CHAPTER 2
RAIN ATTENUATION
THEORY AND LITERATURE REVIEW

2.1 Introduction

The growing demand of communication services has congested the currently available radio spectrum to such an extent that a need has been felt for larger bandwidth and new frequency band above 20 GHz is being explored. However, the rain attenuates the upper spectrum and frequencies suffer strong impairment as the rain drop diameter approaches the size of operating wavelength. In tropical countries like India, a great diversity of climatic conditions has been witnessed in the recent past and a search is on to find out a prediction model, useful for all ranges of rain fall rate as well as frequencies.

In the past, several theoretical and experimental studies were made in respect of rain attenuation to obtain better service reliability in communication. Theoretically calculated attenuation for a known rainfall intensity along a path shows in [34]. During 1980 and onwards, prediction techniques for statistical estimation of attenuation probability for a particular path have been studied. Two approaches are made - one based on the use of large number of attenuation measurements at different frequencies, locations and path geometries and the other based on the synthesis of attenuation values from meteorological data. Latter approach is of great interest in modeling since a large number of data are available.

2.2 Rain Induced Specific Attenuation

Rain induced specific attenuation $\alpha$ (dB/km) or attenuation per unit distance is a fundamental quantity in the calculation of rain attenuation statistics [15]. The specific rain attenuation at any point in space depends upon the rain rate at that point through the properties characterizing the rain such as shape, size, orientation, temperature, size distribution of the rain drop [14] and the properties of the incident
electromagnetic wave (such as the frequency, polarization and the direction of propagation) at that point [17]. The specific rain attenuation has been estimated theoretically by employing a uniformly random distribution of raindrops modeled as water spheres based on the Mie scattering theory [33] by various authors [9], [13], [22], [34]–[36] or more complex shapes which makes it to be modeled as oblate spheroids [15], [27]. And in the latter case, the scattering solution is more complex and has been studied by [10], [14], [37], [38].

Besides the shape of the rain drops, the specific rain attenuation, $\alpha$ depends on the forward scattered electromagnetic wave (and its effects are influenced by the water temperature, the refractive index of water and the radio link operating frequency) from which the extinction cross-section is calculated. When an electromagnetic wave propagates through a medium containing raindrops, part of its energy is absorbed by the raindrops and dissipated as heat, and the remainder is scattered in all directions [27], [39], [40]. This scattered part introduces unwanted or interfering signals into the communication receiver that may mask the desired signal [17], thereby causing attenuation (reduction of signal strength or power). Fig.2.1 shows the scattering and the absorption effect of radio wave when it is incident on a rain-filled medium. At wavelengths long compared with the drop-size, absorption will be greater; while at shorter wavelengths, scattering will be predominant [39], [41]. How scattered or absorbed the electromagnetic wave can be depends on the raindrop size, shape and the materials of which the raindrop is made up of [30]. The attenuation experienced by a radio wave crossing a rainy medium is given by the sum of the individual contributions of the drops that constitute the medium. Since rainfall consists of drops of various dimensions, the specific attenuation is calculated by integrating each raindrop contribution [7], [32], [39]. Basically, most of rain attenuation studies are based on three assumptions which are:

- As the wave propagates through the volume of rain, its intensity decays exponentially.
- The raindrops are assumed to be spherical which cause attenuation. This attenuation is due to both energy absorption losses in the rain drops and to scattered energy by water droplets from the incident radio wave.
Fig. 2.1: Interaction of an incident radio wave in a rain filled medium

- The raindrops are assumed to be spherical which cause attenuation. This attenuation is due to both energy absorption losses in the raindrops and to scattered energy by water droplets from the incident radio wave.

- Each drop’s contributions are independent of the other drops, and the contributions of the drops are additive.

In the prediction techniques based on the use of rain gauge cumulative distribution of rain rate are measured at a point. The problem of spatial inhomogeneity of rainfall intensity is taken into account by using an effective path length, where the path is divided into small volumes of spherical and uniformly distributed water drops. As radio wave propagate through it, the reduction and the dispersion occurs on the signal amplitude caused by each rain drops, which is known as rain attenuation, as shown in Fig. 2.2.
According to Ippolito (1986), the total attenuation \( A \) in the direction of wave propagation in (dB) can be expressed as:

\[
A(dB) = \int_{0}^{L} \alpha \, dl \tag{2.1}
\]

where \( \alpha \) is the specific attenuation (dB/km) along the rain volume (km), and the total rain attenuation \( A \) is integrating the specific attenuation over the path. On the other hand, the path is divided into small incremental volumes, where the rainfall is almost uniform. The rainfall rate in each small volume is associated with a corresponding attenuation called specific attenuation [11].

