Analytical Modeling of Rain Attenuation and Its Application to Terrestrial LOS Links

Modupe O. Odedina, Thomas J. Afullo
School of Electrical, Electronic and Computer Engineering
University of KwaZulu-Natal, Durban, South Africa, 4041
Tel: +27-72-808-6386, Fax: +27-31-260-500
Email: {Odedinam, Afullot}@ukzn.ac.za

Abstract—The aim of this paper is to propose an analytical model for the calculation of rain attenuation on terrestrial line-of-sight link. This work employs Mie theory for electromagnetic scattering by dielectric sphere on raindrops, under the assumption that the shapes of the raindrops are spherical. Complex forward scattering amplitudes of the spherical raindrops are computed and the extinction cross-sections for the spherical raindrops are calculated. Applying the power-law regression to the extinction cross-section calculated, power-law coefficients are determined. The rain attenuation is modeled analytically by integrating the extinction power-law model over different established raindrop-size distribution (DSD) models. From the terrestrial line-of-sight link set-up in Durban, South Africa, experimental rain attenuation measurements were recorded at 19.5 GHz along a 6.73 km propagation path length. These rain attenuation measurements were compared with the results obtained from the analytical models with the same propagation parameters to establish the best attenuation models that describes the behaviour of radio link performance in the presence of rain.

Index Terms—Electromagnetic scattering, power-law coefficient, rain attenuation, scattering amplitudes

I. INTRODUCTION

Advances in radio communication systems in recent times make it inevitable for service providers to ask for higher frequency bands to accommodate the ever increasing demands on radio services. However, the reliability of such systems in these frequency bands may be severely degraded due to some natural atmospheric phenomenon, of which rain is the dominant factor [1]. Therefore, communication systems may experience an extreme loss of signal due to rain-induced attenuation and make the system temporarily unavailable for use [2]. Thus, it is of great need to establish a model capable of predicting the behaviour of these systems in the presence of rain.

The propagation of high frequency electromagnetic waves through rain are affected by two attenuating factors; absorption and scattering [3] [4 [5]. For absorption, part of its energy is absorbed by the raindrops and transformed into heat [4] [5] while the scattering aspect may introduce unwanted or interfering signals into the communication receiver that may mask the desired signal and these create several problems [2], [5]. The solution of these scattering problems is mostly easily obtained for simple raindrop geometry such as sphere [4]. Rain consists of drops of various diameters ranging from 0.01 to 0.7 cm [5] which may assume a flattened shape at the bottom and rounded at the top [6]. This phenomenon becomes conspicuous as the rain diameter increases due to the free fall nature of rain [6]. This makes the raindrops to be model as oblate spheroids with the scattering problem solution being studied by several authors ([7], [8], and [9]).

The attenuation calculation has been observed to improve with increasing frequency as the smaller raindrops are those which contribute most to the attenuation in the higher frequency range. This has been verified in the dual-polarised radar measurements reported by Hall [10] and later by Moupfouma et al. [11], who explains that at high microwave frequencies, the attenuation is greatly influenced by the mean and small raindrops, which are more numerous than large raindrops. Therefore, in this work, the raindrops are considered to be spherical. The calculation of rain attenuation depends considerably on the raindrop-size distribution (DSD) and the radio link operating frequency. The later depends mainly on the geographical characteristic of the area in which the radio link is implemented [3]. Apart from the dependence of rain attenuation on raindrop-size distribution, specific rain attenuation (reduction of power per unit length on the path [2]) depends upon the forward scattered electromagnetic wave of the raindrops (water drops) which are influenced by the water temperature, the water complex refractive index, the radio link operating frequency [3].

The analytical rain attenuation models developed in this paper are limited to two different established raindrop-size distribution (DSD) models. They are; the negative exponential and the lognormal DSD model. These models have been tested by many authors [12], [13], [14], [15] and they appear to be capable of approximating most observed drop-size spectra fairly well [14]. The analytical models developed are based on the computation of forward scattering amplitudes of spherical raindrops and the calculated extinction cross-section of the raindrops. This is modeled with a power law fit and integrated over the different raindrop-size distribution models to develop the analytical rain attenuation model. The results from these analytical models are compared with the experimental observations obtained for one year on a terrestrial line-of-sight link of 6.73 km path length and operating frequency of 19.5 GHz.

