College of Computer & Information Science — Spring 2007
Northeastern University — Lecture 2
CSG250: Wireless Networks — 12 January 2007

Antennas and Propagation

The notes in this document are based almost entirely on Chapter 5 of the textbook [Sta05]. Rappaport's text is also a good reference for wireless signal propagation [Rap95].

1 Antennas

An antenna is an electrical conductor or a system of conductors that radiates/collects (transmits or receives) electromagnetic energy into/from space. An idealized isotropic antenna radiates equally in all directions. The directivity of an antenna is captured by its beam width; it is the angle within which power radiated is at least half of that in the most preferred direction (that is, half of the maximum power).

Antenna gain is the power output, in a particular direction, compared to that produced in any direction by an idealized omnidirectional antenna. If f is the carrier frequency and A_e is the effective area of the antenna, then the antenna gain is given by

$$G = \frac{4\pi A_e f^2}{c^2},$$

where c is the speed of light. The effective area of an antenna depends on the size and shape of the antenna. The effective area of an idealized isotropic antenna is 1, by definition.

2 Propagation modes

Wireless transmissions propagate in three modes: *ground-wave*, *sky-wave*, and *line-of-sight*. Ground wave propagation follows the contour of the earth, while sky wave propagation uses reflection by both earth and ionosphere. Finally line of sight propagation requires the transmitting and receiving antennas to be within line of sight of each other. Which of these propagation modes dominates depends on the frequency of the underlying signal.

Examples of ground wave and sky wave communication are AM radio and international broadcasts such as BBC. Above 30 MHz, neither ground wave nor sky wave propagation operates and the communication is through line of sight.

If h is the height of a transmitting (resp., receiving) antenna in meters, then the distance to the receiver (resp., transmitter) for line-of-sight transmission should be at most

$$d = 3.57\sqrt{h} \text{ kms.}$$

This can be proved using elementary geometry. Since microwaves are bent or refracted by the atmosphere, the "effective" line of sight is, in fact, larger than the true line of sight. We introduce

an adjustment factor K to capture the refraction effect and obtain

$$d = 3.57\sqrt{Kh} \text{ kms.}$$

If the two antenna have heights h_1 and h_2 meters, then the distance between them for LOS propagation should be at most

$$3.57\sqrt{K}(\sqrt{h_1} + \sqrt{h_2}) \text{ kms.}$$

3 Transmission limitations

There are four classes of limitations that affect electromagnetic wave transmissions.

Attenuation. The strength of signal falls with distance over transmission medium. The extent of attenuation is a function of distance, transmission medium, as well as the frequency of the underlying transmission. Even in free space, with no other impairment, the transmitted signal attenuates over distance simply because the signal is being spread over a larger and larger area. For an ideal isotropic antenna, the ratio between the transmitted power P_t and the received power P_r for a separation distance of d is given by

$$\frac{P_r}{P_t} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2},$$

where λ, f, and c are the wavelength, frequency, and the speed of the signal.

One can express the above ratio in terms of antenna gains and effective areas of the antennas by applying the appropriate formulae.

Distortion. Since signals at different frequencies attenuate to different extents, as the above formula indicates, a signal comprising of components over a range of frequencies gets distorted; i.e., the shape of the received signal changes. A standard method of resolving this problem (and recovering the original shape) is to amplify higher frequencies and thus equalize attenuation over a band of frequencies.

Dispersion. Dispersion is the phenomenon of spreading of a burst of electromagnetic energy during propagation. It is especially prevalent in wireline transmissions such as an optical fiber. Bursts of data sent in rapid succession tend to merge due to dispersion. The longer the length of the wire, the more severe is the effect of dispersion. The effect of dispersion is to limit the product $R \times L$, where R is the data rate and L is distance.

Noise. The most pervasive form of noise is thermal noise, which is often modeled using an additive Gaussian model. Thermal noise is due to thermal agitation of electrons and is uniformly distributed across the frequency spectrum. The thermal noise to be found in 1 Hz of bandwidth is

$$N_0 = kT \text{ W/Hz},$$

where T is the absolute temperature of the medium (conductor) and k is Boltzmann's constant (1.3803×10^{-23} Joules/Kelvin). The amount of thermal noise in B Hz of bandwidth is simply $N_0 B$. Other forms of noise include intermodulation noise (caused by signals produced at frequencies that are sums or differences of carrier frequencies), crosstalk (interference between two signals), and

impulse noise (irregular pulses of high energy caused by external electromagnetic disturbances). While an impulse noise may not have a significant impact on analog data, it has a noticeable effect on digital data, causing burst errors.