As discussed earlier, specific attenuation is the fundamental quantity in the calculation of rain attenuation statistics for terrestrial path and slant paths representing as rain attenuation per unit distance (dB/km). Two general approaches used to calculate the specific attenuations, theoretical and empirical methods.

Many of the theoretical discussions of rain attenuation prediction have centered on the specific attenuation. According to [42], because of the variation of rain drops size modeling in radar the integration of rain drop size distribution \( N(D) \) is used with Mie scattering theory to calculate the specific attenuation \( \alpha \) in (dB/km) as:

\[
\alpha = 4.343 \int Q_{\text{ext}}(D, \lambda, m) \times N(D) \tag{2.2}
\]

where \( D \), is the rain drop diameter in mm, \( N(D) \) is the number of rain drops per m\(^3\) with the function of diameter \( D \) and can be determined by drop size distribution (DSD) model.

Drop Size Distribution (DSD) describes the number and sizes of the precipitation particle. These parameters are important in understanding the development and evolution of precipitation. A realistic rainfall rate consists of drops of various sizes (rather than identical drops) [32], [39]. Due to the complexity involved in the physical formation of rainfall, and its spatial and temporal variability, it is therefore quite challenging to find a model that is simple and at the same time
relatively precise to describe the distribution of raindrop [13], [27]. However, the need to know the raindrop size distribution governing a given rain intensity is paramount, the reason being that it is one of the major parameters required for the modeling and calculation of rain attenuation. Many researchers have proposed different methods to determine raindrop size distribution in different climatic regions. To find out the suitable drop size distribution, nowadays two types of distributions are used specially in tropical regions

- Gamma Distribution
- Lognormal Distribution

The number and sizes of drops arrived at from drop size distribution are used to calculate extinction cross-section. Extinction cross section, $Q_{ext}$ is the function of radius $r$, wavelength $\lambda$, and refractive index for water $m$. The extinction cross-section, $Q_{ext}$ is a hypothetical area which describes the radiation being scattered by a particle. In general, the extinction cross-section is different from the geometrical cross-section of a particle as it depends upon the wavelength and the permittivity in addition to the shape and size of the particle.

In other hand the empirical procedure is based on the approximate relation between attenuation and the rain rate $R$ (mm/hr), where the specific attenuation $\alpha$ depends on rain rate and regression coefficients of the frequency and the polarization [3]. From both theoretical and numerical viewpoints the relation reduces to the simpler form at the frequencies parameters and rainfall rate in approximated power low equation [15].

$$\alpha = kR^a$$

(2.3)

$k$ and $a$ are regression coefficients which depends on DSD, temperature, frequency and polarization of radiowave. The attenuation also depends upon the plane of polarization of electromagnetic radiations due to non-spherical nature of the drops. The vertical polarized waves attenuated less than those are horizontal polarized [43], [44].
2.3 Research Background

A suitable model is needed for predicting the attenuation on a slant path with the variation of rain intensity. The attenuation due to snow or ice is very small and hence neglected [61] – [75]. Liquid rain drop is the only cause of attenuation. Studies on the variation of attenuation with height show that major attenuation occurs below the height of the bright band [76] (0°C isotherm); this fact is also supported from comparisons between radar based attenuation prediction and simultaneous path attenuation measurements [77], [78]. The rain intensity, on the average, does not vary with height between the surface and the base of the bright band as evident from weather radar data [79], [80]. This leads one to model the specific attenuation as constant from the surface up to a height near 0°C isotherm level which also needs to be estimated statistically.

Rain attenuation researches were begun by Ryde [52] carried out in the year immediately following World War II. In 1947 [52] presented a rain attenuation model. After two decades [9] published a revised model of [52] and concluded that “the agreement is not entirely satisfactory; there is a tendency for the measured attenuations to exceed the maximum possible levels predicted by the theory”. A decade later, Crane [34], [35] looked afresh at the model predictions and compared them with the measured values taking the data available to [9] and new data published after that. He found an average matching between model predictions and measurements.

According to ITU-R (formerly CCIR) rain climatic zones have been designed following the characteristics of precipitation for propagation modeling [53]. Prediction of path attenuation by ITU-R underestimates the radiometrically derived cumulative distributions (CDs) of path attenuation, in general. Furthermore, the ITU-R procedure may not match well with the rainfall rate characteristics. The model only predicts rain induced attenuation. The ITU-R prediction model [24] needs knowledge of the rain rate exceeded 0.01% of the time as measured using a gauge with one minute integration time. This factor contributes to the overestimation of attenuation by the ITU-R model. Other factors may also be responsible for the difference between the measured and predicted attenuations. The development of these models has
proceeded from these early studies to the present with further enhancement and improvement.

