Atmospheric Effects

Attenuation by Atmospheric Gases

Uncondensed water vapour and oxygen can be strongly absorptive of radio signals, especially at millimetre-wave frequencies and higher (tens to hundred of GHz). This is due to the existence of *absorption lines* in the elements composing atmospheric gases, or bands of frequencies where these gases naturally absorb photon energy. This occurs at the resonance frequencies of the molecules themselves. The most important gases to consider are water vapour and oxygen. They can significantly attenuate microwave and millimetre wave signals to the point where link margins must be widened substantially, or propagation limited to very short ranges. An example of the attenuation of water and oxygen, as a function of frequency, is shown in Figure 1.

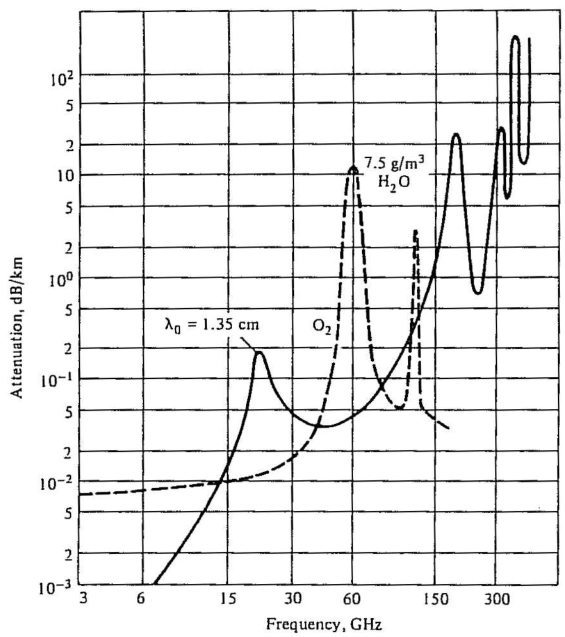

Figure 1: Atmospheric attenuation

An attenuation or absorption constant is defined for oxygen and water vapour, and usually has units of dB/km. The resulting attenuation is in excess of the reduction in radiated signal power due to free-space loss. Approximate expressions for the attenuation constants of oxygen and water (in dB/km), as defined by the International Telecommunications Union (ITU) are:

$$a_o = \begin{cases} 0.001\left[0.00719 + \frac{6.09}{f^2+0.227} + \frac{4.81}{(f-57)^2+1.50}\right] f^2 & f < 57\text{ GHz} \\ a_o(57\text{ GHz}) + 1.5(f-57) & f \geq 57\text{ GHz} \end{cases} \tag{1}$$

$$a_w = 0.0001\left[0.050 + 0.0021\rho + \frac{3.6}{(f-22.2)^2+8.5} + \frac{10.6}{(f-183.3)^2+9.0} + \frac{8.9}{(f-325.4)^2+26.3}\right] f^2\rho \qquad f < 350 \text{ GHz} \tag{2}$$

where f is the frequency in GHz, ρ is the water vapour density in g/m^3 (typically 7.5 g/m^3 at sea level), and $a_o(57\,\text{GHz})$ is the first expression evaluated at 57 GHz. Both constants are in dB/km. For propagation paths that are mostly horizontal, the attenuation constants are fairly constant, and the total attenuation is simply found by multiplying the attenuation constant by the path distance L_{km}:

$$A_a = [a_o + a_w]L_{km} = a_a L_{km} \quad \text{(units: dB)} \tag{3}$$

In general, the attenuation constants are functions of altitude, since they depend on factors such as temperature and pressure. These quantities are often assumed to vary exponentially with height h; for example,

$$\rho(h) = \rho_0 e^{-h/h_s} \tag{4}$$

where ρ_0 is the water vapour density at sea level and h_s is known as the *scale height*, which is typically 1-2 km. For horizontal links, this is not a major problem since the change in altitude is small. However, for vertical links (for example, and earth station-to-satellite link directly overhead), the attenuation varies considerably along the propagation path. The attenuation as a function of height can be approximately modelled as

$$a_a(h) = a_{a0} e^{-h/h_s} \tag{5}$$

where a_{ao} is the attenuation constant at sea level. The total attenuation along a vertical path can be found as

$$A_a = \int_{h_0}^{h_1} a_{a0} e^{-z/h_s} dz = \int_{h_0}^{\infty} a_{a0} e^{-z/h_s} dz. \tag{6}$$

The path of integration is from the altitude h_0, the altitude of the lower station, to the altitude of the higher station h_1. The latter is assumed to be infinity since the path is assume to pass well past the scale height; plus, the integrand does not contribute appreciably to the integral past a few scale heights. This yields the following expression for the total attenuation for vertical links:

$$A_a = a_{ao} h_s e^{-h_0/h_s}. \tag{7}$$

Comparing this to the expression (3) above, we can see that $L_{a,eff} = h_s e^{-h_0/h_s}$ represents the equivalent vertical path length for the link, allowing us to write

$$A_a = a_{ao} L_{a,eff} \tag{8}$$

For slant atmospheric paths at an angle, the effective length can be found using the geometry shown in Figure 2 as

$$A_a = \int_{h_0}^{\infty} a_{a0} e^{-z/h_s} \csc\theta dz = a_{a0} L_{a,eff} \csc\theta \tag{9}$$

