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Proposed Model for Radio Wave Attenuation due to Rain (RWAR)

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Abstract

Radio wave attenuation is primarily caused by the absorption of a radio signals by some atmospheric phenomenon like rain, snow or ice, clouds, dust etc. These losses are more prevalent in the frequency ranges above 10 GHz. Attenuation caused by rain is not only limited to satellite up-link and down-link but it can also affect the point-to-point terrestrial microwave links above 10 GHz. This paper briefly discussed about the work done by researchers at different parts of the world regarding the attenuation caused by the rain for higher frequencies. It then proposes a mathematical model for prediction of radio wave attenuation due to rain. The implementation results of proposed model were also compared with the ITU-R model.

Keywords Radio wave propagation · Rain attenuation · Rain fade · Satellite communication · Terrestrial communication

1 Introduction

Various models developed on rain attenuation show that the distribution of rain is inhomogeneous along the path of radio waves, it has been observed that attenuations due to rain and gases at higher frequencies are significant. The heavy rainfall is usually confined to smaller

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areas and have shorter span of time as compared to lighter rain. The rain attenuation is also dependent on the uncertainties of rainfall rates and rain cells size. There are different mathematical models present in order to predict the radio wave attenuation due to rain. Some of them are discussed in details in next section.

1.1 ITU-R Model

The recommendations ITU-R developed by the International Telecommunication Union, Rec. P. 618-10 is the mostly used model world wide for predicting the attention caused by rain in satellite communication [1].

For 99.99% fade depth attenuation is given by:

$$\mathrm{Att}_{0.01} = \mathrm{kR}^{\alpha}\mathrm{dr\ dB} \tag{1}$$

where R is given by 99.99% of rain rate for particular geographical area in mm/h, kRα is the specific attenuation in dB/km and d is the link distance in km. The formula for r is given as:

$$\mathrm{r} = 1/(1 + \mathrm{d}/\mathrm{d0}) \tag{2}$$

where

$$\mathrm{d}_0 = 35\mathrm{e}^{-0.015\mathrm{R}}\ \mathrm{km} \tag{3}$$

where d0 is the effective path length and r is called the distance factor. K and α are the regression coefficient for frequencies and polarization [1].

1.2 Simple Attenuation Model

In order to predict the attenuation caused by rain simple attenuation model [2] has been proposed. It was effectively based on 10–35 GHz. The attenuation due to rain can be calculated by:

$$A = \gamma \frac{1 - e\left[-\gamma b ln\left(\frac{R_{\%p}}{10}\right)\right] L_s Cos\theta}{\gamma b ln\left(\frac{R_{\%p}}{10}\right) cos\theta} R_{\%p} > 10\ \mathrm{mm/h} \tag{4}$$

where L_s is called slant path in km, θ is elevation angle in degree which was between the slant path and horizontal projection. Specific attenuation is calculated by the formula $\gamma = k\left(R_{0.01}\right)^{\alpha}$ (dB/km), empirical constant is given by b = 1/22.

Following expression for effective rain height H_R based on calculated data can be obtained as,

$$H_R = \begin{cases} H_0; & R \leq 10\ \mathrm{mm/h} \\ H_0 + log\left(\frac{R}{10}\right); & R > 10\ \mathrm{mm/h}. \end{cases} \tag{5}$$

1.3 García-López's Method

A simple method developed by García-López et al. [3] by inserting different parameters. This model calculated the values of rain attenuation by using different coefficients for tropical region as shown below

$$A = \frac{kR^{\alpha} L_S}{\left[a + \left\{ \frac{L_S(bR + CL_S + d)}{e} \right\}\right]} \tag{6}$$

where R denotes amount of rainfall in mm/h, k and α are the coefficients based on parameters like frequency, polarization, and elevation angle, a, b, c, d, e are constants values given by the model, and L_S (km) is the slant path up to rain height. In expression (6), e is a scaling factor of rain attenuation and by taking $e = 10^4$, worldwide coefficients: a = 0.7, b = 18.35, c = − 16.51, and d = 500 (based on geographical area). For tropical climates, a = 0.72, b = 7.6, c = −4.75, and d = 2408. In this model, the rain height H_R is given by,

$$H_R\ (\text{km}) = \begin{cases} 4.0 < |\varphi| < 36^\circ \\ 4 - 0.075(|\varphi| - 36^\circ \end{cases} \tag{7}$$

where φ denotes latitude of the earth station and are calculated in degrees.

1.4 Brazil Model

This model was developed for different rain distribution [3]. Attenuation is calculated by:

$$A_p = k\left[1.763R^{0.753+0.197/L_S cos\theta}\right]^{\alpha} \frac{d}{1 + \frac{d}{119R^{-0.244}}} \tag{8}$$

where elevation angle is denoted by θ.

