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RF Communications and Path Loss

"*Wireless is all very well but I'd rather send a message by a boy on a pony*" , Lord Kelvin [1].

Every time I work on an ISM (Industrial, Scientific, Medical) unlicensed communications band product, the top concern is usually: "What is the maximum distance can we realize for communications?" This question is most conveniently answered by knowing the transmit power, antenna gains, the receiver sensitivity, and an approximation of the path loss. The remainder of this technical note discusses path loss and communications distance, and when the simple calculation can be misleading.

Most estimates of communications distance begin with the Friis Equation [3]. In most reference material, this is given as:

$$P_r = P_t \bullet G_t \bullet G_r \bullet \left(\frac{\lambda}{4 \bullet \pi \bullet d} \right)^2$$

where:
Pr = the received power
Pt = the transmitted power
Gr = the received antenna gain
Gt = the transmitter antenna gain
d = the distance between transmitter and receiver
λ = the wavelength.
Reminders:

- Usage of the commonly presented formula requires linear values for all variables.
- Wavelength and distance must be in common units (for example: meters and meters)
- The wavelength is related to the communications frequency F, by:

$$\lambda = \frac{299.792 \bullet 10^6}{F} (in\ meters) = \frac{983.57}{F_{(in\ MHz)}} (in\ \ feet)$$

- The Friis equation calculation is only valid for unobstructed free space communications in the far field where the polarizations match and the antennas "point" correctly at each other. The near field is known as the Fresnel zone, and the far field is known as the Fraunhofer zone. The far field is considered to be > λ/2 for a dipole antenna, see [5].

From the commonly presented Friis equation shown above, it looks like we pay a penalty by going to higher frequencies (smaller wavelength), since the received power decreases by wavelength squared. This seems unfair, but is the logical conclusion from the Friis equation derivation [3], [6], made a bit clearer by considering the effective antenna aperture.

Although convenient, I must admit that the term "antenna gain" bothers me since it does not describe well the true nature of an antenna. It is more useful for me to think of antennas as passive transducers characterized by an effective aperture and directivity. However, you will most commonly see an antenna only spec'd with a gain. Just remember, you only obtain gain with directivity; the antenna becoming more restricted in performance in a certain angular direction.

Easing calculation, we will use the 10*log of the Friis equation. Using the log version of Friis makes quick calculations more convenient when the transmit power, receive sensitivity and antenna gains are given in dB.

Starting from the common Friis equation, we will do a slight modification to get:

$$P_r = P_t \bullet G_t \bullet G_r \bullet \left(\frac{\lambda}{4 \bullet \pi \bullet d} \right)^N$$

and separating out just the communications path loss gives:

$$path\ loss\ (in\ dB) = -N \bullet 10 \bullet [\log(\lambda) - \log(4 \bullet \pi \bullet d)]$$

