15-496 : A Hand-on Introduction to Wireless Networks
Lecture 3: Physical Layer

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http://www.cs.cmu.edu/~prs/wireless08/

Outline

- RF introduction
- Modulation and multiplexing
- Spectrum and channel capacity
- Antennas and signal propagation
  - How do antennas work
  - Propagation properties of RF signals
- Equalization and diversity
- Channel coding

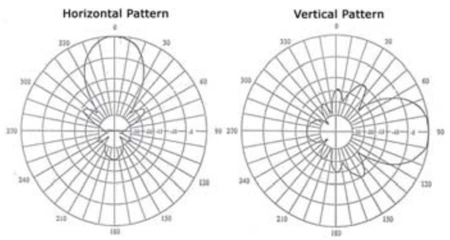
What is an Antenna?

- Conductor that carries an electrical signal and radiates an RF signal.
  - The RF signal "is a copy of" the electrical signal in the conductor
- Also the inverse process: RF signals are "captured" by the antenna and create an electrical signal in the conductor.
  - This signal can be interpreted (i.e. decoded)
- Efficiency of the antenna depends on its size, relative to the wavelength of the signal.
  - E.g. half a wavelength

Types of Antennas

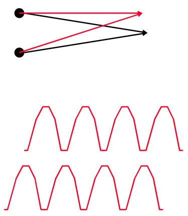
- Abstract view: antenna is a point source that radiates with the same power level in all directions – omni-directional or isotropic.
  - Not common – shape of the conductor tends to create a specific radiation pattern
  - Note that isotropic antennas are not very efficient!!
    - Unless you have a very large number of receivers
- Common shape is a straight conductor.
  - Creates a "disk" pattern
- Shaped antennas can be used to direct the energy in a certain direction.
  - Well-known case: a parabolic antenna
  - Pringles boxes are cheaper

Directional Antenna Properties



- dBi: antenna gain in dB relative to an isotropic antenna with the same power.
  - Example: an 8 dBi Yagi antenna has a gain of a factor of 6.3 (8 db = 10 log 6.3)

Multi-element Antennas



- Multi-element antennas have multiple, independently controlled conductors.
  - Signal is the sum of the individual signals transmitted (or received) by each element
- Can electronically direct the RF signal by sending different versions of the signal to each element.
  - For example, change the phase in two-element array.
- Covers a lot of different types of antennas.
  - Number of elements, relative position of the elements, control over the signals, …

Propagation Modes

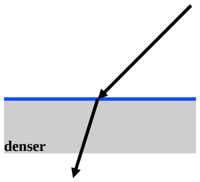
- Line-of-sight (LOS) propagation.
  - » Most common form of propagation
  - » Happens above ~ 30 MHz
  - » Subject to many forms of degradation (next set of slides)
- Ground-wave propagation.
  - » More or less follows the contour of the earth
  - » For frequencies up to about 2 MHz, e.g. AM radio
- Sky wave propagation.
  - » Signal “bounces” off the ionosphere back to earth – can go multiple hops
  - » Used for amateur radio and international broadcasts

Propagation Degrades RF Signals

- Attenuation in free space: signal gets weaker as it travels over longer distances
  - » Radio signal spreads out – free space loss
  - » Refraction and absorption in the atmosphere
- Obstacles can weaken signal through absorption or reflection.
  - » Part of the signal is redirected
- Multi-path effects: multiple copies of the signal interfere with each other.
  - » Similar to an unplanned directional antenna
- Mobility: moving receiver causes another form of self interference.
  - » Node moves ½ wavelength -> big change in signal strength

Refraction

- Speed of EM signals depends on the density of the material
  - » Vacuum: 3×10^8 m/sec
  - » Denser: slower
- Density is captured by refractive index
- Explains “bending” of signals in some environments
  - » E.g. sky wave propagation
  - » But also local, small scale differences in the air



Free Space Loss

$$\text{Loss} = P_t / P_r = (4\pi\, d)^2 / (G_r\, G_t\, \lambda^2)$$
$$= (4\pi\, f\, d)^2 / (G_r\, G_t\, c^2)$$

- Loss increases quickly with distance (d^2).
- Need to consider the gain of the antennas at transmitter and receiver.
- Loss depends on frequency: higher loss with higher frequency.
  - » Can cause distortion of signal for wide-band signals

Log Distance Path Loss Model

- Log-distance path los model captures free space attenuation plus additional absorption by of energy by obstacles:

$$\text{Loss}_{db} = L_0 + 10\, n \log_{10}(d/d_0)$$

- Where L_0 is the loss at distance d_0 and n is the path loss distance component
- Value of n depends on the environment:
  - » 2 is free space model
  - » 2.2 office with soft partitions
  - » 3 office with hard partitions
  - » Higher if more and thicker obstacles

