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

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http://www.cs.cmu.edu/~prs/wirelessS24/





## 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 and MIMO

## 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 ($d^2$)
  - Remember why?
- Need to consider the gain of the antennas at transmitter and receiver.
- Loss also depends on frequency: higher loss with higher frequency
- This impacts the transmission range across spectrum bands
  - Lower frequencies (100s of MHz) have much longer range
  - This is a big deal: 900 MHz versus 60 GHz

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## Log Distance Path Loss Model

- The log-distance path loss model captures the space attenuation relative to a reference distance

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

Loss at distance d — Loss at distance $d_0$

- The path loss exponent n captures the energy loss by absorption by obstacles
- The value of n depends on the environment:
  - 2 - free space model (exponent 2 in previous slide)
  - 2.2 and 3 - office with soft and hard partitions
  - Higher if more and thicker obstacles
- Simplifies measuring free space path loss
  - Given $L_0$, you can calculate $L_x$, at any distance x

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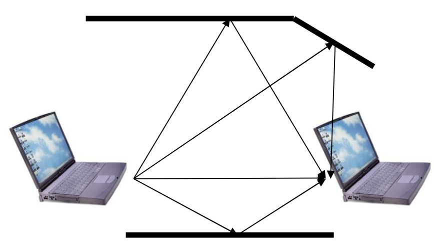
# Obstacles and Atmosphere

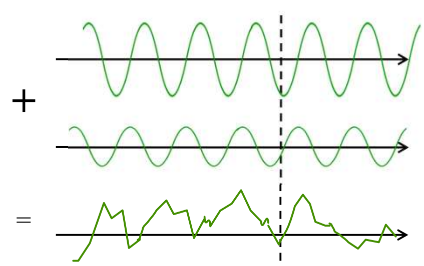
- Objects absorb energy as the signal passes through them
  - » Degree of absorption depends strongly the material
  - » Paper versus brick versus metal
- Absorption of energy in the atmosphere.
  - » Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)
- Refraction in 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

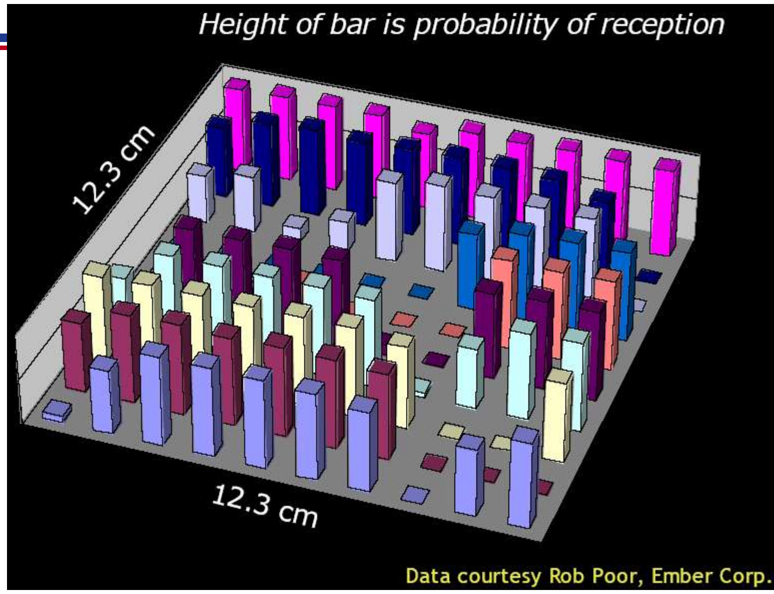
- Receiver receives multiple copies of the signal, each following a different path
- Copies can either weaken or strengthen or each other
  - » In-phase versus out of phase
- Changes of half a wavelength affect the outcome
  - » E.g. 2.4 Ghz → 12 cm, 60 GHz → ~5 mm






Cartoon!

# Example: 900 MHz

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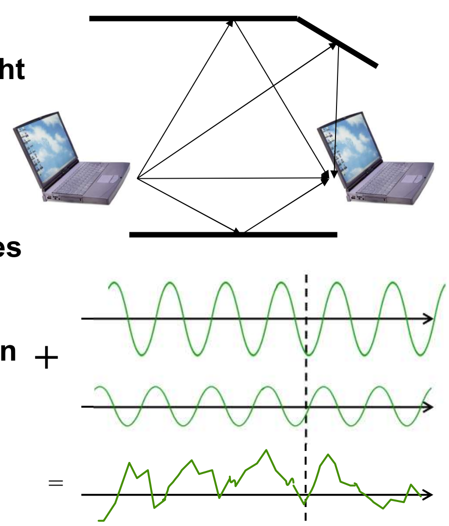
# Multipath Effect for Wideband Signals

- We measure path lengths in meters, but for signals the right metric is wavelengths
- 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
- Constructive, destructive, or in between, depending on the wavelength
- Can result in distortion for wideband signals!