II. Scattering of Spherical Raindrops by Electromagnetic Waves

The Mie scattering theory is applied to a region containing raindrops, under the assumption that each raindrop illuminated by a plane wave is uniformly distributed in a rain-filled medium. Also, it is assumed that the distance of each drop is sufficiently large to avoid any interaction between them. When the incident electromagnetic plane wave hits the spherical raindrop (or a dielectric sphere), a scattered wave is generated and the corresponding scattered electric field in the far-field region for the spherical raindrop is given as [8]: (the $\exp(+j\omega t)$ time convention is assumed and suppressed)

$$E_{sca}(r,\phi,\theta) = \frac{f(\hat{K}_i,\hat{K}_s)}{r}\exp(-jk_0 r) \tag{1}$$

where (r,ϕ,θ) are the spherical coordinates of the observer, $\hat{K}_i$ is the unit vector directed toward the propagation direction of the incident wave, $\hat{K}_s$ is a unit vector directed from the origin to the observation point, r is the distance from the origin to the observation point, and $f(\hat{K}_i,\hat{K}_s)$ is a function denoting vector scattering amplitude, k_0 is the free space propagation constant and j is the imaginary unit [8]. The symbol θ is the field incidence angle and ϕ is the angle between the direction of the wave propagation and the drop axis, which is observation angle. The scattering amplitude polarized in the same direction as the incident wave at observation angle $\phi = 0$ corresponds to the forward scattering and $\phi = \pi$ corresponds to the backward scattering. [3], [7], [16], [17]. The geometry for the incident electromagnetic plane wave on dielectric sphere is shown in Figure 1.

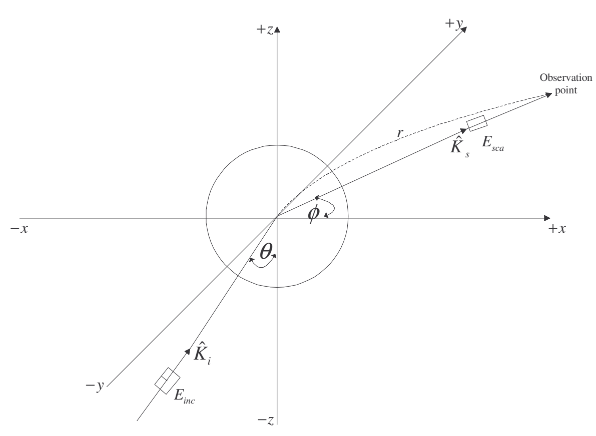

Fig. 1: Incident electromagnetic plane wave on a dielectric sphere

III. Forward Scattering Amplitudes of Spherical Raindrops

Scattering in the incident wave propagation direction is considered in this work. Therefore the complex forward scattering amplitude $S(0)$ for the spherical rain drop function can be written as [16], [17]:

$$S(0) = \frac{1}{2}\sum_{n=1}^{\infty}(2n+1)(a_n + b_n) \tag{2}$$

where a_n and b_n are the Mie coefficients.

A complete mathematical description of the above phenomenon enables the complex scattering function to be dependent on drop radius, drop shape, drop water complex permittivity ε and on the frequency (wavelength, λ) of the transmitted radio signal [5]. Therefore the Mie coefficients a_n and b_n can be described by [17], [18]:

$$a_n(m,\alpha) = \frac{m^2 j_n(m\alpha)[\alpha j_n(\alpha)]' - j_n(\alpha)[m\alpha j_n(m\alpha)]'}{m^2 j_n(m\alpha)[\alpha h_n^{(1)}(\alpha)]' - h_n^{(1)}(\alpha)[m\alpha j_n(m\alpha)]'} \tag{3a}$$

$$b_n(m,\alpha) = \frac{j_n(\alpha)[m\alpha j_n(m\alpha)]' - j_n(m\alpha)[\alpha j_n(\alpha)]'}{h_n^{(1)}(\alpha)[m\alpha j_n(m\alpha)]' - j_n(m\alpha)[\alpha h_n^{(1)}(\alpha)]'} \tag{3b}$$

where m is the complex refractive index of the spherical drop (water drop) which is a function of frequency and temperature $m(T,f)$, $\alpha = k\bar{a}$ is the size particle, $\bar{a}$ the radius of the sphere and $k = 2\pi/\lambda$ is the wave number and λ the wavelength. The function $j_n(x)$ is the spherical Bessel function of the first kind and $h_n^{(1)}(x)$ is the spherical Bessel function of the third kind (or Hankel function of the first kind) which are of order n $(n = 1,2,\ldots)$ and the primes at the square brackets indicate differentiation with respect to the argument of the spherical Bessel function inside the brackets [17], [18] .

