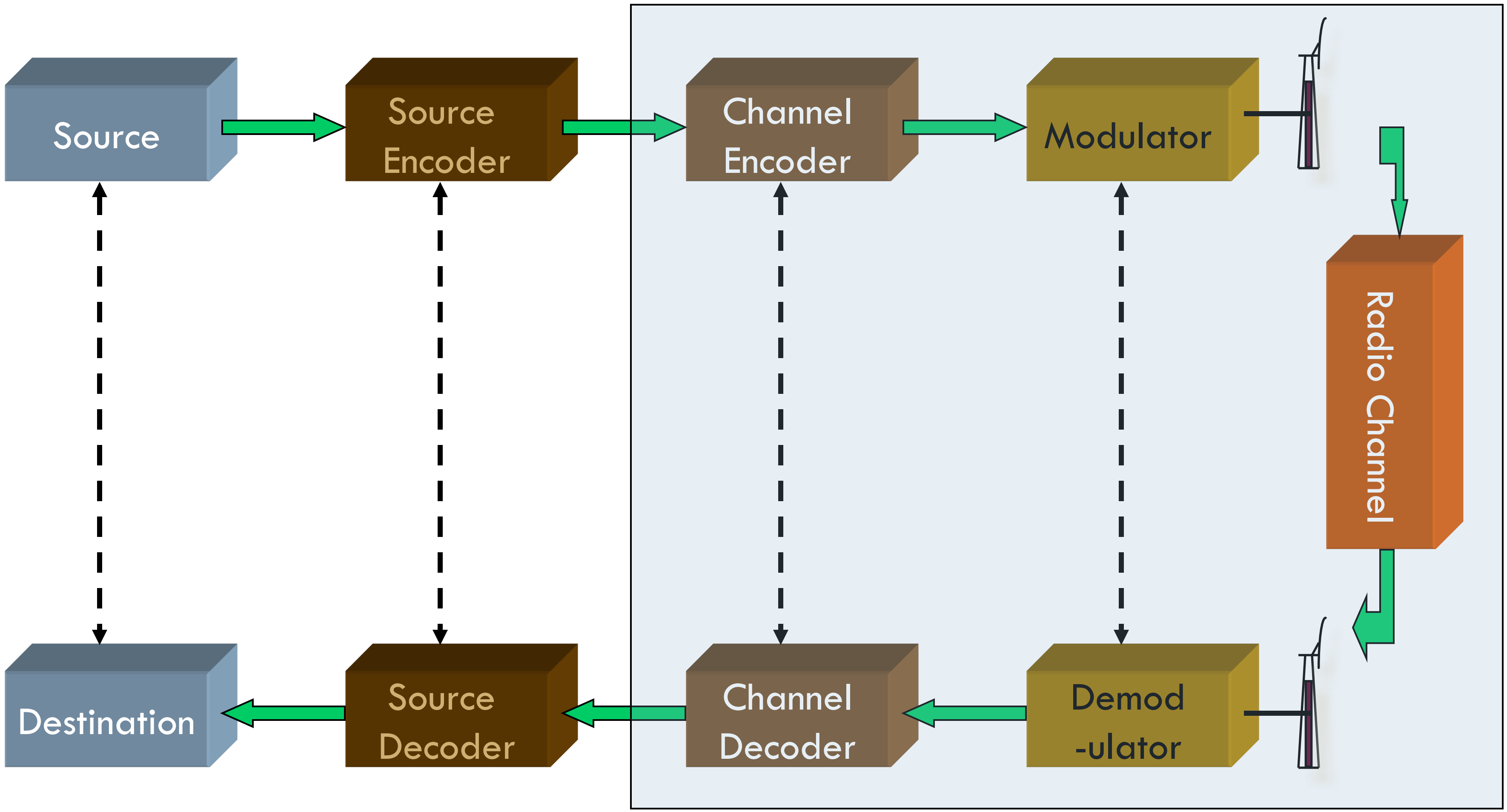
LECTURE 3

Radio Propagation

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

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)

