Prediction of Specific Attenuation of Rain for Wireless Networks by Probability Density Analysis in South Africa

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Abstract-In this paper, specific attenuation of rainfall is examined at four locations in South Africa using the lognormal rainfall dropsize distribution (DSD) from Durban. The probability density function (PDF) analysis undertaken for each location, relative to the control site in Durban, is applied to develop equivalent lognormal models. By applying the scattering parameters for each location at 2.5 GHz, 12 GHz and 25 GHz, the specific attenuation accrued to each location is predicted. From the results, it is seen that the coastal city of Durban may experience higher specific attenuations at the examined frequencies. This is followed by the cities of Richards Bay, Pretoria and Pietermaritzburg, particularly beyond 10 GHz transmission frequency.

Index Terms—Lognormal distribution, rainfall specific attenuation, probability density function, rainfall DSD.

I. INTRODUCTION

Resource allocation for wireless system is increasingly becoming an important subject, particularly for outdoor applications involving high-capacity Broadband Wireless Access networks [1-2]. The behavioural preference of contemporary users has resulted in excessive bandwidth usage, thereby leading to the saturation of existing allocated bandwidth and spectrum designations. At present, efficient modulation algorithms could provide temporary solutions, but this is often at the expense of high computational power consumption for implementing those routines [3]. However, a much more realistic and acceptable method is by migrating to higher microwave bands, which is also vulnerable to effects of precipitations particularly beyond 10 GHz [4-5].

Studies on precipitations, particularly rainfall attenuation, or fading, have been approached worldwide by using two microstructural parameters – rainfall rate and rainfall dropsize distribution. The subject of rain fade has basically been investigated using these parameters. For terrestrial network planning at microwave frequencies, the destructive effects of rain fade can be compensated for, either by adding static or dynamic power level to link requirements [6]. Of particular interest to this paper is the influence of rainfall induced fade to basic terrestrial links for wireless networks at microwave frequencies.

In this study, the concept of probability density function analysis is approached to resolve the rainfall DSD of three other locations in South Africa, from rainfall measurements in Durban. The lognormal rainfall DSD model is selected as the statistical model, used in the determination of spatial dropsize variability for the selected locations. Furthermore, we apply the spherical droplet assumption from the Mie droplet scattering technique to compute specific attenuation from rainfall. Since scattering technique requires a transmission frequency for rain water, we utilise three prominent frequencies applied in the microwave industry – 2.5 GHz, 12 GHz and 25 GHz. The first frequency serves a carrier frequency in major ISM services, the second frequency is useful for X-band services and the third, is useful in future deployment of WiMax services.

II. RAINFALL DSD AND SPECIFIC ATTENUATION STUDIES IN DURBAN

Rainfall DSD research in Durban, South Africa has mainly been developed empirically by the application of statistical models such as Weibull model, modified gamma model, lognormal model and negative exponential power law [7-11]. Recent studies have also shown that the lognormal DSD model is the most suitable for drop-size modelling at this particular location because of the quasi-tropical (or subtropical) nature of the climate [9-11]. The lognormal rainfall DSD function is given by *Ajayi and Olsen* [12] as:

$$N(D_i) = N_T\left(\sigma_m D_i \sqrt{2\pi}\right)^{-1} \exp\left[-0.5\left(\frac{Ln(D_i) - \mu_m}{\sigma_m}\right)^2\right]$$
$$\text{for } D_i > 0,\ \sigma_m > 0,\ -\infty < \mu_m < +\infty \text{ and } N_T > 0 \qquad (1)$$

where N_T is the scale parameter, μ_m is the mean of Ln(D_i), σ_m is the corresponding standard deviation and D_i is the mean diameter of rainfall droplets in mm.

Alonge [13] in his recent study on annual rainfall DSD in Durban, undertaken at the University of KwaZulu-Natal for two years, found that the temporal functions of rainfall rate, R, for the lognormal rainfall DSD can be written as:

$$N_T = 220.85R^{0.3922} \qquad (2)$$
$$\mu_m = -0.267 + 0.1373\, Ln(R) \qquad (3)$$
$${\sigma_m}^2 = 0.0772 + 0.0099\, Ln(R) \qquad (4)$$

where 0.003 mm/h ≤ R ≤ 120 mm/h.