1.5 RAL Model

A proposed model given by Rutherford Appleton Laboratory (RAL) [3] for rainfall rate measurements which is used to develop a new model to demonstrate number of events of given time frame with rainfall having specific thresholds. The comprises rain rate measurement of 3 years data using three rapid response rain gauge and space size 200 m apart. All the measurements were carried out at Chilbolton, Hampshire (ITR-U) having sampled at 10 s intervals. The power law model and lognormal model were consider in this approach.

Attenuation can be calculated by

$$A = kR^{\alpha} dr(R, d) \tag{9}$$

$$\text{r} = \frac{1}{0.874 + 0.0255\left(R^{0.34} - 1.7\right)d^{0.7}} \tag{10}$$

Table 1 Different parameters used in rain models

S.No	Model	Parameters
1	ITU-R [1]	k, α, d, R, f
2	SAM [2]	k, α, L_s, θ, b, H_r, R
3	Gracia-Lopez [3]	k, α, L_s, R, f, θ, a, b, c, d, e, scaling factor, H_r
4	RAL [3]	k, α, d, R
5	Brazil [3]	k, α, R, f, θ

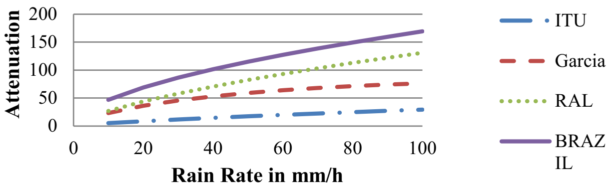


Fig. 1 Comparison of various rain models

where d is the path length in km, r(R, d) is path length reduction factor, A is in dB, k and α are regression coefficients. d is path length in km.

Different above discussed models are used for the prediction of rain attenuation like crane, ITU-R, Brazil, DAH etc. The models discussed above uses different parameters. Tabular representation of different parameters are shown in Table 1.

Comparative study of implementation of some rain attenuation models like ITU, Gracia, RAL and Brazil are presented in the Fig. 1. Common parameters are used in the implementation of these models are R is in mm/h, F in 60 GHz, d is 1 km. Elevation angle of 45° is used while implementation of the models. From the implementation results it has observed that ITU-R model give best results as compare to the other models.

2 Rain Attenuation in Terrestrial Links

The work done by Ulaganathen et al. [4] describes the overall comparative study of various other attenuation models proposed by researchers specially for tropical zone. Results from experiments has shown that they are useful for researchers and engineers in decision making for predicting the attenuation due to rain at different zones of tropical environment. It has also be observed that results obtained from the model proposed by ITU-R, are underestimates for higher frequencies.

Another research has been carried out by Tamošiūnaitė et al. [5] for the region of Lithuania. The relationship obtained from experimentation between the rain rate date of 1-min data and the real time values of rain rate observed for longer duration are used. It has also been observed that the mathematical calculation of specific attenuation caused by rain by using the real time data are two times higher than the attenuation calculated using ITU-R model.

In the work done by Semire et al. [6], 2 year rainfall rate data at the region of Ogbomosho station have been used in order to study of integration time effect on cumulative distribution of rain rate. It has been observed that different factors of conversion are required for different scenarios even for the same climatic zones for the conversion from one integration time to another as against the ITU-R unified time integration regression coefficients.

An analytical study has been carried out for the measurement of distributed fade slop which was obtained from rain attenuation values, measured at the site of Eindhoven University of Technology from the satellite Olympus Max van de Kamp [7]. It has been found that standard deviation parameter is directly prepositional to attenuation and depends on the type of rainfall. It has also been observed that fade slope deviation depends on elevation angles and on climatic conditions.

The experimental study done by Obiyemi et al. [8], conversion coefficients are obtained for predicting the equivalent 1-min rain rate statistics available from 5 to 30-min over Akure, South-Western Nigeria. From the observed coefficients derived for Akure, the 5-min conversion provides a more satisfactory results and hence more suitable for predicting the 1 min rain rate for the region of Akure.

The drop size distributions (DSD) of rain are calculated with the help of instrument called disdrometers at various climatic zones of Indian subcontinents [9]. The results observed from the experimental studies were used to understand the different patterns of rain.

The work done by Ulaganathen et al. [10] shows the preliminary results obtained from effects of rain at 23 GHz point-to-point terrestrial 1.3 km long communication link. A solution which was based on frequency variation has been proposed in this work. Another radio link was placed parallel to the main link which was based on frequency ranges not affected by the rain. This experimentation provide the effective solution for the outage condition due to the different rain rate.