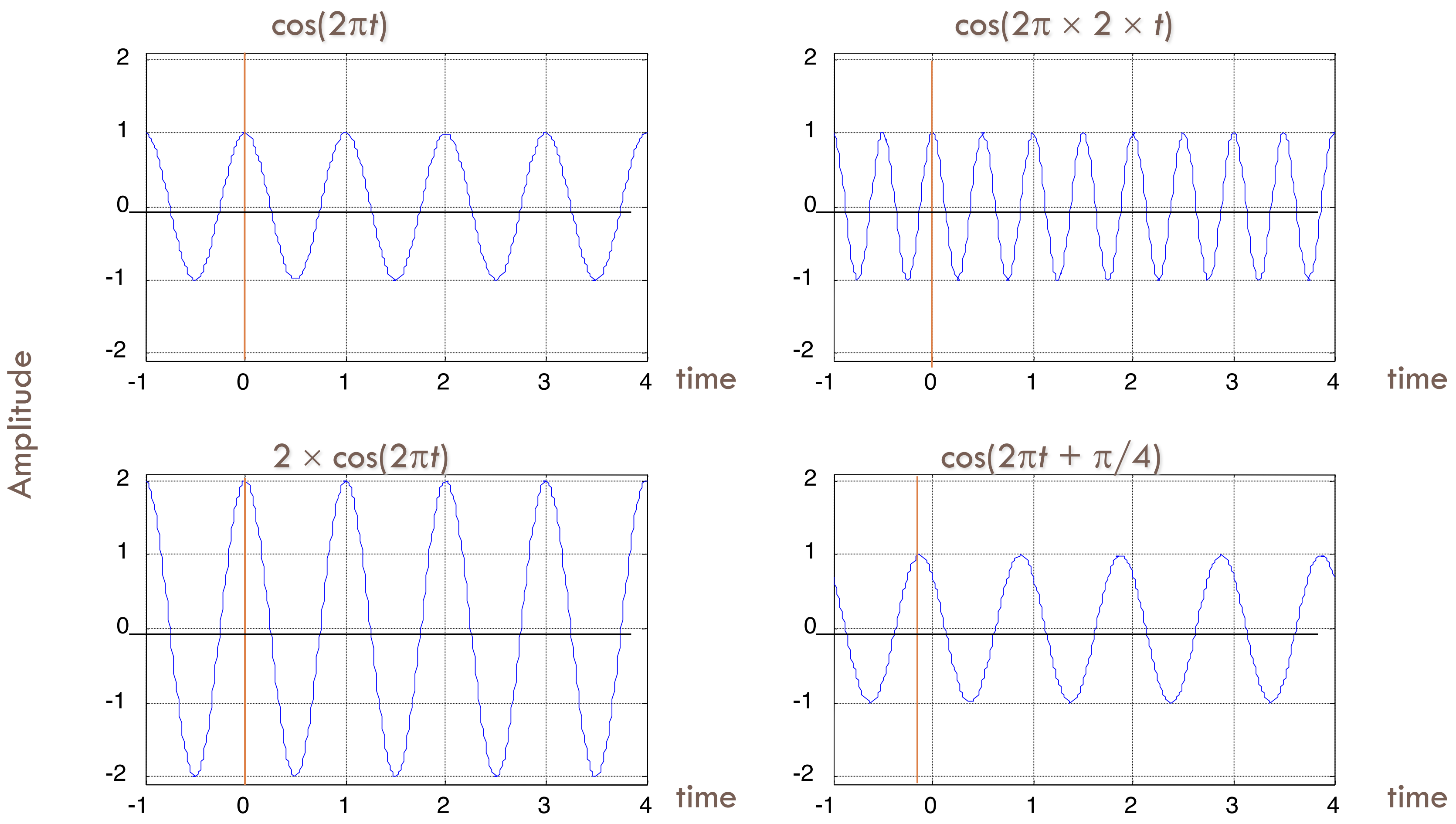
Unguided Media

- 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

Terminology - Sinusoid

- Period (T) - amount of time it takes for one repetition of the signal
  - $T = 1/f$
- Phase (ϕ) - measure of the relative position in time within a single period of the signal
- Wavelength (λ) - physical distance occupied by a single cycle of the signal
  - Or, the distance between two points of corresponding phase of two consecutive cycles
- For electromagnetic waves in air or free space, $\lambda = cT = c/f$ where c is the speed of light

The sinusoid – A cos(2πft + ϕ)



The sinusoid continued

- General sine wave
  - $s(t) = A\cos(2\pi ft + \phi)$
- Previous slide shows the effect of varying each of the three parameters
  - $A = 1$, $f = 1$ Hz, $\phi = 0 \Rightarrow T = 1$s
  - Increased peak amplitude; $A=2$
  - Increased frequency; $f = 2 \Rightarrow T = 1/2$
  - Phase shift; $\phi = \pi/4$ radians (45°)
- Note: 2π radians = 360° = 1 period