Based on the knowledge of Joss-Waldvogel RD-80 distrometer calculation, we know the rainfall DSD can be independently calculated as thus:

$$N(D_i) = \frac{C_i}{S \times T \times v(D_i) \times \Delta D_i} \quad [mm^{-1} m^{-3}] \qquad (6)$$

where S is the sampling area of the distrometer impact cone taken as 0.005 m^2, T is the sampling time of the distrometer system taken as 60 seconds, $v(D_i)$ is the terminal velocity of the rain droplets and ΔD_i is the diameter interval of succeeding diameter classes.

Since rainfall attenuation is an important index in link budget for microwave networks, it is necessary to utilize a much more applicable index, the specific attenuation of rain. Specific attenuation of rainfall, A_s, computable for discretized DSD samples from 20 distrometer channels is given in [5] as:

$$A_s = 4.343 \times 10^{-3} \sum_{k=1}^{20} N(D_i) Q_{ext}(D_i) \Delta D_i \ [dB/km] \quad (6)$$

where $Q_{ext}(D_i)$ is the extinction cross section (ECS) of the interacting rain droplets at incidence with travelling electromagnetic wave transmitted at a particular frequency, in this case, within the microwave band specification.

By comparing the specific attenuation derived from the model in (1) with parameters from (2)-(4) and the actual calculation in (6), we can observe the fluctuations in the predicted specific attenuation. As seen in Figure 1, the lognormal model is observed to conveniently track the specific attenuation computed from the distrometer for drizzle event duration. To understand the range of values for which our proposed model is valid, we apply the self-consistency rule. Therein, we found that the proposed model is self-consistent with:

$$R_{model} = 0.8557 R_{actual} + 2.0856 \quad [mm/h] \quad (7)$$

The model is only seen to have minimal deviations due to the fewer number of samples at high rainfall rates in Durban. Hence, the average deviation is 6.64 mm/h.

III. Derivation of Rainfall DSD Parameters for Other Locations

The absence of adequate rainfall measuring instruments at other locations, particularly the known Joss-Waldvogel distrometer, has led to mathematical improvisation. In our earlier attempt to derive spatially correlated models for other South African locations [13], the power-law functions representing one-minute rainfall rate conversion were applied. An empirical rainfall DSD model derived for Durban was then extended to other locations via comparison with the derived rainfall rate conversion functions. However, the derived models have poor self-consistency resolution, which has led to significant deviation errors in the generated values of the computed rainfall rates.

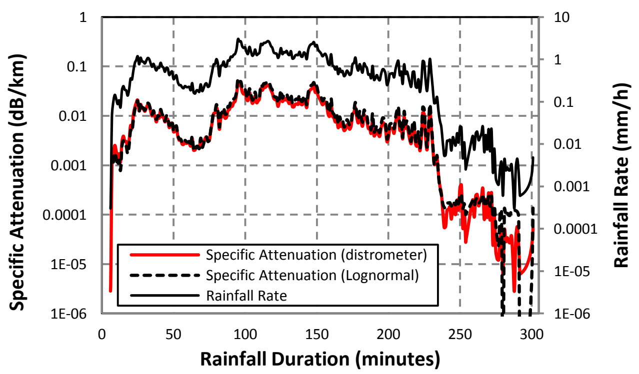

Fig. 1: Times series attenuation prediction from lognormal model for a drizzle event occurring between 8:54 hrs and 13:54 hrs on 20 January, 2010 at 12 GHz.

In this current effort, the probability density functions (PDFs) of rainfall rate for different locations are considered. The locations considered in this study are: Pretoria, Pietermaritzburg and Richards Bay. By employing the rainfall data obtained from SAWS in 2004, a one-minute rainfall rate conversion for all locations is undertaken using the approach proposed by *Akuon and Afullo* [14]. The PDF for each of these locations are then generated as power-law functions, with rainfall rate as the independent variable. Mathematically, the power-law PDF, $f(r_{i,x})$ and $f(r_{i,y})$ - for two different locations x and y - can be written as:

$$f(r_{i,x}) = \beta_{1,x} r_{i,x}^{\beta_{2,x}} \quad (8)$$

and,

$$f(r_{i,y}) = \beta_{1,y} r_{i,y}^{\beta_{2,y}} \quad (9)$$

where $r_{i,x}$ and $r_{i,y}$ are the rainfall rate samples at location x and y respectively. $\beta_{1,x}$ and $\beta_{2,x}$ are the power-law coefficients at location x, while, $\beta_{1,y}$ and $\beta_{2,y}$ are coefficients at location y.

