18-452/18-750
Wireless Networks and Applications
Lecture 4: Physical Layer - Channel Capacity and Antennas

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http://www.cs.cmu.edu/~prs/wirelessS17/

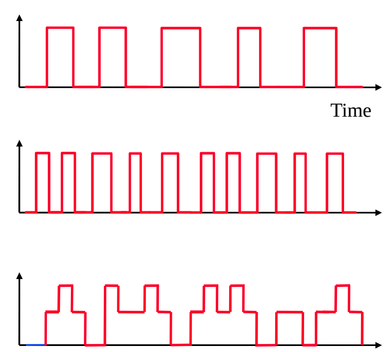
Outline

- RF introduction
- Modulation and multiplexing - review
- Channel capacity
- Antennas and signal propagation
- Modulation
- Diversity and coding
- OFDM

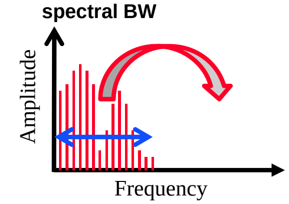
Relationship between Data Rate and Bandwidth

- The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal
- Intuition: if a signal can change faster, it can be modulated in a more detailed way and can carry more data
  - » E.g. more bits or higher fidelity music
- Extreme example: a signal that only changes once a second will not be able to carry a lot of bits or convey a very interesting TV channel
- Can we make this more precise?

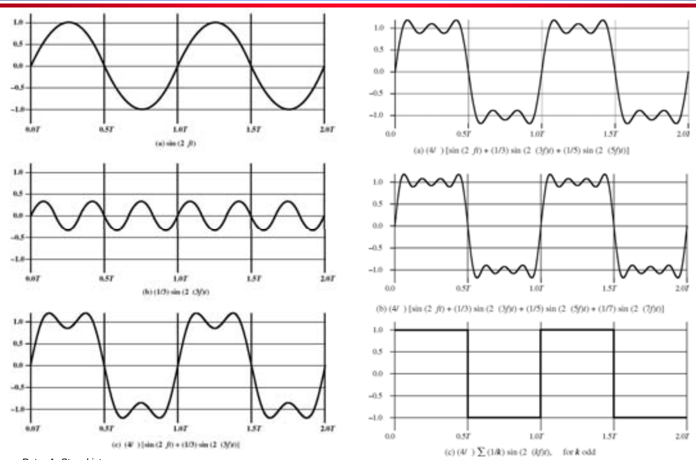
Increasing the Bit Rate



- Increases the rate at which the signal changes.
  - » Proportionally increases all signals present, and thus the spectral bandwidth
- Increase the number of bits per change in the signal
  - » Adds detail to the signal, which also increases the spectral BW

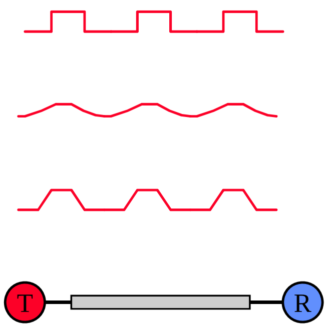


Adding Detail to the Signal



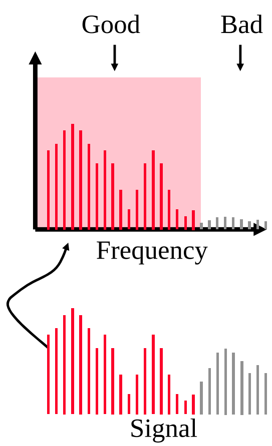
So Why Don't we Always Send a Very High Bandwidth Signal?

- Channels have a limit on the type of signals they can carry
- Wires only transmit signals in certain frequency ranges
  - Stronger attenuation and distortion outside of range
  - Distortion makes it hard for receiver to extract the information
- Wireless radios are only allowed to use certain parts of the spectrum
  - The radios are optimized for that frequency band



Transmission Channel Considerations

- Example: grey frequencies get attenuated significantly
- For wired networks, channel limits are an inherent property of the wires
  - » Different types of fiber and copper have different properties
  - » Capacity also depends on the radio and modulation used
  - » Improves over time, even for same wire
- For wireless networks, limits are often imposed by policy
  - » Can only use certain part of the spectrum
  - » Radio uses filters to comply



Channel Capacity

- Data rate - rate at which data can be communicated (bps)
  - » Channel Capacity – the maximum rate at which data can be transmitted over a given channel, under given conditions
- Bandwidth - the bandwidth of the transmitted signal as constrained by the transmitter and the nature of the transmission medium (Hertz)
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - » Error = transmit 1 and receive 0; transmit 0 and receive 1

