SPUTNIK

White Paper

RF Propagation Basics

April 2004

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Summary

This white paper steps through the theoretical calculations that are useful in planning deployments of 2.4 GHz wireless networks. The calculations illustrate how either directional or omni-directional antennas can be used to effectively cover an area. Omni-directional antennas are generally better for “area” coverage, whereas directional antennas offer greater “range” in a given direction which may be useful for linking APs to each other for backhaul.

The estimates here are conservative, taking into account environmental factors and assuming standard WiFi-enabled laptops on the client side. In fairly open outdoor areas, a 200mW transmit power AP with 8dB omni-directional antenna can cover about 45 acres (182K sq m) for connectivity to standard WiFi-enabled laptops. In a lightly populated clutter of trees, the estimated area drops to about 10 acres.

Propagation Basics

The propagation of radio waves in 802.11 applications is characterized by several factors:

- Signal power is diminished by geometric spreading of the wavefront, commonly known as free space loss
- Signal power is attenuated as the wave passes through solid objects such as trees, walls, window and the floors of buildings
- The signal is scattered and can interfere with itself if there are objects in the beam of the transmit antenna even if these objects are not on the direct path between the transmitter and the receiver

Free space loss. Geometric spreading happens because the wavefront radiated signal energy expands like a big column as a function of the distance from the transmitter. When the distance from the transmitter is measured in units of the signal wavelength (λ), the free space loss (L_{fsl}) in signal power at a distance (r) from the transmitter is:

$$L_{fsl} = r^2 (4\pi)^2/\lambda^2 \qquad \text{Eq 1}$$

Using decibels to express the loss and using 2.45GHz as the signal frequency for 802.11b/g APs, the equation can be simplified to:

$$L_{fsl} = 40 + 20*\log(r) \qquad \text{Eq 2}$$

Where L_{fsl} is expressed in dB and r is expressed in meters.

Attenuation. When the RF signal passes though solid objects, some of the signal power is absorbed. The most convenient way to express this is by adding an "allowed loss" to the Free Space loss. Attenuation can vary greatly depending upon the structure of the object the signal is passing through. Metal in the barrier greatly increases the attenuation. Thickness also increases the loss. General rules of thumb on attenuation are:

- Trees account for 10 to 20 dB of loss per tree in the direct path. Loss depends upon the size and type of tree. Large trees with dense foliage create greater loss.
- Walls account for 10 to 15 dB depending upon the construction. Interior walls are on the low end and exterior walls, especially those with stucco, create more loss.
- Floors of buildings account for 12 to 27 dB of loss. Floors with concrete and steel are at the high end and wood floors are at the low end.
- Mirrored walls have very high loss because the reflective coating is conductive.

Scattering. RF signals can reflect off of many things and the direct signal combines with signals that have reflected off of objects that are not in the direct path. This effect is usually described as multipath, fading, Rayleigh fading or signal dispersion.

When RF signals combine they can be distorted. The distortion degrades the ability of the receiver to recover the signal in a manner much like signal loss. While a great deal of research has gone into the characterization of signal scattering, a simple and common way of applying the effects of scattering is to change the exponent on the distance factor in Equation 1.

When the Free Space Loss, Attenuation and Scattering are combined the loss is:

$$L = r^n (4\pi)^2/\lambda^2 + L_{allowed} \qquad \text{Eq 3}$$

Expressed in decibels:

$$L\,(dB) = 40 + 10*n*\log(r) + L_{allowed} \qquad \text{Eq 4}$$

One difficulty in using the exponent to model the effect of scattering is that the exponent tends to increase with range in an environment with a lot of scattering. Calculating a range can often require some iteration of the exponent to be used.

Link Margin. In addition to environmental factors described above, the performance of any communication link depends on the quality of the equipment being used. Link margin is a way of quantifying equipment performance. An 802.11 communication link has an available link margin that is determined by four factors:

- Transmit power
- Transmit antenna gain
- Receive antenna gain
- Minimum received signal strength or level.

The link margin is:

$$L_{margin} = TX_{power} + TX_{ant\ gain} + RX_{ant\ gain} - RSL \qquad \text{Eq 5}$$

The link factors are usually listed in the manufacture's data sheets for the equipment being used. For instance, if Sputnik's AP160 is used as an access point with an external 8.5 dBi antenna to communicate with a laptop computer having a D-Link DWL-G650 station card, the factors to be used are:

- TX power = 13 dBm
- TX antenna gain = 8.5 dBi
- RX antenna gain = 0 dBi
- Min RSL = -89 dBm
- Link margin = 110.5 dB

Note that the Min RSL is dependent upon rate and the 1 Mbps rate is used for maximum range. TX power can also be rate dependent but manufacturers rarely indicate this.

Maximum range. The maximum range is achieved when the signal loss expressed in Equation 4 is less than the link margin expressed in Equation 5. The system operator needs to know the equipment parameters and must estimate the allowed loss and the scattering exponent to complete the calculation. Example parameters are shown in Tables 1 and 2.

