This lecture is being recorded

18-452/18-750
Wireless Networks and Applications
Lecture 4: Physical Layer - Signal Propagation

Peter Steenkiste

Carnegie Mellon University

Spring Semester 2022

http://www.cs.cmu.edu/~prs/wirelessS22/

Announcements

- **Waiting list as of noon today**
  - » **8 people on the waiting list**
  - » **5 have pending reservations**
- **Handout to check on Wireshark compatibility of your laptop**
  - » **On course website: handouts/Wireshark-check-S22.pdf**
  - » **Short poll on gradescope**
  - » **Please fill in, even if you are waitlisted**

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

Bad News
Good News
Story

From Last Lecture: 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 ½ wavelength -> big change in signal strength

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 also depends on frequency: higher loss with higher frequency
  - » Impacts transmission range in different spectrum bands
    - – Lower frequencies (100s of MHz) have better range and are more attractive
    - – Higher frequencies have much shorter range
  - » Can cause distortion of signal for wide-band signals

Log Distance Path Loss Model

- Log-distance path loss model captures space attenuation relative to a reference distance
  - » Easier to measure!
- Can also include additional absorption by of energy by obstacles using path loss exponent n

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

Loss at distance d

Loss at distance d_0

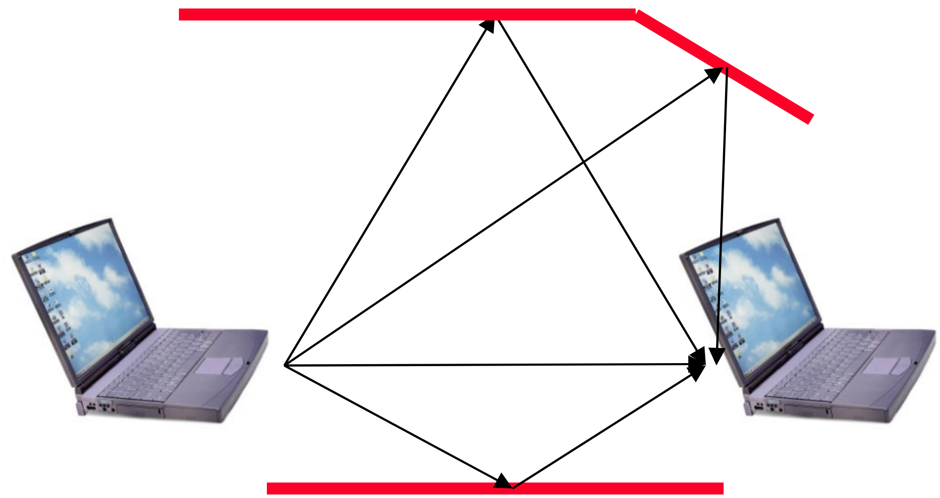
- Value of n depends on the environment:
  - » 2 is free space model (exponent 2 in previous slide)
  - » 2.2 office with soft partitions
  - » 3 office with hard partitions
  - » Higher if more and thicker obstacles

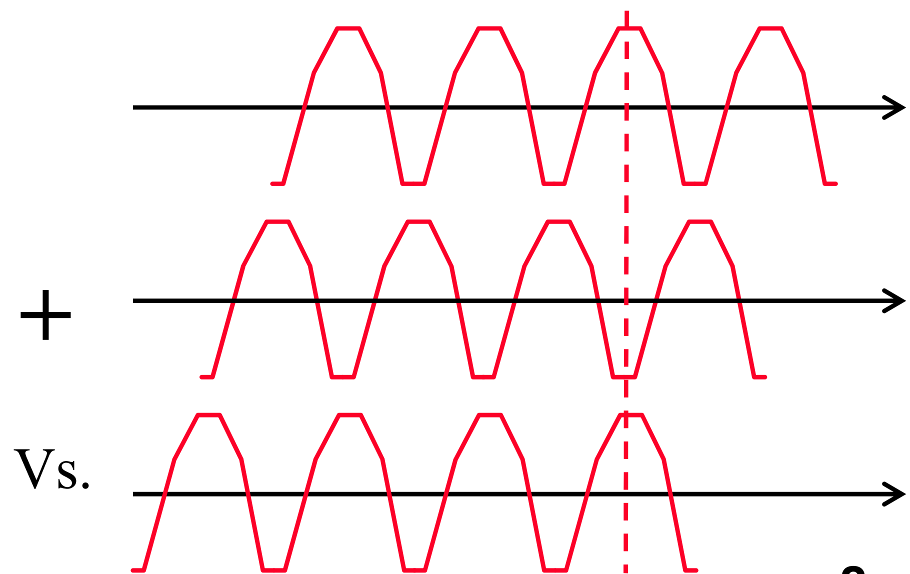
Obstacles and Atmosphere

- 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 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