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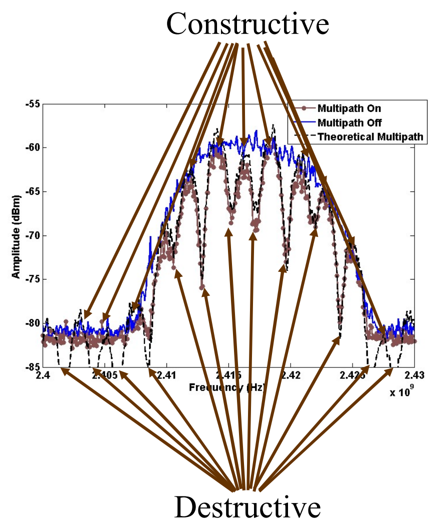
# Distortion of Wideband Signal

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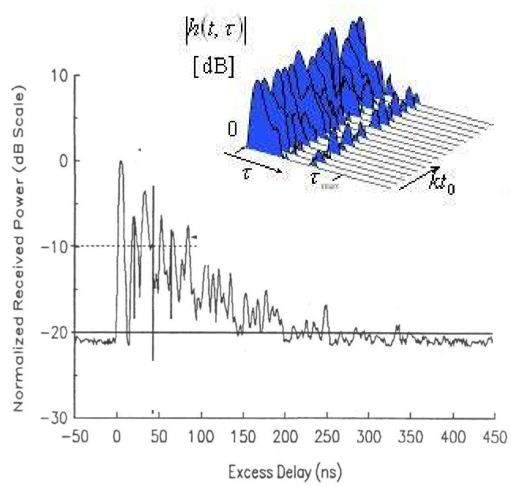
# Channel Sounding

- **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**

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

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# 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

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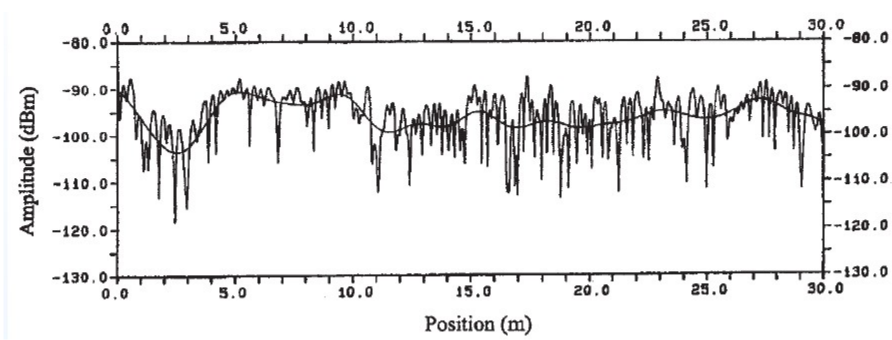
# Fading - Example




- Frequency of 910 MHz or wavelength of about 33 cm

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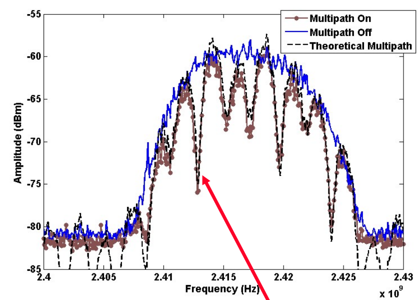
# Frequency Selective versus Non-selective Fading

- 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

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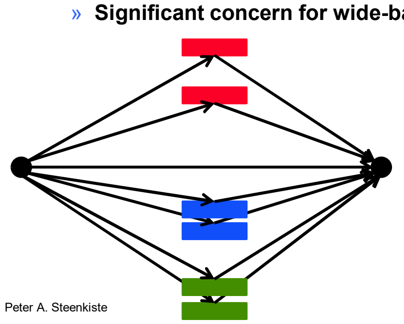
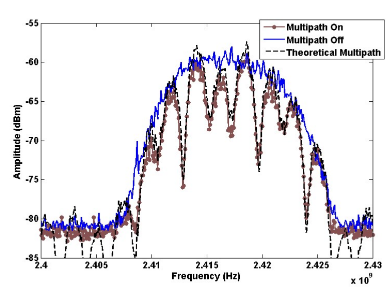
# Some Intuition for Selective Fading