The effect of rain is more critical for countries located in tropical and equatorial regions like India which experience a high rainfall rate and temperature. According to [54], when those models are applied to tropical regions the performances are lower than accepted, and the results of these researches indicate poor agreement between the measured and predicted attenuations. This has been considered due to significant climatic difference between temperate and tropical region. Therefore, researches have been conducted at tropical countries such as Singapore, Brazil, Israel, Nigeria and Malaysia [55]-[60] in order to get a better performance in term of more accurate results and well suited to the local climatic conditions in tropical countries. [6] Indicates that since the rain drops in tropical regions are larger than the temperate regions. The incidence of rainfall becomes more critical at frequencies as low as 7 GHz.

2.4 Prediction of Rain Attenuation

A rain attenuation model should predict both the median distribution for a number of yearly attenuation distributions as well as the amount of expected deviations of distribution of attenuation for any single year of observation from the long term median distribution. Old and early models considered raindrop sizes, shapes, uniform rain rates along a path, etc. For uniformity in rain rate, the time average of rain rate at a point was considered to approximate the path average rain rate along a link [81]. Considering the specific attenuation to be proportional to rain rate, such a model works well, but the physics involved in the process was very much complicated. Earlier models give estimation of point rain rate statistics and the statistics of variation of rain along a path. Statistics of path length through rain has also been modeled with the advent of satellite communication.

Initially, the models were physical observation based, but with the availability of attenuation statistics such models were adjusted. Today, enough data are available for a standard model. However, the practical methods, which are adopted to measure the attenuation statistics do not give a reliable model and compels one to turn back to
the models that are physical in nature. Development and evaluation of models require a method to control the quality of data observation in the model [51], [82] – [85]. The ITU-R (formerly known as CCIR) gathers round the clock global data, which measures attenuation. Such data used in [85] and noticed that the statistical deviations of attenuation from model predictions were log-normal and the parameters used in log-normal process practically did not change significantly for different models. The ITU-R recommended models did show the smallest deviations.

The deviations of observations from USA in the ITU-R database were analyzed for a physically based model in [17]. Fig.2.3 shows the cumulative distribution function (CDF) for log ratio of measured and modeled attenuation at 0.01% of a year. As the statistical distribution for path-to-path variation is log-normal, the log ratios were plotted on a normal probability paper. The CDF must lie on a straight line provided the log-normal hypothesis is correct. In order to display all the observations on a single graph, the attenuation prediction model was used to normalize the data. The same general result is valid for a different prediction model. Only the bias value (intercept with zero value for reduced variate) changes, but the slopes of best fit curve to the deviations remain unaltered.

Modification of refractive condition of atmosphere depending upon the moisture content has been investigated in India by many workers. It is found that LOS links are affected around the coastal regions up to a few kilometers due to land-sea breeze. The change of refractive profile, in turn, reduces the microwave signal [86]. Deterioration of a communication link at 13 GHz in monsoon month revealed that the communication link did not serve the purpose 5% of time [87]. Full communication link can be achieved during monsoon months if an extra gain of 12-15 dB is provided to the transmitting system. The attenuation is found to be 0.5dB/km at 22.235 GHz during monsoon months as shown in Fig.2.4. Ground-based zenith looking radiometer has a window [88] and the signal suffers no change with respect to the total attenuation within 1% height limit. Disdrometer is an important instrument to estimate the microstructure of rain cell [89]. A detail of precipitation structure is also calculated in [90] using combined microwave and IR rain algorithm during a Bay cyclone.
According to ITU-R rain climatic zones have been designed following the characteristics of precipitation for propagation modeling [47]. Prediction of path attenuation by ITU-R underestimates the radiometrically derived cumulative distributions (CDs) of path attenuation, in general. Furthermore, the ITU-R procedure may not match well with the rainfall rate characteristics. The model only predicts rain induced attenuation. Fig. 2.5 shows total attenuation statistics for measured annual, worst month and predicted (ITU-R method) cumulative statistics. The ITU-R prediction model [91] needs knowledge of the rain rate exceeded 0.01% of the time as measured using a gauge with one minute integration time. This factor contributes to the overestimation of attenuation by the ITU-R model.