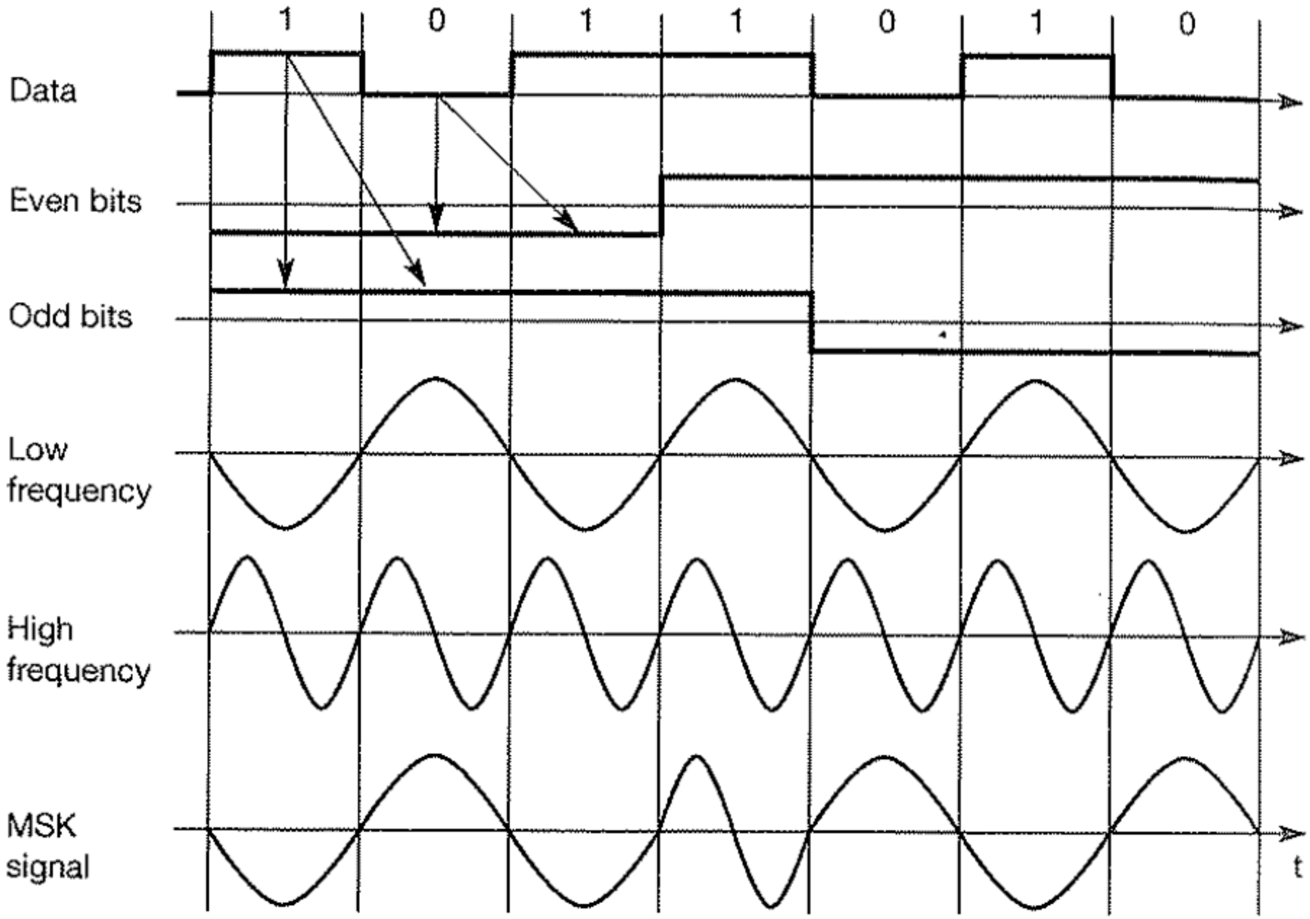
Modulation

- Process wherein, encoded bits are mapped onto a signal
- The values of the encoded bits translate into changes in amplitude, phase or frequency of the signal.
- AM, FM and PM are the most basic methods.
- A combination of changes are possible.

MSK

- One could have abrupt phase changes in phase shift keying or frequency shift keying.
- Minimum Shift Keying alleviates this.
- First, encoded bits are separated into even and odd bits.
- Two frequencies, a lower freq f1 and a higher f2 are used.
  - $f2 = 2f1$
- Set of rules to determine which frequency to use when.

MSK Example



Odd-Even

0-0 → inv (f2)

0-1 → inv (f1)

1-0 → f1

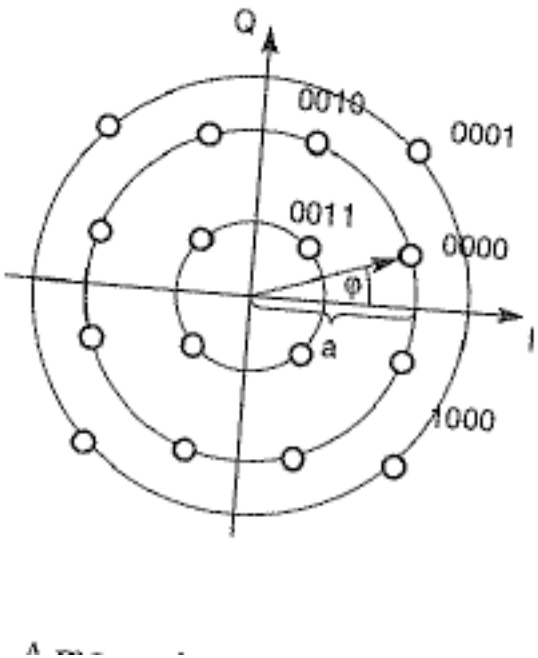
1-1 → f2

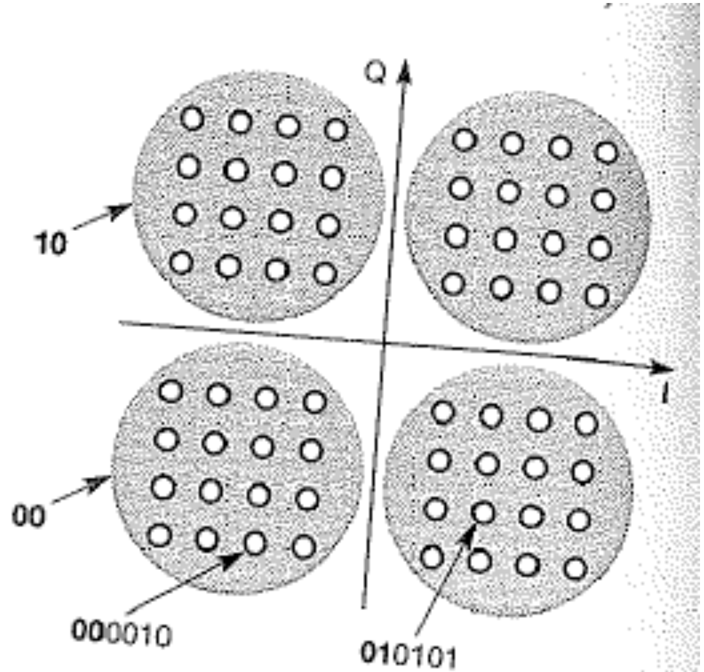
inv(f1) – f1 with a phase shift of 180 deg.

inv(f2) – f2 with a phase shift of 180 deg.