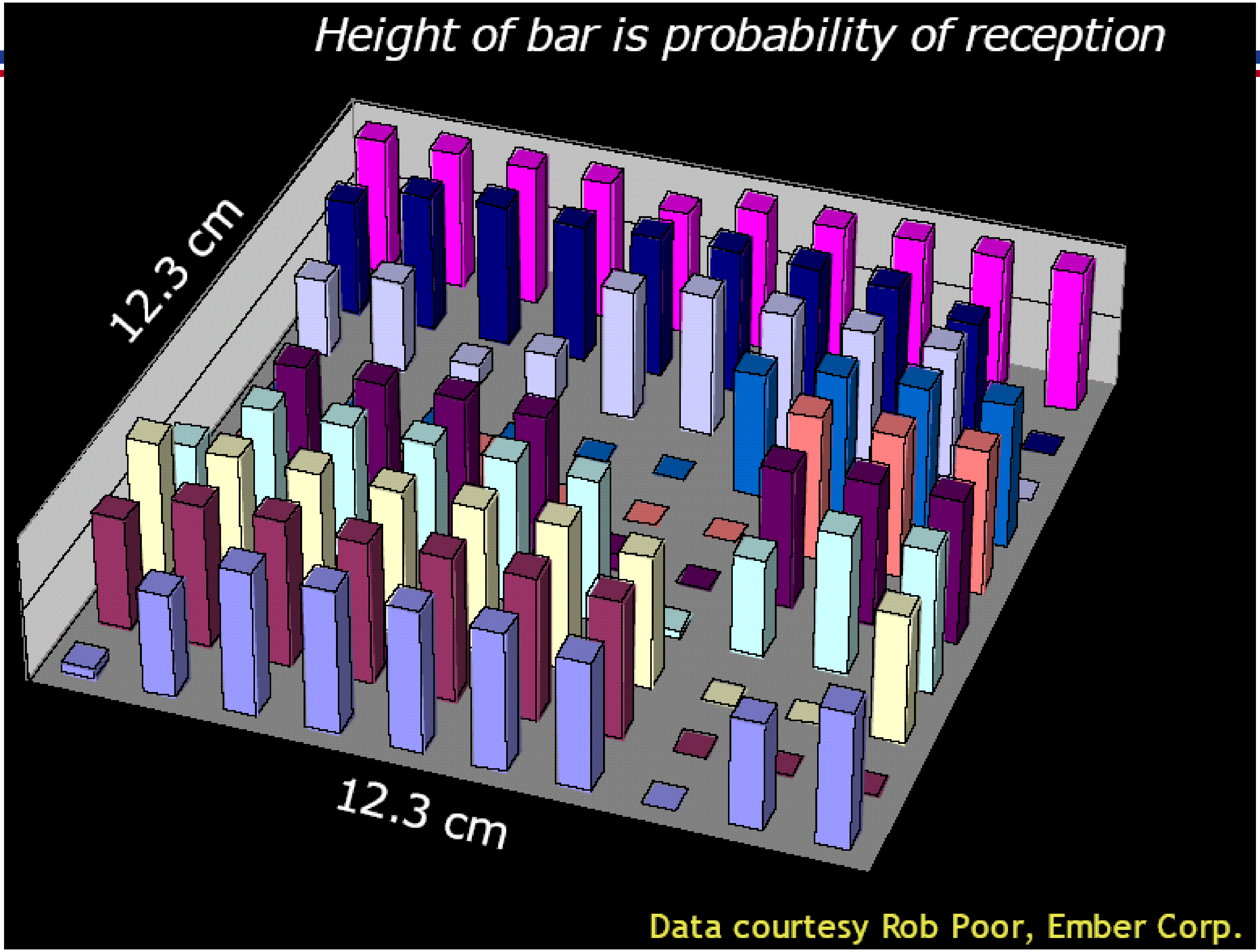
Multipath Effect

- **Receiver receives multiple copies of the signal, each following a different path**
- **Copies can either weaken or strengthen or each other**
  - » **In-phase versus out of phase**
- **Changes of half a wavelength affect the outcome**
  - » **E.g. 2.4 Ghz → 12 cm, 60 GHz → ~5 mm**