The infinite series of the summation n in equation (2) were limited to the $n_{\max}$ term given by [18], [20] to the value of

$$n_{\max} = \alpha + 4\alpha^{1/3} + 2 \tag{4}$$

where $\alpha = 2\pi\bar{a}/\lambda$

With the help of the MATLAB's built-in double precision Bessel functions, the Mie coefficients a_n and b_n are computed. This is then used to calculate the scattering amplitudes for the entire spherical drop radius at 19.5 GHz. It should be noted that the refractive index of water at 20^0C (293K) for a frequency of 19.5 GHz from Liebe et al. [19] is used in this work. Table I shows the scattering amplitudes results at 19.5 GHz for 14 sizes of spherical raindrops

IV. Extinction Cross-section of Spherical Raindrops

From the forward scattering amplitudes shown in Table 1 which consists of the real and the imaginary part, the extinction cross-section Q_{ext} is calculated.

TABLE I

FORWARD SCATTERING AMPLITUDES f=19.5 GHz , T=293 K

m=6.70992+2.76083i AND λ=1.538cm

Sphere radius $\bar{a}$ **(cm)**	**spherical drop size** $\alpha = k\bar{a}$	Forward scattering amplitudes	
		Real part	Imaginary part
0.025	0.1021735	0.00004183589	-0.001029566i
0.050	0.2040816	0.00039247068	-0.008349796i
0.075	0.3065205	0.00190813784	- 0.029128854i
0.100	0.4086940	0.00772007620	-0.071647849i
0.125	0.5108675	0.02740969410	-0.143406704i
0.150	0.6130410	0.07581456728	-0.240641270i
0.175	0.7152145	0.15895399777	- 0.350194553i
0.200	0.8173880	0.27945577892	- 0.455512918i
0.225	0.9195615	0.42379060579	-0.530234551i
0.250	1.0217350	0.55625984731	- 0.56664375i
0.275	1.1239086	0.65232268838	-0.584253056i
0.300	1.2260821	0.70991851443	- 0.602374508i
0.325	1.3282556	0.73386412846	- 0.629267268i
0.350	1.4304291	0.72857254116	-0.6672818892i

The extinction cross-section Q_{ext} is given by [16], [17]:

$$Q_{ext} = \frac{4\pi}{k^2} \operatorname{Re} S(0) \qquad (5)$$

Since $k = 2\pi/\lambda$

Using equation (5) with the real part of the scattering amplitudes $\operatorname{Re} S(0)$ shown in Table 1, the extinction cross-section was calculated for the entire drop radius. The extinction cross-section calculated is plotted against the spherical raindrop radius. Analysis of the obtained curve shows that it can be well modeled with power law as shown in Figure 2.

From Figures 2, the power law extinction cross-section coefficient for 19.5 GHZ can be expressed as

$$\operatorname{Re} Q_{ext}(\phi = 0, \bar{a}, \lambda, T) = 83.956\bar{a}^{4.1142} \qquad (6)$$

This turns out that the extinction cross section calculated from the real part of the forward scattering amplitude can be related to the raindrop radius $\bar{a}$ by a power law so that

$$\operatorname{Re} Q_{ext}(\phi = 0, \bar{a}, \lambda, T) = \kappa\bar{a}^{\varsigma} \qquad (7)$$

where $\operatorname{Re} Q_{ext}$ is the real part of the extinction cross-section which is dependent on the real part of the forward scattering amplitude with $\phi = 0$, radius of the sphere $\bar{a}$, wavelength λ and the water temperature T. For the computation of this work T is taken to be 20°C which equals 293K, and κ and ς are the extinction cross-section of the power law coefficients.

