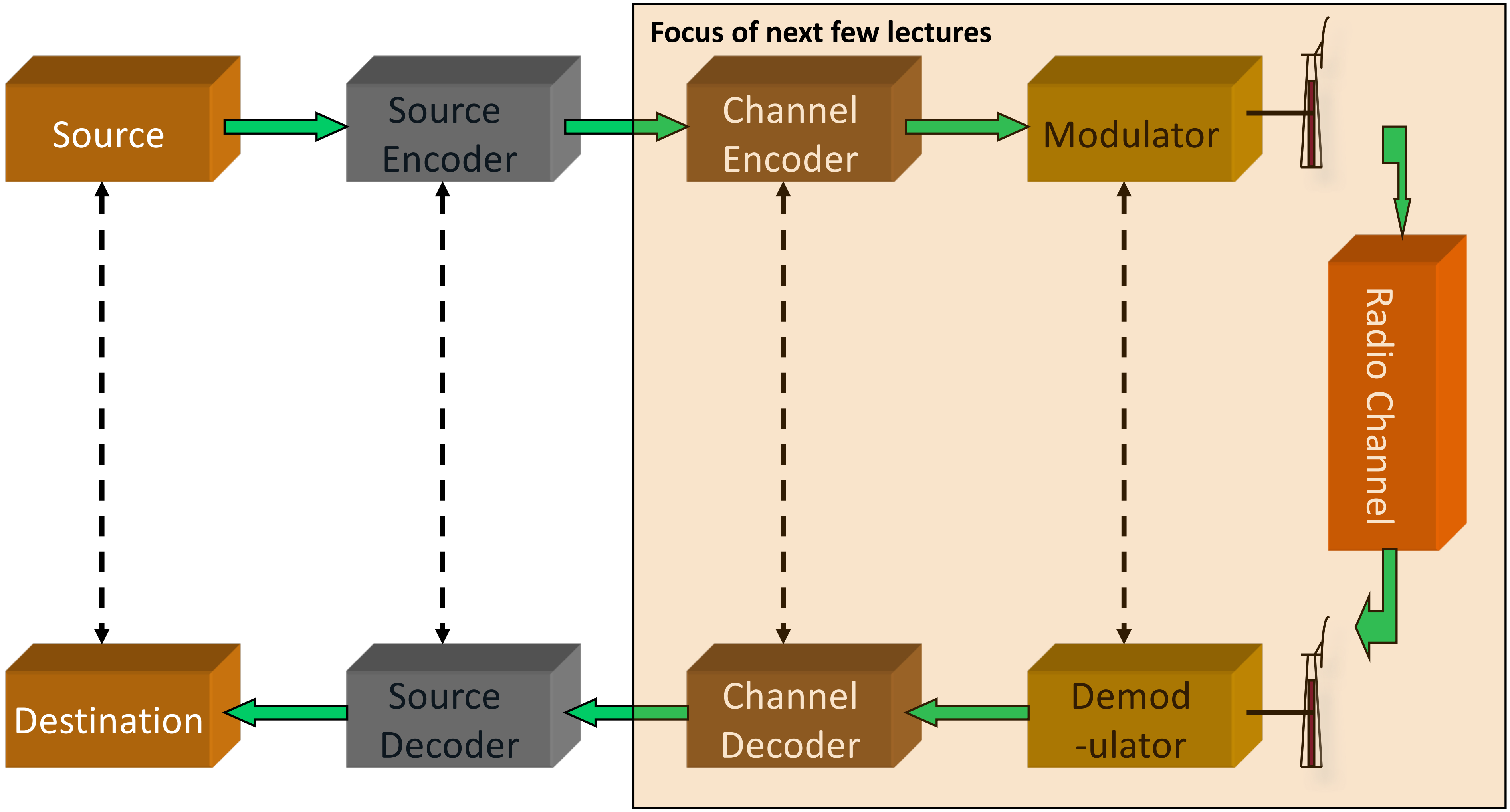
Lecture 4

Antennas, dB, and Introduction to Radio Propagation

+ Overview

- Quickly review some concepts that we make use of repeatedly in this class
  - You may have seen these things in other classes
- Primarily a refresher
  - Not intended to be exhaustive or complete
  - Some concepts are simplified to just meet the needs of this class
- Generation, transmission and reception of signals
  - Modeled as a linear time invariant system with signals as inputs and outputs
  - Wireless systems and the “radio channel” are also often modeled as LTI systems

Simplified model of a digital communication system

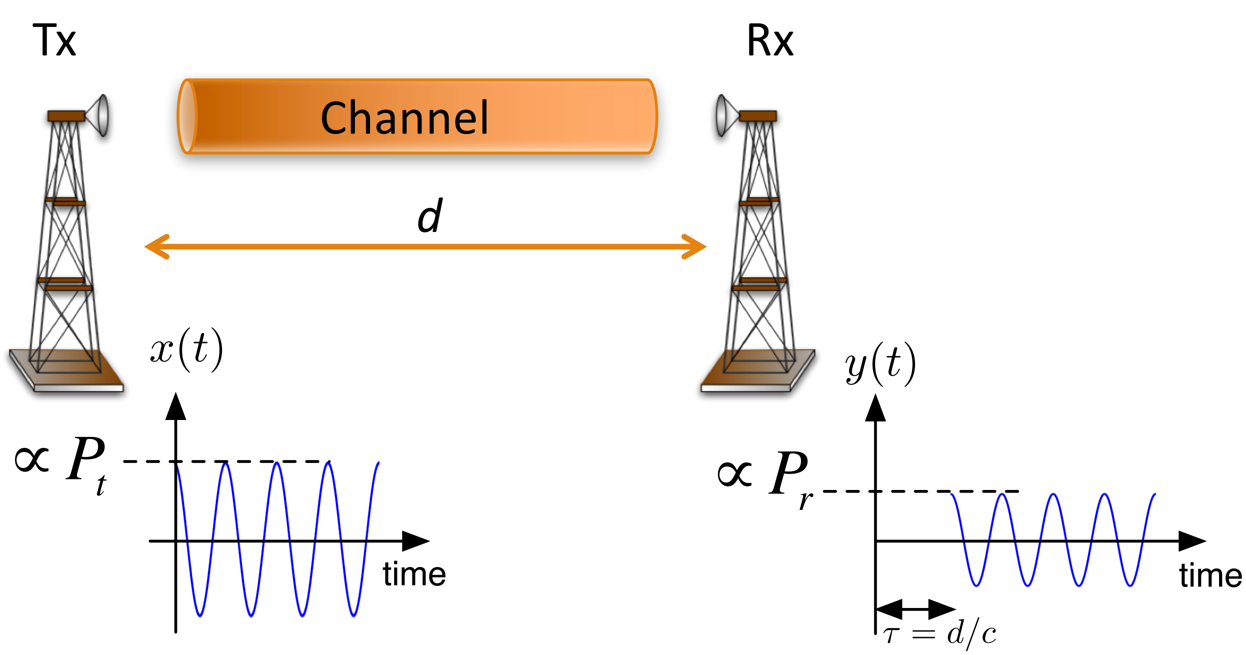


Components of the digital communication system

- Source
  - Produces a finite alphabet for transmission
  - Examples: Quantized voice samples, ASCII alphabets
- Source coder
  - Removes the redundancies and efficiently encodes the alphabet
  - Example: In English, you may encode the alphabet "e" with fewer bits than you would "q"
- Channel encoder
  - Adds redundant bits to the source bits to recover from any error that the channel may introduce
- Modulator
  - Converts the encoded bits into a signal suitable for transmission over the channel
- Channel
  - Carries the signal, but will usually distort it

Communication Link

- Transmitter (Tx)
  - Signal is transmitted at power P_t
- Receiver (Rx)
  - Signal is received at power P_r
- Transmission medium or channel



Classifications of Transmission Media (the channel)

- Transmission Medium
  - Physical path between transmitter and receiver
- Guided Media
  - Waves are guided along a solid medium
  - Example:
    - Copper twisted pair, copper coaxial cable, optical fiber
- Unguided Media
  - Provides means of transmission but does not guide electromagnetic signals
  - Usually referred to as wireless transmission
  - Example: Atmosphere, outer space (free space)

Unguided Media

- Transmission and reception are achieved usually by means of an antenna
- Antennas
  - *Transducers* that allow voltage and current waveforms flowing on a wire to be converted into electromagnetic waves that propagate in free space
  - Capture electromagnetic waves propagating in air and convert them into voltage or current waveforms in a wire
- Configurations for wireless transmission
  - Directional
  - Omnidirectional

dB vs absolute power

- Power (signal strength) is expressed in dB for ease of calculation (all relative quantities)
- dBm: reference to 1 mW
- dBW: reference to 1 W
- Example: 100 mW = 20 dBm = -10 dBW
  - $10 \log_{10} (100 \text{ mW} / 1 \text{ mW}) = 20$ dBm
  - $10 \log_{10} (100 \text{ mW} / 1 \text{ W}) = -10$ dBW
- In general dBm value = 30 + dBW value
- Other relative values are simply expressed in dB

Show in R and Matlab

Examples of using Decibels

- Example 1: Express 2 W in dBm and dBW
  - dBm: $10 \log_{10}$ (2 W / 1 mW) = $10 \log_{10}(2000)$ = 33 dBm
  - dBW: $10 \log_{10}$ (2 W / 1 W) = $10 \log_{10}(2)$ = 3 dBW
- Example 2: The transmit power is 2 W, the RSS is 0.12 W. What is the loss in dB?
  - Loss = Transmit power – RSS = 33 dBm – 20.8 dBm = 12.2 dB
  - Or Loss = 3 dBW – (–9.2 dBW) = 12.2 dB
- The loss in Example 2 is usually called the “path loss”