At equal probabilities or similar PDF value, the ith rainfall rate for both locations would be different. Thus, by using location x as a reference point, we can derive a mathematical relationship linking the two locations. Thus, we have:

$$r_{i,x} = \left(\frac{\beta_{1,y}}{\beta_{1,x}}\right)^{\frac{1}{\beta_{2,x}}} r_{i,y}^{\frac{\beta_{2,y}}{\beta_{2,x}}} \quad (10)$$

or we simply write (10) as,

$$r_{i,x} = \varphi_1 r_{i,y}^{\varphi_2} \quad (10a)$$

where $\varphi_1 = \left(\frac{\beta_{1,y}}{\beta_{1,x}}\right)^{\frac{1}{\beta_{2,x}}}$ and $\varphi_2 = \frac{\beta_{2,y}}{\beta_{2,x}}$ respectively.

Following the lognormal model for Durban given in (2), (3) and (4), we have our model parameter equations as:

$$N_T = a_o r_{i,x}^{b_o} \quad (11)$$
$$\mu_m = a_\mu + b_\mu Ln(r_{i,x}) \quad (12)$$
$$\sigma_m^2 = a_\sigma + b_\sigma Ln(r_{i,x}) \quad (13)$$

By replacing the $r_{i,x}$ with the function in (10a), equations (11)-(13) become:

$$N_T = a_o \varphi_1^{b_o} r_{i,y}^{\varphi_2 b_o} \quad (14)$$
$$\mu_m = a_\mu + b_\mu Ln(\varphi_1) + \varphi_2 b_\mu Ln(r_{i,y}) \quad (15)$$
$$\sigma_m^2 = a_\sigma + b_\sigma Ln(\varphi_1) + \varphi_2 b_\sigma Ln(r_{i,y}) \quad (16)$$

The resulting equations lead to a change in the functional parameters for the different locations under consideration.

The essence of this derivation is to transfer the unique rainfall probability characteristics for spatially separated locations into simple models for rainfall attenuation prediction. To implement this method, the following steps have to be employed:

- The rainfall rate PDFs of different locations are developed from the raw data and fitted as power-law functions dependent on one-minute rainfall rate samples using regression techniques.
- The source location with the distrometer data (Durban, in this case), is made the reference point and parameters φ_1 and φ_2 are obtained using (10) and (10*a*).
- The definition of φ_1 and φ_2 are extended to the already available lognormal rainfall DSD model (for location *x*) to estimate N_T, μ_m and σ_m^2 respectively.

IV. Equivalent Lognormal Rainfall DSD Models for Other Locations

Using the approach earlier described in section III, we developed the equivalent lognormal rainfall DSD models for selected locations in South Africa.

Firstly, the one-minute rainfall rate conversion is undertaken for the selected locations using the power-law constants in Table I as proposed by *Akuon and Afullo* [14]. The conversion is necessary because as explained by the authors, one-minute rainfall rate give a better resolution for rainfall attenuation studies [5, 14]. Table I also shows the respective $R_{0.01}$ for these locations. The PDF for different locations are developed from the one-minute data. For example, the generated PDF plots for our selected locations are shown in Figure 2. As seen from the plots in Fig. 2, Richards Bay is observed to have the highest PDF among the considered locations. This is followed in descending manner by Durban, Pietermaritzburg and Pretoria.

The second stage entails the development of power-law functions from various PDF using regression fitting technique. By this method, a single mathematical equation describing the uniqueness of each location based on its PDF is achieved. An adaptation of the approach earlier explained in equations (14), (15) and (16) is considered. This is later used to modify the existing Durban rainfall lognormal DSD model for other locations. Thus, the equations derived for

TABLE I. One-Minute Power-Law Coefficients and $R_{0.01}$ at Selected Locations in South Africa (*Akuon and Afullo* [14])

LOCATION	PROVINCE	β_1	β_2	$R_{0.01}$ (mm/h)
DURBAN	KWAZULU-NATAL	6.3313	0.6837	60.56
RICHARDS BAY	KWAZULU-NATAL	9.8863	0.6426	102.38
P'MARITZBURG	KWAZULU-NATAL	6.1143	0.8393	89.71
PRETORIA	GAUTENG	5.0935	0.6743	39.93

