Lecture 2: Wireless propagation mechanisms

In this lecture we will discuss the basic mechanisms that govern the propagation of electromagnetic waves which are used in wireless communications.

Three basic mechanisms are:
- Reflection
- Diffraction
- Scattering

First we will discuss free space attenuation as the simplest scenario to provide the basics.

1. Free Space Attenuation:

Consider a transmit and a receive antenna in free space, separated by a distance $d$.

The received power at the receive antenna is given by

$$ P_{RX} (d) = P_{TX} \cdot G_{TX} \cdot \frac{1}{4\pi d^2} \cdot A_{RX} $$

$$ = P_{TX} \cdot G_{TX} \cdot G_{RX} \cdot \left(\frac{\lambda}{4\pi d}\right)^2 \text{ (Fried's law)} $$

where:

- $P_{TX}$: transmit power
- $G_{TX}$: transmit antenna gain in the direction of the receiver ($G_{TX} = 1$ for isotropic transmit antenna)
- $G_{RX}$: receive antenna gain, $G_{RX} = \frac{4\pi}{\lambda^2} A_{RX}$

Antenna gains depend on the type of antennas. $A_{RX}$: (area) effective area of the receiver's antenna.
\[ \lambda: \text{wavelength} \quad (\lambda = \frac{c}{f} = \frac{3 \times 10^8}{f}) \]

\[ d: \text{distance between transmit and receive antennas} \]

The validity of Friis' law is restricted to the far field: \( d \gg \lambda \) and \( d \gg \text{largest dimension of the antenna} \)

\[ \text{Free-space path-loss factor} = \left( \frac{\lambda}{4\pi d} \right)^2 \]

We see that signal power decreases as the square of distance. The path-loss factor or path-loss exponent describes how received power varies with distance and is 2 for free space.

\[ \text{Reflection and Transmission:} \]

\[ \begin{align*}
\delta_1 & : \text{dielectric constant} \\
\delta_2 & : \text{dielectric constant} \\
\text{Surface between two dielectric materials}
\end{align*} \]

\[ \text{Reflection:} \quad \frac{E_r}{E_i} = \frac{\sqrt{\delta_1}}{\sqrt{\delta_2}} \]

\[ \text{Transmission:} \quad \frac{E_t}{E_0} = \frac{\sqrt{\delta_2}}{\sqrt{\delta_1}} \]
Reflection and transmission for a layer of dielectric structure (such as through the wall for cell phones indoors) are complicated to model. Multi-layer structures are often described by "effective" dielectric constants or reflection/transmission constants, which are measured directly for each composite structure.

Using a two-ray model: a direct path, and a reflected path off the ground, we can derive a "text book" model:

\[ P_{RX}(d) = P_{TX} G_{TX} G_{RX} \left( \frac{h_{RX} h_{RX}}{d^2} \right) + P_{TX} G_{TX} G_{RX} \left( \frac{h_{RX} h_{RX}}{d^2} \right) \]

This model predicts power attenuation with path loss factor of 4 (~d^{-4}) and is independent of the wavelength. It holds only for \( d \geq \frac{4h_{RX} h_{RX}}{\lambda} \).

In reality, this model is imprecise (because of the over simplification), and path loss exponent can be measured in the range 1.5 < \( \gamma \) < 5.5.

3. Diffraction: While reflection assumes infinitely extended objects/surfaces, all real objects have finite size. These finite-size objects creates diffraction at the edges.
1) Diffraction by a knife edge or screen:

- Wavefront
- Shadow Zone
- Diffraction

2) Diffraction by a wedge:

3) Models for diffraction in urban areas (multiple screen)

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Modeling diffraction by multiple screens is an extremely challenging mathematical problem and usually does not give exact solutions, though many approximation methods exist.
4. **Scattering by rough surfaces**

While reflection assumes a smooth surface, all/most practical surfaces contain some roughness which is usually assumed to be random.

- Specular reflection
- Specular scattering
- Smooth surface
- Rough surface

Reflection has been studied extensively due to radar technology, with two main theories evolved: the Kirchhoff theory and the perturbation theory.

Large scale propagation model:

\[
P_{rx}(d) = P_{tx}(1m) - 20 \log (d_{break}/1m) - \gamma 10 \log \left( \frac{d}{d_{break}} \right)
\]

\[
P_r(d) = P_{tx}(1m) + 10 \log_{10} K - 10 \gamma \log \frac{d}{d_0} - 9 \text{dB}
\]