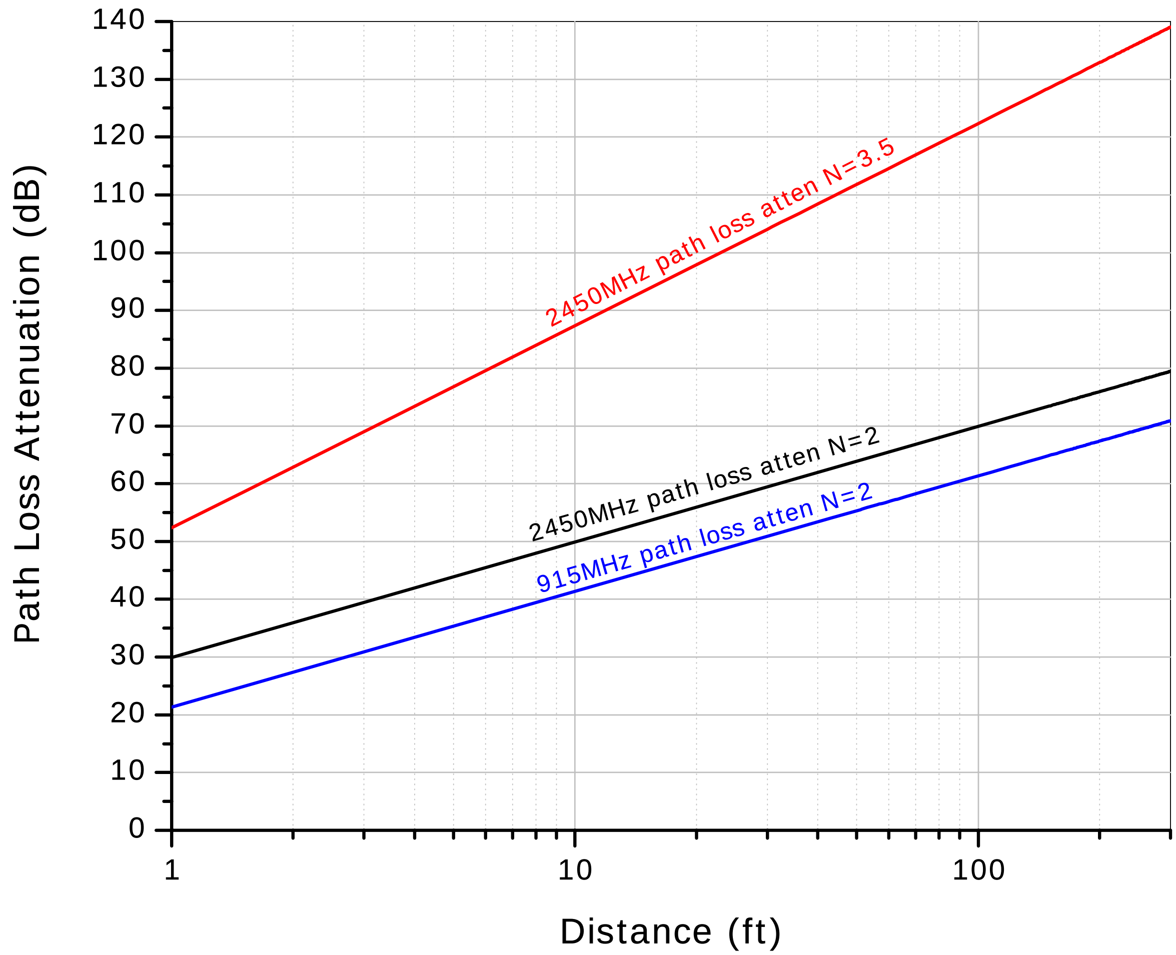
or

$$path\ loss\ (in\ dB) = -N \bullet 10 \bullet \log\left(\frac{78.27}{d_{in\ feet} \bullet f_{in\ MHz}} \right)$$

We then have

$$P_r = P_t + G_t + G_r - path\ loss$$

So, why did I replace the normally seen second power with the Nth power? This allows us make estimates for other environments other than free space and direct line-of-sight. For example: inside of a building, where communications is between rooms, or floors, N can be as low as 2, but more often on the order of 3.5 to 6 [2]. We can plot some examples as shown on the following page:



Note that the antenna gains are normally specified in dBi, the gain with respect to an isotropic antenna. The isotropic antenna is a theoretical antenna that radiates equally in all directions (nope, you can't build or buy one).

The Friis equation gives us the theoretical best case. The terrestrial real world is not quite so friendly. The most commonly seen degradations to what the Friis equation predicts are polarization, directivity, and multipath.

First, polarization. Classic monopole (5.2dBi) and dipole (2.15dBi) antennas are linearly polarized. Transmit and receive antennas must both have the same physical orientation to match the polarization, otherwise the received signal can be dramatically attenuated.

Second, directivity. All real antennas will have a directional aspect to their transmit power, and receive sensitivity. Transmit and receive antennas must be physically oriented correctly to best make use of the antennas' pattern.

Thirdly, multipath. Given antennas pointed at each other with the same polarization, the path loss attenuation you estimate from the equations above is a good indication in the macro sense. At a finer level, multipath effects will dominate, producing big attenuation dips in your path loss (best case adds 3dB, worst case attenuates the signal completely).

Multipath is simply when there is more than one incoming electromagnetic wave being received, due to reflections. Reflections can be generated by ground, building material, Venetian blinds, humans, and some sneaky unusual sources like fluorescent lamps. Multipath is a serious consideration for anything over ~30MHz, and will occur every $\lambda/2$. Thus at 2450Mhz, you can expect to see a multipath null every 2.4" if you are lucky enough to only have a single reflector in your environment.

References:

[1] Erik Larson, *Thunderstruck*. New York, NY: Crown Publishers, 2006.

[2] Theodore S. Rappaport, *Wireless Communications, Principles & Practice*. Upper Saddle River, NJ: Prentice Hall PTR, IEEE Press, 1996.

[3] Harald T. Friis, A Note on a Simple Transmission Formula. *Proceedings of the I.R.E. and Waves and Electron*s. May, 1946. pp254-256.

Good Antenna texts:

[4] John Krauss, *Antennas, 2nd Edition*. New York, NY: McGraw-Hill, 1988.

[5] Constantine Balanis, *Antenna Theory, Analysis and Design, 2nd Edition*. New York, NY: John Wiley & Sons, 1997.

A very readable electromagnetics/antenna text with a highly practical bent:
[6] John Krauss and Daniel Fleisch, *Electromagnetics with Applications, 5th Edition*.

Classic electromagnetics texts:

[7] John Krauss, *Electromagnetics*. New York, NY: McGraw-Hill, 1984.

[8] William H. Hayt, Jr., *Engineering Electromagnetics*. New York, NY: McGraw-Hill, 1967.

[9] Ramo, Whinnery, and Van Duzer, *Fields and Waves in Communication Electronics*. New York, NY: John Wiley & Sons, 1967.

Broad survey (800+ pages) of all things antenna:

[10] John Volakis, Ed., *Antenna Engineering Handbook, 4th Edition*. New York, NY: McGraw-Hill, 2007.