

18-452/18-750
Wireless Networks and Applications
**Lecture 5: Physical Layer -
Channel Capacity and Antennas**

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Fall Semester 2018

<http://www.cs.cmu.edu/~prs/wirelessF18/>

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1

Outline

- RF introduction
- Modulation and multiplexing
- Channel capacity
- Antennas and signal propagation
 - » How do antennas work
 - » Propagation properties of RF signals
 - » Modeling the channel
- Modulation
- Diversity and coding
- OFDM



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2

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.**
 - » Reflection redirects part of the signal
- **Multi-path effects: multiple copies of the signal interfere with each other at the receiver**
 - » Similar to an unplanned directional antenna
- **Mobility: moving the radios or other objects changes how signal copies add up**
 - » Node moves $\frac{1}{2}$ wavelength -> big change in signal strength

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3

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
 - » Impacts transmission range in different spectrum bands

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4

Log Distance Path Loss Model

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

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

- 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

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5

Obstacles and Atmosphere

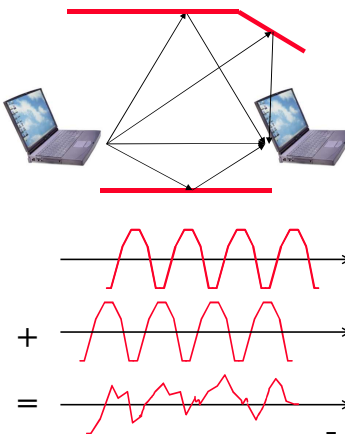
- Objects absorb energy as the signal passes through them
 - » Degree of absorption depends strongly the material
 - » Paper versus brick versus metal
- Absorption of energy in the atmosphere.
 - » Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)
- Refraction refraction in the atmosphere
 - » Pockets of air can have different properties, e.g., humidity, temperature, ...
 - » Redirects the signal in unpredictable ways
 - » Can reduce energy and increase path length

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6

Multipath Effect

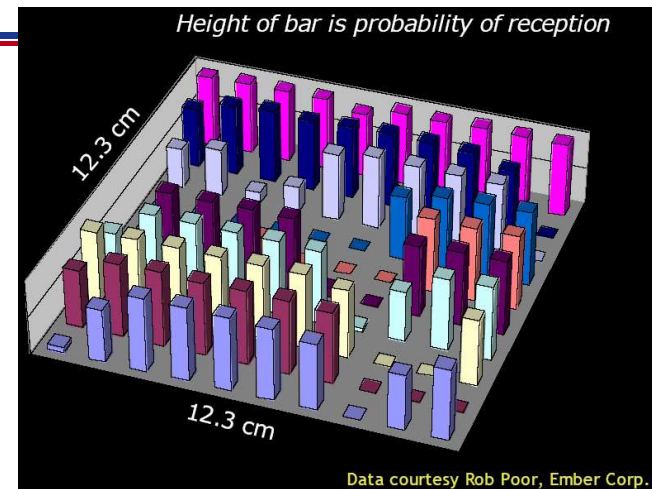
- Receiver receives multiple copies of the signal, each following a different path
- Copies can either strengthen or weaken each other
 - » Depends on whether they are in our out of phase
- Changes of half a wavelength affect the outcome
 - » Short wavelengths, e.g. 2.4 Ghz -> 12 cm, 900 MHz -> ~1 ft
- Small adjustments in location or orientation of the wireless devices can result in big changes in signal strength