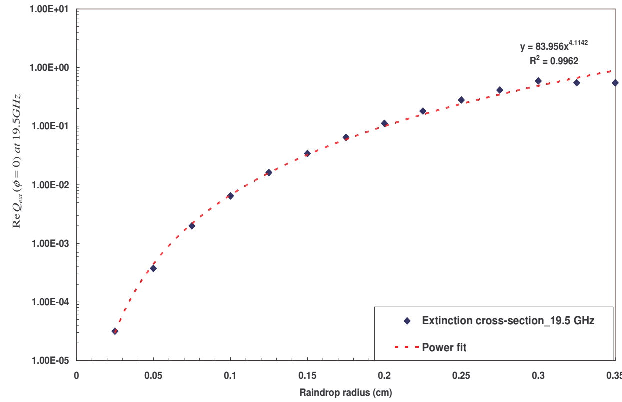

Fig. 2: Modeling the extinction cross-section real part at 19.5 GHz

V. FORMULATIONS OF THE ANALYTICAL RAIN ATTENUATION MODELS

The rain attenuation is formulated by integrating the extinction cross-section power law over the different established drop-size distribution models. From the fundamentals of electromagnetic theory, it has been established that magnitude of an electromagnetic wave traveling through a rain-filled medium in a distance d, decreases or attenuates in amplitude by a factor $e^{-\gamma d}$ where γ is the attenuation coefficient [17] [21], which is given by [16], [17]

$$\gamma = nQ_{ext} \qquad (8)$$

The symbol n is assumed to be spherical drops per unit volume

From [2], [17], the attenuated wave is written as

$$A(dB) = 10\log_{10}\frac{1}{e^{-\gamma d}} \text{ (ratio of power to reference power)}$$

$$A(dB) = \gamma d 10\log_{10}^{e} \qquad (9)$$

where $e = 2.718$, thus attenuation can be written as

$$A(dB) = 4.343\gamma d \qquad (10a)$$

or

$$A(dB/km) = 4.343\gamma \qquad (10b)$$

Equation (10a) and (10b) are path attenuation and specific rain attenuation respectively.

Therefore, in order to calculate the attenuation coefficient γ, models which describe the raindrops in a rain-filled medium are employed. As mentioned earlier, negative exponential and lognormal DSD models are used. The power law model developed from the extinction cross-section plot will be integrated over these DSD models to develop an analytical model for rain attenuation

A. *Negative Exponential Raindrop-size Distribution Models*

The coefficients of the negative exponential DSD models given by Marshall and Palmer [12] (MP) for all rain types and that of Joss et al. (J) [22] for drizzle (JD) and thunderstorm (JT) type of rains were used for this work. The negative exponential raindrop-size distribution can be represented by [12], [22]

$$n(\bar{a}) = N_0 e^{-\Lambda \bar{a}} \tag{11a}$$

and

$$\Lambda = \alpha R^{-\beta} \tag{11b}$$

where α and β are coefficients which depend on the geographical characteristic of the locality, $\bar{a}$ is the radius of the drop, N_0 is the number of concentration of drops $n(\bar{a})$ for radius $\bar{a} = 0$ on the exponential approximation and Λ is its slope per unit volume of space [12]

From equation (7) the extinction cross-section power law model can be written as

$$Q_{ext} = \kappa \bar{a}^{\varsigma} \tag{12}$$

To determine the attenuation coefficient γ, we integrate the extinction cross-section power law coefficients over exponential DSD models to have

$$\int_0^{\infty} \kappa \bar{a}^{\varsigma} \times n(\bar{a}) d\bar{a} = \int_0^{\infty} \kappa \bar{a}^{\varsigma} \times N_0 e^{-\Lambda \bar{a}} d\bar{a} \tag{13}$$

where $n(\bar{a})d\bar{a}$ is the number of drops of radius between $\bar{a}$ and $\bar{a} + d\bar{a}$ in a unit volume of space

Applying gamma function in solving the integral in equation (13)

$$\gamma = \kappa N_0 \Gamma(\varsigma + 1) \int_0^{\infty} e^{-\Lambda \bar{a}} d\bar{a}$$

$$\gamma = \kappa N_0 \frac{\Gamma(\varsigma + 1)}{\Lambda^{\varsigma+1}} \tag{14}$$

with Γ as the gamma function

Substituting equation (14) into (10b), then specific rain attenuation becomes

$$A(dB/km) = 4.343 \times 10^5 \left[\kappa N_0 \frac{\Gamma(\varsigma + 1)}{\Lambda^{\varsigma+1}} \right] \tag{15a}$$

and substituting equation (14) into (10a), path attenuation is

$$A(dB) = 4.343 \times 10^5 \left[\kappa N_0 \frac{\Gamma(\varsigma + 1)}{\Lambda^{\varsigma+1}} \right] d \tag{15b}$$

where d is the propagation path length.