Constellations

- Representation of a signal (amplitude, phase) combination in a two dimensional space.





Could be hierarchical – first decide the quadrant, and then the location within the quadrant.

Communication Issues

- Noise (unwanted interfering signals) is not necessarily additive, white or Gaussian
  - Examples: Inter-symbol interference (ISI), Adjacent channel interference (ACI), Co-channel interference (CCI)
  - In CDMA interference from users etc.
- Noise affects the Bit Error Rate (BER)
  - Fraction of bits that are inverted at the receiver
- Also, the radio channel has multiplicative components that degrade the performance
  - The behavior of the radio channel can increase ISI, reduce the signal strength, and increase the bit error rate

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

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…?

Radio channel characterization

- Radio propagation is modeled as a random phenomenon
- Measurements followed by statistical modeling
  - Signal strength measurements
  - RMS delay spread measurements
- 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
  - 900 MHz : Cellular
  - 1.8 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

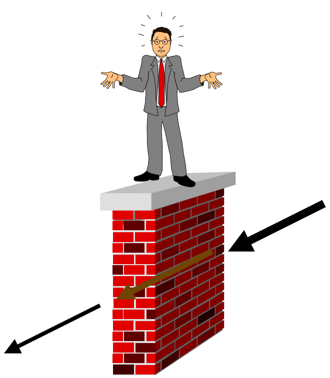
MMDS: Multichannel multipoint distribution system

Transmission of Radio Signals

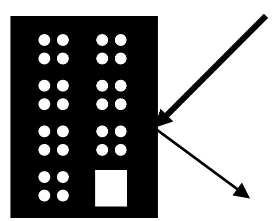
- Radio signals are effected by
  - Ground terrain
  - Atmosphere
  - Objects
  - Interference with other signals
  - Distance (path loss)

Types of Radio Propagation

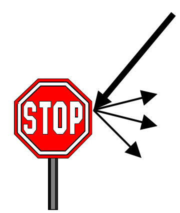
- For a high frequency signal (> 500 MHz)
  - An electromagnetic wave can be modeled as a “ray”
- Basic mechanisms
  - Transmission (propagation through a medium)
  - Scattering (small objects less than wavelength)
  - Reflection (objects much larger than wavelength)
    - Waves may be reflected by stationary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