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7

Example: 900 MHz



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8

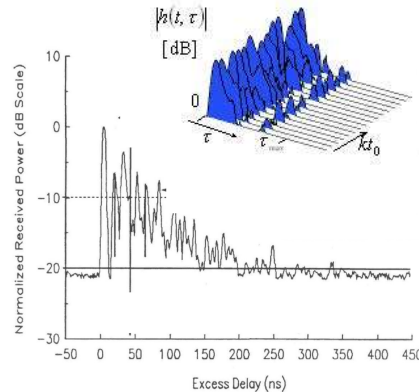
Channel Sounding

- Measure response of channel to an impulse

- » Signals from multiple paths is spread in time in time
- » Many frequencies

- Typically interested in response across frequency range

- » Delay spread, delay spread and impact on phase



Based on www.cs.bilkent.edu.tr/~korpe/courses/cs515-fall2002/slides6.ppt
 Peter A. Steenkiste SAAB MEDAV Technology - http://www.channelsounder.de/csprinciple_site4.html

9

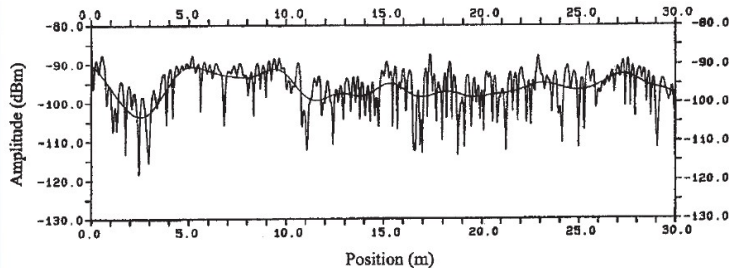
Fading in the Mobile Environment

- Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.
 - » Rain, moving obstacles, moving sender/receiver, ...
- Slow: changes the paths that make up the received signal – results in a change in the average power levels around which the fast fading takes place
 - » Mobility affects path length and the nature of obstacles
- Fast: changes in distance of about half a wavelength – results in big fluctuations in the instantaneous power

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10

Fading - Example



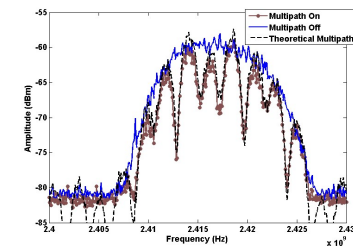
- Frequency of 910 MHz or wavelength of about 33 cm

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11

Frequency Selective versus Non-selective Fading

- Non-selective (flat) fading: fading affects all frequency components in the signal equally
 - » There is only a single path, or a strongly dominating path, e.g., LOS
- Selective fading: frequency components experience different degrees of fading
 - » Multiple paths with path lengths that change independently
 - » Region of interest is the spectrum used by the channel

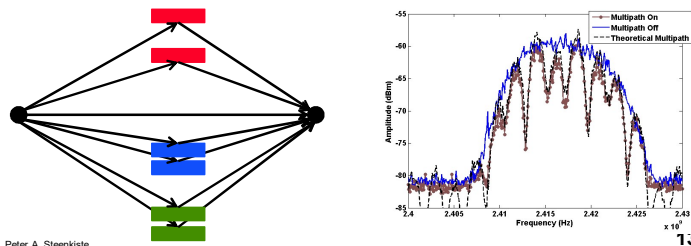


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12

Some Intuition for Selective Fading

- Assume three paths between a transmitter and receiver
- The outcome is determined by the differences in path length
 - » But expressed in wavelengths → outcome depends on frequency
- As transmitter, receivers or obstacles move, the path length differences change, i.e., there is fading
 - » But changes depend on wavelength, i.e. fading is frequency selective
- Significant concern for wide-band channels



Example Fading Channel Models

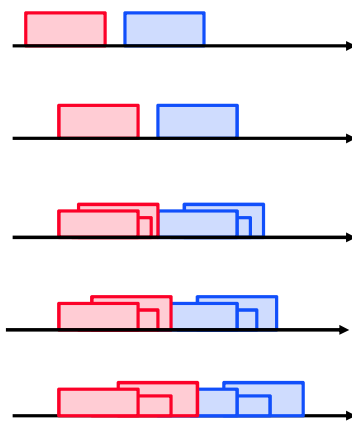
- **Ricean distribution: LOS path plus indirect paths**
 - » Open space or small cells
 - » K = power in dominant path/power in scattered paths
 - » Speed of movement and min-speed
- **Raleigh distribution: multiple indirect paths but no dominating or direct LOS path**
 - » Lots of scattering, e.g. urban environment, in buildings
 - » Sum of uncorrelated Gaussian variables
 - » $K = 0$ is Raleigh fading
- **Nakagami can be viewed as generalization: sum of independent Raleigh paths**
 - » Clusters or reflectors resulting paths with Raleigh fading, but with different path lengths
- Many others!

