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Re:	Call for Contributions (posted 24 September 1999), Specific Area: Propagation Model
Abstract	A fundamental quantity in the calculation of rain attenuation statistics is the specific attenuation (attenuation per unit distance). The power-law form of rain specific attenuation is very convenient and is commonly used. It is expressed as $k \cdot R^{\alpha}$, where k and α are the power-law parameters, and R is the rain rate in mm/h. Limited number of power-law parameters were available in the technical literature for certain raindrop size distributions. Some of these parameters had reservations for rain-rate ranges. New power-law parameters for four different (gamma, lognormal, Laws and Parsons, and Marshall and Palmer) raindrop size distributions are made. For a rain temperature of 0°C, k and α with polarization dependence are presented here for rain rates from 0 to 150 mm/h over the frequency range of $5-100$ GHz.
Purpose	To provide an input to the specific area ‘‘Propagation Model’’
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Power-Law Parameters of Rain Specific Attenuation

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Introduction

The power-law form of rain specific attenuation is very convenient and has been used in calculating rain attenuation statistics. The term specific attenuation is commonly used, accounting for attenuation per unit distance. It is a fundamental quantity in calculating the rain attenuation. Its power-law form is written as $\gamma = k \cdot R^{\alpha}$ in dB/km, where R is the rain rate in mm/h, and k and α are power law parameters, which depend on frequency, raindrop size distribution, rain temperature, and polarization.

For the purpose of calculating the attenuation, it is adequate to assume that raindrops have spherical shape. This assumption makes k and α independent of polarization. For low rain rates below 50.8 mm/h and for high rain rates from 25.4 to 152.2 mm/h, two separate sets of power-law parameters for Laws and Parsons (L-P) raindrop size distribution [1] were presented in [2]. In addition, [2] presents power-law parameters for Marshall and Palmer (M-P) raindrop size distribution [3] in the low rain rate case. For rain rates below 25 mm/h, power-law parameters for gamma [4], lognormal [5], and L-P raindrop size distributions at a rain temperature of $0^{\circ}\mathrm{C}$ were presented in [6].

To account for polarized transmission and rain induced depolarization effects, non-spherical shapes for raindrops have been used in making power-law parameters and some power-law parameters can be found in the literature for certain raindrop size distribution, for example in [7].

The power-law parameters available in the technical literature were limited to certain choices of raindrop size distributions or rain rate ranges. They mostly were presented in conjunction with rain attenuation models for earth-space and terrestrial propagation paths. Other factors contributing to attenuation such as distance reduction factor, rain region, and the statistics of rainfall were also addressed in the models.

Available power-law parameters seem insufficient for use in local multipoint distribution service (LMDS) employing fixed point-to-multipoint terrestrial radio communications. Depending mainly on rain attenuation and transmitter power, the range of LMDS may be shorter. To achieve high quality of service, LMDS systems require to employ high antennas which provide line-of-sight (LOS) propagation paths between a base station and one or more subscriber stations.

New power-law parameters for the above-mentioned four different distributions have been made, available for non-spherical shape of raindrops, as well as for spherical shape of raindrops. The results of non-spherical shape of raindrops for rain rates from 0 to 150 mm/h at a rain temperature $0^{\circ}\mathrm{C}$ are presented in the following.

Rain Specific Attenuation

The rain specific attenuation γ in dB/km is expressed as

$$\gamma = 4.343 \times \int_{0}^{a_{\max}} \sigma_t(a) N(a) da \qquad (1)$$

where $\sigma_t(a)$ is the extinction cross section of a single raindrop derived from the forward scattering theorem [8], a is the equi-volume radius of raindrops, $N(a)$ is the raindrop size distribution function, and $a_{\max}$ is the maximum equi-volume raindrop radius. The assumption of oblate-spheroid shape for raindrops [9] has been taken and the raindrop axial ratio R_o is given by $R_o = 1 - a$, where a is in cm. The raindrop symmetry axis was set along the vertical direction. The computations were made for horizontal- and vertical-polarization and for horizontal propagation path.