The parabolic equation model for predicting radio wave attenuation at mm waves which was based on the effective permittivity is developed by Sheng et al. [11], by modifying the refractive index. Finally, the model is simulating the propagation characteristics of millimeter wave in different geographical regions which has irregular terrain and sea surface are rough in nature, and in complex environmental conditions of standard atmosphere conditions like rain and fog.

In the work [12], author has observed the effects of rain on radio wave propagation. It has been observed that the localized behaviors of rain affect the rain attenuation at both rain rates and path distance.

In order to design a satellite communication link for the frequency ranges of above 10 GHz, 1 min rain rate statistics are important [13]. There is a need for the prediction model for attenuation cause by rain to overcome the degradation in radio signal.

Experimental study shows that different parameters for calculating DSD's affects the radio wave propagation [14]. Regression coefficients k and α in specific rain attenuation formula $\gamma = kR\alpha$ where R is rain rate in mm/h which is derived from the experimentation. From the experimentation it was observed that drop size distribution differ significantly at given two sites.

Experimentation for 60 GHz millimeter wave has been done [15]. The purpose of this experimentation is to find the main objective of this experimentation is to identify the relationship between measured specific attenuation caused by rain and the rainfall rate for the radiowave signals. It has been observed from the experimental study that observed results were higher than results obtained from ITU-R model.

An overview of the ITU recommendations which was based on error and performance objectives is described in the work [16]. In this work both the fade margin and link power budget observations are presented. In this study both the polarization scaling method and ITU-R frequency scaling method and proposed path length scaling method are presented.

An improved version of the EXCELL has been proposed in order to predict attenuation due to rain [17]. With the help of this improved rain model the prediction of rain attenuation from both convective and stratiform rain can be calculated.

Another experimental study has been presented for 50 GHz in which it has shown that there is a relationship exists between attenuation caused by rain and observed scintillation was performed slant path attenuation [18]. This study was based on the probability density function (PDF) for different parameters of scintillation.

For prediction of attenuation caused by rain was presented in this work [19]. The proposed model was based on Mie theory based on scattering phenomenon of electromagnetic wave by assuming that the spherical nature of raindrops. The attenuation caused by rain is modeled by integrating the extinction power-law model over different DSD models.

Rain attenuation leads to degradation in the received strength (C/No) of a signal in Ka Band and in turn deteriorates the performance of the communication satellite systems. Therefore, it is necessary to estimate the expected rain attenuations accurately to design a satellite link in this band [20]. Various process [21] have been designed for optimum design of satellite system to understand the limitation of radiometric measurements [22], specific attenuation has been computed at different mm wave frequencies and its variation as a function of rain rate and frequencies have been assessed [23], the variability of specific rain attenuation in mm wave region is described which shows less attenuation of radio signals at 100 GHz compared to 60 GHz during heavy rainfall event beyond 30 mm/h [24]. Millimeter wave (mmWave) communication is a key technology for fifth generation (5G), the studies [25–29] show the impact of rain attenuation in millimeter wave model at various frequencies. The work in [30] presents the results of rain attenuation measurement using radar data collected. The statistical analysis showed that ITU-R P 530-16 has significantly addressed the problem of rain attenuation, although point accuracy is far-fetched in reality, more improvement is needed on the model so as to address its insufficiency in tropical and equatorial rain attenuation estimation.

From the above literature survey of radio wave attenuation caused by rain some conclusions are made. From some field experimentation results obtained are higher as compared to predicted results for ITU-R Model. It has also observed that fade slope deviation is dependent on elevation angle and climatic conditions. Some researches has concluded that different patterns of rain are depends on different geographical locations. The localized behaviour of rain affects the rain attenuation at both rain rate and path distance. There is a relationship exists between rain attenuation and scintillation. From Table 1 it has also observed that common parameters used to predict rain attenuation are regression parameters k and α, frequency in GHz and rain rate in mm/h. But the problem faced by researchers and engineers are to calculate regression coefficients which are related to frequency. An empirical model for the prediction of radio wave attenuation due to rain are proposed in the next section.