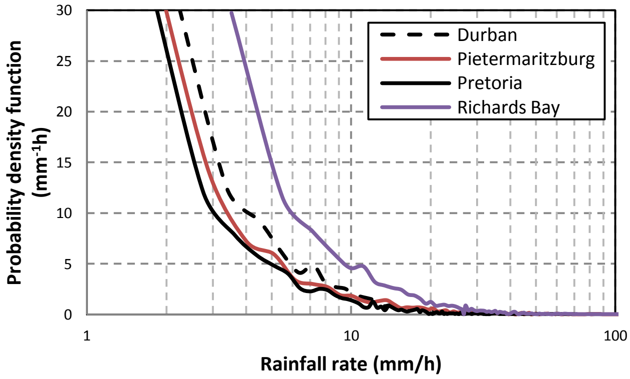

Fig. 2: Generated PDF Plots for Rainfall Rates at different locations in South Africa.

the selected locations in South Africa are:

PIETERMARITZBURG:

$$N_T = 273.21R^{0.3020} \quad (17a)$$
$$\mu_m = -0.1925 + 0.1057\,Ln(R) \quad (17b)$$
$$\sigma_m^{\ 2} = 0.08257 + 0.0076\,Ln(R) \quad (17c)$$

for 1.59 mm/h $\leq R \leq$ 160 mm/h

PRETORIA:

$$N_T = 246.33R^{0.3740} \quad (18a)$$
$$\mu_m = -0.2288 + 0.1309\,Ln(R) \quad (18b)$$
$$\sigma_m^{\ 2} = 0.0799 + 0.0094\,Ln(R) \quad (18c)$$

for 1.73 mm/h $\leq R \leq$ 70 mm/h

RICHARDS BAY:

$$N_T = 167.90R^{0.4295} \quad (19a)$$
$$\mu_m = -0.3629 + 0.1504\,Ln(R) \quad (19b)$$
$$\sigma_m^{\ 2} = 0.0703 + 0.0108\,Ln(R) \quad (19c)$$

for 3.52 mm/h $\leq R \leq$ 130 mm/h

By employing the derived model equations for the selected locations in South Africa, we can obtain graphical plots for the rainfall DSD, particularly at $R_{0.01}$. Figure 3 shows the rainfall DSD spectra obtained at the respective $R_{0.01}$ (see Table I for this information) of each location. From the graph, we observe that the rainfall DSD behaviour is similar for all locations below 1 mm diameter bound. However, beyond this 1 mm bound, a divergence is observed with Richards Bay having higher densities of large-sized raindrops. Durban and Pietermaritzburg are, however, seen to have similar rainfall DSD characteristics, hence the overlapping at $R_{0.01}$. The geographical proximity of Durban and Pietermaritzburg may play a major role in the similarity observed. Pretoria, again, is seen to have the lowest density for large drops among all the locations. Broadly speaking, the rainfall DSD patterns among the selected locations in South Africa have a strikingly similar trend. This generic similarity is expected, as they all belong to the same subtropical climatic zone, with inherent climatic characteristics.

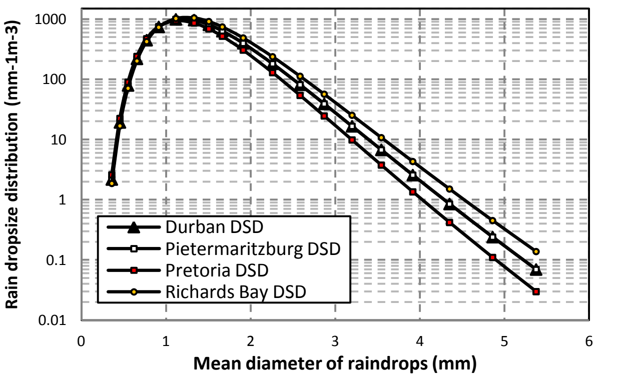

Fig. 3: Rainfall DSD plots for different locations at their respective $R_{0.01}$ values.

V. Rainfall Specific attenuation prediction from Scattering Technique

By applying the scattering technique developed by *Gustav Mie* in 1908 [15], we can estimate the scattering parameters for a spherically assumed rain droplet. Already, *Van de Hulst* proposed that the forward scattering amplitude of the Mie equations can be given as [16]:

$$S(0) = \frac{1}{2}\sum_{n=1}^{\infty}(2n+1)[a_n(m,\alpha) + b_n(m,\alpha)] \quad (20)$$

where n is the number of particles whose maximum is an infinite bound, m is the complex refractive index of rain water and α is the particle size of the raindrop. While $a_n(m, \alpha)$ and $b_n(m,\alpha)$ are the Mie coefficients.