The computation of $\sigma_t(a)$ is performed by using the point-matching technique as adjusted and improved in [10]. The convergence and computation accuracy of $\sigma_t(a)$ depend on the wavelength, the size and shape of raindrops, and the refractive index of the drops. The model of Ray [11] is employed for the refractive index of water that is a function of frequency and temperature. To obtain correct results, the truncation and recurrence relations for $\sigma_t(a)$ have been determined carefully, as done in [10]. The extended Simpson's rule was used in the computation of (1), taking $a_{\max} = 0.35$ cm and a 0.025 cm radius interval, which have been applied to the L-P raindrop size distribution.

Clearly, γ depends on the raindrop size distribution function $N(a)$ as well as on the extinction cross section $\sigma_t(a)$.

The gamma raindrop size distribution [4] employed here is like that used in [12]

$$N(a) = N_0 a^3 \exp(-\Lambda a) \qquad (2)$$

with $N_0 = 1.42 \times 10^{10}\,\text{cm}^{-4}/\text{cm}^3$ and $\Lambda = 1.3 R^{-0.13} 10^2\,\text{cm}^{-1}$. The lognormal raindrop size distribution [5] used can be written as

$$N(D) = \frac{N_0}{\sqrt{2\pi}\sigma D} \exp\left[-\frac{(\ln D - \mu)^2}{2\sigma^2}\right] \qquad (3)$$

where D is the diameter of raindrops in millimeters, $N_0 = 108 R^{0.363}\,\text{m}^{-3}$, $\mu = -0.195 + 0.199 \ln R$, and $\sigma^2 = 0.137 - 0.013 \ln R$. The Laws and Parsons raindrop size distribution was presented in [1] and [13], and the Marshall and Palmer distribution can be found in [3] and [9].

Power-Law Form of Rain Specific Attenuation

The power-law approach [2], [6] to equation (1) of rain specific attenuation calculated by using the point-matching technique is written as

$$\gamma = k \cdot R^{\alpha}. \qquad (4)$$

As done in [6], parameters k and α are calculated by

$$\alpha = \frac{1}{K(K-1)} \sum_{i=1}^{K} \sum_{j \neq i}^{K} \frac{\ln(\gamma_j / \gamma_i)}{\ln(R_j / R_i)} \qquad (5)$$

$$k = \frac{1}{K} \sum_{i=1}^{K} \frac{\gamma_i}{R_i^{\alpha}} \qquad (6)$$

where $\gamma_i = \gamma|_{R=R_i}$ is computed at a rain rate R_i by using the point-matching technique. Obtained by using seven rain rates of 2.5, 5, 12.5, 25, 50, 100, and 150 mm/h, Tables I-IV tabulate parameters $k_{H,V}$ and $\alpha_{H,V}$ (for horizontal- and vertical-polarization, respectively), accompanied by the maximum relative errors $e(\%)$, for $\gamma = k \cdot R^{\alpha}$. The maximum relative error $e_{H,V}$ is calculated by

$$e = MAX\left\{\frac{|\gamma_i - k \cdot R_i^{\alpha}|}{\gamma_i} \times 100\right\}. \qquad (7)$$

For linear and circular polarization, and for all path geometry, k and α can be derived from the results presented in Tables I-IV. This may be made by using the equations as presented in [7]

$$k = \left[k_H + k_V + (k_H - k_V)\cos^2\theta\cos(2\tau)\right]/2 \qquad (8)$$

$$\alpha = \left[k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta\cos(2\tau)\right]/2k \quad (9)$$

where θ is the path elevation angle and τ is the polarization tilt angle relative to the horizontal ($\tau = 45^\circ$ for circular polarization).