RSS = Received Signal Strength

Some notes

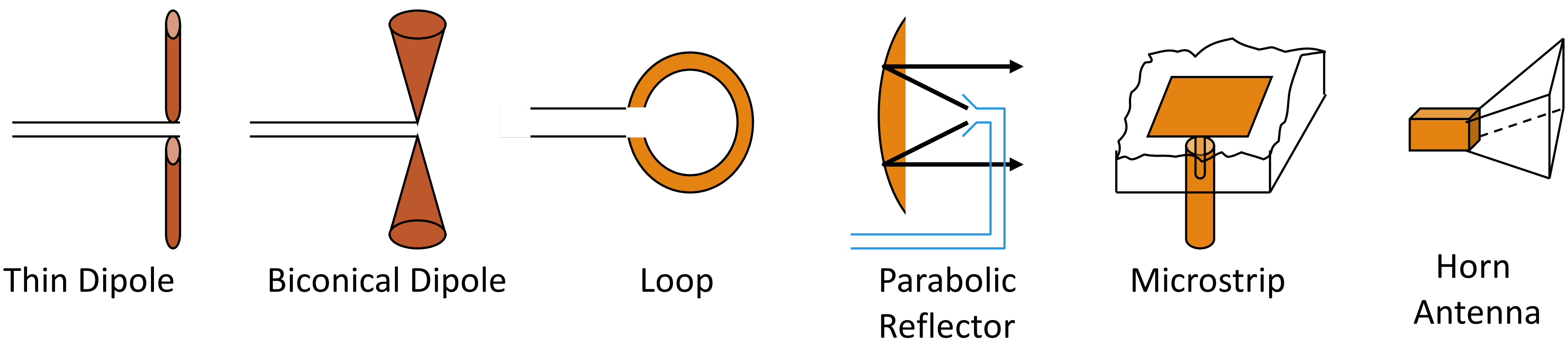
- 1 bel = 10 decibels
  - Hence the multiplication by 10
- If voltages are given instead of power values, it is common to assume a 1 Ω load resistance
  - The dB value is calculated as 20 $\log_{10}$(voltage)
- Path loss
  - Loss in signal strength between transmitter and receiver
  - Primarily due to distance (hence "path"), but loss in signal strength also due to other reasons

Antennas

- What is an antenna?
  - A transducer for converting guided signals in a transmission line or waveguide into electromagnetic radiation in an unbounded medium or vice versa
  - Conversion should be as efficient as possible
    - Match the impedance of the transmission line to that of the unbounded medium
    - Prevent unwanted reflections back to the load
  - Focus radiation in the direction required
- Needs change in the velocity of charges carried in the antenna for radiation to occur
  - Antenna material, shape and size impact the radiation and impedance
  - The dimension of an antenna is measured in units of the wavelength λ of the carrier

What can be an antenna?

- Any conductor or dielectric can serve as the transducer
  - The properties may make it inefficient and thus unsuitable for the application
  - Needs careful design of the structure of the antenna



Show Pringle's cantenna

Radiation Sources and Antenna Types

- Radiation Sources
  - Currents
  - Aperture fields
- Current sources
  - Example: Loops, dipoles
  - Time varying current creates an electromagnetic field that is radiated
- Aperture sources
  - Example: Horn antenna
  - Fields across the aperture serve as the source of the radiation

- Antenna Types
  - Passive Antennas
    - Most common
  - Active (Smart) Antennas
    - More expensive
    - Possibly widespread in the future

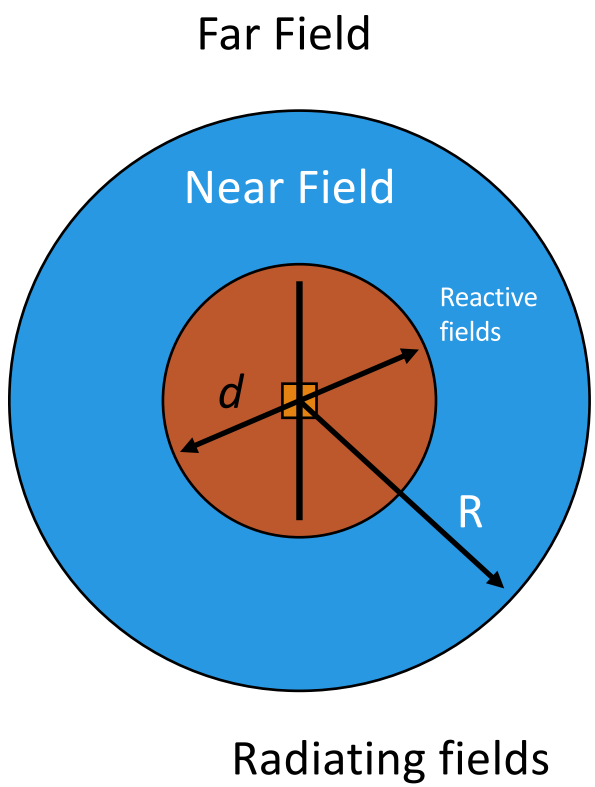
The Near and Far Fields

λ = wavelength

- There are two distinct regions of electric and magnetic fields around an antenna
  - The near field is called the Fresnel region
    - Close to the antenna (around one λ)
  - The far field is called the Fraunhofer region
    - Far away from the antenna (several λ's away)
- The radiation in the far field is similar to plane wave propagation
  - This is usually the region of interest for most applications
  - Allows us to simplify the characteristics of the antenna
- The boundary between the near and far fields is an arbitrary sphere of radius $R_{ff} = 2d^2/\lambda$
  - *d* is the physical dimension of the antenna
    - Diameter of the smallest sphere that completely encloses the antenna

Example of Far Field Calculation

- What is the far field of an antenna for a 1000 MHz carrier if the antenna is a half wavelength dipole?
  - $d = \lambda/2$
  - $R_{ff} = 2(\lambda/2)^2/ \lambda = \lambda/2$
  - $\lambda = c/f = 3 \times 10^8/1000 \times 10^6 = 0.3$ m
  - $R_{ff} = 0.15$ m

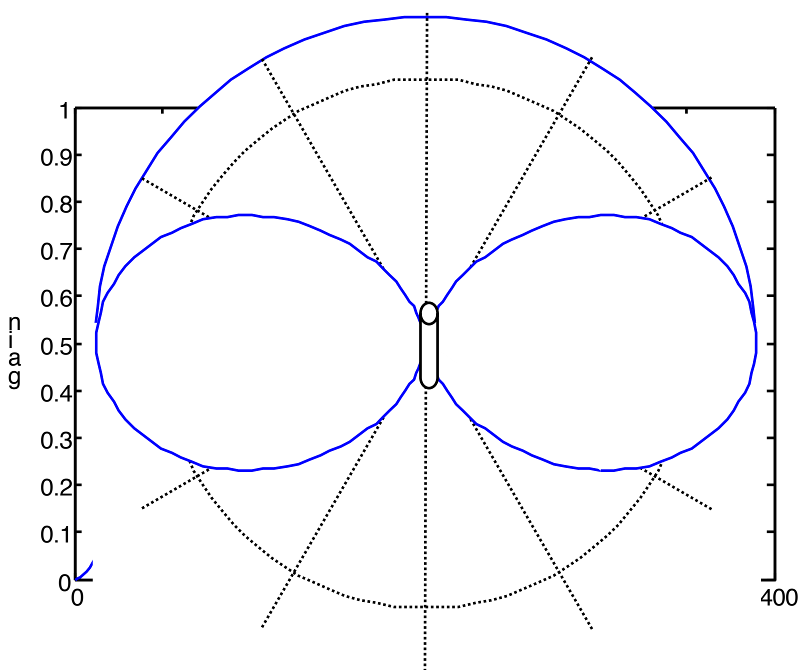


Basics of Antennas (I)

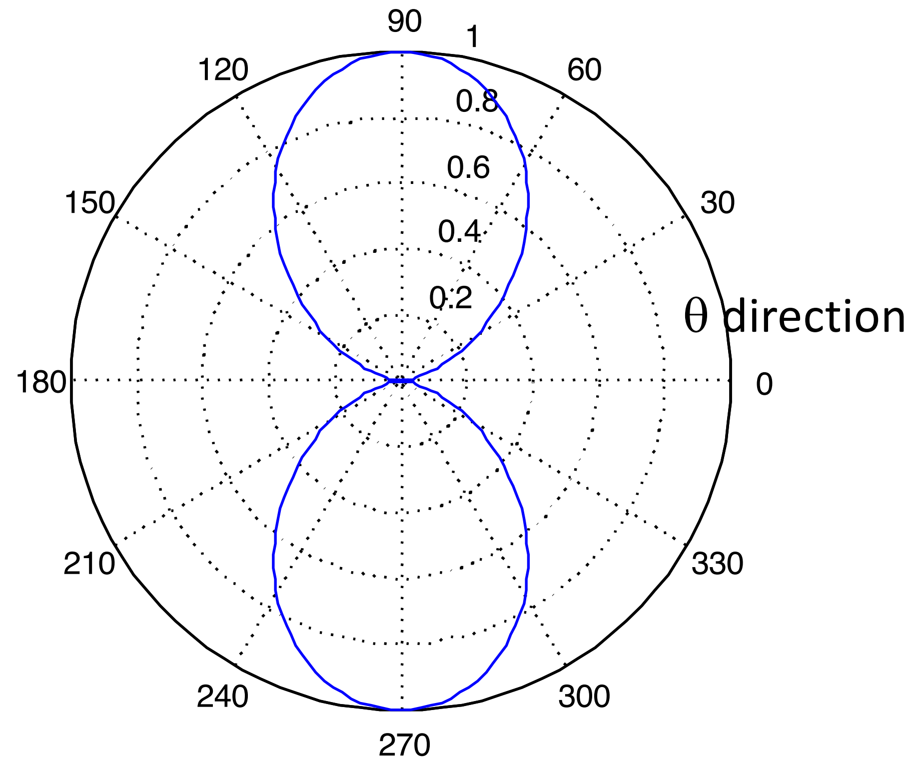
- Radiation pattern – $G(\theta,\varphi)$
  - Also called antenna pattern
  - Directional function of the *relative* distribution of power or intensity in the *far field*
  - Three dimensional plot of the relative strength as a function of the spherical co-ordinates φ and θ
- The radiation pattern is independent of distance
  - It is relative!
- Typically, it is shown as two 2-D plots
  - θ-direction (also called elevation plane)
  - φ-direction (also called azimuth plane)