The Nyquist Limit

- A noiseless channel of bandwidth B can at most transmit a binary signal at a capacity 2B
  - » E.g. a 3000 Hz channel can transmit data at a rate of at most 6000 bits/second
  - » Assumes binary amplitude encoding
- *For M levels:* $C = 2B \log_2 M$
  - » M discrete signal levels
- More aggressive encoding can increase the actual channel bandwidth
  - » Example: modems
- Factors such as noise can reduce the capacity

Decibels

- A ratio between signal powers is expressed in decibels

$$\text{decibels (db)} = 10\log_{10}(P_1 / P_2)$$

- Is used in many contexts:
  - » The loss of a wireless channel
  - » The gain of an amplifier
- Note that dB is a relative value.
- Can be made absolute by picking a reference point.
  - » Decibel-Watt – power relative to 1W
  - » Decibel-milliwatt – power relative to 1 milliwatt

Signal-to-Noise Ratio

- Ratio of the power in a signal to the power contained in the noise that is present at a particular point in the transmission
  - » Typically measured at a receiver
- Signal-to-noise ratio (SNR, or S/N)

$$(SNR)_{\text{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- A high SNR means a high-quality signal
- Low SNR means that it may be hard to “extract” the signal from the noise
- SNR sets upper bound on achievable data rate

Shannon Capacity Formula

- Equation: $C = B\log_2(1+\text{SNR})$
- Represents error free capacity
  - » It is possible to design a suitable signal code that will achieve error free transmission (you design the code)
- Result is based on many assumptions
  - » Formula assumes white noise (thermal noise)
  - » Impulse noise is not accounted for
  - » Various types of distortion are also not accounted for
- We can also use Shannon’s theorem to calculate the noise that can be tolerated to achieve a certain rate through a channel

Shannon Discussion

- **Bandwidth B and noise N are not independent**
  - » N is the noise in the signal band, so it increases with the bandwidth
- **Shannon does not provide the coding that will meet the limit, but the formula is still useful**
- **The performance gap between Shannon and a practical system can be roughly accounted for by a gap parameter**
  - » Still subject to same assumptions
  - » Gap depends on error rate, coding, modulation, etc.

$$C = B\log_2(1+\mathrm{SNR}/\Gamma)$$

Example of Nyquist and Shannon Formulations

- **Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 dB**

$$B = 4\,\mathrm{MHz} - 3\,\mathrm{MHz} = 1\,\mathrm{MHz}$$
$$\mathrm{SNR}_{\mathrm{dB}} = 24\,\mathrm{dB} = 10\log_{10}(\mathrm{SNR})$$
$$\mathrm{SNR} = 251$$

- **Using Shannon's formula**

$$C = 10^6 \times \log_2(1+251) \approx 10^6 \times 8 = 8\mathrm{Mbps}$$

Example of Nyquist and Shannon Formulations

- **How many signaling levels are required?**

$$C = 2B\log_2 M$$
$$8\times10^6 = 2\times(10^6)\times\log_2 M$$
$$4 = \log_2 M$$
$$M = 16$$

- **Look out for: dB versus linear values, $\log_2$ versus $\log_{10}$**

Outline

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

What is an Antenna?

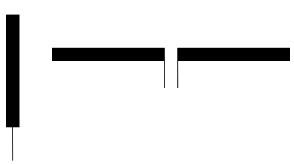
- Conductor that carries an electrical signal and radiates an RF signal.
  - » The RF signal “is a copy of” the electrical signal in the conductor
- Also the inverse process: RF signals are “captured” by the antenna and create an electrical signal in the conductor.
  - » This signal can be interpreted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

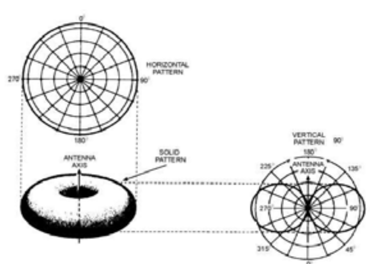
Types of Antennas

- 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, e.g. dipole
- Shaped antennas can be used to direct the energy in a certain direction.
  - » Well-known case: a parabolic antenna
  - » Pringles boxes are cheaper

Antenna Types: Dipoles

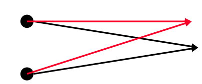
- Simplest: half-wave dipole and quarter wave vertical antennas
  - » Very simple and very common
  - » Elements are quarter wavelength of frequency that is transmitted most efficiently
  - » Donut shape
- May other designs

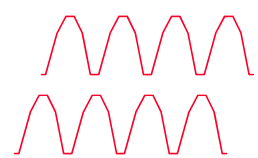




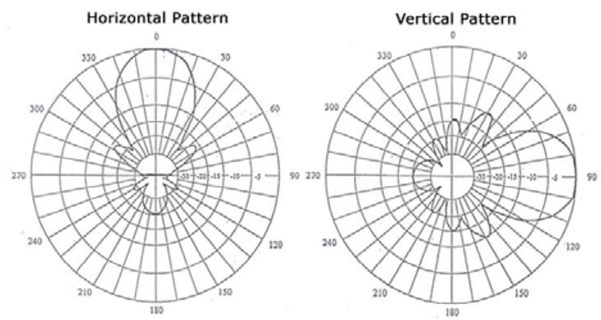
Multi-element Antennas

- 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, …





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)