**Attenuation Prediction Error at 0.01% of Year in USA**

![Graph showing attenuation prediction error](image1)

**Fig. 2.3:** Cumulative distribution of attenuation prediction errors for all observations in the CCIR data bank from USA

**Fig. 2.4:** Electromagnetic wave attenuation profile at mean sea level
2.5 Rain in Tropical and Temperate Climate

The characteristics of rain in the tropics differ appreciably from those in the temperate climates. It has been observed that the empirical relationships obtained in the temperate regions are not suitable for propagation predictions in the tropical climates [7], [45]. Rainfalls in the tropics are largely convective and are characterized by high precipitation rates, which occur over limited extensions with short duration. On the other hand, the temperate climate rain falls are from stratiform cloud. The temperate climates are characterized with widespread rain which can extend over a longer propagation path with lower rain rates of up to 25 mm/h and small embedded showers, and duration exceeding one hour [41], [92].

Experiments over the eastern tropical Atlantic, northern Australia, and the western equatorial Pacific have shown that almost all convection rains occurs in association with stratiform rains [93]. When the convective cloud decays, it becomes stratiform, and the rain extends over wider areas with smaller intensities. Stratiform rain generally occurs more frequently in the tropics, yet convective rainfall accounts for most (~70%) of the cumulative rainfall, because its intensity is so much higher [94]. Generally, tropical regions possess two climatic seasons; wet and dry season. The wet season are characterized with high rain rates and the dry season with rain total of about 50 mm [45]. The equatorial climates which possess similar characteristics with that of the tropics in terms of their formation and drop sizes, have
no dry season and all the months have a mean precipitation values of at least 60 mm. Equatorial climates have no pronounced summer or winter, it is wet and hot throughout the year and rainfall is heavy and falls in the afternoon on an almost daily basis. The equatorial climates exhibit only very small temperature variation both within the day and throughout the year [45], [95].

2.6 Regional Variation of Specific Attenuation

Attenuation of microwave signal by rain is a major problem to designers and service providers all over the world. Since 1940, researchers in Europe and USA are conducting work on microwave attenuation due to moisture, rain, clouds and other factors. It is now well known that different models on rain attenuation and drop size distribution are valid for different regions, i.e., a model which is valid in one region can give much different result in another region. So people gave serious thought on developing attenuation and rain drop size distribution models for different climatic regions.

2.6.1 Rain Attenuation Research in North America

The work of [96], [97] in Canada significantly influenced the ITU-R zonal models approach. This is because of the sufficiently large database of short integration time rain rate data in Canada. Due to the shortcomings of the zonal approach [97] employed contour maps of two parameters of rain rate distribution based on the data for 47 locations within Canada and United States. The work of Crane has also considerably influenced the zonal models of the ITU-R. He has extensively used data in the United States, although a lesser extent in other parts of the world to develop a global rain-rate climatic model [16], [17]. This model can be employed to estimate rain attenuation especially for areas where local rain data is scarce. The Crane global rain rate model classified the globe into eight regions labeled A through H going from dry to wet for each latitude band from the pole to the equator [16], [17]. A significant amount of new data was published for Canada in [96]. The climatic map was then revised by addition of two new sub-regions, B1 and B2; then an adjustment of the contour region boundaries near the U.S. – Canadian border was
made. For the relevance of 1-minute integration time rain rate in the calculation of rain attenuation, [98] developed empirical conversion factors suitable for converting 5- and 10-minute rain-rate data based on the rain rate measurements recorded in 45 locations within Canada to the 1-minute recommended rain rate statistics. The conversion factor, \( \rho_\tau(P) \) for converting rain having an integration time of \( \tau \) minutes to equivalent 1-minute statistics [98]:

\[
\rho_\tau(P) = \frac{R_1(P)}{R_\tau(P)}
\]

(2.4)

where \( R_1 \) and \( R_\tau \) are the rainfall rates exceeded with equal probability \( P \), for the two integration times. \( \rho_\tau(P) \) is also given by the power law:

\[
\rho_\tau(P) = aP^b
\]

(2.5)

over the range \( 0.001\% \leq P \leq 0.03\% \), where \( a \) and \( b \) are constants.