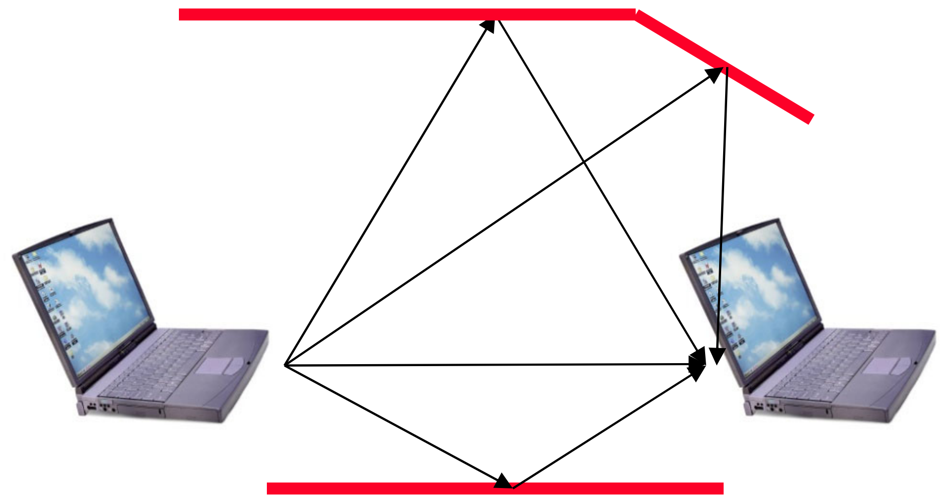


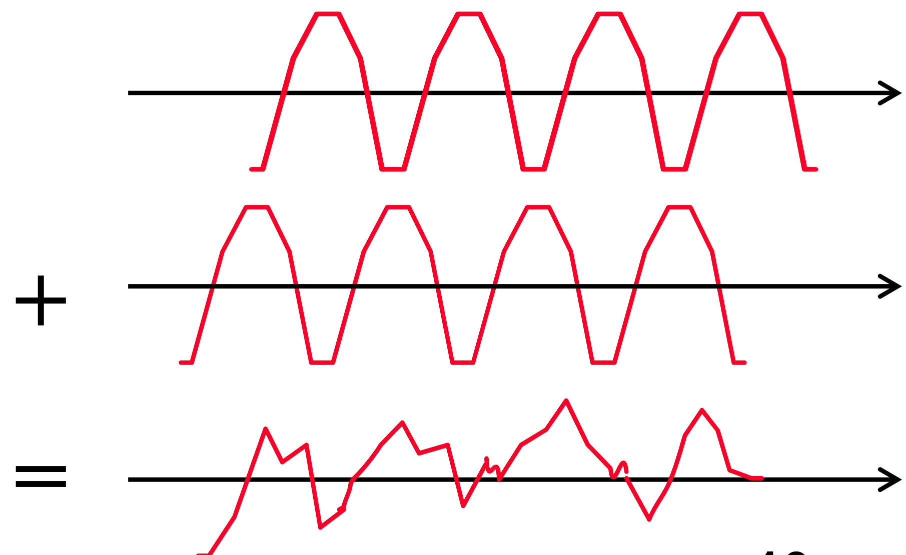
Example: 900 MHz



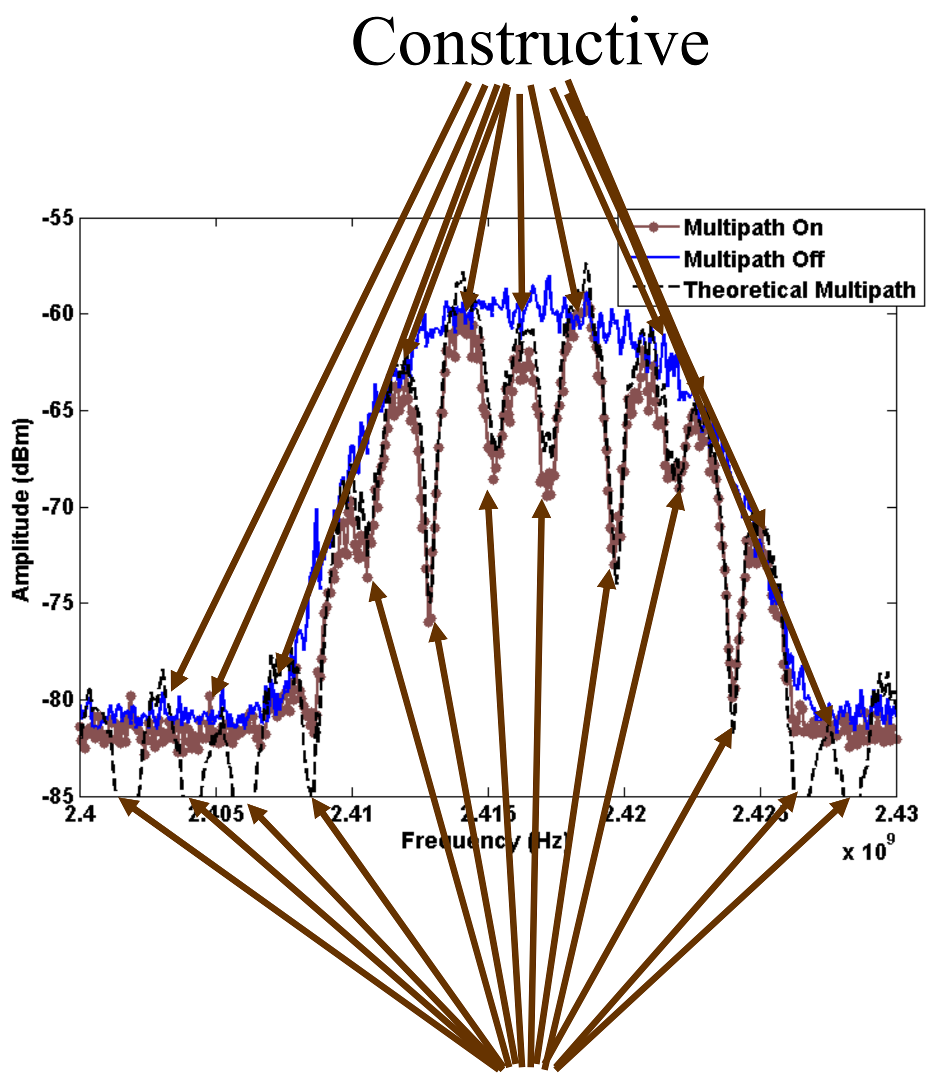
Multipath Effect for Wideband Signals

- The path lengths are measured in meters, but
- Impact of multi-path depends on path length difference in number of wavelengths
- Signals at different frequencies may be impacted differently
  - » # wavelengths = d x f / c
- Impact may be the same, the opposite, or in between
  - » E.g., both destructive … or one destructive and the other constructive interference
- Distortion for wideband signals!