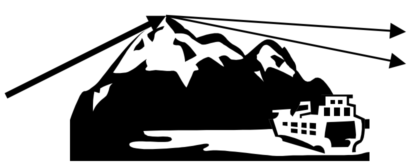
transmission



reflection



scattering



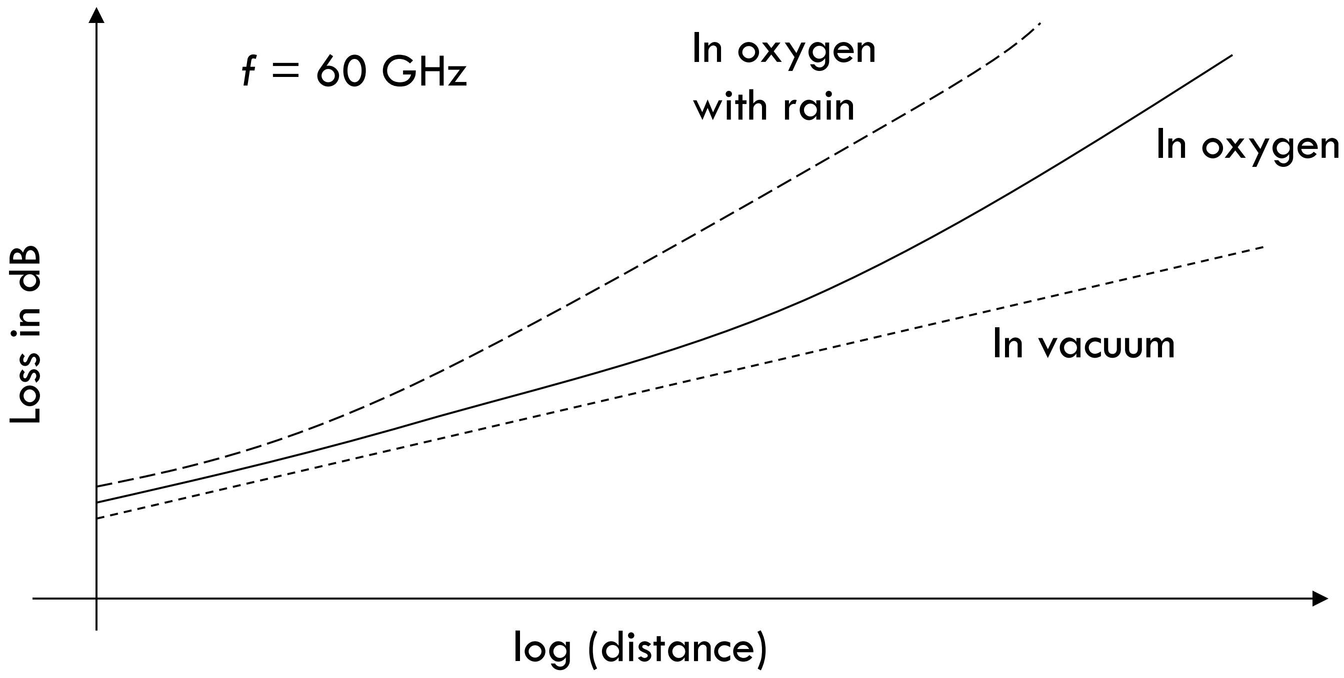
diffraction

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



Diffraction

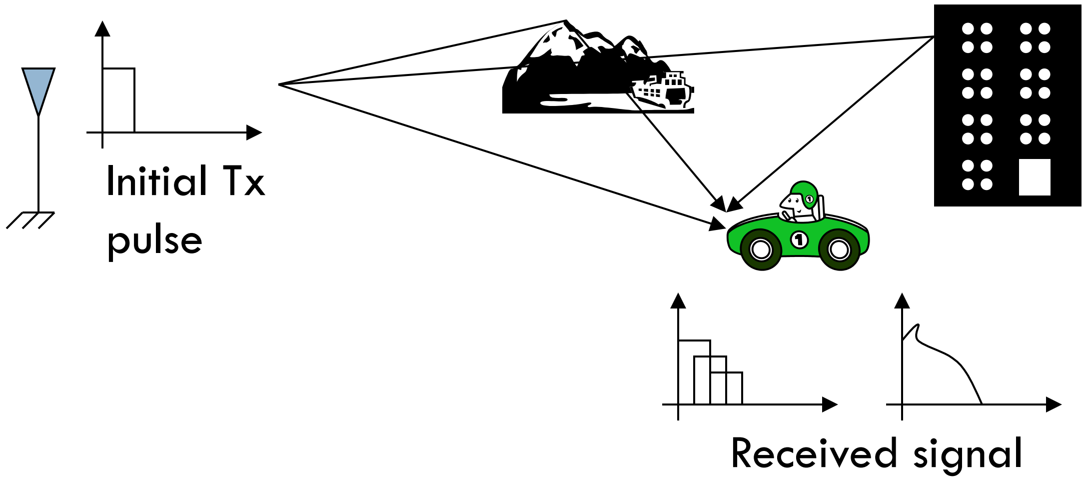
- The radio signal is incident upon the edge of a sharp object
  - Example: Wall, roof edge, door
- Each such object becomes a secondary source
- Losses are much larger than with reflection or transmission
- Important in micro-cells for non-line of sight transmission
  - Propagation into shadowed regions
- 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

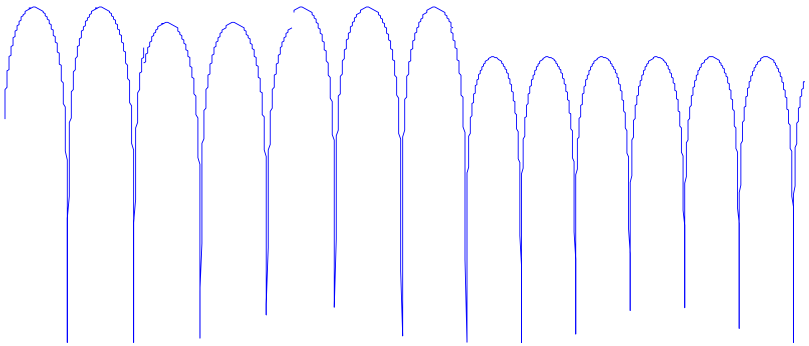
Multipath Propagation

- 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 **inter-symbol interference (ISI)** in digital systems, limits maximum symbol rate

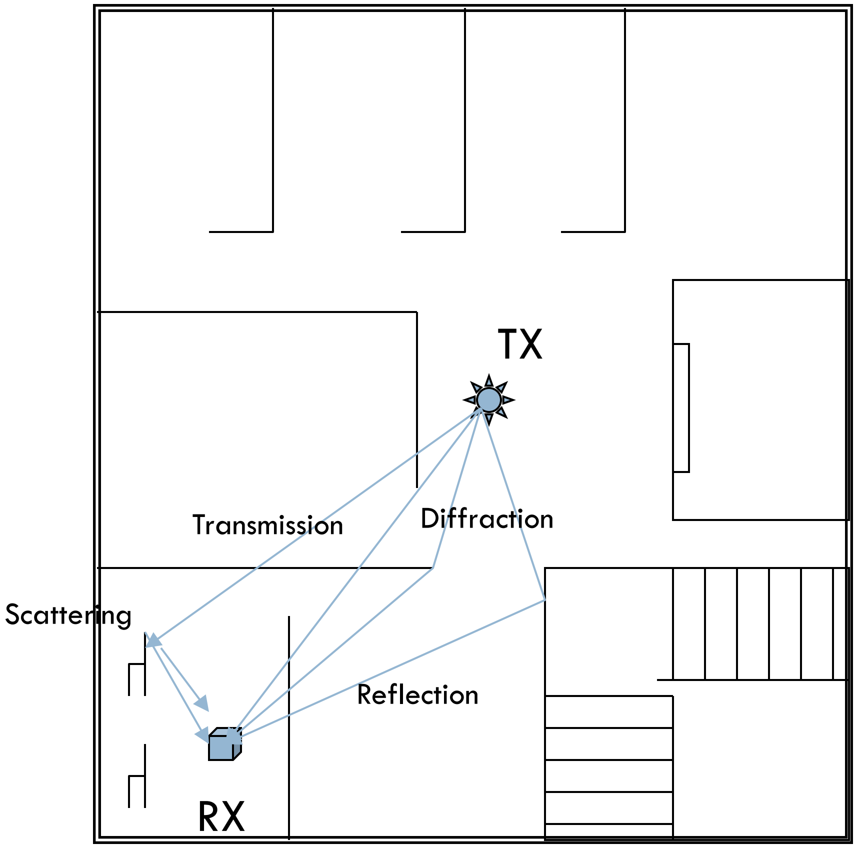


Time Variation of Signals

- 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



Comments



- 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

The Radio Channel

- Three main issues in radio propagation
  - Achievable signal coverage
    - What is area covered by signal
    - Governed by path loss
  - Achievable channel rates (bps)
    - Governed by multipath delay spread
  - Channel fluctuations – effect data rate
    - Governed by Doppler spread and multipath

