribution with a lack of symmetry for both the increasing and decreasing sides. But, as the attenuation events were separated within ranges, the skewness of the fade slope density decreased and became flatter. The fitting with a log-normal distribution was quite good for all sites, but a slight departure at the tails of the high fade slope was observed as well.

In [49], experimental results and rain prediction models were reported based on 18 years of rainfall rate data, along with rain attenuation data over Brazil beginning in 1987. The review emphasized the necessity of location-specific rain attenuation models. A recent study [50] compared a few newly established models in addition to the common models for 10 locations in Brazil. Models like the Crane global, Ramachandran and Kumar, Yeo [72], CETUC [51], and Abdulrahman e Yussuff [52] along with Rec. ITU-R P.618-12 were studied and compared with measured results.

MALAYSIA

A receiver site [52] was established at International Islamic University, Malaysia (IIUM), Kuala Lumpur, to monitor *ASTRO/MEASAT-3* at 91.5° E with an off-set parabolic dish antenna of 2.4 m in diameter. A Ku-band (10.982 GHz) beacon signal with vertical polarization was received at a sampling rate of 0.1 Hz. The data of 0.01% exceedance of rainfall rate from a large number of tropical and equatorial stations were used to derive a new empirical formula for effective path length. Compared with the ITU-R, SAM, and Crane models, the measured

attenuation was found to be more accurately predicted by this new formulation.

An analysis of wind effect on slant path rain attenuation was investigated using the simultaneous recording of the time series of rain rate, along with storm speed, at the University of Science, Malaysia (USM), Penang ($5^{\circ}17' \text{ N}$, $100^{\circ}4' \text{ E}$) [53]. Ku-band satellite signals (12.225 GHz) were received by a 2.4-m diameter parabolic antenna from *SuperBird-C* at an elevation angle of 40.1° . The rain rate and wind speed were used to predict the time series of rain attenuation with the help of the SST model. Irrespective of rain speed values, all the predictions overestimated the experimental rain attenuation values and differed in estimating the duration, even though the pattern was correlated. In another study [54] at the same place and with the same satellite, a rain attenuation and site diversity prediction model of up to 70 GHz and for a low elevation angle was proposed. The formula was based on Gaussian distribution. An experiment [55] was done at the same site, and a model was developed to predict rain attenuation. The proposed model showed superior performance compared to the Rec. ITU-R P. 618-10 and Garcia-Lopez models.

In [56], a 12-GHz signal measurement was carried out near Kuala Lumpur ($101^{\circ}42' \text{ E}$, $3^{\circ}08' \text{ N}$, 66 m) from the *MEASAT* satellite at an elevation angle of 77.43° . In a year, more than 200 fades were observed above the 10-dB threshold and attributed to the diurnal variations of rainstorms. An empirical relationship was also proposed to find time-delay-dependent diversity gain. A two-year campaign [57] on rain attenuation was done on the campus of USM ($5^{\circ}2' \text{ N}$, $100^{\circ}4' \text{ E}$, 57 m) by collecting the *Superbird-C* satellite signal at 12.255 GHz at an elevation angle of 40.1° with horizontal polarization. A comparison of rainfall rates was done with a Rec. ITU-R P.837-4 map, and it was found that the experimental result closely approximated the Rec. ITU-R P.837-4 map predicted result. Here, the experimental result was also compared with several other prediction models like the Ramachandran and Kumar, Bryant, Matricciani, and EXCELL. Only the Ramachandran and Kumar model showed close approximation.

In [58], a Ku-band beacon signal from the *MEASAT-I* satellite was received, and a rain attenuation comparison with Rec. ITU-R P.618-5 for Bukit Jalil, Malaysia ($101^{\circ}42' \text{ E}$, $3^{\circ}08' \text{ N}$, 500 m), was done. A vertically polarized signal was received with a 1.3-m diameter parabolic antenna. Here, Rec. ITU-R P.618-5 performed best. In the same place with the same setup, another study [59] was done using parameters like rainfall rate, rain height, and the specific attenuation coefficients derived from radar measurements. Considering these parameters, the more accurate rain attenuation prediction obtained showed significant improvement over the Rec. ITU-R P. 618-12. In another study over this same location [60], a new power law coefficient was developed to improve the prediction of rain attenuation over the ITU-R prediction.