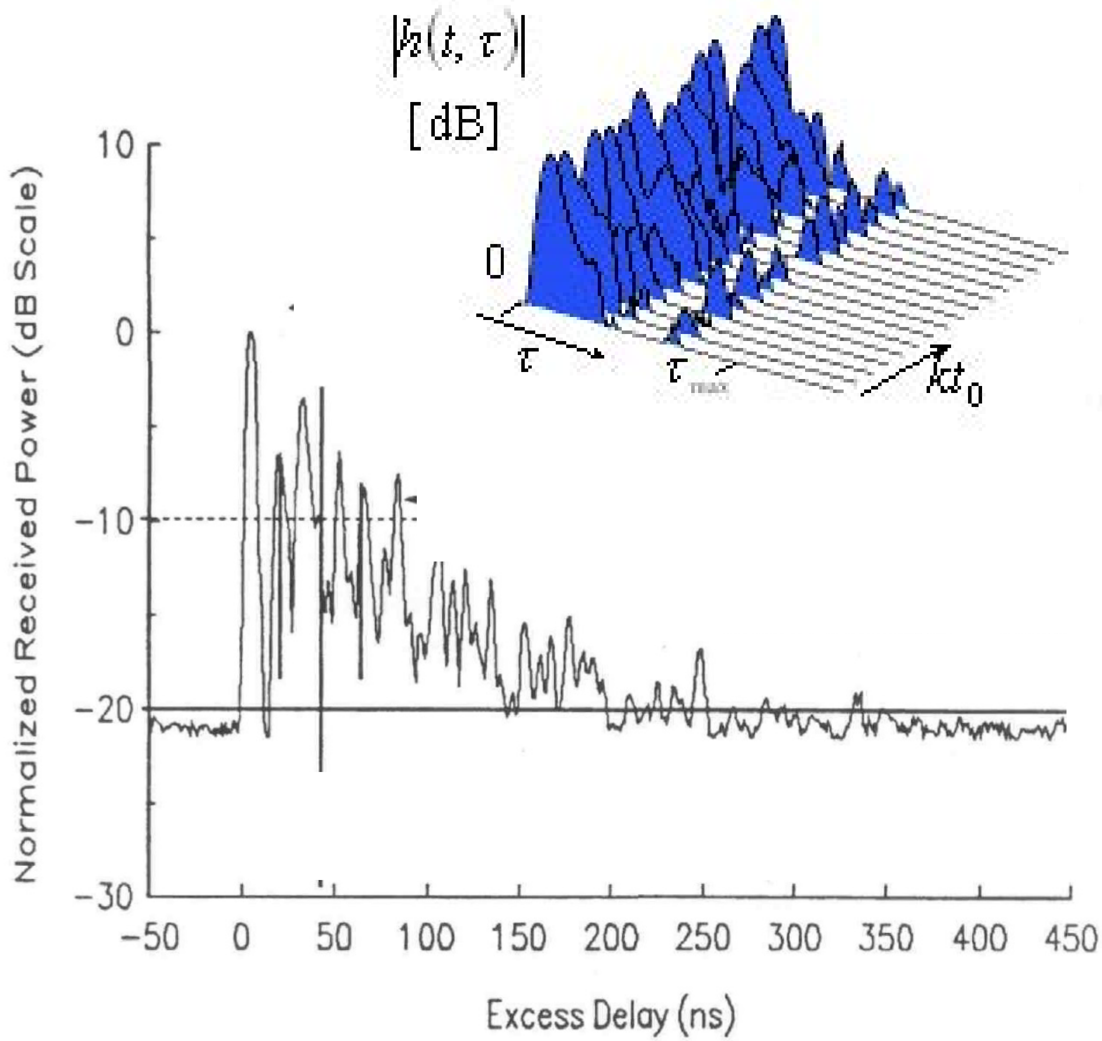


Distortion of Wideband Signal



Channel Sounding

- **Measures response of channel to an impulse**
  - » **Signals from multiple paths arrive spread out in time**
- **Typically interested in response across frequency range**