Examples 2.4 GHz




Summary

- The maximum capacity of a channel depends on the SINR
  - » How close you get to this maximum depends on the sophistication of the radios
  - » Distortion of the signal also plays a role – next lecture
- Antennas are responsible for transmitting and receiving the EM signals
  - » The “ideal” isotropic antenna is a point source that radiates energy in a sphere
  - » Practical antennas are directional in nature, as a result of the antenna shape or the use of multi-element antennas
  - » The antenna gain is expressed in dBi

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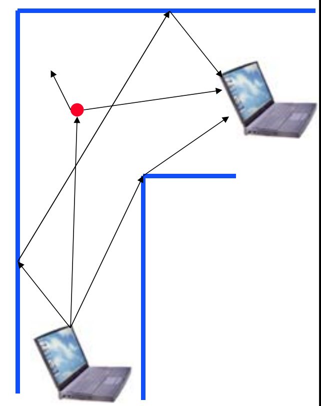
Typical Bad News Good News Story

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)
- Obstacles can redirect the signal and create multiple copies that all reach the receiver
  - » Creates multi-path effects
- Refraction changes direction of the signal due to changes in density
  - » If the change in density is gradual, the signal bends!

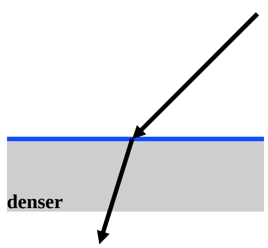
Impact of Obstacles

- Besides line of sight, signal can reach receiver in three “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.



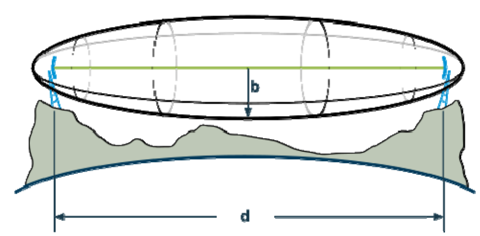
Refraction

- 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: Signal “bounces” off the ionosphere back to earth – can go very long distances
  - » But also local, small scale differences in the air density, temperature, etc.



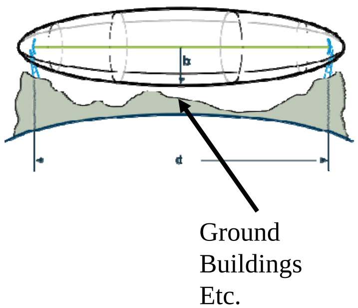
Fresnel Zones

- Sequence of ellipsoids centered around the LOS path between a transmitter and receiver
- The zones identify areas in which obstacles will have different impact on the signal propagation
  - » Capture the constructive and destructive interference due to multipath caused by obstacles

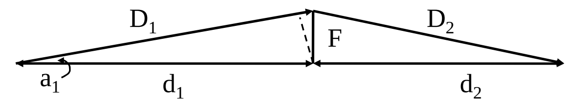


Fresnel Zones

- Zones create different phase differences between paths
  - » First zone: 0-90
  - » Second zone: 90-270
  - » Third zone: 270-450
  - » Etc.
- Odd zones create constructive interference, even zones destructive
- Also want clear path in most of the first Fresnel zone, e.g. 60%
- The radius F_n of the nth Fresnel zone depends on the distances d_1 and d_2 to the transmitter and receiver and the wavelength

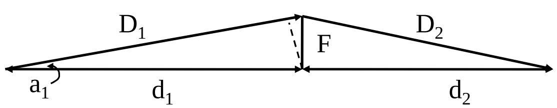


Sketch of Calculation: Difference in Path Length



- Difference in path length (a_1 is small)
  - » $D_1 - d_1 \approx F * \sin a_1$
- But for small a_1 we also have
  - » $\sin a_1 = \tan a_1 = F / d_1$
- So $D_1 - d_1 = F^2 / d_1$

Sketch of Calculation Fresnel Radios



- Given $D_1 - d_1 = F^2 / d_1$
- and $(D_1 + D_2) - (d_1 + d_1) = \lambda * n$
- $(D_1 - d_1) + (D_2 - d_2) = F^2 / d_1 + F^2 / d_2$
- or

$$F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1 + d_2}}$$

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  - » Propagation properties of RF signals (the really sad part)
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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