Example of Antenna Pattern

x-y rectangular plot



polar plot



More on Antenna Patterns

- The antenna patterns are usually normalized to the maximum gain G_{max}
- The gain is often expressed in dB in such a case
- In the previous example
  - The pattern is the same for all values of φ
  - In many cases, there may be a change with φ in which case the azimuthal variation also needs to be shown

Directivity

- Directivity
  - Describes the antenna pattern of a lossless antenna
  - Indicates how much gain is there due to the directionality
  - D = maximum radiation intensity/average radiation intensity

$$D = \frac{G_{\max}}{\frac{1}{4\pi}\iint_{4\pi} G(\theta,\varphi)\, d\Omega}$$

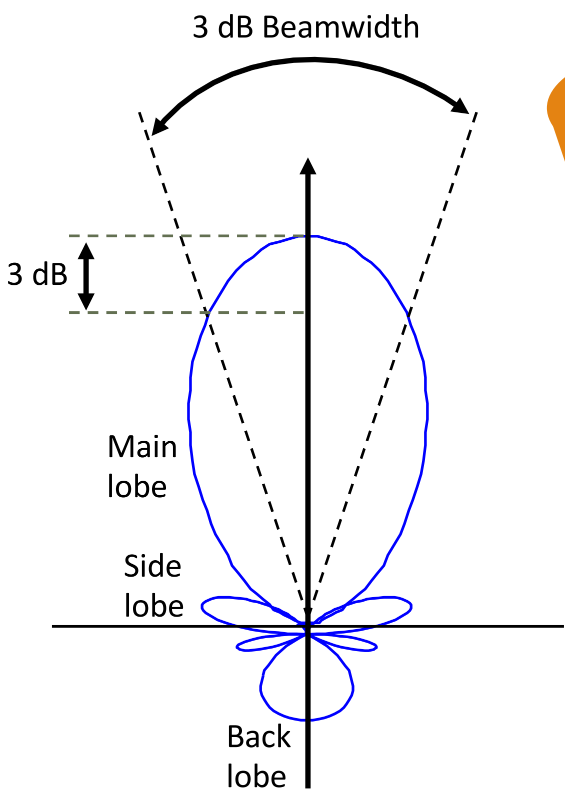
Solid Angle
$\sin\theta \, d\theta \, d\varphi$

Isotropic Antenna

- Radiation propagates equally in all directions
- "Ideal" – does not exist
- What is the directivity of the isotropic antenna?

$$D_{iso} = \frac{G_{\max}}{\frac{G_{\max}}{4\pi}\int_0^{2\pi}\int_0^{\pi}\sin\theta d\theta d\varphi} = \frac{4\pi}{2\pi\int_0^{\pi}\sin\theta d\theta} = 1$$

Radiation lobes



- Ideal antenna
  - Gain = 1 over a certain angle
  - Gain = 0 over the rest of the directions
- Real antenna
  - Radiates power in unwanted directions
  - Has one or more main lobes and many sidelobes
  - Specified “beamwidth”

Radiation Lobes (II)

- Antenna Beamwidth
  - The angle of coverage where the radiated energy is 3 dB down from the peak of the beam (half-power)
  - By narrowing the beamwidth we can increase the gain and create sectors at the same time
- Front-to-Back Ratio
  - The ratio of the power in the main lobe to the power in the lobe created at the back of the antenna
  - Ratio should be as large as possible
  - Front to back ratio of a dipole is 0 dB!

Example: Beamwidth and Directivity

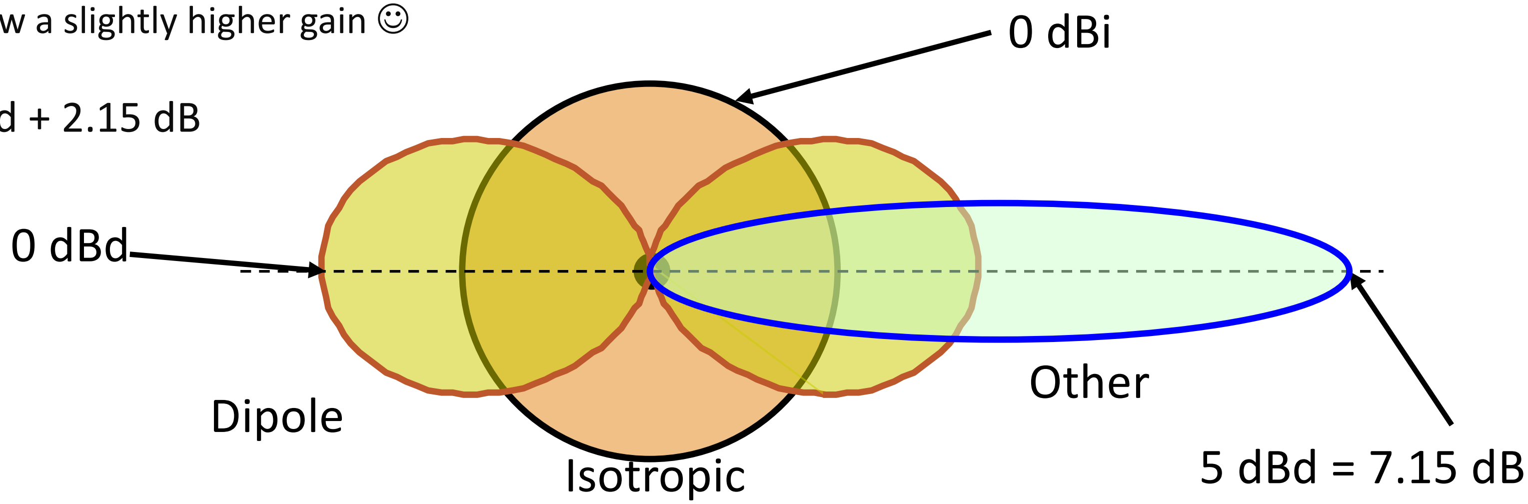
- Compute the 3 dB beamwidth and directivity of an antenna that has the pattern defined by the following equation:

$$G(\theta,\varphi) = \begin{cases} \cos^2\theta\ \text{, if } 0 \le \theta \le \pi/2 \\ 0\text{, elsewhere} \end{cases}$$

- Note that this antenna pattern is independent of the azimuth
- Set G(θ,φ) = 0.5 to find the 3 dB beamwidth (solve for θ)
- You can find the directivity by integration
  - The answer is D = 6

Antenna Gain

- The "gain" of an antenna in a given direction is the ratio of the power density produced by it in that direction divided by the power density that would be produced by a **reference** antenna in the same direction
- Two types of reference antennas are generally used
  - Isotropic antenna: gain is given in dBi
  - Half-wave dipole antenna: gain is given in dBd
- Manufacturers often use dBi in their marketing
  - To show a slightly higher gain ☺
- dBi = dBd + 2.15 dB

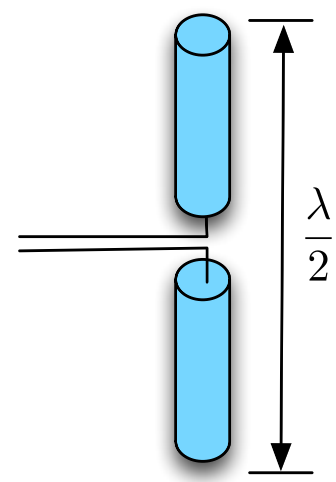


Basics of Antennas (II)

- Reciprocity
  - An antenna can be used both for transmission and reception
  - It performs equally well for both tasks
  - The radiation pattern is identical for transmission and reception
    - Exceptions: Solid state antennas
- Impedance
  - It is important to match the impedance of the antenna to that of the transmission line feeding it

Omnidirectional Antennas

- Omnidirectional antenna
  - Radiation pattern is constant in the azimuth plane
  - Half-wave dipoles and quarter-wave monopoles with a ground plane are good approximations
  - Typically made from some type of collinear array of half-wave dipoles
  - Radiation pattern is in the shape of a donut
  - At $\lambda/2$, impedance matching occurs with the transmission line