But because of the non-homogeneity of rain along a propagation path length [2] [23],[24], [25], [26], the concept of effective path length d_{eff} was introduced. This is done by multiplying the actual path length by a distance factor r known as the reduction factor. This can be given as [26]

$$d_{eff} = rd \tag{16}$$

where

$$r = \frac{1}{1 + d/d_0} \tag{17}$$

$$d_0 = 35 e^{-0.015 R_{0.01}} \tag{18}$$

when $R_{0.01} \leq$ 100mm/h, d_0 is calculated using the real rainfall value, which is exceeded for 0.01% of the time. When $R_{0.01}$ >100mm/h, the value of 100 should be used at $R_{0.01}$ in the equation [26], [27] as this limits the effect of the reduction factor with increasing rainfall rate [27]. This procedure has been considered to be valid in all parts of the world at least for frequencies up to 40 GHz and path lengths up to 60 km [26]

Therefore (15b) can be written as

$$A(dB) = 4.343 \times 10^5 \times d_{eff} \left[\kappa N_0 \frac{\Gamma(\varsigma + 1)}{\Lambda^{\varsigma+1}} \right] \tag{19}$$

The above equations shows the analytical modeling of rain attenuation developed with the negative exponential DSD model

B. Lognormal Raindrop-size Distribution

The coefficients of the general tropical lognormal DSD models given by Ajayi-Olsen (AO) [15] for all rain type and that of Adimula-Ajayi (AA) [28] for drizzle, widespread, shower, thunderstorm and tropical thunderstorm rain are used in this work. The tropical lognormal models coefficients were chosen as against the continental lognormal models because of the similarities that the rain type in the South Africa has with the tropical environment [29]. The lognormal DSD model is given by [15], [28]

$$n(D) = \frac{N_t}{\sigma D \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\ln(D) - \mu}{\sigma} \right)^2 \right] \tag{20}$$

D is the raindrop diameter, $n(D)$ is the number of raindrops in a unit volume of air, σ is the standard deviation, μ is the mean of $\ln D$ and N_t is the total number of drops of all sizes.

Ajayi and Olsen [15], defined parameters N_t, μ and σ as follows

$$\begin{aligned} N_t &= A_o R^{B_o} \\ \mu &= A_{\mu} + B_{\mu} \times \ln R \\ \sigma^2 &= A_{\sigma} + B_{\sigma} \times \ln R \end{aligned} \tag{21}$$

with parameters A_0, B_0, A_{μ}, B_{μ}, A_{σ} and B_{σ} depending on the locality of interest

Integrating the extinction cross-section power law coefficient over lognormal DSD model, we have:

$$\int_0^{\infty} \kappa \left(\frac{D}{2} \right)^{\varsigma} \times n(D) dD =$$

$$\int_0^{\infty} \kappa \left(\frac{D}{2} \right)^{\varsigma} \times \frac{N_t}{\sigma D \sqrt{2\pi}} \exp\left[-\frac{1}{2} \left(\frac{\ln(D) - \mu}{\sigma} \right)^2 \right] dD \tag{22a}$$

$$\gamma = \kappa N_t \left(\frac{1}{2} \right)^{\varsigma} \frac{1}{\sigma \sqrt{2\pi}} \int_0^{\infty} D^{\varsigma - 1} \exp\left(-\frac{(\ln D - \mu)^2}{2\sigma^2} \right) dD \tag{22b}$$

Integrating by parts and applying the bounds, the attenuation coefficient for lognormal DSD model can be given as [3]

$$\gamma = \frac{\kappa N_t}{2^{\varsigma}} \exp\left[\varsigma\mu + \left(\frac{\varsigma\sigma}{\sqrt{2}}\right)^2\right] \quad (23)$$