### 2.6.2 Rain Attenuation Research in Europe

On the basis of 400 stations data rain rate exceedance for 0.1% and 0.01% of an average year mapped for Europe [99]. This approach has been excellent in providing estimates of high quality rain rates, and has been used to update the ITU-R rain zones in Europe [100]. According to [101] the conversion factor \( C_e \) and \( C_R \) for rain gauge integration times in the range of 10 second to 60 minute, where:

\[
C_e(R) = \frac{e_T}{e_\tau}
\]

(2.6)

\[
C_R(t) = \frac{R_T}{R_\tau}
\]

(2.7)

\( C_e(R) \) refers to the ratio of the exceedance (with the same probability \( P \)) for a given rain rate \( R \) measured using gauges with integration times \( T \) and \( \tau \); \( C_R(t) \) refers to the
ratio of rain rates exceeded for a given percentage of time $t$ as measured by rain gauges with integration times $T$ and $\tau$. Here, $C_k(t)$ depends on the percentage of time considered [101].

### 2.6.3 Rain Attenuation Research in South America

The statistical modeling of the cumulative probability distribution function of rain rate in various sites in Brazil presented in [102]. The sites used in their work provide a wide view of rainfall behavior in Brazil. The sites are located in the cities of Belem, Manaus, Recife, Rio de Janeiro, and Sao Paulo. The location of the sites span over 22 degrees of latitude and represented two types of equatorial and three types of tropical climates. Their results indicate that the ITU-R expectations for the rainfall rate distribution in climates P and N tend to overestimate the measured values for the sites studied [102]. [103] also confirmed eleven different rain climatic zones in Brazil as against the two climatic zones P and N allocated by the ITU-R. [104] gave the conversion factors for converting 5-minutes rain rate to a 1-minute integration time rain rate at various probability levels for 5 locations in Brazil. [105] presented a modified ITU-R rain attenuation model for low latitude areas, for terrestrial paths, based on the fact that rain attenuation prediction model currently adopted by ITU-R appears to be inadequate for most tropical regions [45]. [106] suggested that the empirical expression used for scaling the rain rate exceeded for 0.01% of an average year ($R_{0.01}$) to other percentages of time may cause an overestimation of the predicted rain attenuation in the range from 0.01 to 0.001%. Therefore, [105] proposed a modified scaling expression to solve this problem based on 15 years experimental data from Brazil and India. [107] presented an empirical solution based on a given rain cell model to develop a path length factor. This is a very important parameter when deriving a rain attenuation model due to the non-uniformity of rain along propagation paths.

### 2.6.4 Rain Attenuation Research in Australia

The most notable work in Australia is the work by Flavin [108] – [111] which is mostly adapted for satellite radio communication systems between frequencies of 5-
60 GHz. The important aspects of his model are the use of entire rainfall rate distributions and the dependence of the rainfall rate on vertical path reduction factor (for satellite radio links), and its applicability to tropical climates. [109] examined 6-minute and 1-minute cumulative distributions of rain rate for four locations in Europe, three in the United States, one in Canada and five in Australia; he obtained a power law relationship for the conversion of 6-minutes rain rate to 1-minute integration recommended for the estimation of rain attenuation on radio communication links. The relationship is as follows [109]:

\[ R_1 = 0.990 R_6^{0.054} \]  \hspace{1cm} (2.8)

where \( R_1 \) is the 1 minute rain rate, \( R_6 \) the equiprobable 6 minutes rain rate value.

### 2.6.5 Rain Attenuation Research in Africa

During the two years of Joint Radiometric Campaign in Africa, [112] – [114] presented the cumulative distribution of rain rate obtained in Doula (Cameroun), Nigeria, and Nairobi (Kenya) [7]. The highest rain accumulation was recorded in Doula, but has a convective factor which was lower than that of Nigeria; this made the rain rate exceeded for 0.01% of the year comparable at Doula and Nigeria. The cumulative distributions of rainfall rate in Doula and Nairobi show that the rain climate is not well described by the ITU-R predictive distributions. [115] used the [61] technique to predict short integration time (1-minute) rainfall rate from long term precipitation data from thirty-seven stations in Nigeria over a period of thirty years. More recently, [116] developed rain rate maps for Nigeria at 0.01 and 0.1% exceedance value using rain rate models developed for tropical zones on the thirty years rain measurements made from the coast to the arid region of Nigeria [116]. In the conversion of rain rates to recommended 1-minute integration time rain rate, [117] also found that a power law relationship exists between equiprobable rain rates collected in Nigeria between September 1979 and December 1981. The power law relationship is given by [117] as:

\[ R_1 = a R_7^8 \]  \hspace{1cm} (2.9)
where $R$ is the rain rate, $\tau$ is the integration time at which the rain rate is required, and $T$ is the integration time at which the rain rate is available.