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
- Some issues are predominant for certain applications

Coverage

- How far does the signal propagate over a given terrain at a given frequency?
- 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

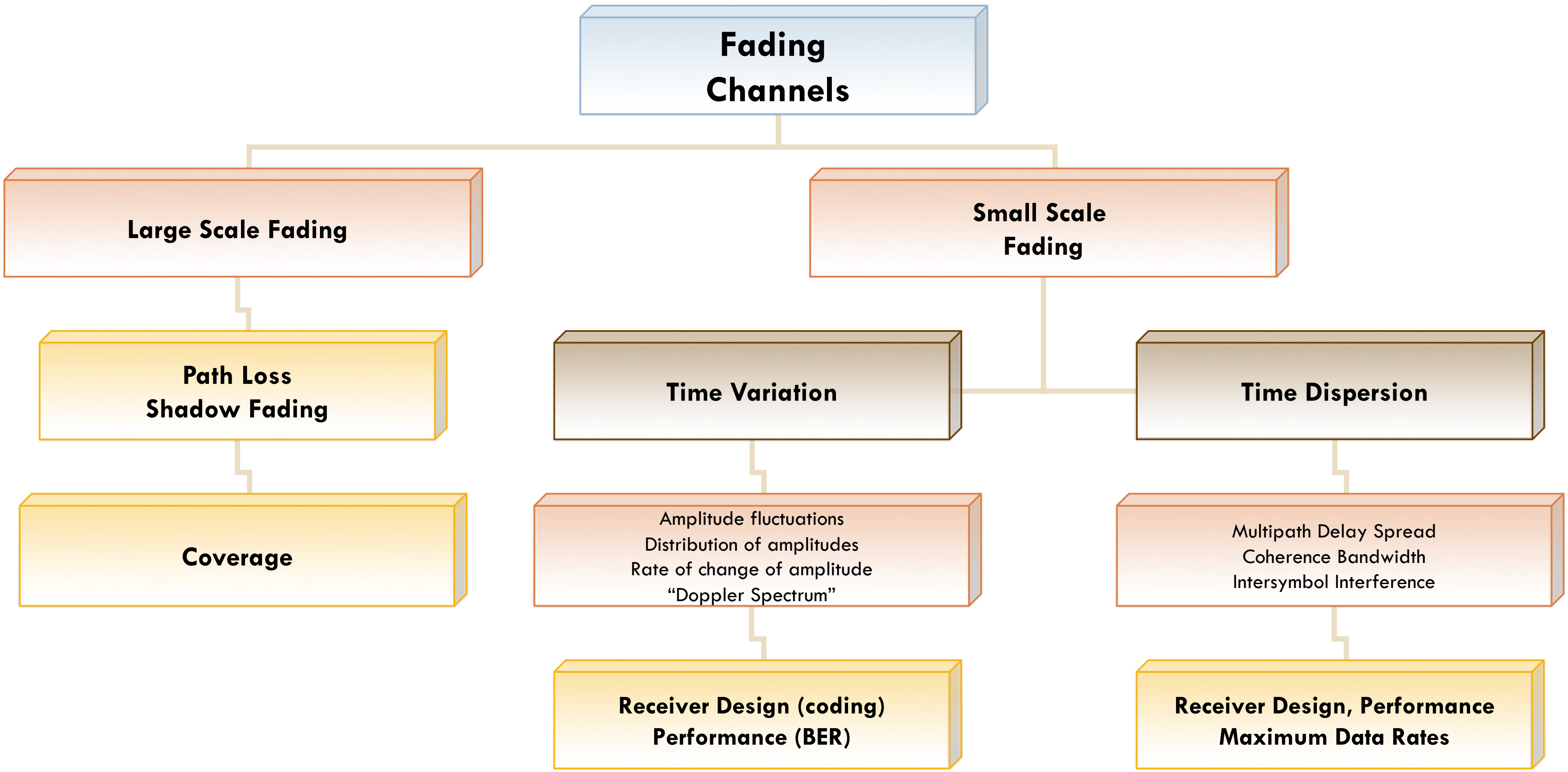
Rate of Channel Fluctuations

- 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

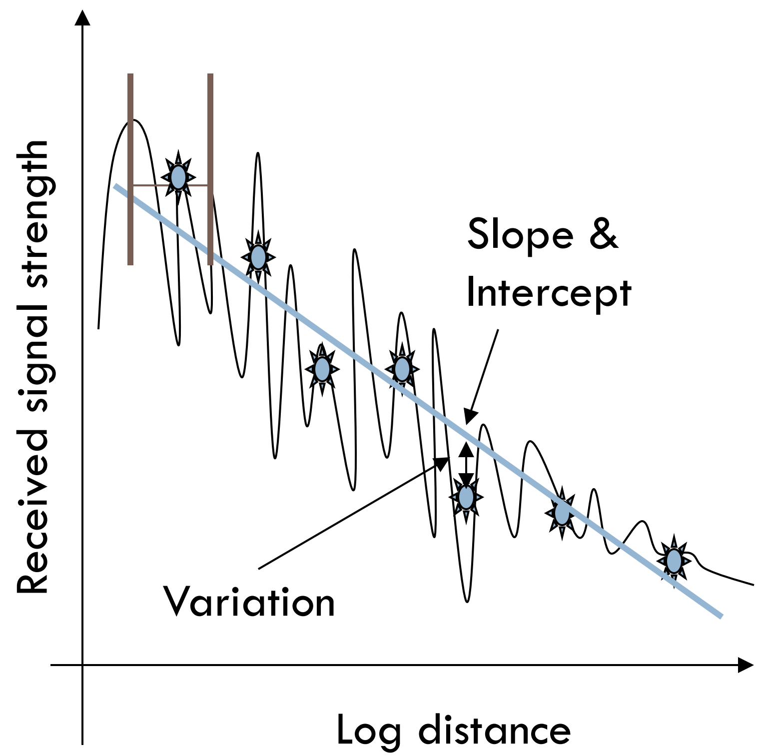
- What is the maximum data rate that can be supported by the channel? What limits it?
- Determines
  - Capacity of the system
  - Complexity of the receiver
  - Application support
- Parameters of importance
  - Multipath delay spread and coherence bandwidth
  - Fading characteristics of the multipath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

Radio Propagation Characterization



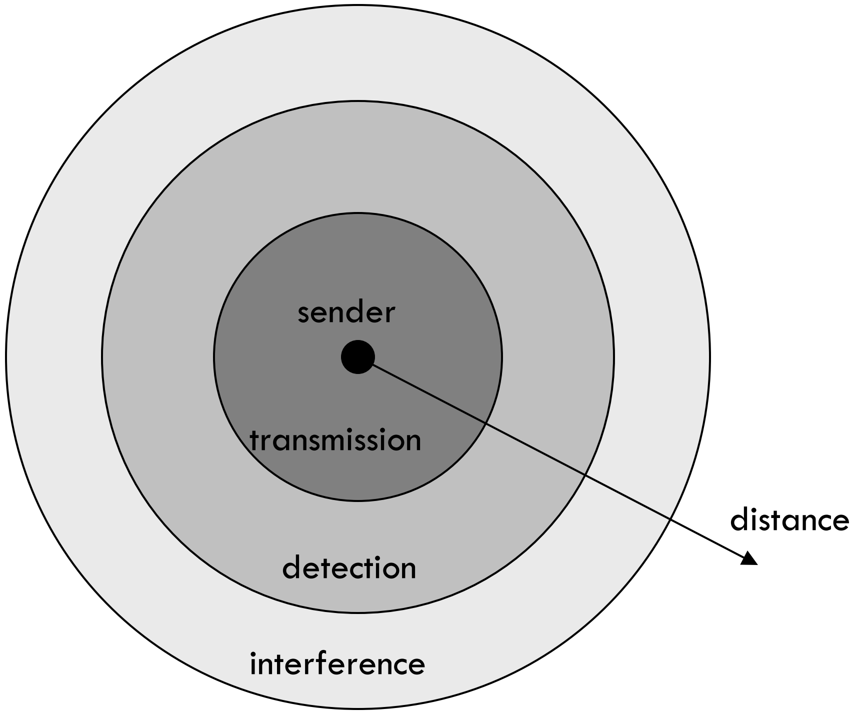
Large Scale Fading