In the study by Singh and Allnutt [61], an experiment was performed in four places: USM; the Bandung Institute of Technology (ITB), Indonesia; Ateneo de Manila University (AdMU), Quezon City, Philippines; and the University of the South

Pacific (USP), Suva, Fiji. At ITB, the receiver antenna with a 2.4-m diameter was pointed at the *JCSAT-1B* satellite located at 128° E. At USP, a 1.8-m antenna was used to measure the signal from the *INTELSAT 701* located at 180° E. At USM and AdMU, a 1.8- and 1.2-m antenna, respectively, were used to obtain the signal from *Superbird-C*, located at 144° E. The corresponding beacon signal frequency for USM and AdMU was 12.255 GHz, and for ITB and USP it was 12.247 and 11.61 GHz, respectively. The rain attenuations were compared with five models: the Flavin, Garcia-Lopez, Yamada, Ramachandran and Kumar, and Rec. ITU-R P. 618-8. It was found that, for low-to-medium rain rates, all of the aforementioned models fit well with the measured attenuation values but deviated at higher rain rates. The Ramachandran and Kumar model was declared the most appropriate model for this location.

At the Universiti Teknologi Malaysia campus in Skudai (1°55' N, 103°64' E, 30 m), an experimental observation [62] was carried out for beacon frequency 11.075 GHz with vertical polarization. The signal was received from the *MEASAT-1* satellite at 91.5° E with an elevation angle of 75.61°. A complementary cumulative distribution function of attenuation, fade slope, and fade duration were derived based on the collected data. The fade duration and slope statistics were compared with Rec. ITU-R P.1623-1 [63]. Per the study, the evening hour (12:00 p.m.–6:00 p.m.) happened to be the occurrence time of the highest rain fade slope due to the presence of local convective events.

A review work [64] was carried out on data collected in various frequencies using both terrestrial and Earth-to-satellite links, along with results from some of the previous experiments. Here, annual and worst-month statistics were studied to identify reduction and frequency scaling factors to predict the total rain attenuation. Rec. ITU-R P.530-14, P. 837-6, P.838-3, and P. 581-2 were used for validation purposed.

SINGAPORE

A Ku-band beacon signal at 11.198 GHz with circular polarization was received at the Bukit Timah Earth Station (1°21' N, 103°46' E, 20 m) [65] at an elevation angle of 42.9°, together with rain rate measurements. Rec. ITU-R P.618-3, CCIR Rep 564-3 [66], and Rep 564-4 [67] were compared, and the latter provided a better estimation than did the other reports, where Rec. ITU-R P.618-3 predicted attenuation underestimated the experimental value.

The linearly polarized Ka-band beacon signals at 20.199 GHz [68] from *IPSTAR* were received at Nanyang Technological University (NTU) (1°34' N, 103°68' E), Singapore, using a 1.8-m dish antenna at an elevation angle of 71.35°. The Rec. ITU-R P.841-4 predicted rain rate at 1-min integration time showed a good match with the rainfall rate measured during the worst month of the year. However, Rec. ITU-R P.618-9 underestimated the measured rain attenuation for this place.