The effect of noise on the achievable information rate is best captured by Shannon's capacity theorem which we derived last week, which relates the capacity to the signal-to-noise ratio. A more convenient form of this equation is in terms a different ratio, referred to as the E_b/N_0 term. Here E_b refers to the energy per bit of the signal and N_0 is the noise power density introduced above. In terms of the signal power P and the information rate R, we can write E_b as P/R. Noting that $N = N_0 B$, we obtain $E_b/N_0 = (P/N)(B/R)$, where B is the bandwidth. Thus, the E_b/N_0 value needed to achieve the capacity of a channel must satisfy the following equation.

$$C = B \log_2 \left(1 + \frac{E_b}{N_0}\frac{C}{B}\right) \Rightarrow \frac{E_b}{N+0} = \frac{B}{C}(2^{C/B} - 1).$$

For signal modulation techniques, the bit-error rate is often expressed as a function of the E_b/N_0 ratio.

4 Fading

Fading refers to the variation of the signal strength with respect to time/distance and is widely prevalent in wireless transmissions. The most common causes of fading in the wireless environment are multipath propagation and mobility (of objects as well as the communicating devices).

Multipath propagation. In wireless media, signals propagate using three principles: reflection, scattering, and diffraction. Reflection occurs when the signal encounters a large solid surface, whose size is much larger than the wavelength of the signal, e.g., a solid wall. Diffraction occurs when the signal encounters an edge or a corner, whose size is larger than the wavelength of the signal, e.g., an edge of a wall. Finally, scattering occurs when the signal encounters small objects of size smaller than the wavelength of the signal. One consequence of multipath propagation is that multiple copies of a signal propagation along multiple different paths, and arrive at any point at different times. So the signal received at a point is not only affected by the inherent noise, distortion, attenuation, and dispersion in the channel but also the interaction of signals propagated along multiple paths.

Delay spread. Suppose we transmit a probing pulse from a location and measure the received signal at the recepient location as a function of time. The signal power of the received signal spreads over time due to multipath propagation. The *delay spread* is determined by the density function of the resulting spread of the delay over time. Average delay spread and root mean square delay spread are two parameters that can be calculated.

Doppler spread. This is a measure of spectral broadening caused by the time rate of change of the mobile radio channel. It is caused by either relative motion between the mobile and base station or by movement of objects in the channel. When a pure sinusoid of frequency f is transmitted the received signal spectrum, the Doppler spectrum, is the range $[f - f_d, f|f_d]$, where f_d is referred to as the Doppler spread, given by

$$f_d = \frac{v}{\lambda}\cos\theta,$$

where v is the relative velocity of the mobile and θ is the angle formed by the direction of the motion and that of the signal, and λ is the wavelength of the carrier.

The relative size of the delay spread, as compared to the symbol period, has an impact on whether the effect of fading is uniform over all frequencies or varies across frequencies in the spectrum of the channel. *Flat fading* occurs when the bandwidth of the signal is less than the bandwidth of the channel, or delay spread is less than the symbol period. *Frequency selective fading* occurs when the bandwidth of the signal is greater than the bandwidth of the the channel, or the delay spread is greater than symbol period.

There are several fading models that capture different multipath propagation characteristics. *Rayleigh fading* models a worst-case scenario in which no path dominates (in fact, a LOS path may not even exist). *Rician fading* assumes that one of the paths, usually LOS, dominates all the other paths.

When the velocity of the mobile is high, the Doppler spread is high, and the the resulting channel variations are faster than that of the baseband signal; this is referred to as *fast fading*. When channel variations are slower than the baseband signal variations, then the resulting fading is referred to as *slow fading*.

References

[Rap95] Theodore S. Rappaport. *Wireless Communications: Principles and Practice*. Prentice-Hall, Inc., Upper Saddle River, NJ, USA, 1995.

[Sta05] William Stallings. *Wireless Communications and Networks*. Prentice Hall Professional Technical Reference, 2005. 2nd edition.