- “Large” scale variation of signal strength with distance
  - Consider **average** signal strength values
  - The average is computed either over short periods of time or short lengths of distance
  - A straight line is fit to the average values
- The slope and the intercept give you the expression for the *path loss*
- The variation around the fit is the shadow fading component



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



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

Examples of using Decibels

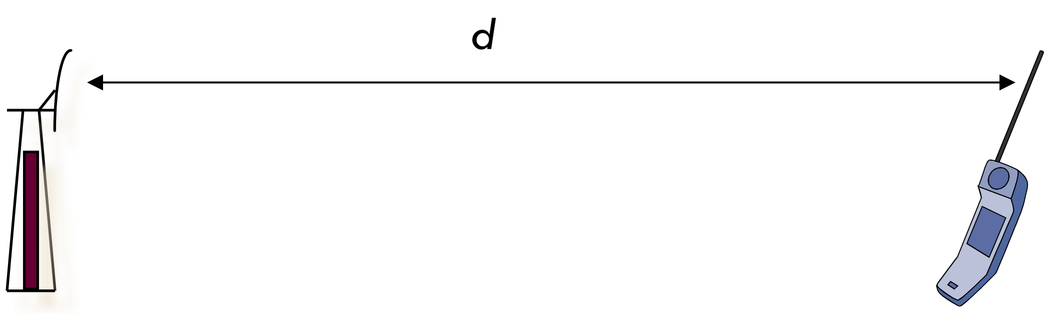
- Example 1: Express 2 W in dBm and dBW
  - dBm: $10 \log_{10} (2 \text{ W} / 1 \text{ mW}) = 10 \log_{10}(2000) = 33$ dBm
  - dBW: $10 \log_{10} (2 \text{ W} / 1 \text{ W}) = 10 \log_{10}(2) = 3$ dBW
- Example 2: The transmit power is 2 W, the RSS is 0.12 W. What is the loss in dB?
  - Loss = Transmit 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"