Since the power-law parameters presented here are for the rain rates of from 0 to 150 mm/h, one may use them to calculate total attenuation due to rainfall without detailed classification of rain, i.e., widespread or convective.

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Table I

Power-Law Parameters and Maximum Relative Errors for the gamma Raindrop Size Distribution at a Rain Temperature 0°C

f(GHz)	k_H	α_H	e_H (%)	k_V	α_V	e_V (%)
5.0	.223E-2	.105E+1	.363E+1	.178E-2	.104E+1	.413E+1
6.0	.324E-2	.108E+1	.532E+1	.271E-2	.108E+1	.470E+1
7.0	.454E-2	.111E+1	.552E+1	.394E-2	.110E+1	.473E+1
8.0	.635E-2	.113E+1	.487E+1	.555E-2	.111E+1	.416E+1
9.0	.862E-2	.113E+1	.394E+1	.756E-2	.112E+1	.336E+1
10.0	.114E-1	.113E+1	.300E+1	.100E-1	.112E+1	.250E+1
11.0	.143E-1	.113E+1	.198E+1	.129E-1	.111E+1	.172E+1
12.0	.180E-1	.113E+1	.131E+1	.162E-1	.111E+1	.107E+1
13.0	.221E-1	.112E+1	.805	.200E-1	.110E+1	.536
14.0	.267E-1	.112E+1	.443	.241E-1	.110E+1	.470
15.0	.317E-1	.111E+1	.371	.286E-1	.109E+1	.579
16.0	.371E-1	.111E+1	.383	.336E-1	.109E+1	.677
17.0	.429E-1	.110E+1	.435	.389E-1	.108E+1	.749
18.0	.492E-1	.110E+1	.485	.446E-1	.108E+1	.910
19.0	.559E-1	.110E+1	.542	.507E-1	.108E+1	.104E+1
20.0	.631E-1	.110E+1	.613	.572E-1	.107E+1	.114E+1
21.0	.708E-1	.109E+1	.710	.641E-1	.107E+1	.125E+1
22.0	.791E-1	.109E+1	.869	.715E-1	.107E+1	.135E+1
23.0	.879E-1	.109E+1	.105E+1	.793E-1	.106E+1	.147E+1
24.0	.975E-1	.109E+1	.126E+1	.877E-1	.106E+1	.159E+1
25.0	.108	.108E+1	.149E+1	.966E-1	.106E+1	.173E+1
26.0	.119	.108E+1	.173E+1	.106	.106E+1	.189E+1
27.0	.130	.107E+1	.199E+1	.116	.105E+1	.206E+1
28.0	.143	.107E+1	.226E+1	.127	.105E+1	.224E+1
29.0	.156	.106E+1	.254E+1	.138	.104E+1	.244E+1
30.0	.170	.106E+1	.282E+1	.150	.104E+1	.264E+1
35.0	.252	.103E+1	.403E+1	.220	.102E+1	.362E+1
40.0	.349	.998	.468E+1	.305	.991	.426E+1
45.0	.455	.968	.474E+1	.401	.963	.446E+1
50.0	.567	.938	.449E+1	.504	.936	.434E+1
55.0	.682	.910	.414E+1	.611	.909	.407E+1
60.0	.800	.884	.380E+1	.722	.885	.377E+1
65.0	.918	.862	.350E+1	.833	.864	.350E+1
70.0	.103E+1	.843	.328E+1	.944	.845	.328E+1
75.0	.114E+1	.828	.313E+1	.105E+1	.830	.313E+1
80.0	.124E+1	.815	.304E+1	.115E+1	.817	.304E+1
85.0	.133E+1	.805	.300E+1	.123E+1	.807	.299E+1
90.0	.139E+1	.798	.299E+1	.130E+1	.800	.297E+1
95.0	.143E+1	.792	.300E+1	.135E+1	.794	.297E+1
100.0	.145E+1	.789	.301E+1	.138E+1	.790	.297E+1