In South Africa, [118], [119] propose a rain rate model based on Southern Africa extreme rain rate data and classified South Africa into twelve different climatic rain zones using the Köppen classification system. In 2006, [120] presented the cumulative distributions of rain rate for twelve different geographical locations in South Africa based on a 5-year rain fall data recorded by the South African Weather Services (SAWS). The rainfall data which was recorded for 1-hour integration times were converted to 1-minute integration time by using the [121] and [117] approaches together with 1-minute rain rate recorded in Durban. From these approaches, a simple power law fit was also generated for converting the 1-hour rain rate to 1-minute integration time, and this is given as:

$$R_{1\text{min}} = 9.228 R_{60\text{min}}^{0.8207}$$  \hspace{1cm} (2.10)

The power law coefficients are $a = 9.228$ and $b = 0.8207$, and $R_{1\text{min}}$ and $R_{1\text{hr}}$ are the rain rates at 1-minute and 1-hour integration time respectively [120], [122].

From the cumulative distribution of the converted 1-minute rain rate, rain rate exceeded at 1, 0.3, 0.1, 0.03, and 0.01% percentages of time are determined [122]. From these distributions, four new climatic rain zones are determined, namely; N, M, P, and Q. This means that an additional three climatic rain zones, M, P, and Q are added to the original C, D, E, K and N climatic rain zones designated by the ITU-R [120], [122]. In 2007, [123] determine an empirical rain rate distribution model, and the worst month statistics for eight different geographical locations in South Africa.

2.6.6 Rain Attenuation Research in Asia

In China, [124] obtained contours of rainfall rate exceeded for 0.01% and 0.0% of the time based on data from several convectional meteorological stations all over China. From measurements made in 3 different locations – (Xinxiang, Nanjing and Guangzhou), [124] expressed the conversion factor of rain rate statistics for 10-minutes to 1-minute based on the Segal conversion factor.
In Indonesia, [125] presented a 2-year experimental result which indicates that the measured rainfall rate exceeded at 0.01% of the time is quite different from the ITU-R estimations. The ITU-R has classified most of the Indonesian cities to be of P climatic rain zone, whereas the cities fall in the Q climatic rain zone [126], [127]. Based on rain rate measurements in Indonesia, [125] developed a new prediction model of 0.01R value for Indonesia cities.

The rain attenuation measurements conducted in Japan by [128] at four different frequencies; 50.4, 81.8, 140.7, and 254.5 GHz on 0.81 km terrestrial line-of-sight link has shown that, for the Japanese climate, the results from the ITU-R rain attenuation model underestimate the rain attenuation at frequencies above 80 GHz. It was further concluded that the higher the propagating frequency the more appreciable is deviation of the ITU-R model to the Japanese climate [128].

In Singapore, [129] presented a two-year measurement of rain rate and rain attenuation from a vertically polarized 21.225 GHz microwave link. From their measurements a modified version of the ITU-R model for the cumulative percentage time of which the specific attenuation level is exceeded was proposed. This is given as:

\[
\frac{A_p}{A_{0.01}} = 0.12p^{-(0.74+0.14\log p)}
\]  

(2.11)

where \( A_{0.01} \) is the path attenuation for 0.01% of time. Also from the measurements, a new negative exponential distribution model with coefficients different from that of [130] was used to calculate the specific rain attenuation. With drop concentration \( N \) related to drop diameter \( D \) and rain rate \( R \), the drop–size distribution function was obtained. This is given by [129] as:

\[
N(D) = 0.333\exp\left[-45.2R^{-0.013}D\right]
\]  

(2.12)

In 1995, [131] also calculated the specific rain attenuation from the Marshall-Palmer drop-size distribution [130] at different operating frequencies from the local rainfall data in Singapore. These results were compared with the ITU-R predicted specific attenuation for moderate climatic region. It was observed that the [130] drop-
size distribution gave a fairly good fit for prediction of specific rain attenuation in moderate climatic region in Singapore where the mean drop-spectrum ranges from 1-50 mm/h [131]. Two microwave links operating at two different frequencies; 15 and 38 GHz was added to the 21.225 GHz experimental set up. The experimental results from these set-ups showed that the ITU-R attenuation model cannot be used in the attenuation prediction for tropical Singapore. This is because it was observed that the measured specific attenuation in Singapore tropical environment was twice those predicted by the ITU-R model [131]. Later in 2000, [132] presented the cumulative distributions of rainfall rate, cumulative distributions of rain attenuation, the relationship between specific attenuation and rain rate, and frequency scaling formulae from the experimental results of the 15, 21.225, and 38.6 GHz radio links set up in Singapore. Comparing their results with the ITU-R, it was concluded that the ITU-R underestimates the rainfall rate and propagation characteristics in Singapore.