3 Proposed Model

It is observed that the ITU-R rain model is very complex in nature and purely depends on the regression coefficients α and k, these coefficients are frequency dependent and in order to predict the attenuation due to rain the values of these coefficients need to be known which tedious task to calculate. In order to predict attenuation due to rain a mathematical model (RWAR) is introduced in this section. This model is used for both vertical and

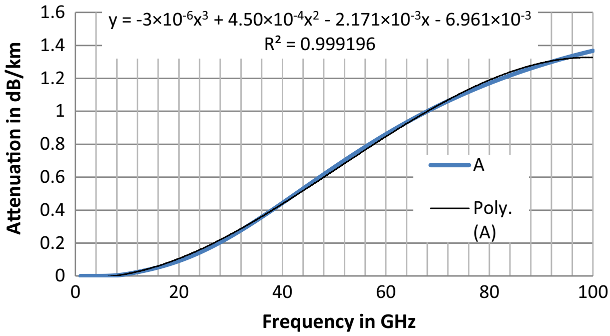


Fig. 2 Approximation curve for frequency versus specific attenuation for 1 mm/h

Table 2 Different values of constants at different rain rate

Rain rate (mm/h)	a	b	c	d
1	-2.952×10^{-6}	4.502×10^{-4}	-2.17×10^{-3}	-6.961×10^{-3}
10	-1×10^{-5}	1.05×10^{-3}	6.1375×10^{-2}	-0.3523
30	-1.044×10^{-5}	2.0×10^{-6}	0.2494	-1.1721
50	-4.77×10^{-6}	-1.951×10^{-3}	0.4523	-1.9601
100	2.029×10^{-5}	-8.368×10^{-3}	0.9798	-3.782
150	5.331×10^{-5}	-1.587×10^{-2}	1.5182	-5.426
200	9.09×10^{-5}	-2.397×10^{-2}	2.0605	-6.9242
300	1.745×10^{-4}	-4.125×10^{-2}	3.1474	-9.5547

horizontal polarization. For the designing of the model different steps are explained as follows.

For frequency ranges from 1 to 100 GHz specific attenuation in dB/km are calculated using ITU-R rain model. After calculation of specific attenuation, graph are drawn between specific attenuation and frequency in GHz at different rain rate in mm/h. Approximation curves are drawn using these graphs. From these approximation curves different equations are obtained for each rain rate. Example for this curve in given in the Fig. 1 for horizontal polarization and for rain rate of 1 mm/h. Different curves is drawn likewise (Fig. 2).

After getting all the graphs, cubic equations are obtained whose generalized form is given in Eq. (10).

$$A\left(\frac{dB}{km}\right) = af^3 + bf^2 + cf + d \tag{11}$$

As the Eq. (10) is in generalized form so different values of coefficients a, b, c and d are given in the Table 1.

From Table 2 four different curves are drawn between rain rate in mm/h and different constants a, b, c, d. These figures are given from Figs. 3, 4, 5 and 6.

From the graphs obtained in Figs. 3, 4, 5 and 6 approximation curves are drawn using curve fitting tool in MATLAB. From this curve four equations are obtained for horizontal polarization. In case of vertical polarization similar steps are repeated. The equations from (12) to (15) are for horizontal polarization and equation from (16) to (19) are for vertical polarization.

