Deterministic Propagation Models

EM Field Solutions

For simple geometries and boundary conditions defined by conductors, dielectrics, sources and terminations, it's possible to solve Maxwell's equations and solve for the field strengths. This is practical for problems such as determining the impedances of transmission lines and simple antennas.

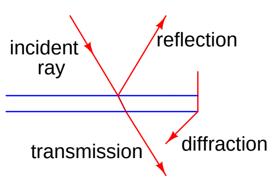
For more complex geometries and materials it's possible to use finite element methods to obtain numerical solutions for the field strengths. This a practical method for analyzing antennas and predicting the effectiveness of shielding for circuit layouts.

But both of these techniques are impractical for predicting field strengths for predicting propagation of signals used for wireless communication because the number of objects interacting with the fields is so large.

Ray Tracing

Since EM waves propagate in straight lines and superposition applies at reasonable field strengths, another approach is to model the transmitted signal as a number of straight-line rays.

The interaction with physical objects can result in several different phenomena: transmission, reflection and diffraction.



Refraction and scattering are also important in some specialized wireless communication systems.

We will review a few solutions resulting from simple ray-tracing models. Although they are not very useful for predicting real-world propagation, they provide insights into the mechanisms involved.

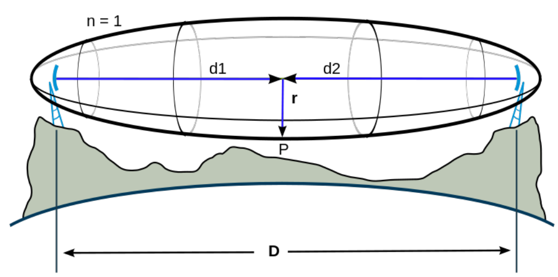
Reflection

There are various propagation models that only take into account a limited number of specular reflections. These give a wide range of estimates of path loss and are more useful for insights they provide than for real-world predictions.

Fresnel Zones

A Fresnel zone is the group of locations where the difference between the length of the direct path and the length of a reflected path is a multiple of a half wavelength ($\lambda/2$). Rays from odd-numbered Fresnel zones cause destructive interference (reduction in received signal level) while even-numbered ones cause constructive interference (and an increase in received signal level).

Fresnel zones are ellipsoids consisting of all points where the path length difference is $n\lambda/2$ as shown in the following diagram from Wikipedia:



For $d_1 \gg r$ and $d_2 \gg r$ the radius of the nth Fresnel zone radius at distances d_1 and d_2 can be approximated by:

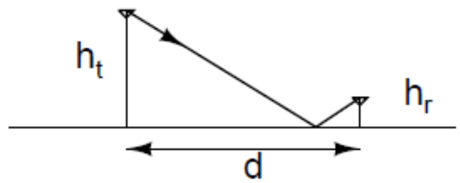
$$r_n \approx \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

A practical implication of Fresnel zones is that for point-to-point links a simple line of sight is not sufficient. Objects should also be kept out of (at least) the first Fresnel zone to avoid causing destructive interference and signal loss.

Exercise 1: An cellular base station antenna is mounted on a tower above a building. The line-of-sight path from the antenna to the nearest user passes near the edge of the building. The distance from the antenna to the edge is 3 metres and from the edge to the user is 100m. The system operates at a frequency of 900 MHz. By how much must the line-of-sight (LOS) path clear the edge of the building to ensure that diffraction effects are negligible?

Two-Ray Ground-Reflection Model

This is a simple model for propagation over ground.



Assume two components arrive at receiver: one line-of-sight (LOS) and one reflected from the ground.

At large distances compared to the antenna heights the two components will have approximately equal amplitude and a small phase difference:

$$\theta_\delta = \frac{2\pi\delta}{\lambda}$$

where δ is the path length difference which can be approximated as:

$$\delta \approx \frac{2h_t h_r}{d}$$

For large d ($\gg \sqrt{h_t h_r}$) it can be shown that:

$$P_r \approx P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

For this model the path loss varies as d^4, the square of the antenna heights and is independent of frequency.

This approximation does not apply for distances that are short relative to the antenna heights.

Exercise 2: You want to set up an over-water link to provide data service to a ferry. The maximum distance from the terminal to the ferry is 10km. The antenna heights are 20m at the terminal and 10m at the ferry. You can use 20dBi antennas at each end and 1W transmit power. On a very calm day (no waves) what will be the received power in Watts and dBm?

Ten-Ray Urban-Canyon Model

This model of propagation in dense urban areas takes into account the LOS path as well as one-, two- and three-bounce reflections from buildings along both sides of a street and the ground.