TABLE II

POWER-LAW PARAMETERS AND MAXIMUM RELATIVE ERRORS FOR THE LOGNORMAL RAINDROP SIZE DISTRIBUTION AT A RAIN TEMPERATURE 0° C

f(GHz)	k_H	α_H	e_H (%)	k_V	α_V	e_V (%)
5.0	.206E-2	.112E+1	.639E+1	.160E-2	.112E+1	.679E+1
6.0	.305E-2	.117E+1	.770E+1	.257E-2	.115E+1	.659E+1
7.0	.452E-2	.119E+1	.658E+1	.393E-2	.117E+1	.576E+1
8.0	.663E-2	.120E+1	.509E+1	.577E-2	.118E+1	.439E+1
9.0	.934E-2	.119E+1	.357E+1	.814E-2	.117E+1	.300E+1
10.0	.126E-1	.118E+1	.223E+1	.110E-1	.116E+1	.174E+1
11.0	.163E-1	.117E+1	.101E+1	.144E-1	.115E+1	.105E+1
12.0	.207E-1	.116E+1	.103E+1	.183E-1	.113E+1	.127E+1
13.0	.256E-1	.115E+1	.120E+1	.227E-1	.112E+1	.158E+1
14.0	.308E-1	.114E+1	.129E+1	.275E-1	.111E+1	.179E+1
15.0	.366E-1	.113E+1	.136E+1	.326E-1	.110E+1	.190E+1
16.0	.428E-1	.112E+1	.139E+1	.382E-1	.109E+1	.213E+1
17.0	.495E-1	.112E+1	.146E+1	.442E-1	.109E+1	.236E+1
18.0	.566E-1	.111E+1	.155E+1	.506E-1	.108E+1	.254E+1
19.0	.644E-1	.111E+1	.170E+1	.575E-1	.108E+1	.269E+1
20.0	.727E-1	.110E+1	.190E+1	.647E-1	.107E+1	.284E+1
21.0	.816E-1	.110E+1	.215E+1	.725E-1	.107E+1	.299E+1
22.0	.913E-1	.109E+1	.244E+1	.808E-1	.106E+1	.317E+1
23.0	.102	.109E+1	.278E+1	.897E-1	.106E+1	.337E+1
24.0	.113	.108E+1	.316E+1	.991E-1	.105E+1	.360E+1
25.0	.125	.108E+1	.357E+1	.109	.105E+1	.386E+1
26.0	.138	.107E+1	.401E+1	.120	.104E+1	.416E+1
27.0	.152	.106E+1	.448E+1	.132	.103E+1	.448E+1
28.0	.167	.105E+1	.496E+1	.144	.103E+1	.483E+1
29.0	.183	.104E+1	.546E+1	.157	.102E+1	.521E+1
30.0	.200	.103E+1	.598E+1	.171	.101E+1	.560E+1
35.0	.297	.978	.832E+1	.252	.969	.754E+1
40.0	.405	.930	.971E+1	.346	.926	.890E+1
45.0	.510	.889	.971E+1	.442	.887	.915E+1
50.0	.605	.854	.863E+1	.533	.853	.839E+1
55.0	.689	.824	.704E+1	.616	.825	.701E+1
60.0	.764	.799	.533E+1	.690	.800	.541E+1
65.0	.833	.777	.368E+1	.759	.779	.380E+1
70.0	.898	.758	.222E+1	.823	.760	.235E+1
75.0	.957	.742	.984	.882	.745	.112E+1
80.0	.101E+1	.729	.669	.936	.732	.571
85.0	.105E+1	.718	.131E+1	.981	.721	.120E+1
90.0	.108E+1	.710	.184E+1	.102E+1	.713	.175E+1
95.0	.110E+1	.703	.220E+1	.104E+1	.706	.214E+1
100.0	.111E+1	.699	.239E+1	.106E+1	.702	.237E+1