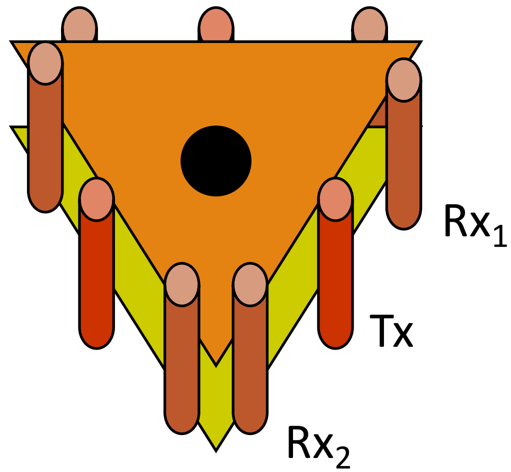


Effective Area

- Characterizes the ability of an antenna to
  - Capture energy from an incident wave and convert it into an intercepted power
  - Also called effective aperture and receiving cross-section
- It is not dependent on the physical area of the antenna although that could affect it
- You can show that the effective area is given by
  - $A_e = \lambda^2 D/4\pi$ for any antenna (D = directivity)
    - Assumes matched impedance
  - What is it for an isotropic antenna? (remember – free space loss)

Importance of antennas

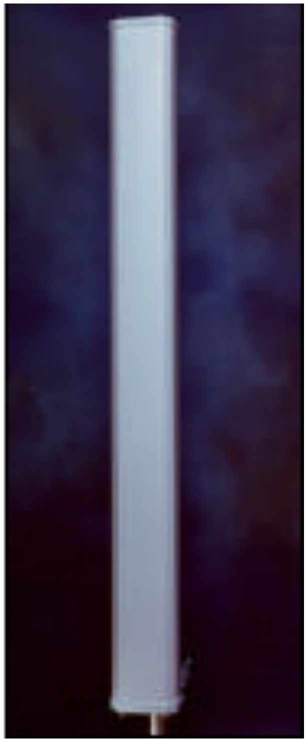
- Capacity of the system can be increased
  - Co-channel interference can be reduced with directional antennas
- Multipath effects can be reduced
  - If a highly directional antenna is used for both transmission and reception, the number and spread of multipath components are reduced
- Diversity gains are possible
  - Using antenna elements that are spaced apart, spatial diversity gains are achieved
- MIMO – Multiple Input Multiple Output and smart antennas



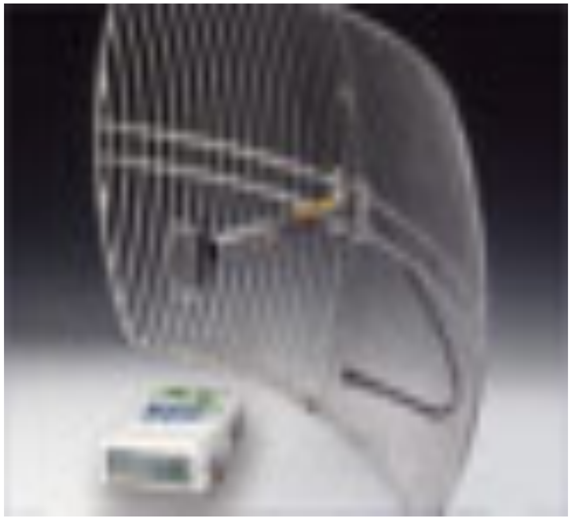
- Three sector antenna for a cellular system with two orders of receive diversity
- There are two receiving elements per sector and one transmitting element

Antenna Examples

Monopole
Omnidirectional



Panel Array of
dipoles
for sectored cell



Grid Reflector
Antenna

Antenna Location

- Trend is to co-locate cells from multiple companies due to cost of cell site land/tower
  - American Tower
  - Crowncastle

The Radio Channel

- The radio channel is different
  - Extremely harsh environment compared to “wired” or guided media
  - Channel is time variant
    - Movement of people
    - Switching off and on of interference
    - Movement of mobile terminals
    - Sensitivity to a variety of other factors
    - “Fading” and “Multipath”
- Need a framework that characterizes the radio channel
  - Common to approximate it as an LTI system

What is Radio Propagation?

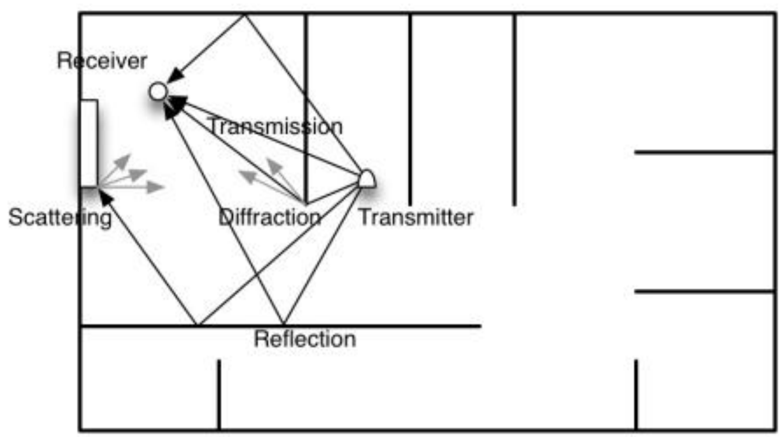
- How is a radio signal transformed from the time it leaves a transmitter to the time it reaches the receiver
  - What is the “radio channel”?
- Important for the design, operation and analysis of wireless networks
  - Where should base stations be placed?
  - What transmit powers should be used?
  - What radio channels need be assigned to a cell?
  - How are handoff decision algorithms affected…?

Propagation Mechanisms (1)

- EM radiation propagates as various waves depending on wavelength and distance
- Ground (surface) wave travels close to ground level
  - Dominant for low frequencies (30 kHz - 3 MHz)
  - Scatters off terrain and buildings
- Tropospheric waves propagate in lower atmosphere and refract back to ground level
  - Amount of refraction increases with frequency, causes significant annoyance above 30 MHz
- Ionospheric waves can be reflected between upper atmosphere and ground to propagate thousands of miles
  - Effected by sunspot activity, cause signal distortion

+ Propagation Mechanisms (2)

- For a high frequency signal (> 500 MHz)
  - An electromagnetic wave can be modeled as a “ray”
- Basic mechanisms
  - Transmission (propagation through a medium)
  - Scattering (small objects less than wavelength)
  - Reflection (objects much larger than wavelength)
    - Waves may be reflected by stationary or moving objects
  - Diffraction at the edges



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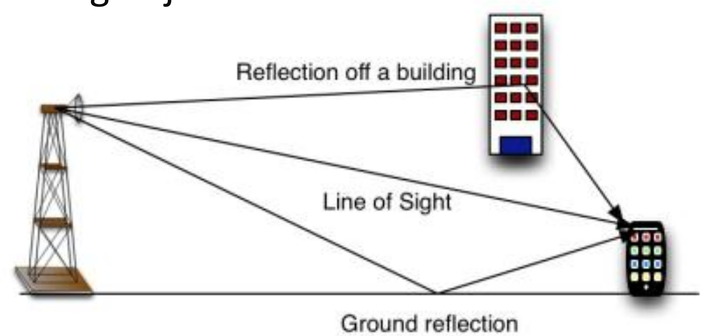

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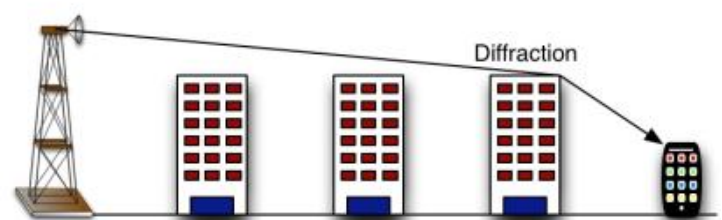


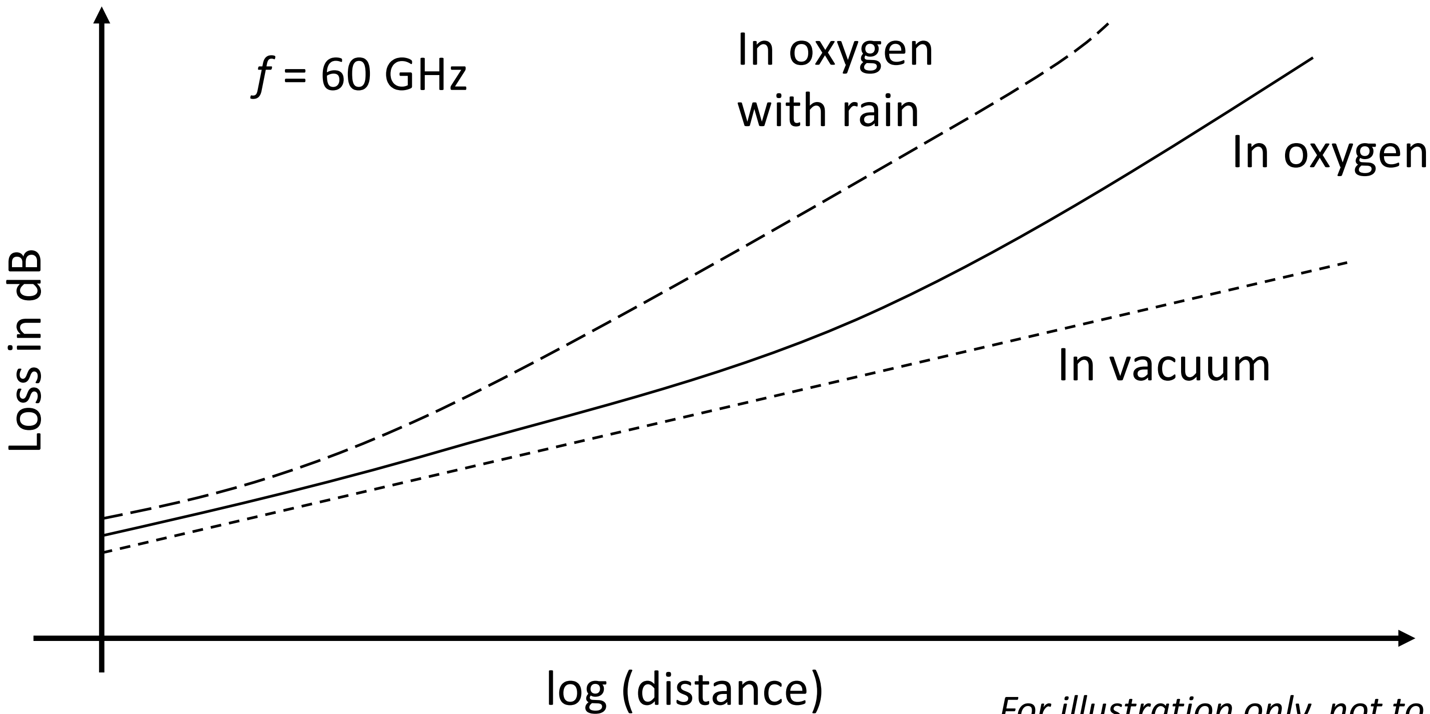
(c)