Rain attenuation in northern Taiwan from two-year raindrop size distribution measurements recorded along a vertically polarized 28.35 GHz terrestrial path [133]. The drop-size distribution measurements were analyzed for different seasons over a 1-minute rain rates, and a relationship between drop-size distributions and the rain rates was established. Regression fit was performed to match the data to known distributions, and it was observed that the gamma distribution gave the best description for the data regardless of the seasons, except for light rain rate, where lognormal distribution looks better. The three parameters coefficients for the gamma distribution for the seasons are obtained and these are used to develop a semi-empirical rain attenuation model. The attenuation results from this model are then compared with the measured data of the 28.35 GHz terrestrial link and the results from Crane and ITU-R attenuation model. It was concluded that both the ITU-R and the Crane model either underestimate or overestimate the rain attenuation for each season [133].

2.6.7 Study of Rain Attenuation over Indian Locations

In India, work on the rain drop size distribution data started during 1989, and 1100 rain events of 1 min duration's DSD data were used to develop rain drop size distribution model and compared with MP [130] and LP [134] DSD model of
attenuation coefficients. Specific attenuation shows a significant difference in attenuation in 60 and 100 GHz due to presence of different types of rain drop sizes above a certain higher rain rate [135]. In 1992, [136] produced a reference data manual for rain rate distributions over the Indian sub-continent, making use of the heavy rainfall data of 5-minutes and 15- minutes available at 35 different geographical regions in Indian, using the fast response rain gauge. The rapid response rain gauges measure rain rate with 10-seconds integration time in Delhi, Shillong, Calcutta, Bombay and Tirupati. They produced the cumulative distributions of rainfall rate for different integration times from 10-seconds to 1-hour for 17 different stations in India. 30/20 GHz radiometric measurements were done in [83], disdrometer data have been analysed to evaluate rate of rain fall, drop size distribution (DSD) and specific attenuation. experiment were conducted at 30/20 GHz for LOS link distance of 6 km for prediction of horizontal characteristics of rain attenuation [83], Similarly radiometer were used at the same frequency for vertical characteristics of rain and rain height for prediction of slant path attenuation. At WAR (World Administrative Radio) conference, India was allotted two geosynchronous satellite positions at 56°E and 68°E longitudes at 12 GHz broadcasting frequency. This prompted Indian worker to study rain attenuation at 12 GHz. [137] has compared several prediction methods of rain attenuation.

Rain attenuation at 11.7 GHz has been compared with prediction models [50] by utilizing INSAT-2C satellite signals. Theoretically estimated attenuation of radio waves using the concept of decay of rain path profile at 11 GHz and 13.4 GHz for 56° elevation angle over Delhi [51] showed that CCIR model underestimates the attenuation over India.

The prediction model of rain attenuation developed by [138] based on the experiment conducted in India is available for communication system designer for providing appropriate fade margin for reliable communication above 10 GHz; otherwise the communication system designed, based on rain attenuation data of temperate climate, can provide outage of radio signals leading to link failure for higher rain rate as experienced in Singapore by Singapore Telecommunications, which lead to the detailed study of rain attenuation. Raina and Uppal [139] have also
collected some data from radiometric studies over New Delhi, although these are not enough for a good understanding of propagation mechanism in the tropics [50].

2.7 Rain Attenuation models for different Regions

From the above discussions, it can be deduced that all the rain attenuation prediction models basically need information about the rain rate statistics or the raindrop size distribution governing a particular climatic region. The rain rate statistics can either be in the form of point rain rate data or cumulative distributions, so that rain rate exceeded at different percentages of time can be determined. As explained above, the International Telecommunication Union-Radio Communication research group (ITU-R), has come up with a global climatic map which shows the rain rates exceeded for 0.01% of the time for all the climatic rain zones in the world. With these, geographical locations with no rain rate data can use the global climatic map of the ITU-R to estimate the rain attenuation for the particular location considered. However, the ITU-R prediction models have instigated a lot of questions from researchers around the world, especially those from the high rainfall rate regions like the tropical and equatorial climates. Most of these researchers observed that when the attenuation results from the ITU-R model are compared with the actual local rain attenuation measurements, there is always a measure of discrepancy between the two results, and these have been traced down to the raindrop size distribution employed by the ITU-R to develop the rain attenuation model [129]. The ITU-R has adopted the Laws-Parsons drop-size distribution model [7], [58], [129] which has taken a functional form of the negative exponential distribution of Marshall-Palmer [45]. According to [129], the Law-Parson drop-size distribution is not a representative of weather outside Europe and North America continents.