Fig. 3 Approximation curve for rain rate versus constant a

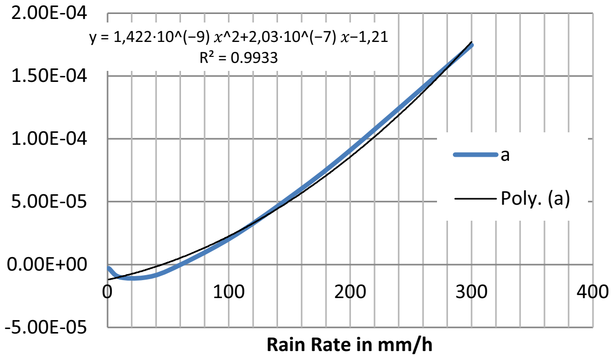


Fig. 4 Approximation curve for rain rate versus constant b

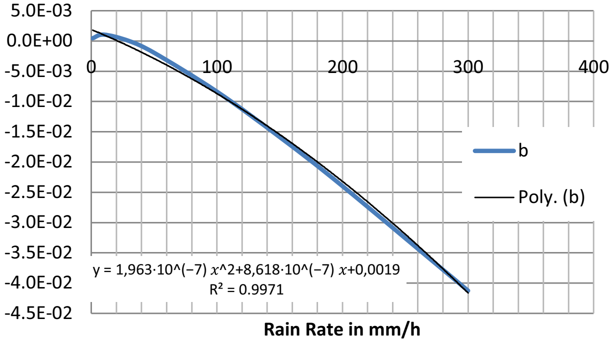


Fig. 5 Approximation curve for rain rate versus constant c

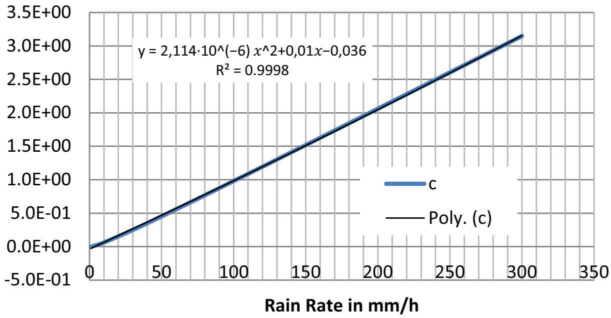
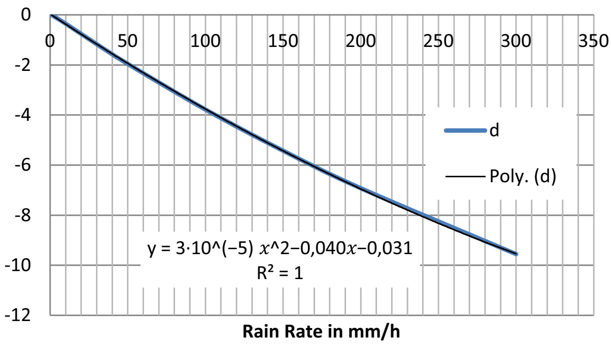


Fig. 6 Approximation curve for rain rate versus constant d



$$\mathrm{ah} = 1.422 \cdot 10^{-9}\mathrm{x}^2 + 2.03 \cdot 10^{-7}\mathrm{x} - 1.21 \tag{12}$$

$$\mathrm{bh} = 1.963 \cdot 10^{-7}\mathrm{x}^2 + 8.618 \cdot 10^{-7}\mathrm{x} + 0.0019 \tag{13}$$

$$\mathrm{ch} = 2.114 \cdot 10^{-6}\mathrm{x}^2 + 0.01\mathrm{x} - 0.036 \tag{14}$$

$$\mathrm{dh} = 3 \cdot 10^{-5}\mathrm{x}^2 - 0.040\mathrm{x} - 0.031 \tag{15}$$

$$\mathrm{av} = -5.520 \cdot 10^{-12}\mathrm{x}^3 + 3.26 \cdot 10^{-9}\mathrm{x}^2 - 1.21\mathrm{x} \cdot 10^{-7} - 6 \cdot 10^{-6} \tag{16}$$

$$\mathrm{bv} = 8 \cdot 10^{-10}\mathrm{x}^3 - 4.552 \cdot 10^{-7}\mathrm{x}^2 - 3.03\mathrm{x} \cdot 10^{-5} + 0.001 \tag{17}$$

$$\mathrm{cv} = -5.71 \cdot 10^{-9}\mathrm{x}^3 + 6 \times 10^{-7}\mathrm{x}^2 + 8.707\mathrm{x} \cdot 10^{-3} - 0.018 \tag{18}$$

$$\mathrm{dv} = -1.073 \cdot 10^{-7}\mathrm{x}^3 + 1.068 \cdot 10^{-4}\mathrm{x}^2 - 0.0598\mathrm{x} + 0.0442 \tag{19}$$

where x is rain rate in mm/h.

From constants obtained from Eqs. (12) to (19), specific attenuation due to rain can be calculated for different polarization using Eq. (20).

$$\mathrm{A}\left(\frac{\mathrm{dB}}{\mathrm{km}}\right) = \mathrm{Pf}^3 + \mathrm{Qf}^2 + \mathrm{Rf} + \mathrm{S} \tag{20}$$

where P, Q, R and S are constants such that P is av for vertical polarization and ah for horizontal polarization, Q is bv for vertical polarization and bh for horizontal polarization, R is ch for horizontal polarization and cv for vertical polarization and S is dh for horizontal polarization and dv for vertical polarization. The Eq. (19) will be proposed rain model.

4 Algorithm for Proposed Model for Radio Wave Attenuation Model for Rain

STEP 1: Obtain the value of rain rate (x) in mm/h.
STEP 2: Put the value in Eqs. (12)–(15) for horizontal polarization or from Eqs. (16) to (19) for vertical polarization.
STEP 3: After calculating the values of a, b, c and d, put the values for particular frequency f in Eq. (20).
STEP 4: After solving STEP 3 values of specific attenuation for rain in dB/km is obtained.

Various experimental researches are conducted for the calculation of attenuation caused by rain at higher frequencies. It has been observed that attenuation due to rain at higher frequencies is significant. It has also observed that uncertainties of rainfall rate and rain cell size may leads to incorrect estimations of rain attenuation. It has also been observed that the main problem of calculating rain attenuation is the vertical non homogeneity of rain structure and the possibility of having more than one rain cell along the propagation path.