Noise Sources

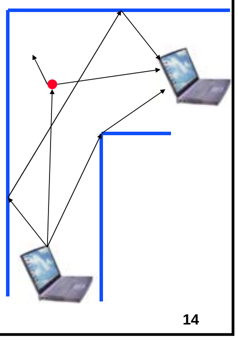
- Thermal noise: caused by agitation of the electrons
  - » Function of temperature
  - » Affects electronic devices and transmission media
- Intermodulation noise: result of mixing signals
  - » Appears at $f_1 + f_2$ and $f_1 - f_2$ (when is this useful?)
- Cross talk: picking up other signals
  - » E.g. from other source-destination pairs
- Impulse noise: irregular pulses of high amplitude and short duration
  - » Harder to deal with

Fairly Predictable
➢Can be planned for or avoided

Other LOS Factors

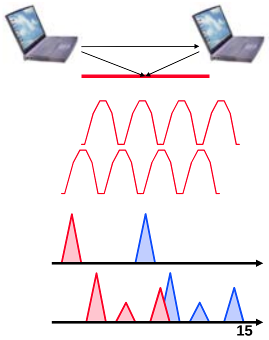
- Absorption of energy in the atmosphere.
  - Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)
  - Obviously objects also absorb energy

Propagation Mechanisms



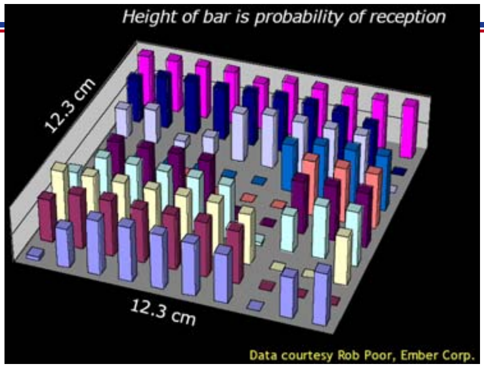
- Besides line of sight, signal can reach receiver in three other “indirect” ways.
- Reflection: signal is reflected from a large object.
- Diffraction: signal is scattered by the edge of a large object – “bends”.
- Scattering: signal is scattered by an object that is small relative to the wavelength.

Multipath Effects



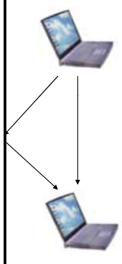
- Receiver receives multiple copies of the signal, each following a different path
- Copies can either strengthen or weaken each other
  - Depends on whether they are in our out of phase
- Small changes in location can result in big changes in signal strength
  - Short wavelengths, e.g. 2.4 Ghz -> 12 cm, 900 MHz -> ~1 ft
- Larger difference in path length can cause intersymbol interference (ISI)
  - More significant for higher bit rates (shorter bit times)

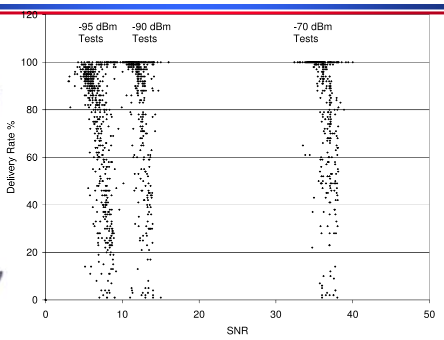
Example



Data courtesy Rob Poor, Ember Corp.

Multipath: “Random” Delivery Rates

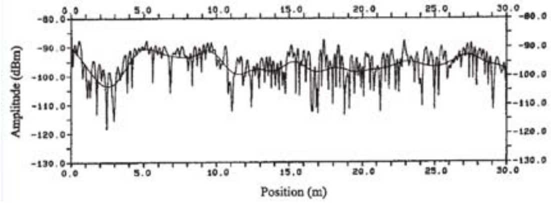




Fading in the Mobile Environment

- Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.
  - Rain, moving objects, moving sender/receiver, …
- Fast versus slow fading.
  - Fast: changes in distance of about half a wavelength – result in big fluctuations in the instantaneous power
  - Slow: changes in larger distances affects the paths – result in a change in the average power levels around which the fast fading takes place
- Selective versus non-selective (flat) fading.
  - Does the fading affect all frequency components equally
  - Region of interest is the spectrum used by the channel

Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

Fading Channel Models

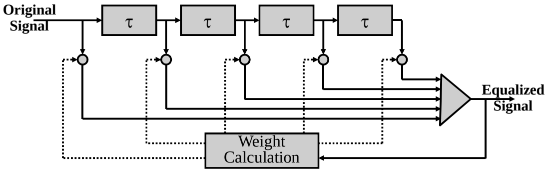
- Statistical distribution that captures the properties fading channels due to mobility
  - Fast versus slow fading
  - Flat versus selective fading
- Ricean distribution: LOS path plus indirect paths
  - Open space or small cells
  - K = power in dominant path/power in scattered paths
  - Speed of movement and minspeed
- Raleigh distribution: multiple indirect paths but no dominating, direct LOS path
  - E.g. urban environment with large cells, in buildings
  - K = 0 is Raleigh fading

Outline

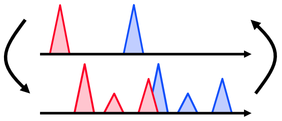
- RF introduction
- Modulation
- Antennas and signal propagation
- Equalization and diversity
  - Dynamic equalization
  - Diversity in space, frequency, and time
- Channel coding