- 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 $\rightarrow$ 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



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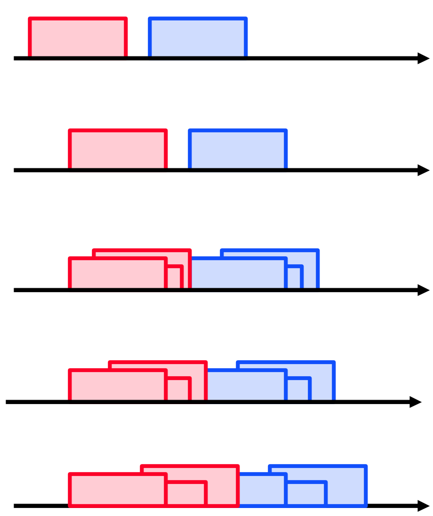
# Example Fading Channel Models

- 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)



# ISI versus Fast Fading
# How Bad is the Problem?

- **ISI depends on the symbol length of baseband signal**
  - » Time to send a single-bit or multi-bit symbol
  - » I.e., property of the <u>baseband</u> signal
  - » Example: 802.11ac has a symbol time of 3.2 microsec
- **Fast fading depends on wavelength of <u>carrier</u> wave**
  - » Relevant differences in distance are orders of magnitude shorter!
  - » Example: 802.11ac uses 2.4 and 5 GHz bands

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

| Rate GHz | Time 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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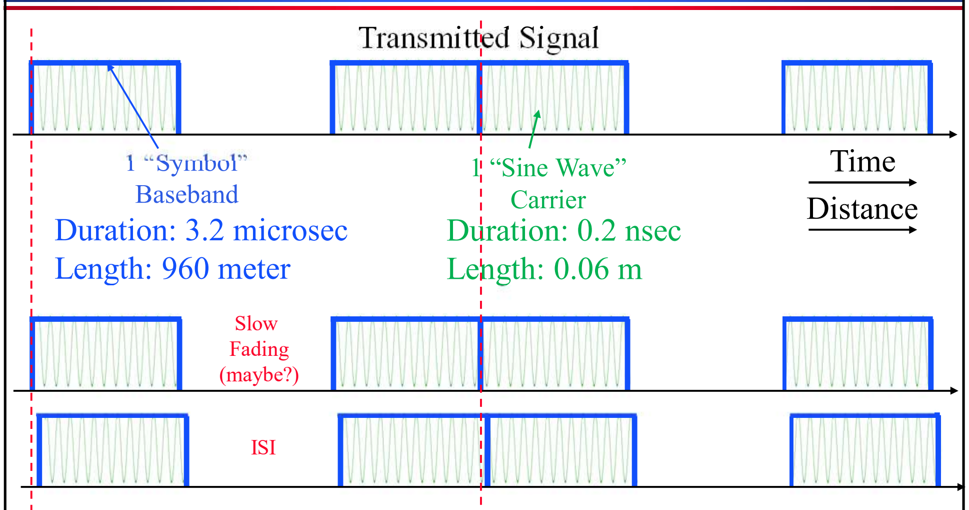
# Inter-Symbol Interference versus Slow Fading




Example: 802.11ac, 5GHz, Symbol time = 3.2 microsec

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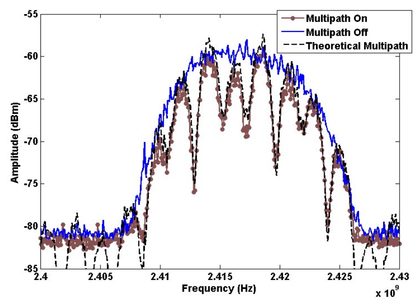
# Summary Path Loss and Fading for Wideband Signals

- 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

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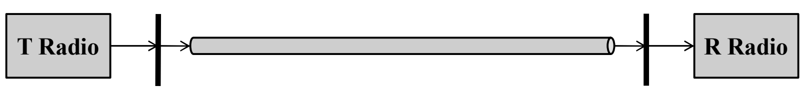
## Power Budget




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

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## 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

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## 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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# 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