Substitute the attenuation coefficient γ in (23) into (10b) the specific attenuation with a lognormal distribution model can be written as

$$A(dB/km) = 4.343\times10^5 \times N_t \times \frac{\kappa}{2^{\varsigma}} \times \exp\left[\varsigma\mu + \left(\frac{\varsigma\sigma}{\sqrt{2}}\right)^2\right] \quad (23a)$$

and path attenuation can be written as

$$A(dB) = 4.343\times10^5 \times d_{eff} \times N_t \times \frac{\kappa}{2^{\varsigma}} \times \exp\left[\varsigma\mu + \left(\frac{\varsigma\sigma}{\sqrt{2}}\right)^2\right] \quad (23b)$$

This is the analytical rain attenuation model from lognormal DSD model.

VI. Application to Terrestrial Line-of-Sight Link

Using the analytical rain attenuation models developed in equations (19) and (23b) respectively from negative exponential and lognormal DSD models with practical propagation parameters and the above mentioned DSD model coefficients in [12], [15], [22] and [28] analytical rain attenuation results were calculated. From the experimental rain attenuation observed in Durban for 1-year, the maximum, average and minimum measured rain attenuation values per rain rate determined by [30] at 19.5 GHz along 6.73 km propagation path length were compared with the results obtained from the analytical rain attenuation models. It should be noted that the analytical rain attenuation results were calculated from with the 1-minute rain rates recorded along the 6.73 km path length.

Fig. 3a and 3b shows the experimental rain attenuation and the analytical rain attenuation values for Durban at 19.5 GHz along the 6.73km path length. Fig. 3a shows the measured rain attenuation at the 3 bounds (maximum, minimum and average attenuation values per rain rate), the rain attenuation calculated from the ITU-R model [26], and the analytical attenuation models developed from the negative exponential DSD model. Fig. 3b also shows the measured rain attenuation at the 3 bounds and the analytical attenuation models developed from the lognormal DSD model of Ajayi-Olsen and Adimula-Ajayi.

From these figures (Fig. 3a and 3b), the analytical attenuation models that best fit into the measured attenuation values for each bounds were determined by using the chi-square statistic. Table II shows the chi-square results of all the analytical attenuation models as compared with the maximum, average and minimum measured attenuation From Table II, the analytical attenuation models developed from the negative exponential DSD model of Joss et al. for thunderstorm (JT) rain type, lognormal model of Adimula-Ajayi (AA) for tropical thunderstorm rains (TT) and tropical shower (TS) type of rains give the lowest chi-square values for the minimum, average and maximum measured attenuat-

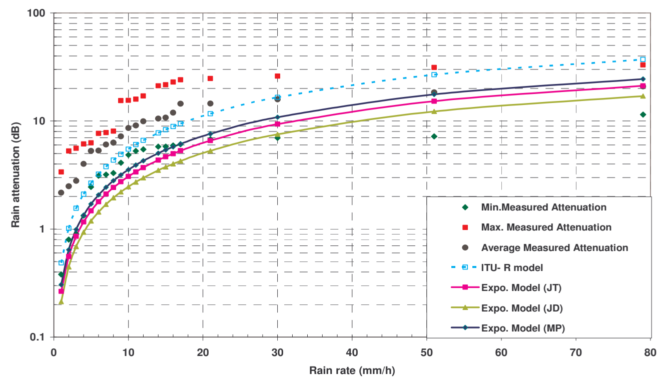

Fig. 3a Experimental and analytical rain attenuation along the 6.73 km path length at 19.5 GHz in Durban

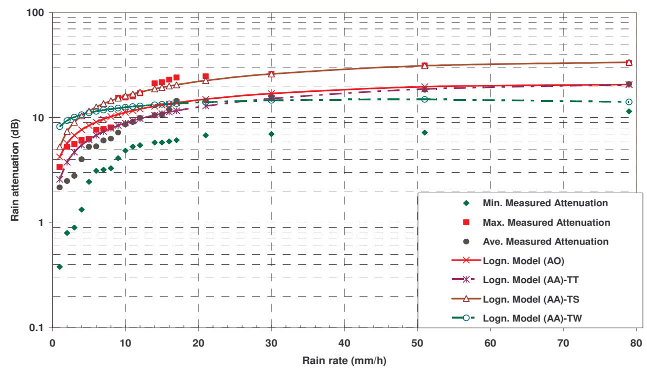

Fig. 3b Experimental and analytical rain attenuation along the 6.73 km path length at 19.5 GHz in Durban