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14

Inter-Symbol Interference

- Larger difference in path length can cause inter-symbol interference (ISI)
 - » Different from effect of carrier phase differences
- Delays on the order of a symbol time result in overlap of the symbols
 - » Makes it very hard for the receiver to decode
 - » Corruption issue – not signal strength
 - » Significant concern for high bit rates (short symbol times)



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15

How Bad is the Problem?

- **ISI depends on the symbol time**
 - » Time to send a single or multi-bit symbol
 - » I.e., property of the baseband signal
- **Fast fading depends on wavelength of carrier wave**
 - » Distances are much shorter!

Rate MSps	Time microsec	Distance meter
1	1	300
5	0.2	60
10	0.1	30
50	0.02	6

Rate GHz	Wavelength nanosec	Length cm
0.9	1.11	33.3
2.4	0.417	12.5
5	0.2	6
60	0.0167	0.5

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16

Doppler Effect

- Movement by the transmitter, receiver, or objects in the environment can also create a doppler shift:

$$f_m = (v / c) * f$$

- Results in distortion of signal
 - » Shift may be larger on some paths than on others
 - » Shift is also frequency dependent (minor)
- Effect only an issue at higher speeds:
 - » Speed of light: $3 * 10^8$ m/s
 - » Speed of car: 10^5 m/h = 27.8 m/s
 - » Shift at 2.4 GHz is 222 Hz – increases with frequency
 - » Impact is that signal “spreads” in frequency domain

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18

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
 - » Interference from various RF transmitters
 - » Should be dealt with at protocol level

Fairly Predictable
➤ Can be planned for or avoided

↓
Noise Floor

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19

Outline

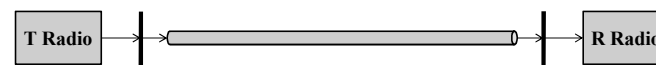
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20

Power Budget



$$R_{\text{power}} (\text{dBm}) = T_{\text{power}} (\text{dBm}) + \text{Gains} (\text{dB}) - \text{Losses} (\text{dB})$$

- Receiver needs a certain SINR to be able to decode the signal
 - » Required SINR depends on coding and modulation schemes, i.e. the transmit rate
- Factors reducing power budget:
 - » Noise, attenuation (multiple sources), fading, ..
- Factors improving power budget:
 - » Antenna gains, transmit power

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21

Channel Reciprocity Theorem

- If the role of the transmitter and the receiver are interchanged, the instantaneous signal transfer function between the two remains unchanged
- Informally, the properties of the channel between two antennas is in the same in both directions, i.e. the channel is symmetric
- Channel in this case includes all the signal propagation effects and the antennas

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22

Reciprocity Does not Apply to Wireless "Links"

- "Link" corresponds to the packet level connection between the devices
 - » In other words, the throughput you get in the two directions can be different.
- The reason is that many factors that affect throughput may be different on the two devices:
 - » Transmit power and receiver threshold
 - » Quality of the transmitter and receiver (radio)
 - » Observed noise
 - » Interference
 - » Different antennas may be used (spatial diversity - see later)

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23

Summary

- The wireless signal can be several degraded as it travels to the receiver:
- Attenuation increases with the distance to the receiver and as a result of obstacles
- Reflections create multi-path effects that cause distortion and inter-symbol interference
- Mobility causes slow and fast fading
 - » Fast fading is often frequency selective
- For higher speeds the Doppler effect can be a concern

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24