TABLE III

POWER-LAW PARAMETERS AND MAXIMUM RELATIVE ERRORS FOR LAWS AND PARSONS RAINDROP SIZE DISTRIBUTION AT A RAIN TEMPERATURE 0° C

f(GHz)	k_H	α_H	e_H (%)	k_V	α_V	e_V (%)
5.0	.177E-2	.121E+1	.935E+1	.144E-2	.119E+1	.846E+1
6.0	.272E-2	.125E+1	.818E+1	.234E-2	.122E+1	.706E+1
7.0	.415E-2	.126E+1	.591E+1	.364E-2	.123E+1	.505E+1
8.0	.618E-2	.125E+1	.390E+1	.543E-2	.122E+1	.302E+1
9.0	.877E-2	.123E+1	.197E+1	.771E-2	.120E+1	.130E+1
10.0	.119E-1	.121E+1	.930	.105E-1	.118E+1	.119E+1
11.0	.153E-1	.120E+1	.123E+1	.137E-1	.116E+1	.158E+1
12.0	.193E-1	.118E+1	.137E+1	.174E-1	.115E+1	.196E+1
13.0	.237E-1	.117E+1	.157E+1	.214E-1	.113E+1	.248E+1
14.0	.285E-1	.116E+1	.170E+1	.259E-1	.112E+1	.281E+1
15.0	.337E-1	.115E+1	.185E+1	.305E-1	.111E+1	.296E+1
16.0	.394E-1	.115E+1	.196E+1	.357E-1	.110E+1	.311E+1
17.0	.456E-1	.114E+1	.210E+1	.412E-1	.110E+1	.320E+1
18.0	.523E-1	.113E+1	.231E+1	.472E-1	.109E+1	.331E+1
19.0	.596E-1	.113E+1	.258E+1	.536E-1	.108E+1	.344E+1
20.0	.675E-1	.112E+1	.293E+1	.604E-1	.108E+1	.361E+1
21.0	.761E-1	.111E+1	.334E+1	.678E-1	.107E+1	.381E+1
22.0	.855E-1	.110E+1	.379E+1	.757E-1	.107E+1	.406E+1
23.0	.956E-1	.109E+1	.427E+1	.842E-1	.106E+1	.434E+1
24.0	.107	.108E+1	.477E+1	.933E-1	.105E+1	.464E+1
25.0	.118	.107E+1	.527E+1	.103	.105E+1	.498E+1
26.0	.131	.106E+1	.575E+1	.113	.104E+1	.532E+1
27.0	.144	.105E+1	.622E+1	.124	.103E+1	.567E+1
28.0	.158	.104E+1	.666E+1	.136	.102E+1	.601E+1
29.0	.173	.103E+1	.706E+1	.149	.101E+1	.635E+1
30.0	.189	.102E+1	.744E+1	.162	.100E+1	.667E+1
35.0	.277	.970	.868E+1	.236	.962	.785E+1
40.0	.372	.928	.880E+1	.320	.923	.814E+1
45.0	.465	.894	.794E+1	.406	.891	.753E+1
50.0	.551	.866	.649E+1	.488	.865	.632E+1
55.0	.630	.843	.489E+1	.565	.843	.486E+1
60.0	.705	.824	.337E+1	.638	.824	.342E+1
65.0	.777	.807	.203E+1	.708	.808	.210E+1
70.0	.847	.792	.126E+1	.776	.794	.122E+1
75.0	.912	.780	.157E+1	.840	.782	.153E+1
80.0	.970	.770	.186E+1	.899	.772	.181E+1
85.0	.102E+1	.762	.225E+1	.949	.764	.220E+1
90.0	.105E+1	.756	.257E+1	.989	.758	.252E+1
95.0	.108E+1	.752	.281E+1	.102E+1	.754	.276E+1
100.0	.109E+1	.749	.298E+1	.104E+1	.750	.294E+1