In another study over the same place [69], signals from the *WINDS* and *GE-23* satellites at 18.9 and 12.75 GHz, respectively, were received with elevation angles of 44.5 and 13.2°, respectively. An S-band (2.71-GHz) radar reflectivity profile was simultaneously obtained at Changi Airport, situated

32.2-km east of NTU. It was found that the calculation of rain attenuation from the Z-R (radar reflectivity–rain rate) relations using Kumar [70] and Wilson [71] matched well with the measured rain attenuation for both *WINDS* and *GE-23*. But the calculated attenuation at the time of convective rain underestimated the observed attenuation. In another study with same experimental setup [72], Rec. ITU-R P. 618-10 was modified by including a path reduction factor that depends on the elevation angle, rainfall rate at 0.01% of time, frequency, and rain height. Four models like the Yamada, DAH, Karasawa, the Ramachandran and Kumar were compared with measured rain attenuation. It was found that the Ramachandran and Kumar model was the best and the Yamada model was the worst predictor in this case. The DAH model failed at the time of convective rain. Rec. ITU-R P.837-5 performed very well with locally measured data.

In another experimental observation [73], attenuation was measured at the Ku- and Ka-bands at NTU (1°20' N, 103°40' E). The Ku-band signals were received from *INTELSAT 602*, with the Ka-band signals from both *IPSTAR* and *WINDS*. For *IPSTAR*, *WINDS*, and *Intelsat*, the receiving antenna diameters were 1.8, 1.8, and 3 m, with the polarization of left-hand circular polarized, right-hand circular polarized (RHCP), and RHCP, respectively. The corresponding elevation angles were 71.3535, 44.4644, and 42.9431°. This article proposed the modification of Rec. ITU-R P. 618-9, taking a new path-adjustment factor into consideration.

THAILAND

The measurements were performed at King Mongkut's Institute of Technology Ladkrabang (KMITL) (13°7' N, 100°6' E, 20 m), Bangkok, Thailand, at 12.7 GHz and a 54.6° elevation angle [74]. The rain attenuation was found to be 20 dB at KMITL when the rain rate was 120 mm/h. In a study [75] at KMITL with the same experimental setup but at a different frequency, namely, 12.594 GHz, a comparison of the results of the cumulative distribution of rain attenuation with Rec. ITU-R P. 618-9 and the Crane model was done. Up to the rain rate of 60 mm/h, Rec. ITU-R P. 618-9, P.837-4, and P. 311-11 performed well but failed above that rain rate. At the same site, with the *JCSAT* satellite, another study [76] at 12.7 GHz showed that a yearly cumulative distribution with an integration time of 10 s and 1 min did not agree very well with Rec. ITU-R P.837-3. The Crane global model and Rec. ITU-R P.837-3-based H-rain zone attenuation, on the other hand, matched closely with the measured rain attenuation.

Another finding was that, for a rainfall rate of more than 200 mm/h, the integration time became an important parameter to obtain an accurate intense rainfall rate as well as an accurate attenuation value. In a separate work, a one-year measurement [77] of rain attenuation at 12.594 GHz (horizontal polarization), using the *THAICOM 3* satellite with a 0.5-antenna at KMITL, was made with experimental rain rate measurements at the National University of Laos (NUOL) (17°95' N, 102°6' E, 30 m), Vientiane, and at Paksong (15°16' N, 106°21' E, 70 m). It was observed that Rec. ITU-R P.837-4 zone N was applicable at NUOL.

A satellite beacon-measurement campaign [78] at 12.594 GHz (horizontal polarization) from *THAICOM 3* located at 78.5° E was carried out at three sites: KMITL at a 59.8° elevation angle, Vientiane at a 55.3° elevation angle, and Paksong at a 53.5° elevation angle. The experimental results of attenuation for all three sites were compared with models, such as Flavin, Garcia-Lopez, Bryant, and Rec. ITU-R P. 618-7. For a certain percentage of time (such as 0.01–1% of the time), Rec. ITU-R P. 618-7 showed acceptable results (tending underestimation) in all three locations. The Flavin and Garcia-Lopez models followed the same trend of underestimation between 1 and 0.001% of the time for all three sites.

