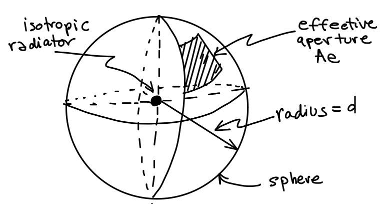
Free-Space Propagation

Free Space Propagation

As predicted by Maxwell and demonstrated by Hertz, time-varying electromagnetic fields propagate through free space. Frequencies between 3 kHz and 3 THz can be used for wireless communication.

Consider an isotropic source – one that transmits equally in all directions – at the center of a sphere of radius d (distance) transmitting power P_T and a receiving antenna of area A_e that collects all of the power incident ("shining") on it:



Since the transmit power is equally distributed over the surface of the sphere (of area $= 4\pi d^2$), the ratio of the received power to transmitted power, the "path loss," is:

$$\frac{P_R}{P_T} = \frac{A_e}{4\pi d^2}$$

Exercise 1: If the effective area of an antenna is 1 m^2, what is the path loss, in dB, at a distance of 100 m? At the distance to a geostationary satellite ($\approx 36,000$ km)? How does it increase (in dB) with distance?

Antennas

An antenna is a device that couples electromagnetic fields in space to those in a conductor.

Pattern. The power radiated from an antenna as a function of direction is called the antenna pattern. The antenna pattern is typically specified in spherical coordinates (azimuth, θ and elevation, ϕ).

Reciprocity. For linear (passive) antennas and linear propagation media (e.g. air) the coupling between fields and currents is independent of the direction of energy flow. Thus antenna patterns are reciprocal – the pattern of an antenna is the same whether it is transmitting or receiving.

Directivity. The directivity (D) of an antenna is the the ratio of the maximum power density (U_m) to the average power density (U_0):

$$D = \frac{U_m}{U_0}\,.$$

Exercise 2: What is the directivity of an isotropic radiator?

Effective Area and Directivity

Because currents in an antenna affect nearby fields, the effective area of a many antennas is not closely related to their physical area.

Consider the power received at a point in space. Since it is proportional to both the directivity and the effective area, we expect that effective area and directivity will be proportional for any antenna and A_e/D will be a constant. The value of this ratio can be obtained by analyzing *any* antenna for which A_e and D can be conveniently computed.

Consider an electrically-short dipole antenna. We can compute the electric field by integrating the field produced by infinitesimally small electric dipoles. By integrating the electric field over the surface of a sphere we can compute both the peak and average power densities and from this the directivity which is found to be

$$D(\text{short dipole}) = 3/2\,.$$

We can also derive the power at the antenna terminals resulting from this power density and from this obtain the effective area which is found to be

$$A_e(\text{short dipole}) = \frac{3\lambda^2}{8\pi}\,.$$

From this we find that

$$\frac{A_e}{D} = \frac{\lambda^2}{4\pi}$$

which applies to any antenna.

Directivity and Gain

Measuring directivity requires measuring the power density in all directions in order to compute the average. A more practical measurement is the *gain* of an antenna which is the ratio of the maximum power density to the power density of a lossless reference antenna U_r, typically an ideal (lossless) isotropic radiator:

$$G = \frac{U_m}{U_r}$$

The ratio of gain to directivity:

$$\frac{G}{D} = \frac{U_0}{U_r} = k$$

is the antenna's *efficiency*: the ratio of the average radiated power of the real antenna to the average radiated power of an ideal isotropic source. This difference is due to resistive losses in the antenna.

Exercise 3: What is the maximum value of k?

Antenna gain, like most quantities in communications is usually specified in dB. If the reference antenna is an ideal (lossless) isotropic antenna the units are specified as dBi.

We can now relate the effective area of a (lossy) antenna to its gain:

$$G = \frac{4\pi A_e}{\lambda^2} .$$

Friis Equation

Substituting G for A_e we get the Friis equation:

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi r} \right)^2$$

where P_R and P_T are the received and transmitted powers, G_R is the gain of the receive antenna, λ is the wavelength and r is the distance from transmitter to receiver. The additional term G_T is used to account for the common case of a non-isotropic transmit antenna that serves to increases the transmit power by a factor (gain) G_T in the direction of the receiver compared to an isotropic radiator.

This equation only applies at distances that are in the "far field" where the field strength is uniform. This happens at distances that are many wavelengths and many antenna dimensions. Typically $L^2/\lambda >> 1$ where L is the largest dimension of the antenna.

Exercise 4: A point-to-point link uses a transmit power of 1 Watt, transmit and receive antennas with gains of 20dB and operates at 3 GHz. How much power is received by a receiver 300m away?

Exercise 5: What is the far-field distance for an cell phone antenna operating at 3 GHz that has a physical size of $1 \times 1 \times 3$ cm? For a 100 m diameter antenna?

Loss vs Frequency

From the relationship between antenna gain and effective aperture we note that the gain increases as the square of the frequency. This means that for a given antenna size (area) the antenna becomes more directional as the frequency increases. Conversely, for a given antenna gain the effective area (power collected) decreases with the square of the frequency.

This is the reason that the propagation "loss" given by the last factor of Friis equation above appears to increase as the square of the frequency.

However, it's important to understand that the reason the propagation loss appear to increase with frequency is simply because, for an antenna with a fixed gain, the effective aperture decreases as the frequency increases. Propagation loss is ***not*** a result of power being absorbed by the medium through which the signal is propagating.

Exercise 6: If we kept the *effective aperture* constant at one end of a link (transmitter or receiver), how would the path loss change as a function of frequency? What if we kept it constant at both ends? Is this a feasible approach for mobile systems?