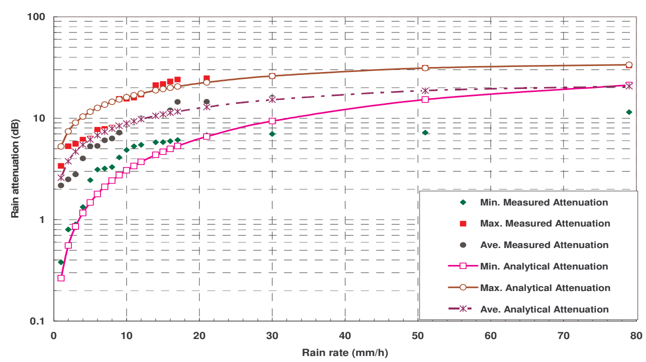

Fig. 4 Best fit analytical rain attenuation for the maximum, average and minimum experimental attenuation values

TABLE II

The χ^2 statistic of the analytical attenuation models as compared with experimental attenuation values

Analytical attenuation models	Experimental attenuation values		
	Minimum	Average	Maximum
Negative exponential model (MP)	17.496	112.741	596.298
Negative exponential model (JT)	**16.656	156.69	753.963
Negative exponential model (JD)	23.308	243.898	1051.059
Lognormal model (AO)	88.811	16.347	60.432
Lognormal model (AA)-TT	55.534	**3.819	103.606
Lognormal model (AA)-TS	185.181	73.55	**15.935
Lognormal model (AA)-TW	105.245	41.455	103.558
*ITU-R model [26]	44.559	38.774	256.386

*For the purpose of comparison, **Lowest χ^2 values of the analytical attenuation model that best fit the measured rain attenuation

ion respectively. Hence, these three analytical models are accepted to give the best fit that describes the minimum, average, and maximum signal level measurement values. Fig. 4 shows the measured and the analytical rain attenuation for Durban at 19.5 GHz on the 6.73 km link.

VII. Conclusion

Analytical models for the calculation of rain attenuation on terrestrial line-of-sight links are proposed in this work. These models are developed by integrating the extinction cross-section power-law model developed from the scattering amplitudes of spherical raindrops over the negative exponential and lognormal DSD models. The attenuation results obtained from these models were compared with the experimental signal level measurement recorded in Durban at 19.5 GHz along a 6.73 km path length. For the purpose of cross referencing, it was also compared with the ITU-R rain attenuation model.

The results show that the analytical attenuation developed from the negative exponential model of Joss et al. thunderstorm rain type, lognormal model of Adimula-Ajayi tropical thunderstorm rains and tropical shower type of rains gave the best fits for the minimum, average and maximum experimental attenuation values, respectively. These proposed analytical attenuation models can be applied to various geographical locations around the world to estimate the behaviour of a radio link in the presence of rain, especially when either the rain rate statistics or the raindrop-size distribution governing the locality is known.

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Modupe O. Odedina obtained her B.Sc (Hon.) Physics (Electronics specialization) from the Federal University of Technology, Nigeria in 2001. Her MSc(Eng) in Electronic Engineering from the University of KwaZulu-Natal, South Africa in 2006. She is presently pursuing her Ph.D in Electronic Engineering in the same school. Her research interests include electromagnetic wave propagation on terrestrial and satellite communication systems with main focus on rain-field modeling for radio propagation applications

Thomas J. Afullo holds the BSc. (Hon) Electrical Engineering from the University of Nairobi Kenya (1979), the MSEE from West Virginia University, USA (1983), and the Bijzondre License in Technology and Ph.D in Electrical Engineering from the Vrije Universiteit Brussel (VUB), Belgium (1989). He has held various positions in industry and university for 25 years. He is currently Associate Professor, School of Electrical, Electronic & Computer Engineering, University of KwaZulu-Natal (UKZN), Durban, South Africa. Former Director of Centre of Excellence in Rural Telecommunications at UKZN Westville campus