NIGERIA

Measurements [79] at the 12.245-GHz frequency from the *NIGCOMSAT-RI* satellite at 36.0° E were performed at seven locations: Akure (7°257' N, 5°2058' E, 350 m); Lagos (6°35' N, 3°2' E, 380 m); Abuja (9°0765' N, 7°3986' E, 840 m); Jos (9°8965' N, 8°8583' E, 1,217 m); Port Harcourt (4°8156' N, 7°0498' E, 16 m); Makurdi (7°7322' N, 8°5391' E, 104 m); and Nsukka (6°8429' N, 7°3733' E, 552 m). The measured rain attenuations were compared with the SST model and Rec. ITU-R P.618–10. The rain attenuation exceedance values calculated by Rec. ITU-R P. 618-10 were closely approximated by the measured data and SST model below the value of 2 dB. However, above 2 dB, Rec. ITU-R P. 618-10 overestimated the actual rain attenuation. The SST model was found to be better attenuation prediction model in this case.

In another measurement [80] over Ota (6°7' N, 3°23' E), vertically polarized 12.245-GHz signals from the *Astra* satellite were received. It was found that the observed rain attenuation can be well approximated by Rec. ITU-R P. 837-4, as explained in the ITU-R-defined Q region instead of the P region.

The rain attenuation models were compared for the rainforest area of Lagos (6°35' N, 3°2' E, 380 m) [81], a coastal station in southwest Nigeria. The vertically polarized 12.437-GHz beacon signals from the *Eutelsat W4* satellite were monitored and recorded. The measured data were compared with models like the SAM, SST, Bryant, and Rec. ITU-R P. 618-11; however, none of them matched with the measured data for all the percentages of time, even though, after a certain percentage of time exceedance, Rec. ITU-R P. 618-11 followed the measured data closely. At a 99.999% link availability, the SST exhibited the best performance. Another experimental setup [82] was installed at the Federal University of Technology, Akure (7°170' N, 5°180' E, 358 m), with a 90-cm offset parabolic antenna, receiving horizontal polarization at 12.245 GHz at a 53.2° elevation angle. A comparison of Rec. ITU-R P.837-6 and models like the Kitami, R-H, and Moupfouma was performed. Among the four models compared, only the Moupfouma closely approximated the experimental values of rain rate over this place.

DISCUSSION AND CONCLUSIONS

Satcom in millimeter/microwave frequency bands can be used as the back-end support for high network coverage anywhere

and at any time; however, the prediction and mitigation of rain attenuation are essential to ensure communication during heavy rainfall situations. As rainfall is more probabilistic than deterministic over any locations, designing satellite links needs more experimental data to quantify rain attenuation accurately on the communication paths that are valid for both tropical and temperate regions. This article focused on gaining further insight into the performance of the existing models and opens up scopes for future work.

In general, none of the models was suitable for all locations and percentage-exceedance levels; however, both the ITU-R and DAH models are more satisfactory than are other models, especially for low rain rate. The Breakpoint models, considering the stratiform and convective rain, also performed well. Models like the Moupfouma, Flavin, Ramchandran and Kumar, and Garcia-Lopez also matched with the experimental data for different exceedance-probability ranges.

Another important observation is that the characteristics of the rain attenuation differed significantly from those of the temperate regions. The fade slope characteristic showed a tendency to have positive mean values for all regions (tropical and equatorial) and for all attenuations. The performances of the models were also strongly dependent on the integration time of rainfall measurement. The applicability of these models was significantly varied among tropical, subtropical, and equatorial regions. Rain attenuation due to absorption was an important factor at the high end of the rain rate distribution. The incorporation of local meteorological considerations, particularly the varied rain structure of stratiform and convective rain, improved the performance of these models.

The limited number of experimental analyses of beacon measurements in tropical countries thus far suggests that propagation impairment models used in temperate regions have limitations over tropical parts of the world. Further studies are required to gain a better understanding of rain structure, path-reduction factor, and types of rain. Most of these previous studies were done in the Ku-band and only limited attempts were made in the Ka-band. Moreover, the number of studies were concentrated on a few locations, and vast areas of tropical/equatorial regions are unrepresented. Studies on fade-mitigation techniques, particularly diversity techniques and dynamic rain attenuation characteristics, are also significantly less. These are some of the areas in need of urgent attention.

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