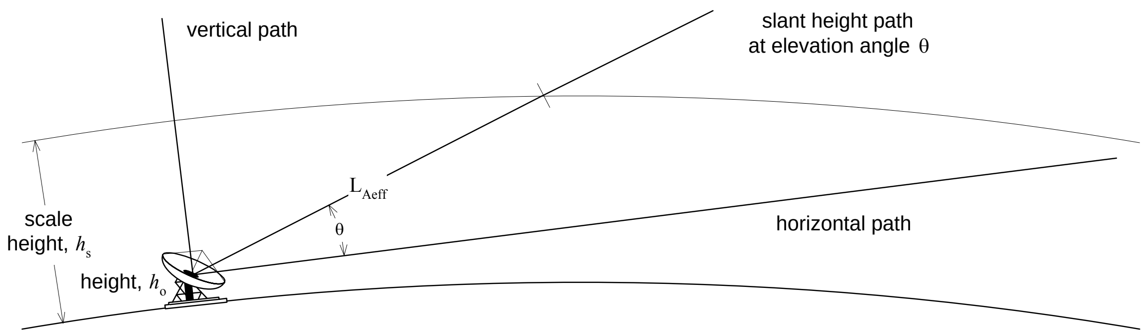

Figure 2: Scale height and slanted paths

where we note that in the diagram, θ denotes the angle from the horizon as opposed to the usual convention of the elevation angle (angle from vertical). θ is constant over the path of integration.

The effect of attenuation on millimetre-wave communication systems is significant. For terrestrial systems such as local multipoint communication systems, the attenuation limits the ranges or cell size of such systems. For satellite systems, the attenuation can play a strong role in determining the overall system link budget.

Attenuation by Rain

Given the highly variable nature of rain with time, and its variation from location to location, it is possible to predict the occurence of rain with certainty. Therefore, our immediate goal when studying rain attenuation is to determine the percentage of the time that a given amount of rain attenuation will be exceeded at a certain location. This information can be used to plan for "rain margin" in link budgets so guarantee that links operate a certain percentage of the time.

When a plane wave strikes a raindrop, some of the energy in the plane wave is absorbed by the water (since it is a lossy dielectric), while some of it is scattered. Scattering loss is relevant because power may be scattered in directions other than the desired direction of interest. These two phenomena leads to an overall effect called "extinction" by the raindrop. Characterizing the effect of rain attenuation on a communication system is quite involved, for two reasons:

1. The calculation of the scattering and attenuation of a plane wave by a water droplet is quite complex, and depends to some extent on the assumed shape of the water droplet: assuming the droplet is a spheroid is a good starting point, but in general an ellipsoid shape is assumed and the ellipse falls at an angle (which is called *canting*). The net result is that the attenuation depends strongly on the type of rain, wind conditions, frequency, and incident wave polarization. Wave passing through rain falling at an angle may also be *re-polarized*, i.e. converted from one polarization to another, though we will not delve into this process here.

2. The rainfall process is stochastic. Therefore, we are less interested in the instantaneous characteristics of the rain attenuation and more with the cumulative effect in terms of the

probability that outages will occur with a given link budget.

Empirical formulas are useful for predicting the attenuation constant at any given time. One such expression is

$$a_r = kR^{\alpha} \quad \text{units: dB/km} \tag{10}$$

where R is the rain rate in mm/hour, and k and α are constants that depend on the frequency, and temperature of the rain. The total rain attenuation through a cell is computed using

$$A_r = a_r L_{r,eff} \quad \text{(units: dB)} \tag{11}$$

where $L_{r,eff}$ is the effective path length through the rain cell, as shown in Figure 3. Note that this formula assumes that the rain attenuation is uniform through the cell. In practise, this is not the case and $L_{r,eff}$ is empirically adjusted higher or lower so that that the rain can be treated as homogeneous within the cell.