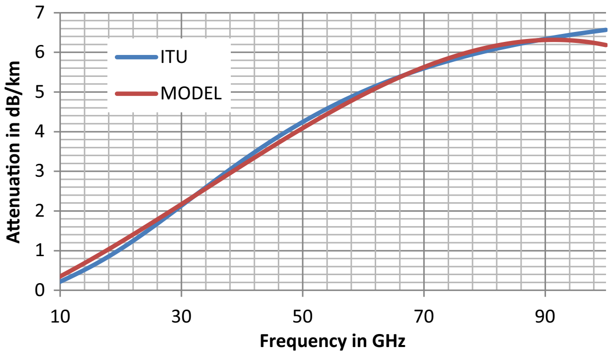


Fig. 7 Specific attenuation calculated by new rain model versus ITU model at 10 mm/h rain rate for horizontal polarization

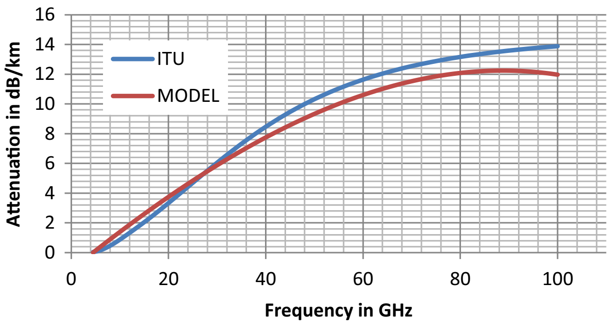


Fig. 8 Specific attenuation calculated by new rain model versus ITU model at 30 mm/h rain rate for horizontal polarization

A common observation had made that ITU-R model for rain attenuation generally underestimates the rain attenuation at higher frequencies.

The proposed RWAR model is designed in order to overcome some of the problems depicted by the researchers in order to predict the attenuation caused by the rain for higher frequencies from 10 to 100 GHz. This model is very simple together proposed model like ITU, Crane, RAL, SAM etc. as those other models uses very complex equations which are very tedious task to solve and also depends on lot of regression coefficients. The coefficients which are taken are based on experimentation results. Different experiments are done for different geographical locations and for different conditions. So generalization is difficult. Proposed RWAR model contains only square and cubic equations which are only depend on frequency and rain rates. So it is very easy to calculate the values of attenuation caused by higher frequencies at any given frequency and at any given rain rate.

5 Results and Discussion of Proposed RWAR Model

Our empirical model proposed for predicting attenuation due to rain presented in chapter 3 is implemented in this section. The mathematical implementation results obtained from new model are compared with the ITU-R rain model and results are described in Figs. 7, 8, 9, 10, 11, 12 and 13 for horizontal polarization and from Figs. 14, 15, 16, 17, 18 and 19 for vertical polarization.

The results obtained from Figs. 9, 10, 11, 12, 13, 14, 15, 16, 17, 18 and 19 clearly shows that proposed model is closely matching with the ITU-R model. It has also observed that

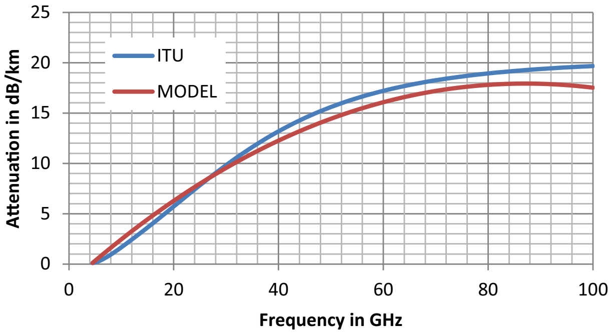


Fig. 9 Specific attenuation calculated by new rain model versus ITU model at 50 mm/h rain rate for horizontal polarization

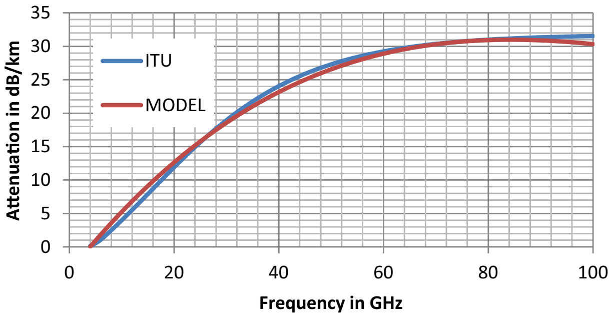


Fig. 10 Specific attenuation calculated by new rain model versus ITU model at 100 mm/h rain rate for horizontal polarization