Reflection and Transmission

- Electromagnetic "ray" impinges on object larger than the wavelength λ
  - It bounces off the object
  - Examples:
    - Walls, buildings, ground
- Signal is attenuated by a reflection factor
  - Attenuation depends on
    - Nature of material
    - Frequency of the carrier
    - Angle of incidence
    - Nature of the surface
- Usually transmission through an object leads to larger losses (absorption) than reflection
  - Multiple reflections can result in a weak signal

Oxygen absorption at 60 GHz

- Signals are attenuated (fade) over distance depending on frequency and weather conditions



For illustration only, not to scale

Diffraction

- The radio signal is incident upon the edge of a sharp object
  - Example: Wall, roof edge, door
- Each such object becomes a secondary source
- Losses are much larger than with reflection or transmission
- Important in micro-cells for non-line of sight transmission
  - Propagation into shadowed regions
- Not significant in indoor areas because of large losses

Scattering

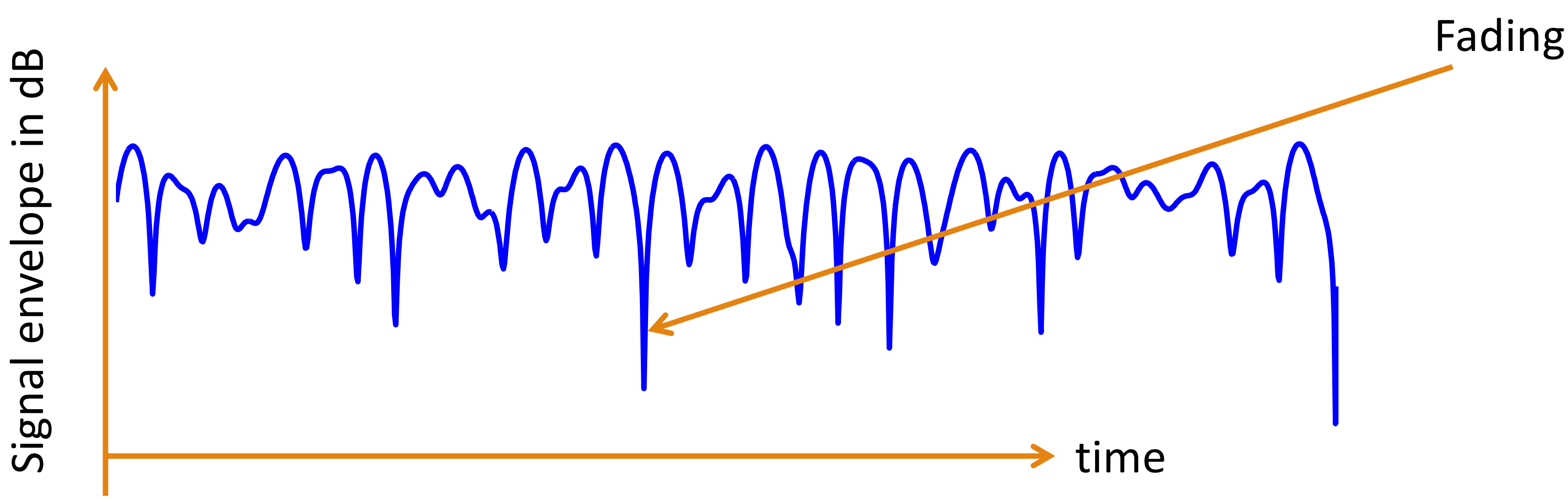
- Caused by irregular objects comparable in size to the wavelength
- These objects scatter rays in all directions
- Each scatterer acts as a source
  - Signal propagates in all directions
  - Large losses in signal strength
  - Insignificant except when the transceiver is in very cluttered environments
- Examples of scatterers
  - Foliage, furniture, lampposts, vehicles

Multipath Propagation

- Multipath
  - Receiver gets combined radio waves from different directions with different path delays
    - Received signal is very dependent on location - different phase relationships can cause signal fading and delay spread
- Causes **time variation** and **inter-symbol interference** in digital systems
    - Causes “burst errors”
    - Limits maximum symbol rate

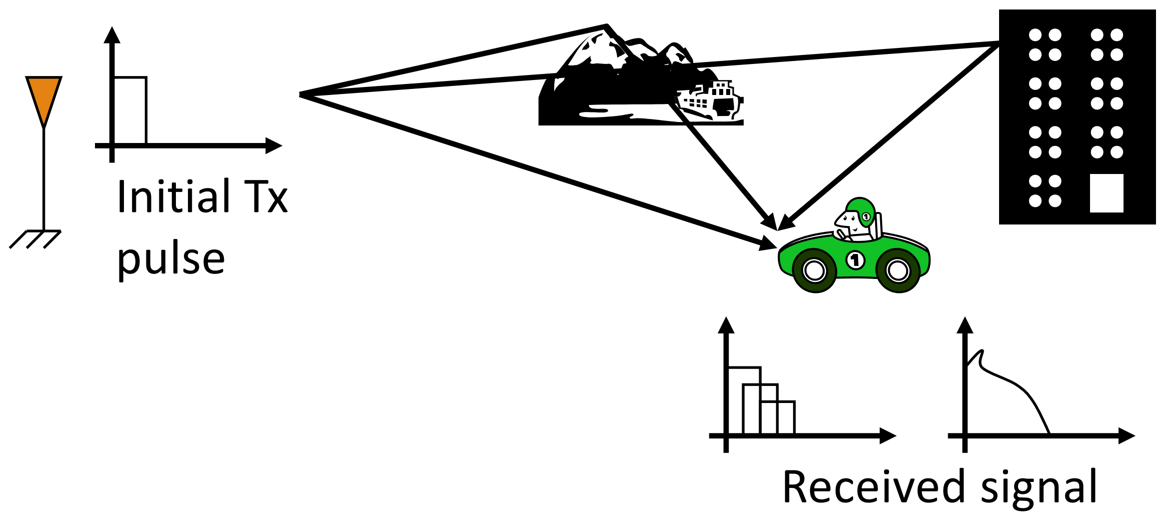
Time Variation of Signals

- A moving receiver can experience a positive or negative Doppler shift in received signal, depending on direction of movement
  - Results in widening frequency spectrum
  - Rapid fluctuations of signal envelope

