Free-Space Path Loss Lecture Note Draft

Mobile and Distributed Comp Systems (CS3333-01)
Wireless Networks/Mobile Systems (IT3323-01)

September 17, 2020

Abstract

In telecommunication, the free-space path loss (FSPL) is the attenuation of radio energy between the feedpoints of two antennas that results from the combination of the receiving antenna's capture area plus the obstacle-free, line-of-sight path through free space (usually air).[1] The "Standard Definitions of Terms for Antennas", IEEE Std 145-1993, defines "free-space loss" as "The loss between two isotropic radiators in free space, expressed as a power ratio."[2] It does not include any power loss in the antennas themselves due to imperfections such as resistance. Free space loss increases with the square of distance between the antennas because the radio waves spread out by the inverse square law and decreases with the square of the wavelength of the radio waves. The FSPL is rarely used standalone, but rather as a part of the Friis transmission formula, which includes the gain of antennas.[3] It is a factor that must be included in the power link budget of a radio communication system, to ensure that sufficient radio power reaches the receiver such that the transmitted signal is received intelligibly.

Contents

1 Free-space path loss formula

The free-space path loss (FSPL) formula derives from the Friis transmission formula.[3] This states that in a radio system consisting of a transmitting antenna transmitting radio waves to a receiving antenna, the ratio of radio wave power received P_r to the power transmitted P_t is:

$$\frac{P_r}{P_t} = D_t D_r \left(\frac{\lambda}{4\pi d}\right)^2 \tag{1}$$

$$\frac{P_r}{P_t} = G_l \left(\frac{\lambda}{4\pi d}\right) \tag{2}$$

where D_t is the directivity of the transmitting antenna D_r is the directivity of the receiving antenna λ is the signal wavelength, d is the distance between the antennas. For convenience, we define

$$G_l = D_t D_r \tag{3}$$

which is the product of the transmit and receive antenna field radiation patterns in the line of sight direction.

The distance between the antennas d must be large enough that the antennas are in the far field of each other $d \gg \lambda$.[4] The free-space path loss is the loss factor in this equation that is due to distance and wavelength, or in other words the ratio of power transmitted to power received assuming the antennas are isotropic and have no directivity ($D_t = D_r = 1$

$$\text{FSPL} = \left(\frac{4\pi d}{\lambda}\right)^2 \tag{4}$$

Since the frequency of a radio wave f is equal to the speed of light c divided by the wavelength, the path loss can also be written in terms of frequency

$$\text{FSPL} = \left(\frac{4\pi d f}{c}\right)^2 \tag{5}$$

Beside the assumption that the antennas are lossless, this formula assumes that the polarization of the antennas is the same, that there are no multipath effects, and that the radio wave path is sufficiently far away from obstructions that it acts as if it is in free space. This last restriction requires an ellipsoidal area around the line of sight out to 0.6 of the Fresnel zone be clear of obstructions. The Fresnel zone increases in diameter with the wavelength of the radio waves. Often the concept of free space path loss is applied to radio systems that don't completely meet these requirements, but these imperfections can be accounted for by small constant power loss factors that can be included in the link budget.

2 Influence of distance and frequency

n free space the intensity of electromagnetic radiation decreases with distance by the inverse square law, because the same amount of power spreads over an area proportional to the square of distance from the source.

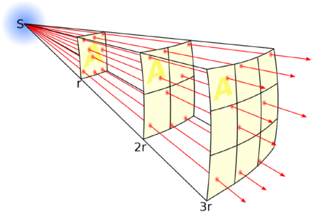

Figure 1: In free space the intensity of electromagnetic radiation decreases with distance by the inverse square law, because the same amount of power spreads over an area proportional to the square of distance from the source.

The free-space loss increases with the distance between the antennas and decreases with the wavelength of the radio waves due to these factors[6]

Intensity (I) – the power density of the radio waves decreases with the square of distance from the transmitting antenna due to spreading of the electromagnetic energy in space according to the inverse square law[1] Antenna capture area (A_{eff}) – the amount of power the receiving antenna captures from the radiation field is proportional to a factor called the antenna aperture or antenna capture area, which increases with the square of wavelength.[1] Since this factor is not related to the radio wave path but comes from the receiving antenna, the term "free-space path loss" is a little misleading.

3 Derivation

The radio waves from the transmitting antenna spread out in a spherical wavefront. The amount of power passing through any sphere centered on the transmitting antenna is equal. The surface area of a sphere of radius d is $4\pi d^2$. Thus the intensity or power density of the radiation in any particular direction from the antenna is inversely proportional to the square of distance

$$I \propto \frac{P_t}{4\pi d^2} \tag{6}$$

For an isotropic antenna which radiates equal power in all directions, the power density is evenly distributed over the surface of a sphere centered on the antenna

$$I = \frac{P_t}{4\pi d^2} \qquad (1)$$

The amount of power the receiving antenna receives from this radiation field is

$$P_r = A_{\text{eff}} I \qquad (2)$$

The factor A_{eff} , called the effective area or aperture of the receiving antenna, which has the units of area, can be thought of as the amount of area perpendicular to the direction of the radio waves from which the receiving antenna captures energy. Since the linear dimensions of an antenna scale with the wavelength λ , the cross sectional area of an antenna and thus the aperture scales with the square of wavelength λ^2.[6] The effective area of an isotropic antenna (for a derivation of this see antenna aperture article) is

$$A_{\text{eff}} = \frac{\lambda^2}{4\pi}$$

Combining the above (1) and (2), for isotropic antennas

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

$$\text{FSPL} = \frac{P_t}{P_r} = \left(\frac{4\pi d}{\lambda}\right)^2$$

4 Free-space path loss in decibels

A convenient way to express FSPL is in terms of decibels (dB)

$$\begin{aligned}
\text{FSPL(dB)} &= 10\log_{10}\left(\left(\frac{4\pi df}{c}\right)^2\right) \\
&= 20\log_{10}\left(\frac{4\pi df}{c}\right) \\
&= 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \\
&= 20\log_{10}(d) + 20\log_{10}(f) - 147.55,
\end{aligned}$$

where the units are as before.

For typical radio applications, it is common to find f measured in units of GHz and d in km, in which case the FSPL equation becomes

$$\text{FSPL(dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 92.45 \qquad (7)$$

For d, f in meters and kilohertz, respectively, the constant becomes – -87.55
.

For d, f in meters and megahertz, respectively, the constant becomes -27.55
.

For d , f d, f in kilometers and megahertz, respectively, the constant becomes 32.44.[7]

See also:

Computation of radiowave attenuation in the atmosphere Friis transmission equation Radio propagation model ITU-R P.525 Link budget Two-ray ground reflection model

5 References

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4. Johnson, Richard (1984). Antenna Engineering Handbook (2nd ed.). New York, NY: McGraw-Hill, Inc. pp. 1–12. ISBN .
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6. Cerwin, Steve (2019). Radio Propagation and Antennas: A Non-Mathematical Treatment of Radio and Antennas. Author House. pp. 31–35. ISBN ., Section 1.8
7. Poole, Ian. "Free Space Path Loss: Details, Formula, Calculator". radio-electronics.com. Adrio Communications Ltd. Retrieved 17 July 2017.

Further reading

1. C.A. Balanis, "Antenna Theory", 2003, John Wiley and Sons Inc.
2. Derivation of the dB version of the Path Loss Equation
3. Path loss Pages for free space and real world – includes free space loss calculator