These problems have made many researchers in tropical and equatorial climates like Nigeria [58], [140] – [142], Brazil [143], [144], Singapore [129], [131], [132], [145], [146], Malaysia [147], Indonesia [48], [125], India [83], [135], [148], [149], [150], and others to initiate propagation studies in their geographical locations. And from their experimental works, the deficiencies of the Marshall-Palmer drop-size distribution model are confirmed for convective thunderstorm rain which is usually common in the tropical and equatorial climates [151]. In a comparative study of rain
Fig. 2.6: Comparison models of the raand Malaysia at rainfall rate of 100 mm/h
drop distribution in some tropical climates, namely Malaysia, Singapore, Nigeria and Brazil [152]. This was achieved by using the lognormal drop-size distributions coefficients determined from their local measurements in Nigeria [151], Brazil, [143], Singapore [153], and Malaysia [154], the drop-size distribution is shown in Fig. 2.6. It can be seen that even for the same lognormal drop-size distribution, each geographical location has its own drop-size distribution function. This can be used to accurately predict the rain attenuation for the particular geographical location. Therefore, the validity of one attenuation prediction model in a geographical location, may not accurately predict the attenuation in other geographical location.

Some authors have attempted to adjust the Marshall- Palmer drop-size distribution [130] parameters so as to give a closed agreement with the measured local data in their environment [129], 146], but caution needs to be taken for any variability that may affect adjustment of parameters [45]. All in all, for a rain induced specific attenuation model to accurately predict rain attenuation along a terrestrial radio link or a satellite link, an accurate prediction of the rain rate statistics, and the drop-size distribution, must be readily available for the particular climatic rain zone in which the prediction is to be made. It should also be noted that for path attenuation, the effective path length of the terrestrial link should also be considered to accommodate
the non-uniformity of rain along radio paths. That is why the rain attenuation model predicted in one climatic region may not be adequate or valid for the other climatic region. Many studies have been carried out in temperate and tropical climates, but less has been reported about tropical climates, in which India falls; hence, this work seeks to fill that void.

2.8 Research Gaps

Several methods have been reported in the literature for estimation of rain induced attenuation. While numerous studies have demonstrated good agreement between model predictions and field measurements in the estimation of propagation impairment, but still lot of work has to be done specially in tropical regions like India, which is planning to go at higher frequencies for better communication. After a critical literature review, finally the research gaps are identified as:

1. India is planning to launch Ka band satellite (GSAT-4), but there are very less work has been done on propagation impairments at higher frequencies. So it is necessary to study propagation effects at higher frequencies for Indian climate.

2. Most of the literature available in International Telecommunication Union (ITU) reports (R-618) is based on data collected in the temperate regions of the world which experience low rain rate. The prediction models given there in are inadequate when applied to tropical regions like India which is characterized by heavy monsoon rains and relatively high temperature. Therefore, it is highly needed to study propagation effects on the data which is collected in India.

3. Compared to temperate climate rain is much more severe and so is the attenuation at millimeter wave frequencies in tropical and equatorial regions. The drop size distribution (DSD) varies with different climatic regions. It is therefore necessary to develop drop size distribution (DSD) for Indian region.

4. For the design of a millimeter wave communication link it is necessary to have better understanding of rain statistics to provide sufficient fade margin, not only the annual fade margin due to rain is required but also the knowledge of
worst month attenuation statistics is needed to predict the maximum outage of the communication link. So there is a need of analysis of rain rate exceedance characteristics for Indian regions.

5. The depolarization of the radio signals at millimeter wave frequencies due to hydrometeors restricts the use of orthogonal polarization oftenly used to increase the capacity of the satellite communication systems. Therefore, Estimation of depolarization of electromagnetic radiations caused by rain drops is highly required.

6. Most of the literature available is based on constant temperature throughout the year and throughout the country. In most of the cases it is around 20°C. As India has regions like Kashmir, Rajasthan and coastal areas which have very huge variation in temperature. It is therefore necessary to calculate forward scattering amplitude with respect to the temperature of location.

7. Most of the rain attenuation models are capable to find out the specific attenuation for the range of rain rates but at a fixed frequency, because of modeling of extinction cross-section is not used in most of the models. So, for the rain attenuation model which works on range of rain rates as well as range of frequencies, it is necessary to develop extinction cross-section model for that frequency range.