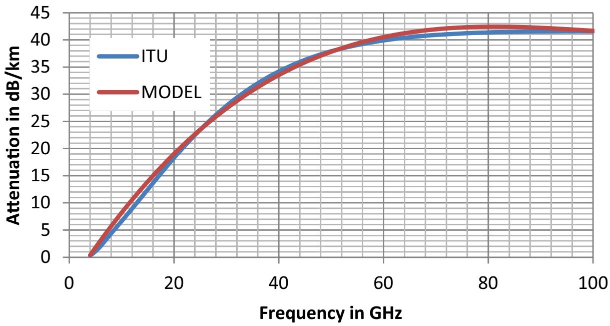


Fig. 11 Specific attenuation calculated by new rain model versus ITU model at 150 mm/h rain rate for horizontal polarization

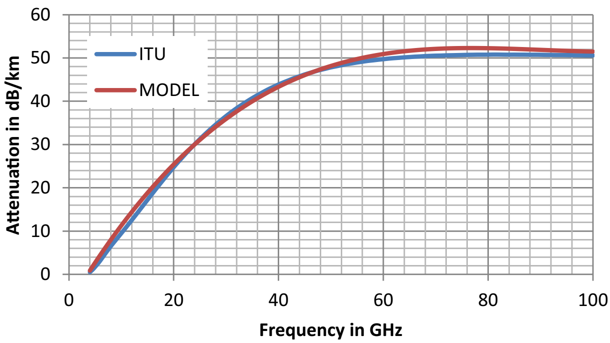


Fig. 12 Specific attenuation calculated by new rain model versus ITU model at 200 mm/h rain rate for horizontal polarization

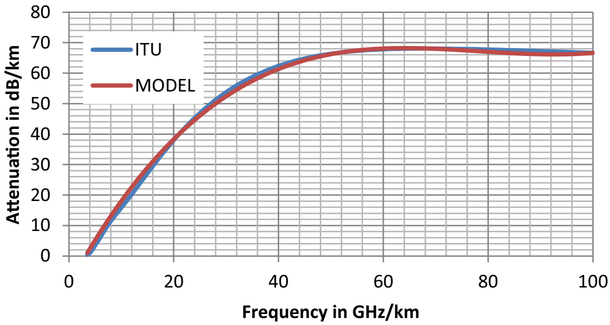


Fig. 13 Specific attenuation calculated by new rain model versus ITU model at 300 mm/h rain rate for horizontal polarization

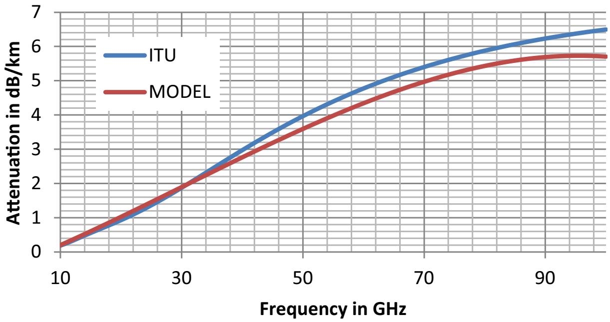


Fig. 14 Specific attenuation calculated by new rain model versus ITU model at 10 mm/h rain rate for vertical polarization

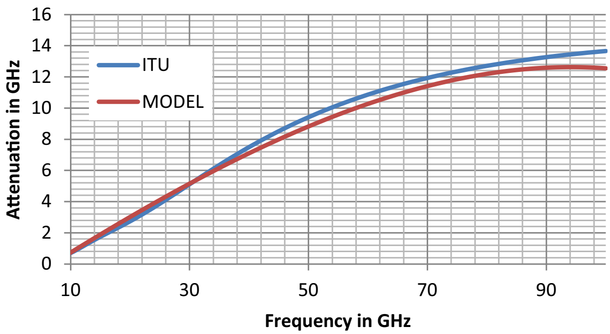


Fig. 15 Specific attenuation calculated by new rain model versus ITU model at 30 mm/h rain rate for vertical polarization

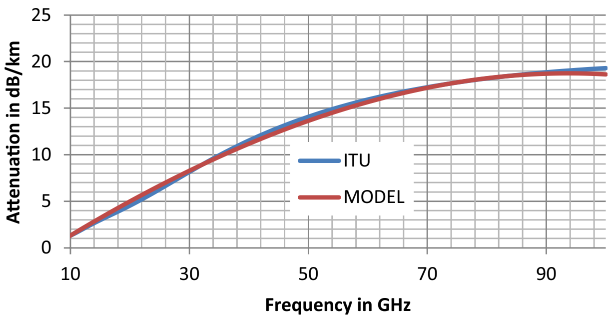


Fig. 16 Specific attenuation calculated by new rain model versus ITU model at 50 mm/h rain rate for vertical polarization