  - » **Delay spread, delay spread and impact on phase**

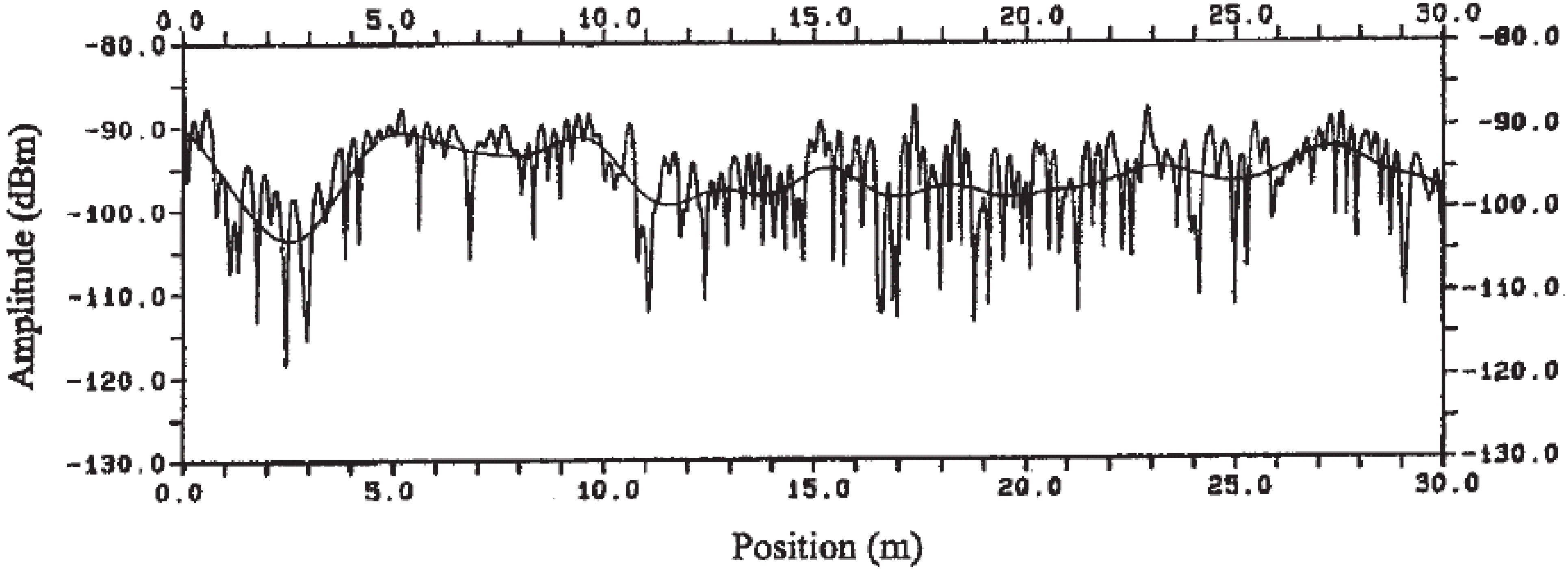


Based on www.cs.bilkent.edu.tr/~korpe/courses/cs515-fall2002/slides6.ppt
SAAB MEDAV Technology - http://www.channelsounder.de/csprinciple_site4.html