In this case it's possible to show that the the path loss is approximately proportional to the square of the distance ($P_r \sim d^{-2}$).

Exercise 3: What is the path loss exponent for a signal propagating along a perfectly-conducting waveguide?

Diffraction

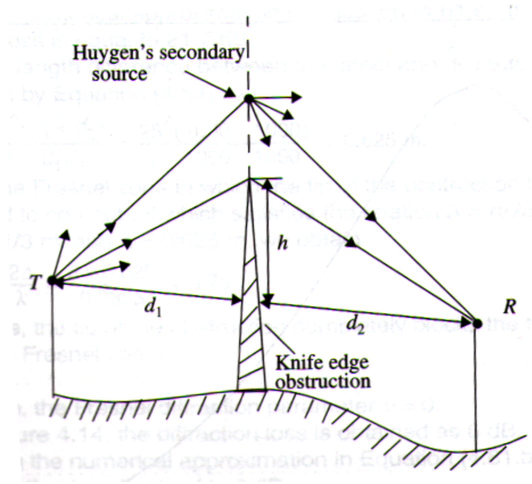
Diffraction is probably the most important non-line of sight (NLOS) propagation mechanism. Cellular systems rely on diffraction over rooftops and indoor systems rely on diffraction around wall edges and door openings for coverage.

Diffraction can be explained by the Huygens-Fresnel principle which states that each point on a wavefront acts as a point source. This means that even if the direct path between the transmitter and receiver is blocked, some energy can reach the receiver from the portions of space that are visible to both the transmitter and receiver.

Knife-Edge Diffraction Model

Analytical solutions for the diffracted signal level are difficult even for relatively simple geometries and they are impractical for real-world situations. However, the simple model of diffraction over a "knife edge" can give an idea of the magnitude of the signal level provided by diffraction.

The model is that a plane shields a portion of the wavefront that would normally propagate from the transmitter to the receiver. Diffraction takes place due to the contribution of points on the portion of the plane that is not hidden by the "knife edge". The following diagram (from the text by Rappaport) shows the geometry:



For this geometry we can compute a parameter called the Fresnel-Kirchoff diffraction parameter, ν:

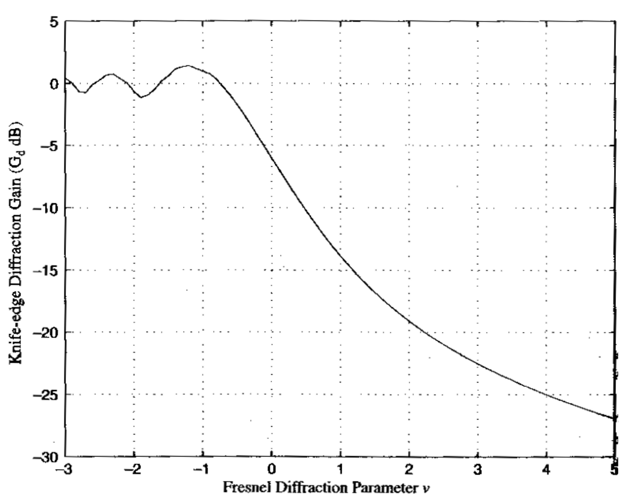
$$\nu = h\sqrt{\frac{2(d_1 + d_2)}{\lambda d_1 d_2}}$$

The signal level due to knife-edge diffraction is given by integrating the contributions from the unobstructed portions of the wavefront. The solution is given in terms of the Complex Fresnel Integral, $F(\nu)$.

The actual path gain (typically, a loss) in dB is given by:

$$G_d(\text{dB}) = 20 \log |F(\nu)|$$

The following graph (again from Rappaport) shows the value of the complex Fresnel Integral in dB:



When h is negative (knife edge below the line of sight) the loss due to diffraction is relatively low. At $h = 0$ half the signal power is lost (-6dB) as might be expected. As h increases the diffraction loss increases.

The total path loss for such a path will be given by the sum (in dB) of the loss due to diffraction and the loss given by the Friis equation for the total path length.

Practicla Use

Various propagation mechanisms (transmission, reflection, diffraction, scattering) will have an effect in most NLOS propagation situations. The geometries of the propagation paths will be complicated and the received signal will be the vector sum of all of these components.

For wireless communication systems involving NLOS propagation, it's impossible predict the dominant propagation mechanism or paths. For planning NLOS wireless communication systems we must therefore rely on statistical descriptions of propagation (next lecture).