Table 1. Application Dependent Environment Parameters

Application	**Allowed Loss (dB)**	**Scattering Exponent**	**Example**
Outdoor free space	0	2	
Outdoor, no barriers	0	2.5 at 200m 3 at 400m 3.5 > 500m	Marina
Outdoor with trees	10 to 20	3 to 4	Park
Outdoor buildings	0	4	Urban café
Indoor - no barriers	0	2.5	Conference room
Indoor partitions	0	3.5	Office cubicles
Indoor walls & floors	12 to 27 (floors) 10 to 15 (walls)	4 to 5	Condo, apartment

Table 2. Equipment Dependent Parameters

	TX Power (dBm)	TX Antenna Gain (dBi)	RX Antenna Gain (dBi)	RX Sensi-tivity (dBm)	Max Loss (dB)	Antenna notes
AP160 to AP160 (omni)	13	8	8	-87	**116**	with 8 dB omni
AP160 to AP160 (dir)	13	8.5	8.5	-87	**117**	with 2 x 70° antennas
AP160 to Laptop (dir)	13	8.5	0	-89	**110.5**	with 1 x 70° antenna
AP 200 to AP 200 (omni)	23	8	8	-95	**134**	with 8 dB omni
AP 200 to AP 200 (dir)	23	12	12	-95	**142**	with built-in 12 dB x 40° antenna
AP 200 to Laptop (dir)	23	12	0	-89	**124**	with built-in 12 dB x 40° antenna

For example, suppose a service provider wanted to provide coverage in a public park to customers using laptop computers using Sputnik's AP 160 access points equipped with external 8.5 dBi gain antennas. We would estimate the allowed loss to be 10 dB if the park had a modest number of trees mixed with open spaces and use a scattering exponent of 3. From equation 5, the maximum loss (L_{margin}) is 110.5 dB. To get the maximum range we would solve Eq 4 for range:

$$110.5 = 40 + 10*3*\log(r_{max}) + 10 \;\rightarrow\; r_{max} = 102 \text{ meters}$$

Using the same equation to calculate the range assuming free space loss (where the exponent = 2, and allowed loss = 0) provides a rather different answer:

$$110.5 = 40 + 10*2*\log(r_{max}) + 0 \;\rightarrow\; r_{max} = 3{,}264 \text{ meters}$$

This example shows that environmental factors can play a significant role in diminishing the signal strength. However, since choosing the exponent and allowed loss is partly a guessing game, and partly a recursive exercise, it is common practice to take a few real-world measurements of range in the area of the deployment, using the equipment to be deployed. Such measurements will improve the estimate of the exponent and allowed loss used to calculate the "coverage area" described in the next section. Dividing the total area by the coverage per node provides the estimated density and total number of wireless nodes that should be deployed.

Coverage Area. In the example above, the AP160 has an antenna with a 70° beamwidth and can effectively operate with a laptop to a range of 102 meters. The coverage area is approximately a 70° sector of a circle with a radius of 102 meters so the coverage area is 3,186 sq meters or about 0.8 acres. If we were to repeat the same exercise for the AP160 with a 8 dBi gain omni-directional antenna, the range would be reduced to 98 meters. However, the coverage area increases to 15,174 sq meters or about 3.8 acres. While directional antennas can increase the range of a communication link, their impact on coverage area is less clear. The decision to use a directional antenna is often made based upon convenience; it might be simpler to install an access point on the edge of the area to be covered rather than in the center.

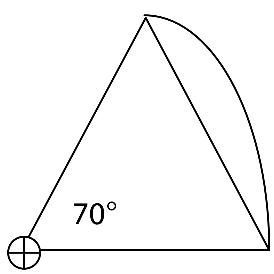
Table 3. Estimating coverage area from an AP to a laptop. (Assumes 0dB allowed loss and scattering exponent of 3.15).

Area	**AP160 w/ 8.5 dB 70° dir ant**	**AP160 w/ 8dB omni**	**AP 200 w/ 12dB 40° dir ant**	**AP 200 w/ 8dB omni**
sq meters	8,847	42,293	36,385	182,471
sq mi	0.003	0.016	0.014	0.070
acres	2.2	10.5	9.0	45.1
Max range to laptop (m)	170	164	457	341

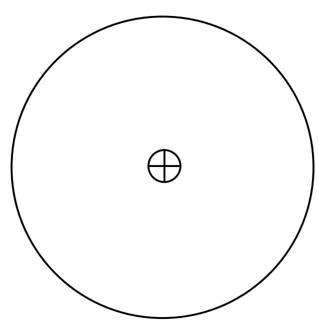
Table 4. Estimating coverage area from an AP to a laptop. (Assumes 10dB allowed loss and scattering exponent of 3.15).

Area	**AP160 w/ 8.5 dB 70° dir ant**	**AP160 w/ 8dB omni**	**AP 200 w/ 12dB 40° dir ant**	**AP 200 w/ 8dB omni**
sq meters	2,051	9,803	8,433	42,293
sq mi	0.001	0.004	0.003	0.016
acres	0.5	2.4	2.1	10.5
Max range to laptop (m)	82	79	220	164

Area geometry. The area geometry for the directional and omni-directional antennas is shown below.



70° directional antenna



360° omni-directional antenna