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 in the paths traversed by 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 (of the carrier!) – results in big fluctuations in the instantaneous power

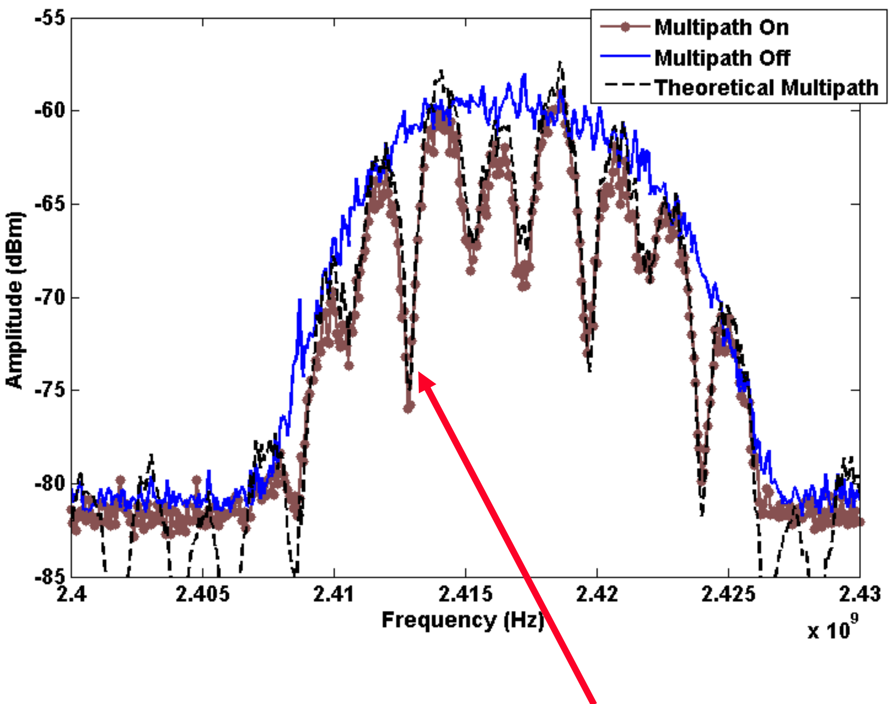
Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

Frequency Selective versus Non-selective Fading

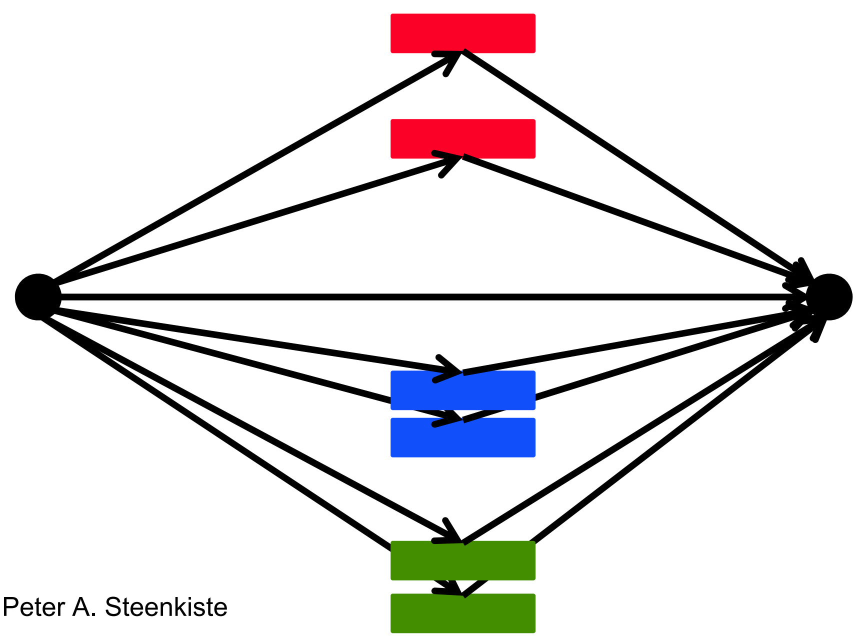
- **Non-selective (flat) fading: fading affects all frequency components in the signal equally**
  - » **There is a single path, or a strongly dominating path, e.g., LOS**
- **Selective fading: frequency components experience different degrees of fading**
  - » **Multiple paths with path lengths that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