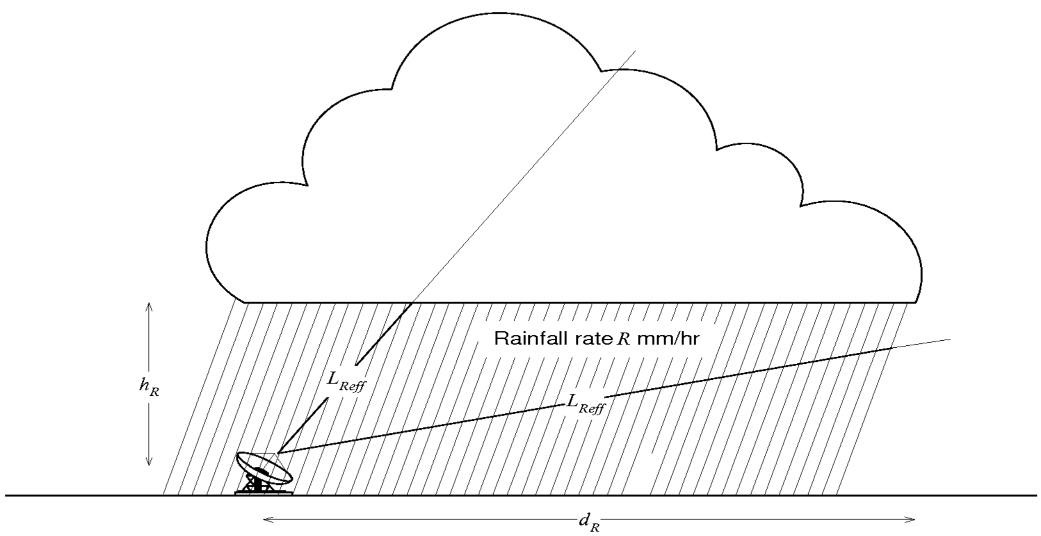

Figure 3: Rain cell

Constants in the equation have been evaluated empirically based on measured statistics at radio sites. Multiple models exist for these constants, ranging from tables, graphs, to empirical formulas.

The International Telecommunications Union (ITU)-R) provides simple attenuation models for rainfall that are very statistically accurate and are used worldwide. Table 1 shows values for k and α for frequencies between 4 and 50 GHz [1]. The suffices V and H refer to vertical and horizontal polarization, respectively. It is interesting to note that the attenuation rate is polarization-dependent, which is a consequence of the raindrop having an elongated shape in the vertical direction, which in turns produces different scattering behaviour for vertical polarization and horizontal polarization.

A typical rain attenuation characteristic is shown in Figure 4.

Frequency (GHz)	k_H	k_V	α_H	α_V
4	0.000650	0.000591	1.121	1.075
6	0.00175	0.00155	1.308	1.265
8	0.00454	0.00395	1.327	1.310
10	0.0101	0.00887	1.276	1.264
12	0.0188	0.0168	1.217	1.200
20	0.0751	0.0691	1.099	1.065
30	0.0187	0.167	1.021	1.000
40	0.350	0.310	0.939	0.929
50	0.536	0.479	0.873	0.868

Table 1: Coefficients for Estimating Rainfall Attenuation [1]

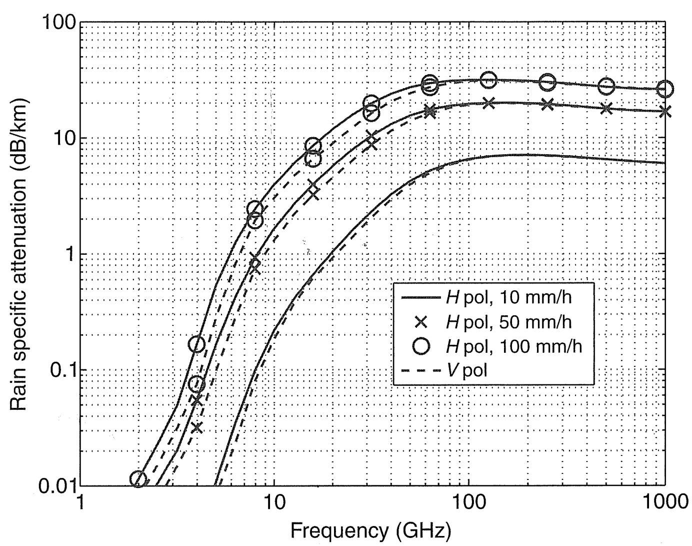

Figure 4: Rain attenuation as a function of rain rate, polarization, and frequency [2]

For values in between frequency points, interpolation can be employed whereby a logarithmic scale for frequency and k are used, and a linear scale for α is used. Also, the coefficients can be modified for other polarizations according to

$$k = \frac{k_H + k_V + (k_H - K_V)\cos^2\theta\cos 2\tau}{2} \tag{12}$$

and

$$\alpha = \frac{k_H\alpha_H + k_V\alpha_V + (k_H\alpha_H - k_V\alpha_V)\cos^2\theta\cos 2\tau}{2}, \tag{13}$$

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

Rain attenuation can produce large changes in the received signal power, forcing margins in a link budget to be much larger than if the rain did not exist. 20-30 dB changes in received signal power can produce outages for significant periods of time if the link budget margin does not adequately cover the ranges of attenuation expected over the course of normal weather patterns.

References

[1] Rec. ITU-R P.838, "Specific attenuation model for rain for use in prediction methods," 1992.

[2] C. A. Levis, J. T. Johnson, and F. L. Teixeira, *Radiowave Propagation*. Hoboken, NJ: John Wiley and Sons, 2010.