Odedina and Afullo [17] confirmed a power-law function as sufficient for predicting the extinction cross section (ECS) from the radius of the assumed spherical raindrop, as a modification ECS function, proposed by *Hulst* [16] in (20). Thus, the extinction cross section (or Q_{ext}) is given as:

$$ECS = \frac{4\pi}{k^2}Re\{S(0)\} \cong k_{ext}r^{\zeta_{ext}} \ [mm^2] \quad (21)$$

where k is the wave number; k_{ext} and ζ_{ext} are the power-law coefficients of the ECS for raindrops of radius, r.

The results for computed ECS at our selected locations are provided in Table II at 2.5 GHz, 12 GHz and 25 GHz. It should be noted that assumed ambient temperatures for each location are obtained from annual average values in [18]. Hence, we have Durban (20.18°C), Pietermaritzburg (18.7°C), Richards Bay (22°C) and Pretoria (18.7°C). Regression technique is then utilised to derive power-law functions corresponding to the ECS for each locations at different frequencies. A closer look at Table II shows that Richards Bay has the highest shape parameters (α_{ext}) for all frequencies, while Durban has the highest scale parameters (k_{ext}). Pietermaritzburg and Pretoria are both seen to have the similar coefficients since they have the same annual average temperature value.

Applying the equation proposed in (6), the corresponding

TABLE II. Computed Values of Extinction Cross Section Coefficients for Locations in South Africa

LOCATION	FREQUENCY (GHz)	REFRACTIVE INDEX, *m*	k_{ext}	ς_{ext}
DURBAN	2.5	8.8774 + j0.6024	0.0068	3.4022
	12	7.7755 + j2.2594	0.5866	4.4443
	25	6.1024 + j2.8534	2.4567	4.0186
RICHARDS BAY	2.5	8.8473 + j0.5724	0.0046	3.3884
	12	7.8260 + j2.1881	0.5821	4.4659
	25	6.2016 + j2.8310	2.4354	4.0208
P'MARITZBURG/ PRETORIA	2.5	8.9015 + j0.6287	0.005	3.3926
	12	7.7289 + j2.3183	0.5901	4.4263
	25	6.0184 + j2.8680	2.4411	4.0091

specific attenuation for different locations can be computed. The plots for the computed specific attenuation shown in Figures 4, 5 and 6 show the variation in the computed specific attenuation at different locations around South Africa at varied transmission frequency.

At 2.5 GHz, the city of Durban is predicted to experience larger specific attenuation than other cities. At this lower spectrum of microwave band, the average difference in the specific attenuation figures for all rainfall rates, between Durban and other cities, is of the order of 10^{-3} dB/km. For example, the city of Pretoria is seen to have an average deviation of 0.0064 dB/km at all rainfall rates from that of Durban. Richards Bay deviates with an average specific attenuation of 0.0068 dB/km and Pietermaritzburg with 0.0069 dB/km. At this low frequency, implementation of design link witnesses smaller "lost" decibels since the rain fade per km is evidently low.

At 12 GHz, Durban again is seen to have higher specific attenuation figures with an average deviation of the order of

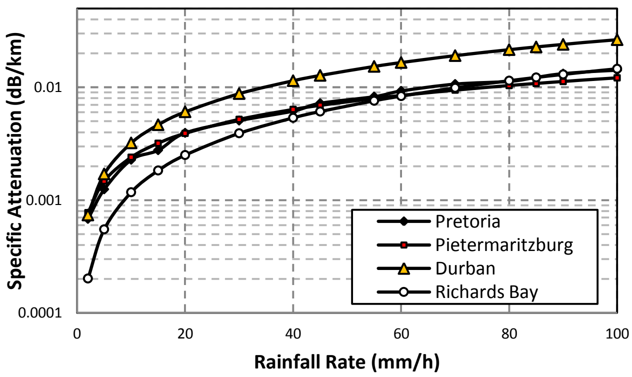

Fig. 4: Computed specific attenuation for different locations in South Africa at 2.5 GHz.