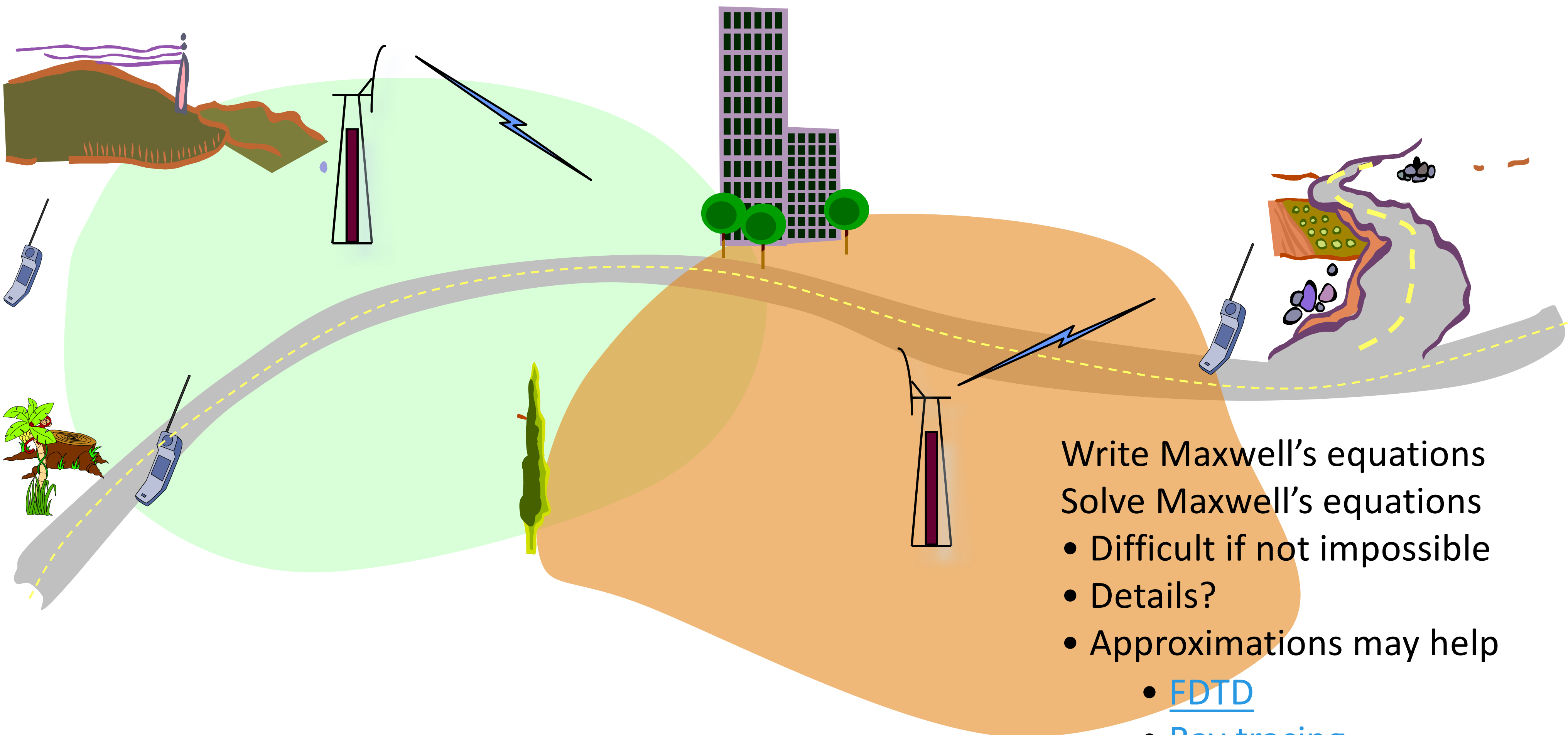


Time Dispersion and ISI

- Suppose we transmit a single narrow pulse
  - Assume there are three paths
  - What do we receive?
- What happens if we send *two* narrow pulses?



First possibility

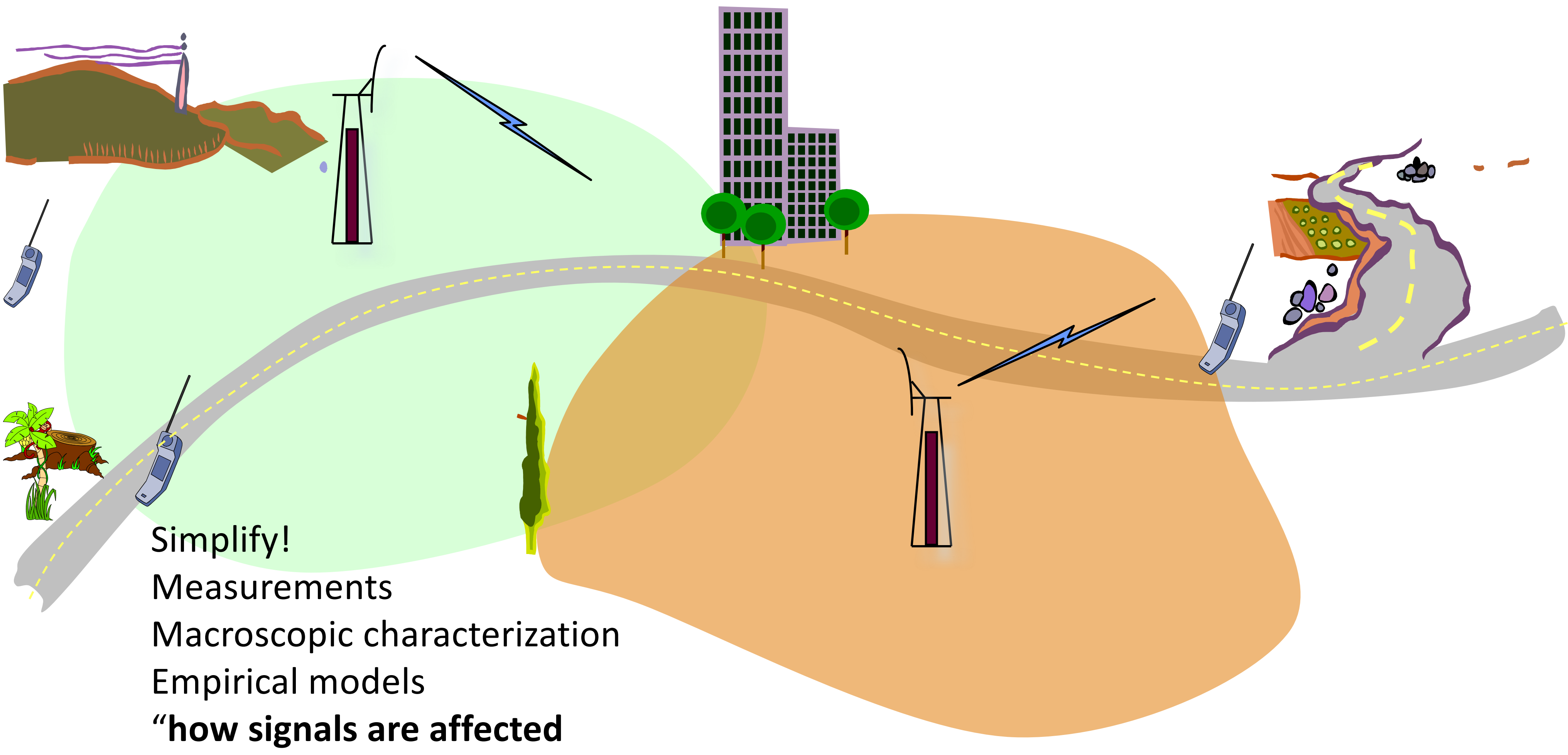


Write Maxwell's equations

Solve Maxwell's equations

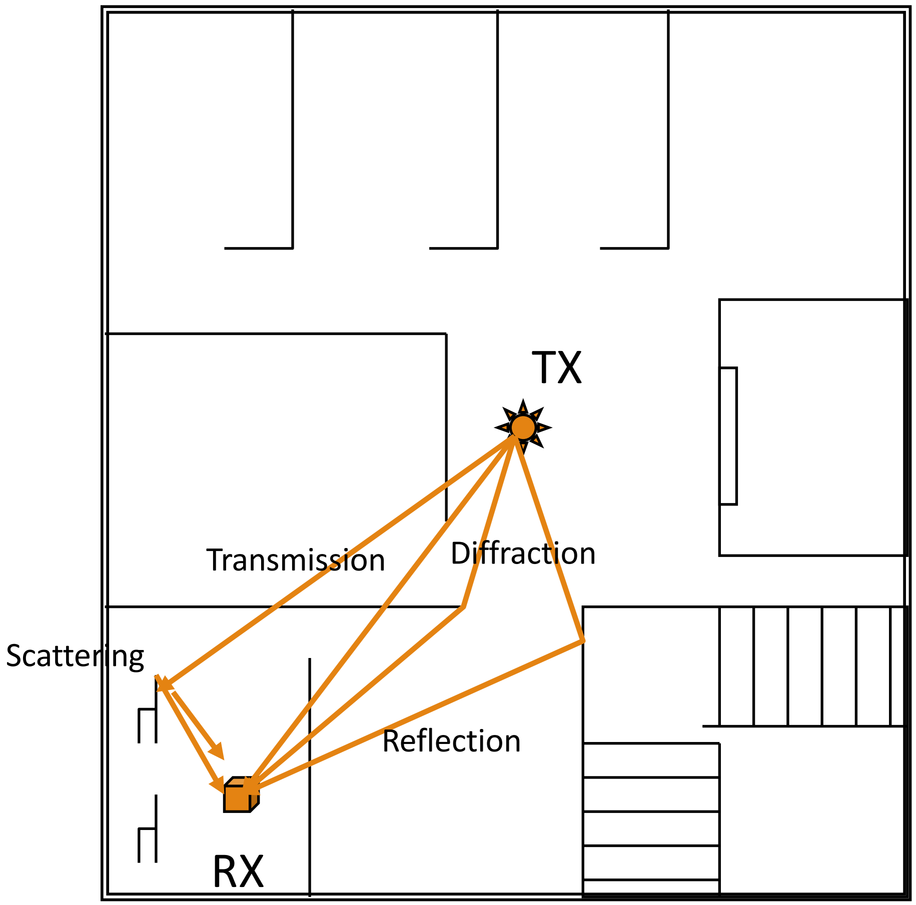
- Difficult if not impossible
- Details?
- Approximations may help
  - FDTD
  - Ray tracing

Second possibility



Simplify!
Measurements
Macroscopic characterization
Empirical models
"how signals are affected vis-à-vis some parameters"

Summary



- Several paths from Tx to Rx
  - Different delays, phases and amplitudes
  - Add motion – makes it very complicated
- Very difficult to look at all of the effects in a composite way
  - Use empirical models
  - Use statistical models
  - Breakdown phenomena into different categories

Radio channel characterization

- Radio propagation is modeled as a random phenomenon
- Measurements followed by statistical modeling
  - Signal strength measurements
  - RMS delay spread measurements
    - Use spread spectrum or linear FM
- Measurements to fine tune simulations and simulations followed by statistical modeling
  - Ray tracing: Approximate the radio propagation by means of geometrical optics