TABLE IV

POWER-LAW PARAMETERS AND MAXIMUM RELATIVE ERRORS FOR MARSHALL AND PALMER RAINDROP SIZE DISTRIBUTION AT A RAIN TEMPERATURE 0°C

f(GHz)	k_H	α_H	e_H (%)	k_V	α_V	e_V (%)
5.0	.210E-2	.119E+1	.970E+1	.176E-2	.116E+1	.812E+1
6.0	.320E-2	.122E+1	.824E+1	.279E-2	.119E+1	.645E+1
7.0	.486E-2	.123E+1	.495E+1	.432E-2	.119E+1	.358E+1
8.0	.721E-2	.121E+1	.246E+1	.644E-2	.118E+1	.182E+1
9.0	.102E-1	.119E+1	.209E+1	.912E-2	.116E+1	.260E+1
10.0	.138E-1	.117E+1	.250E+1	.123E-1	.114E+1	.297E+1
11.0	.176E-1	.116E+1	.286E+1	.161E-1	.113E+1	.396E+1
12.0	.222E-1	.115E+1	.338E+1	.204E-1	.111E+1	.459E+1
13.0	.272E-1	.114E+1	.361E+1	.251E-1	.110E+1	.502E+1
14.0	.327E-1	.113E+1	.378E+1	.303E-1	.109E+1	.530E+1
15.0	.388E-1	.112E+1	.402E+1	.358E-1	.108E+1	.545E+1
16.0	.455E-1	.111E+1	.431E+1	.419E-1	.107E+1	.564E+1
17.0	.528E-1	.111E+1	.465E+1	.485E-1	.106E+1	.580E+1
18.0	.607E-1	.110E+1	.506E+1	.556E-1	.106E+1	.600E+1
19.0	.694E-1	.109E+1	.551E+1	.632E-1	.105E+1	.622E+1
20.0	.789E-1	.108E+1	.600E+1	.714E-1	.104E+1	.647E+1
21.0	.891E-1	.108E+1	.650E+1	.803E-1	.104E+1	.675E+1
22.0	.100	.107E+1	.700E+1	.898E-1	.103E+1	.705E+1
23.0	.112	.106E+1	.748E+1	.100	.103E+1	.736E+1
24.0	.125	.105E+1	.794E+1	.111	.102E+1	.767E+1
25.0	.139	.104E+1	.837E+1	.123	.101E+1	.798E+1
26.0	.153	.103E+1	.877E+1	.135	.100E+1	.829E+1
27.0	.169	.102E+1	.912E+1	.148	.997	.858E+1
28.0	.185	.101E+1	.945E+1	.162	.990	.886E+1
29.0	.203	.100E+1	.974E+1	.177	.982	.912E+1
30.0	.221	.993	.100E+2	.192	.975	.936E+1
35.0	.325	.948	.109E+2	.282	.937	.102E+2
40.0	.443	.908	.111E+2	.385	.901	.106E+2
45.0	.565	.874	.107E+2	.498	.869	.104E+2
50.0	.690	.843	.100E+2	.614	.841	.983E+1
55.0	.817	.815	.926E+1	.733	.815	.919E+1
60.0	.946	.790	.860E+1	.855	.791	.858E+1
65.0	.108E+1	.769	.807E+1	.978	.770	.806E+1
70.0	.121E+1	.750	.768E+1	.110E+1	.752	.767E+1
75.0	.133E+1	.734	.742E+1	.122E+1	.736	.739E+1
80.0	.144E+1	.721	.724E+1	.133E+1	.723	.721E+1
85.0	.154E+1	.710	.712E+1	.143E+1	.713	.708E+1
90.0	.161E+1	.703	.703E+1	.151E+1	.705	.699E+1
95.0	.166E+1	.697	.696E+1	.157E+1	.699	.691E+1
100.0	.169E+1	.693	.689E+1	.161E+1	.694	.684E+1