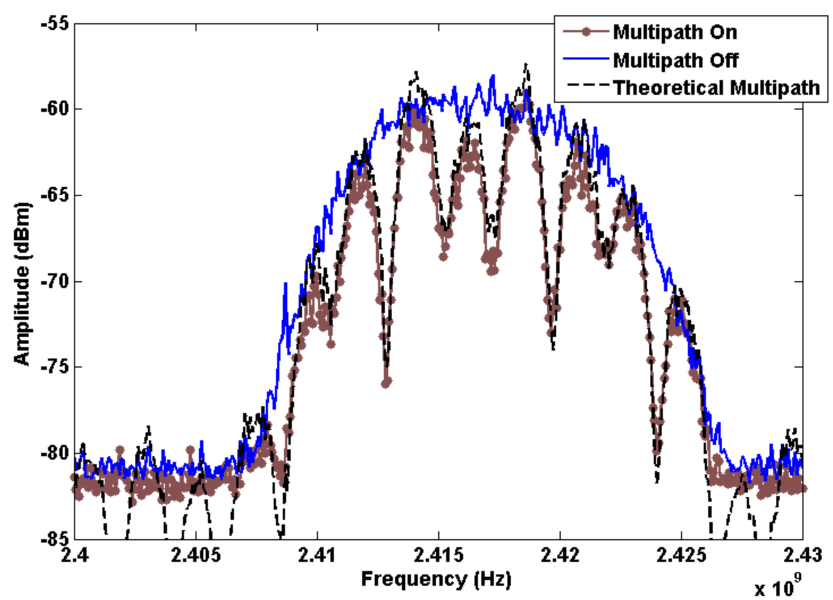


Over time, Peaks and Valleys change and shift in frequency

Some Intuition for Selective Fading

- Assume three paths between a transmitter and receiver
  - » Will have a difference in path length (e.g., 12.3 cm)
- The outcome is determined by in path length differences in terms of wavelengths → outcome depends on frequency
- As transmitter, receivers or obstacles move, the path length differences change, i.e., there is fading
  - » In versus out of phase depends on wavelength/frequency
  - » Significant concern for wide-band channels



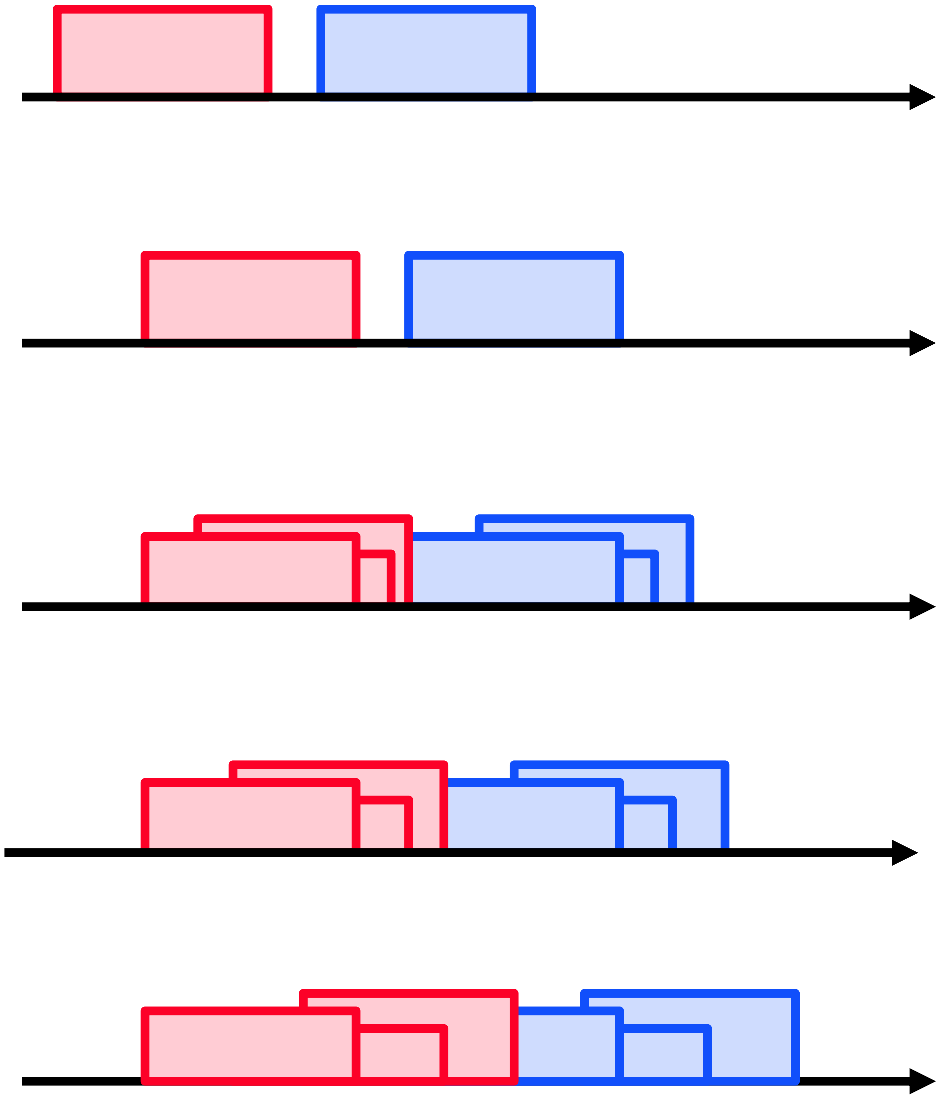


Example Fading Channel Models

- 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 result in paths with Raleigh fading, but with different path lengths
- Many others!