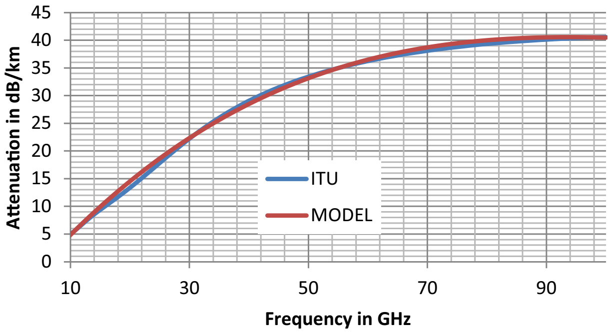


Fig. 17 Specific attenuation calculated by new rain model versus ITU model at 150 mm/h rain rate for vertical polarization

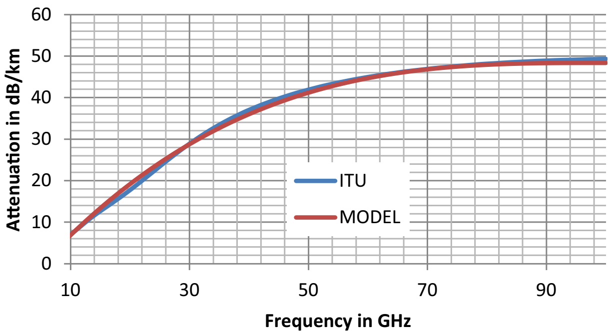


Fig. 18 Specific attenuation calculated by new rain model versus ITU model at 200 mm/h rain rate for vertical polarization

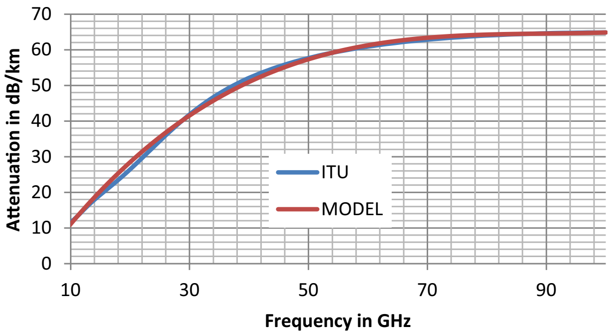


Fig. 19 Specific attenuation calculated by new rain model versus ITU model at 300 mm/h rain rate for vertical polarization

with the higher frequency, the specific attenuation is also increased. The proposed model is simplier to use as compare to complex ITU-R model.

It has also been observed that for rain rate 30 mm/h, 50 mm/h at horizontal polarization and for rain rate 10 mm/h and 30 mm/h at vertical polarization slight deviation with ITU model is observed above 30 GHz frequency bands.

The proposed rain model's error analysis has been done using Eq. (20). Proposed model is compared with ITU-R rain model at different rain rates from 10 to 300 mm/h. Results are described in Tables 3 and 4. It has been observed that for horizontal polarization the error rate is higher for 10 GHz and 15 GHz but above 20 GHz the error rate is

Table 3 Error analysis for rain model at horizontal polarization

Rain rate in mm/h	Average % error	f (GHz)	Average % error
10	1.215862	10	14.85888
30	9.612869	20	6.042186
50	11.02816	30	5.335574
100	6.177366	40	7.680219
150	8.36225	50	5.779106
200	12.18925	60	7.61633
300	8.440672	70	8.172776
		80	9.349502
		90	9.817334
		100	10.18381

Table 4 Error analysis for rain model at vertical polarization

Rain rate in mm/h	Average % error	f (GHz)	Average % error
10	3.679135	10	1.631458
30	5.202705	20	11.20266
50	2.744695	30	1.574097
100	5.850573	40	6.317629
150	5.385005	50	4.473838
200	6.529882	60	4.15285
300	6.677555	70	5.061046
		80	5.111247
		90	5.183695
		100	5.936194

lower than 10%. It has also been observed that with the increase in rain rate the error % became lower. In case of vertical polarization the error % is lower than 10%.

6 Conclusion

Different models have been proposed for prediction of attenuation due to rain but ITU rain model is widely acceptable model. In the ITU model different values of regression coefficients k and α are given for different frequencies. In this work an approximation model for calculation of specific attenuation due to rain is presented. In this model simple cubic equation is given as compare to the ITU-R model. Instead of regression coefficients only values of rain rate in mm/h and frequencies from 10 to 100 GHz are required for calculation of attenuation due to rain. When compared with the ITU-R model it is closely matching with it. It helps researchers and engineers to predict attenuation caused due to rain at different rain rates for given higher frequencies.

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