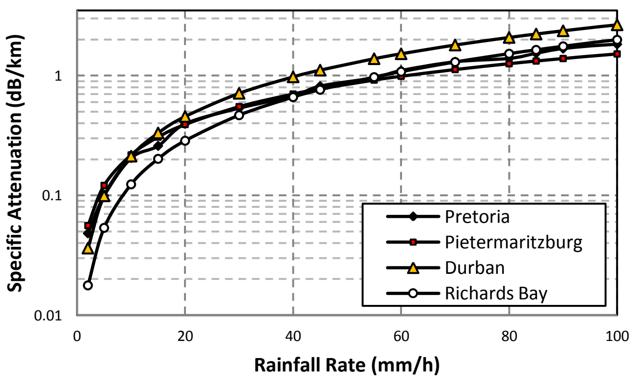

Fig. 5: Computed specific attenuation for different locations in South Africa at 12 GHz.

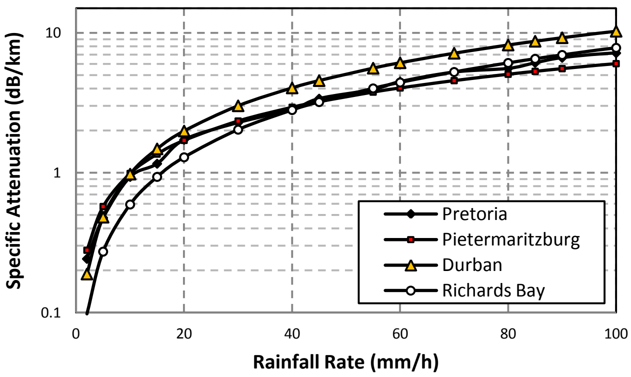

Fig. 6: Computed specific attenuation for different locations in South Africa at 25 GHz.

10^{-1} dB/km above other cities. Although, at rainfall rates less than 10 mm/h, Pietermaritzburg is predicted to have higher estimates compared to other cities. Generally, Richards Bay is seen to have the least average deviation from Durban with 0.3689 dB/km. This is followed by Pretoria and Pietermaritzburg with 0.3679 dB/km and 0.4875 dB/km respectively. At this frequency, the predicted specific attenuation at Richards Bay is seen to be undergoing higher frequency response than Pretoria.

At 25 GHz, Durban again predicted to experience higher levels of specific attenuation when compared to other cities. At this frequency, the average deviation of Durban with other cities is almost 2 dB/km higher, at all rainfall rates. Richards Bay is seen to have the least average deviation with Durban at 1.406 dB/km, Pretoria at 1.53 dB/km and Pietermaritzburg at 1.85 dB/km. Network design, particular for long transmission distance (say above 15 km) at this frequency, may require large power level inputs to conquer the negative effects arising from rain fades.

Broadly speaking, the role of climatic variation is evidently dynamic from the results. For example, this explains why proximate locations such as Pietermaritzburg and Durban may experience different levels of rain fade. Also, coastal locations like Durban and Richards Bay may be influenced by sea current dynamics which modify the overall effects of rain fade. We also observed that a continuous increase in the simulated value of the transmission frequency beyond 25 GHz may result in Richards Bay (and perhaps, Pietermaritzburg) having higher specific attenuation levels than Durban. This is only logical as scattering losses tend to increase as the transmission frequency increases, especially with preponderance in the distribution of larger raindrop sizes. Interestingly, Durban was earlier observed to have lower densities of large rainfall drops than Richards Bay at $R_{0.01}$, this may result in lower effects from scattering losses. Since the effects of rainfall specific attenuation are not investigated beyond 25 GHz in the simulation undertaken in this study, it will be a worthy subject to investigate in the future. Also, it may be pertinent to extend this study to other locations in South Africa in future studies.

VI. CONCLUSION

Probability density function (PDF) as a statistical tool could provide useful information required for the prediction of rainfall attenuation, particularly at locations without adequate measuring instruments. This mathematical practicality is being employed in this paper, to explore rainfall prediction at three locations, in South Africa. It is seen from our prediction that the specific attenuation of a locality is mainly a function of the climatic characteristics and other invisible meteorological dynamics. In the reality of limited funding required for high-level deployment of equipment for localized measurements of rainfall, this method may prove useful for link design engineers to counteract the effects of rain fade at frequencies beyond 10 GHz. However, the results from this study are not conclusive, as long-term measurements of rainfall indices for attenuation prediction need to be undertaken at those locations or alternative attenuation measurements could be used to confirm the accuracy.

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