Inter-Symbol Interference

- Larger difference in path length can cause inter-symbol interference (ISI)
  - » This is for the bit stream (not the carrier wavelength!)
- 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)



How Bad is the Problem?

- ISI depends on the symbol time
  - » Time to send a single-bit or multi-bit symbol
  - » I.e., property of the baseband signal

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

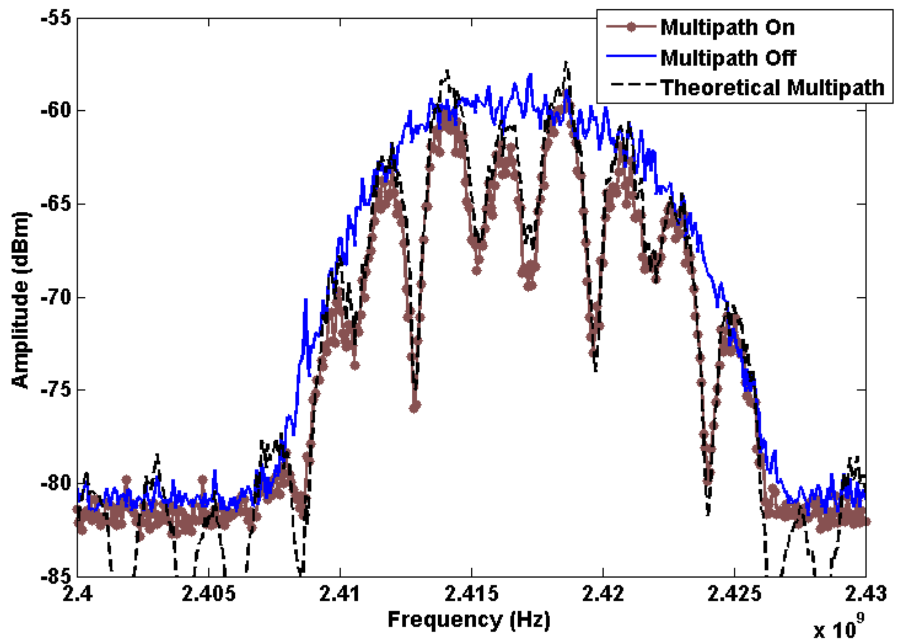
- Fast fading depends on wavelength of carrier wave
  - » Relevant differences in distance are orders of magnitude shorter!

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

Summary Path Loss and Fading for Wideband Signals

- **Environments without mobility:**
  - » **No multipath: received signal is a weaker copy of the transmitted signal**
  - » **Multipath: received signal is weaker and distorted due to frequency selective path loss**

- **Environments with mobility:**
  - » **No multipath: strength of received signal change; no distortion**
  - » **Multipath: both shape and strength of received signal changes**



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

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

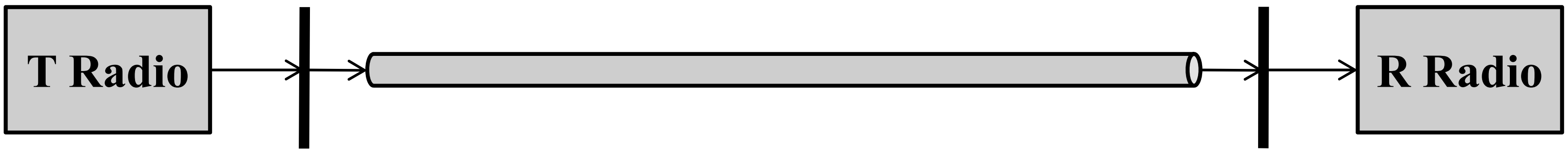
Noise Floor

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

Typical Bad News Good News Story

Power Budget



Rpower (dBm) = Tpower (dBm) + Gains (dB) – Losses (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**

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 wireless channel between the sender and the receiver is the same in both directions, i.e. the channel is symmetric**
- **Channel in this case includes all the signal propagation effects and the antennas**

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)

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 speed mobility, the Doppler effect can be a concern