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

- 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

Log Distance Path Loss Model

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

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

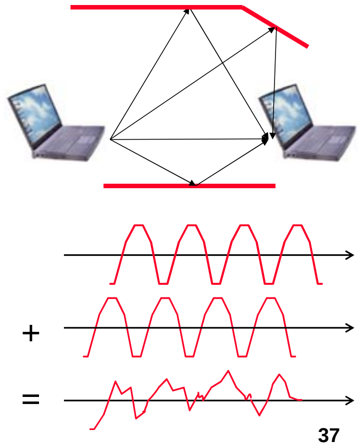
- Where L_0 is the loss at distance d_0 and n is the path loss distance component
- Value of n depends on the environment:
  - » 2 is free space model
  - » 2.2 office with soft partitions
  - » 3 office with hard partitions
  - » Higher if more and thicker obstacles

Obstacles and Atmosphere

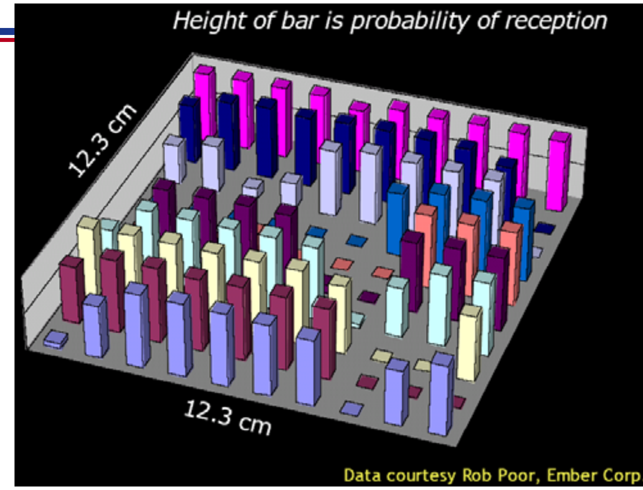
- Objects absorb energy as the signal passes through them
  - » Degree of absorption depends strongly the material
  - » Paper versus brick versus metal
- Absorption of energy in the atmosphere.
  - » Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)
- Refraction refraction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

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



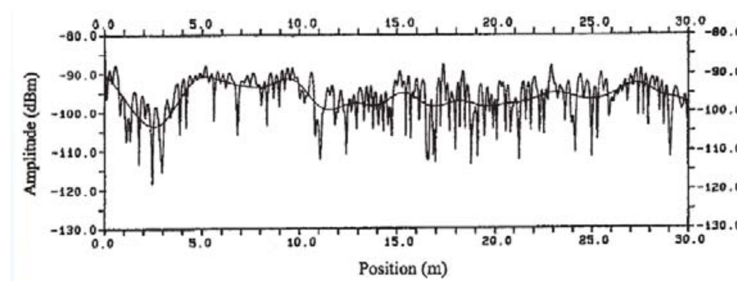
Example: 900 MHz



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

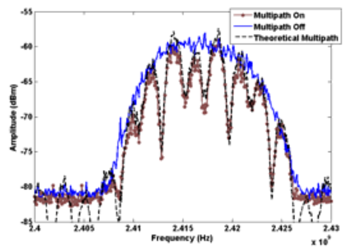
Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

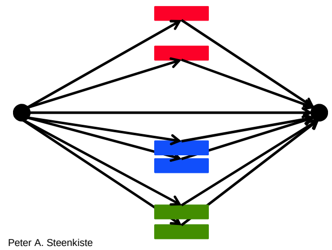
Frequency Selective versus Non-selective Fading

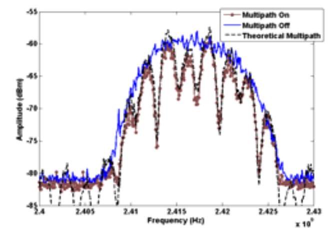
- Non-selective (flat) fading: fading affects all frequency components in the signal equally
  - » There is only a single path, or a strongly dominating path, e.g., LOS
- Selective fading: frequency components experience different degrees of fading
  - » Multiple paths with path lengths that change independently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



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



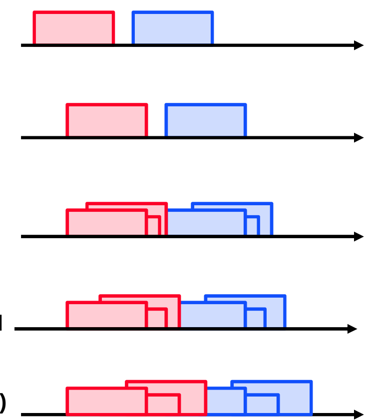


Example Fading Channel Models

- 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!

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)



How Bad is the Problem?

- Assume binary encoding
  - » Times will increase with more complex symbol
  - » More complex encoding also requires higher SINR
- Some bit times and distances:

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

- Distances are much longer than for fast fading!
  - » Wavelength at 2.4 GHz: 14 cm

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

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