Dynamic Equalization

- Goal is to deal with intersymbol interference
- Idea is to combine multiple delayed copies of the signal



Equalization Discussion



- Use multiple delayed copies of the received signal to try to reconstruct the original signal
- Weights are set dynamically
  - Typically based on some known “training” sequence
- Effectively uses the multiple copies of the signal to reinforce each other
  - But only works for paths that differ in length by less than the depth of the pipeline

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Diversity Techniques

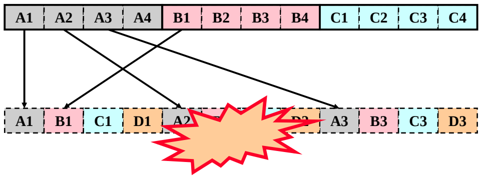
- Distribute signal over multiple “channels”
  - Channels experience independent fading
  - Reduces the error, i.e. only part of the signal is affected
- Time diversity: spread data out over time
  - Useful for bursty errors, e.g. slow fading
  - A specific form of channel coding
- Space diversity: use multiple nearby antennas and combine signals
  - Can be directional
- Frequency diversity: spread signal over multiple frequencies
  - For example, spread spectrum
  - Discussed later

Introducing Redundancy

- Protects digital data by introducing redundancy in the transmitted data.
  - Error detection codes: can identify certain types of errors
  - Error correction codes: can fix certain types of errors
- Block codes provide Forward Error Correction (FEC) for blocks of data.
  - (n, k) code: n bits are transmitted for k information bits
  - Simplest example: parity codes
  - Many different codes exist: Hamming, cyclic, Reed-Solomon, …
- Convolutional codes provide protection for a continuous stream of bits.
  - Coding gain is n/k
  - Turbo codes: convolutional code with channel estimation

Time Diversity

- Spread blocks out over time.
- Can use FEC or other error recovery techniques to deal with burst errors.



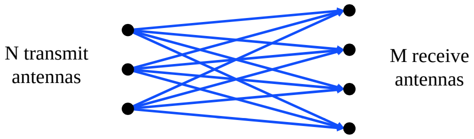
Space Diversity

- Use multiple antennas that pick up the signal in slightly different locations
- If there is no direct path (Raleigh), chances are that the signals are mostly uncorrelated
- If one antenna experiences deep fading, chances are that the other antenna has a strong signal
  - Antennas should be separated by ½ wavelength or more
- Applies to both transmit and receive side
  - Channels are symmetric
- Can use more than two antennas!

Space Diversity Techniques

- On the receiving side:
  - Selection diversity: pick antenna with best SNR
  - Feedback/scanning: only switch if signals becomes weak
  - Maximal ratio combining: combine signals with a weight that is based on their SNR
- Transmitter can also use diversity, but needs help from receiver
  - Needs feedback on which antenna works best
- Diversity is very common in today's 802.11 devices
  - Uses simple techniques, e.g. selection diversity

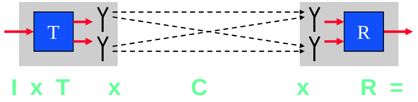
MIMO
Multiple In Multiple Out



- N x M subchannels
- Fading on channels is supposed to be largely independent
- Combines ideas from spatial and time diversity
- Very effective if there is no direct line of sight
  - Subchannels become more independent

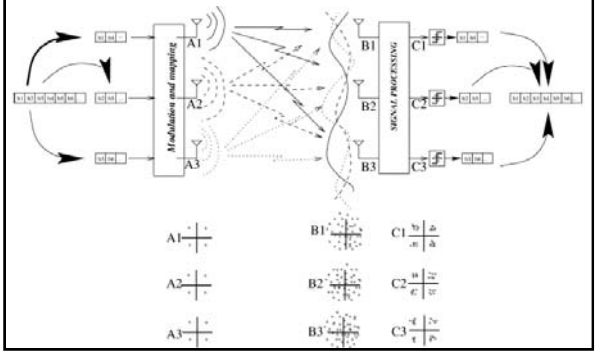
MIMO
How Does it Work?

- Coordinate the processing at the transmitter and receiver to overcome channel impairments
  - Maximize throughput or minimize interference
  - Can be viewed as generalization of earlier techniques



- Optimize T and R to achieve desired effect
  - But: each arrow in the channel represents multiple paths!
- Very effective if there is no direct line of sight
  - Subchannels become more independent

An Example of Space Coding



A Math View

- Transmitted Code Vector:

$$\mathbf{c}_l = [\ c_1(l),\ c_2(l),\ \cdots\ ,\ c_N(l)\ ]^T$$

- Channel Matrix:

$$\mathbf{H} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \cdots & \alpha_{1N} \\ \alpha_{21} & \alpha_{22} & \cdots & \alpha_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{M1} & \alpha_{M2} & \cdots & \alpha_{MN} \end{pmatrix}$$

- Received Signal Vector:

$$\mathbf{r}(l) = \mathbf{H} \cdot \mathbf{c}_l + \mathbf{n}(l)$$