Classified based on site/application specificity

- Propagation Conditions
  - Indoor
    - Commercial
    - Office
    - Residential
    - Tunnel
  - Outdoor to Indoor
  - Outdoor
    - Urban
    - Rural
    - Suburban
  - Forest/Jungle
  - Mountainous
  - Open areas/Free space
  - Over Water

- Frequency dependence
  - 700, 900 MHz : Cellular
  - 1.8, 1.9 GHz : PCS
  - 2.4 GHz : WLANs, BT, Cordless
  - 5 GHz : WLANs, RF tags, MMDS
  - 10 GHz : MMDS
  - 30 GHz : LMDS

LMDS: Local multipoint distribution service
MMDS: Multichannel multipoint distribution system

Communications Issues in Radio Propagation

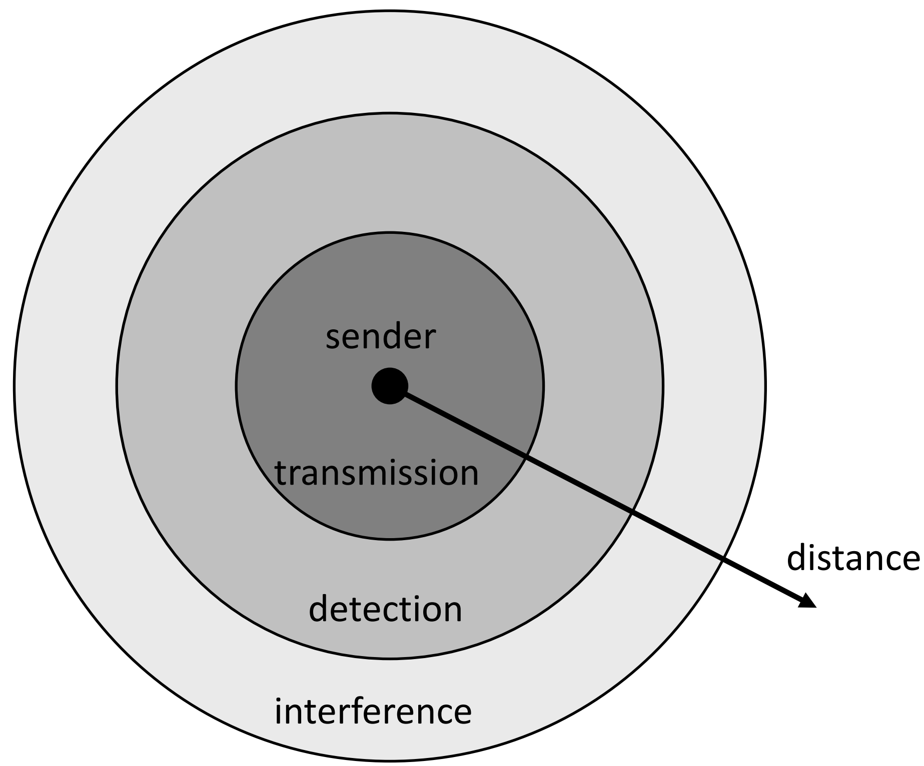
- Coverage
  - How far does the signal propagate over a given terrain at a particular frequency?
    - Power or received signal strength (RSS)
- Performance
  - Bit error rate
    - Statistics of fading – amplitudes and durations
  - Data rate (capacity)
    - Multipath structure
    - MIMO
- Some issues are predominant for certain applications

Coverage

- How far does the signal propagate over a given terrain at a given frequency?
- Same as link budget (in a sense)
- Determines
  - Transmit power required to provide service in a given area
  - Interference from other transmitters
  - Number of base stations or access points that are required
- Parameters of importance
  - Path loss
  - Shadow fading

Signal propagation ranges

- Transmission range
  - Communication possible
  - Low error rate
- Detection range
  - Detection of the signal possible
  - No reliable communication possible
- Interference range
  - Signal may not be detected
  - Signal adds to the background noise



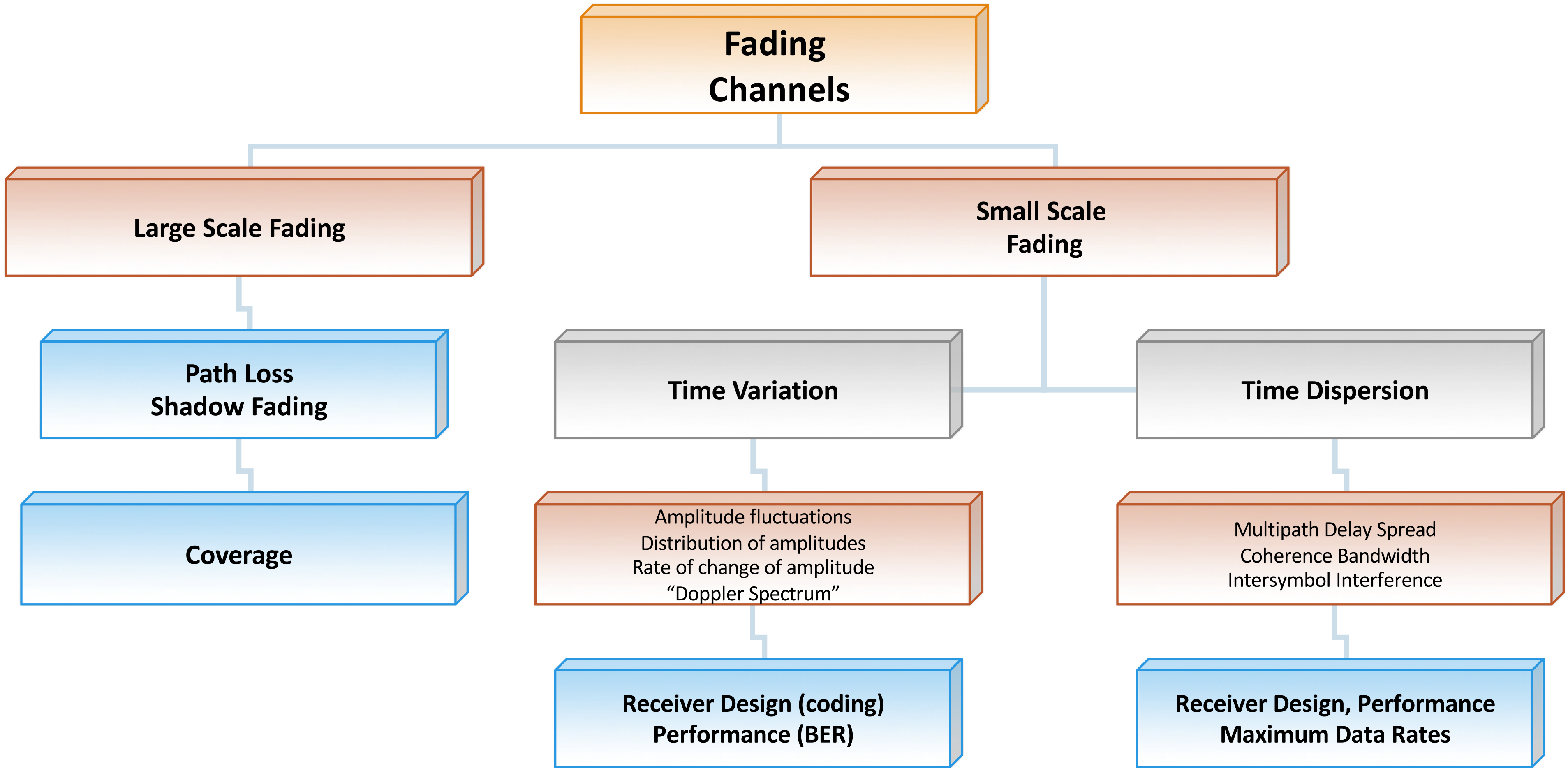
Rate of Channel Fluctuations

- What are the changes in the channel? How fast are these changes? How do they influence performance?
- Determines
  - Performance of the communication system
    - Outage, probability of error
  - Receiver design
    - Coding, diversity etc.
  - Power requirements
- Parameters of importance
  - Fluctuation characteristics
    - Fade rate, fade duration and Doppler spectrum

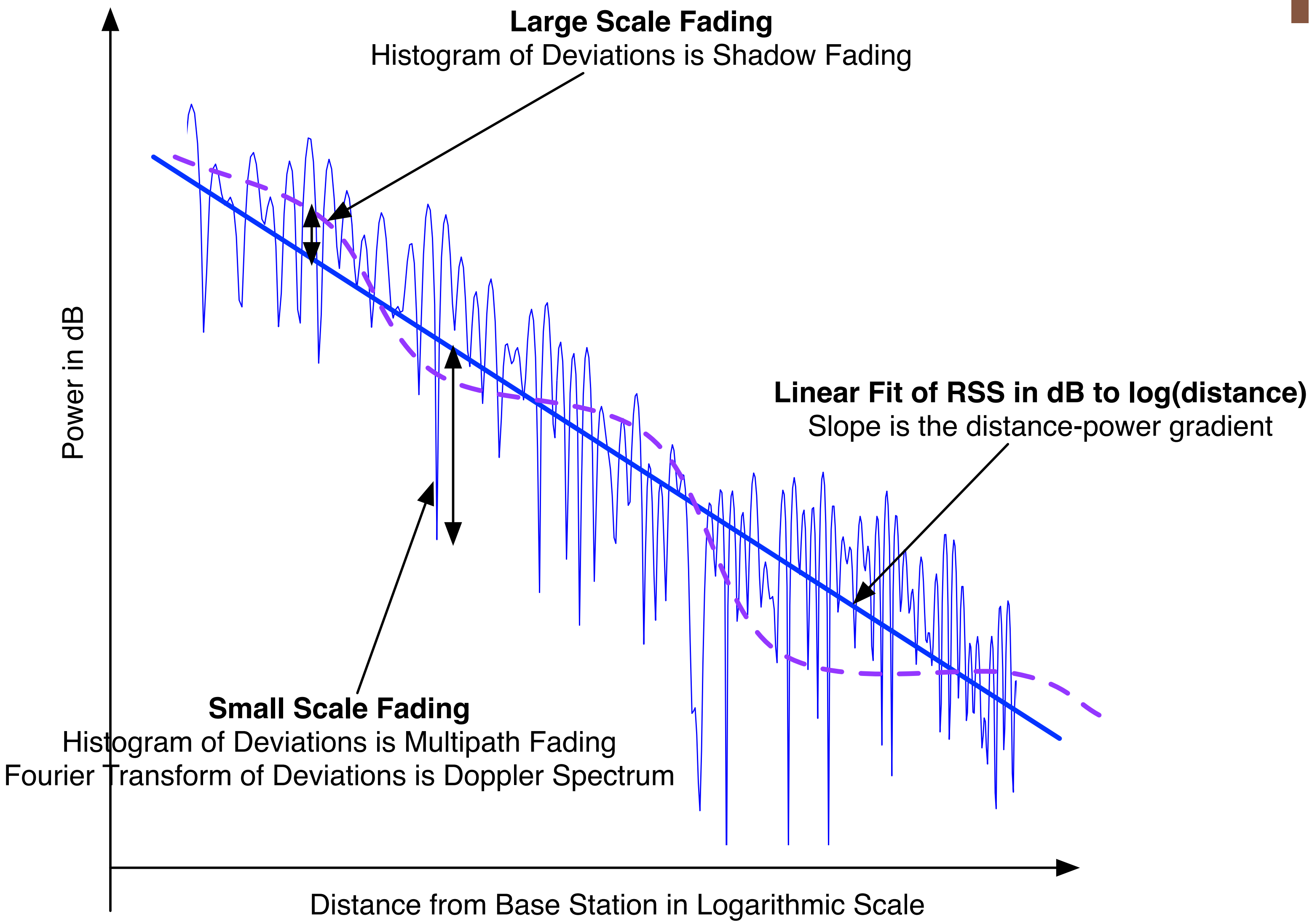
Data Rate Support

- What is the maximum data rate that can be supported by the channel? What limits it?
- Determines
  - Capacity of the system
  - Complexity of the receiver
  - Application support
- Parameters of importance
  - Multipath delay spread and coherence bandwidth
  - Fading characteristics of the multipath components

+ Radio Propagation Characterization



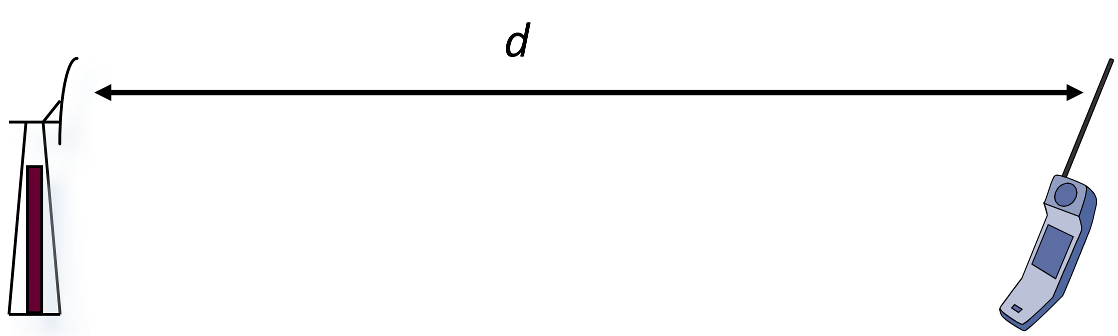
Summary



Large Scale Fading
Histogram of Deviations is Shadow Fading
Linear Fit of RSS in dB to log(distance)
Slope is the distance-power gradient
Small Scale Fading
Histogram of Deviations is Multipath Fading
Fourier Transform of Deviations is Doppler Spectrum
Power in dB
Distance from Base Station in Logarithmic Scale

The Free Space Loss

- Assumption
  - Transmitter and receiver are in free space
  - No obstructing objects in between
  - The earth is at an infinite distance!
- The transmitted power is P_t, and the received power is P_r
- The *path loss* is $L_p = P_t\,(\text{dB}) - P_r\,(\text{dB})$
- Isotropic antennas
  - Antennas radiate and receive equally in all directions with unit gain



The Free Space Model

- The relationship between P_t and P_r is given by

$$P_r = P_t \lambda^2/(4\pi d)^2$$

  - The wavelength of the carrier is $\lambda = c/f$
- In dB

$$P_r\ (\text{dBm}) = P_t\ (\text{dBm}) - 21.98 + 20 \log_{10}(\lambda) - \mathbf{20 \log_{10}(\boldsymbol{d})}$$

$$L_p(d) = P_t - P_r = 21.98 - 20 \log_{10}(\lambda) + \mathbf{20 \log_{10}(\boldsymbol{d})}$$
$$= L_0 + 20 \log_{10}(d)$$

  - L_0 is called the path loss at the first meter (put $d = 1$)
- We say there is a **20 dB per decade** loss in signal strength

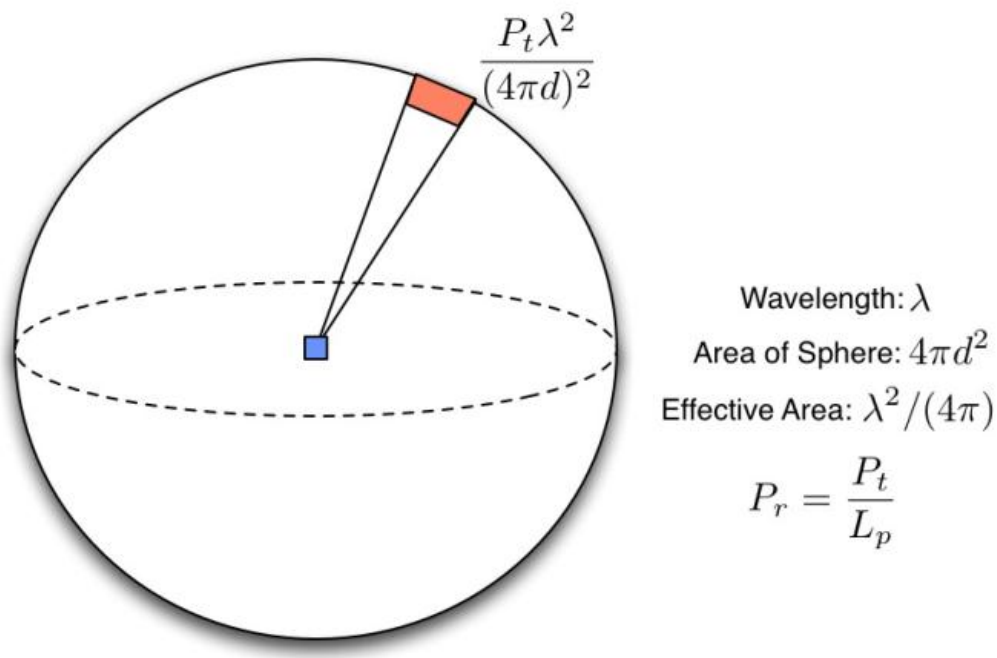
A simple explanation of free space loss

- Isotropic transmit antenna: Radiates signal equally in all directions
- Assume a point source
  - At a distance *d* from the transmitter, the area of the sphere enclosing the Tx is: $A = 4\pi d^2$
  - The "power density" on this sphere is: $P_t / 4\pi d^2$
- Isotropic receive antenna: Captures power equal to the density times the area of the antenna
  - Ideal area of antenna is

$$A_{ant} = \lambda^2/4\pi$$

- The received power is:

$$P_r = P_t / 4\pi d^2 \times \lambda^2/4\pi = P_t \lambda^2/(4\pi d)^2$$



Isotropic and Real Antennas

- Isotropic antennas are "ideal" and cannot be achieved in practice
  - Useful as a theoretical benchmark

- Real antennas have gains in different directions
  - Suppose the gain of the transmit antenna in the direction of interest is G_t and that of the receive antenna is G_r
  - The free space relation is:

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

- The quantity $P_t G_t$ is called the effective isotropic radiated power (EIRP)
  - This is the transmit power that a transmitter should use were it having an isotropic antenna

Summary: Free space loss

- Transmit power P_t and received power P_r
- Wavelength of the RF carrier $\lambda = c/f$
- Over a distance *d* the relationship between P_t and P_r is given by:

$$P_r = \frac{P_t \lambda^2}{(4\pi)^2 d^2}$$

- where *d* is in meters

In dB, we have:

$$P_r\ (dBm) = P_t\ (dBm) - 21.98 + 20 \log_{10}(\lambda) - 20 \log_{10}(d)$$

$$\text{Path Loss} = L_p = P_t - P_r = 21.98 - 20\log_{10}(\lambda) + 20\log_{10}(d)$$

+ Example

- The transmit power of a wireless communication system is 2 W. If the propagation is similar to free space, what is the received power at a frequency of 1 GHz at a distance of 1 km? Assume isotropic transmit and receive antennas.
- What do we know?

Next Week

- Impact of frequency
- Impact of distance
- Other path-loss models