Path Loss Models

- Path Loss Models are commonly used to estimate link budgets, cell sizes and shapes, capacity, handoff criteria etc.
- "Macroscopic" or "large scale" variation of RSS
- Path loss = loss in signal strength as a function of distance
  - Terrain dependent (urban, rural, mountainous), ground reflection, diffraction, etc.
  - Site dependent (antenna heights for example)
  - Frequency dependent
  - Line of sight or not
- Simple characterization: $PL = L_0 + 10\alpha \log_{10}(d)$
  - L_0 is termed the frequency dependent component
  - The parameter α is called the "path loss gradient" or exponent
  - The value of α determines how quickly the RSS falls with distance

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
- The received power is P_r
- The *path loss* is $L_p = P_t\,(\mathrm{dB}) - P_r\,(\mathrm{dB})$
- 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

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

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

  - 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

Summary: Free space loss

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

Free Space Propagation

- Notice that factor of 10 increase in distance
  - => 20 dB increase in path loss (20 dB/decade)

Distance	Path Loss at 880 MHz
1 km	91.29 dB
10 km	111.29 dB

- Note that higher the frequency the greater the path loss for a fixed distance

Distance	880 MHz	1960 MHz
1 km	91.29 dB	98.25 dB

7 dB greater path loss for PCS band compared to cellular band in the US

Example

- Consider Design of a Point-to-Point link connecting LANs in separate buildings across a freeway
  - Distance .25 mile
  - Line of Sight (LOS) communication
  - Spectrum Unlicensed – using 802.11b at 2.4GHz
  - Maximum transmit power of 802.11 AP is Pt = 24dBm
  - The minimum received signal strength (RSS) for 11 Mbps operation is -80 dBm
- Will the signal strength be adequate for communication?
- Given LOS is available can approximate propagation with Free Space Model as follows

Example (Continued)

- Example
  - Distance .25 mile ~ 400m
  - Receiver Sensitivity Threshold = - 80dBm

- The Received Power P_r is given by

$$P_r = P_t - \text{Path Loss}$$

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

$$= 24 - 21.98 + 20\log_{10}(3\times10^8/2.4\times10^9) - 20 \log_{10}(400)$$

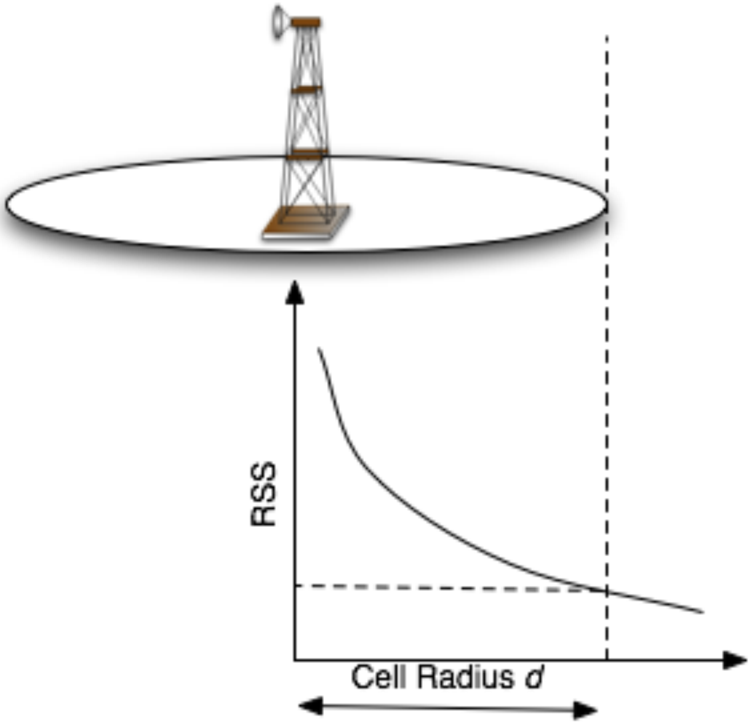
$$= 24 - 21.98 - 18.06 - 52.04$$

$$= 24 - 92.08 = -68.08 \text{ dBm}$$

P_r is well above the required -80 dBm for communication at the maximum data rate – so link should work fine

Cell/Radio Footprint

- The Cell is the area covered by a single transmitter
- Path loss model roughly determines the size of cell



General Formulation of Path Loss

- Depending on the environment, it is seen that the path loss (or the RSS) varies as some power of the distance from the transmitter *d*

$$P_r(d) \propto \left(\frac{P_t}{d^\alpha}\right) \quad \text{OR} \quad P_r(d) = \left(\frac{P_t}{L_0(d/d_0)^\alpha}\right)$$

- Here α is called the path-loss exponent or the path-loss gradient or the distance-power gradient
- The quantity L_0 is a constant that is computed at a reference distance d_0
  - This reference distance is 1m in indoor areas and 100m or 1 km in outdoor areas

More Comments

- Path loss is a function of a variety of parameters
  - Terrain
  - Frequency of operation
  - Antenna heights
- Extremely site specific
  - Varies depending on environment
    - Example: indoor Vs outdoor
    - Example: microcell Vs macrocell
    - Example: rural Vs dense urban
- Large number of measurement results are available for different scenarios, frequencies and sites
- Empirical models are popular

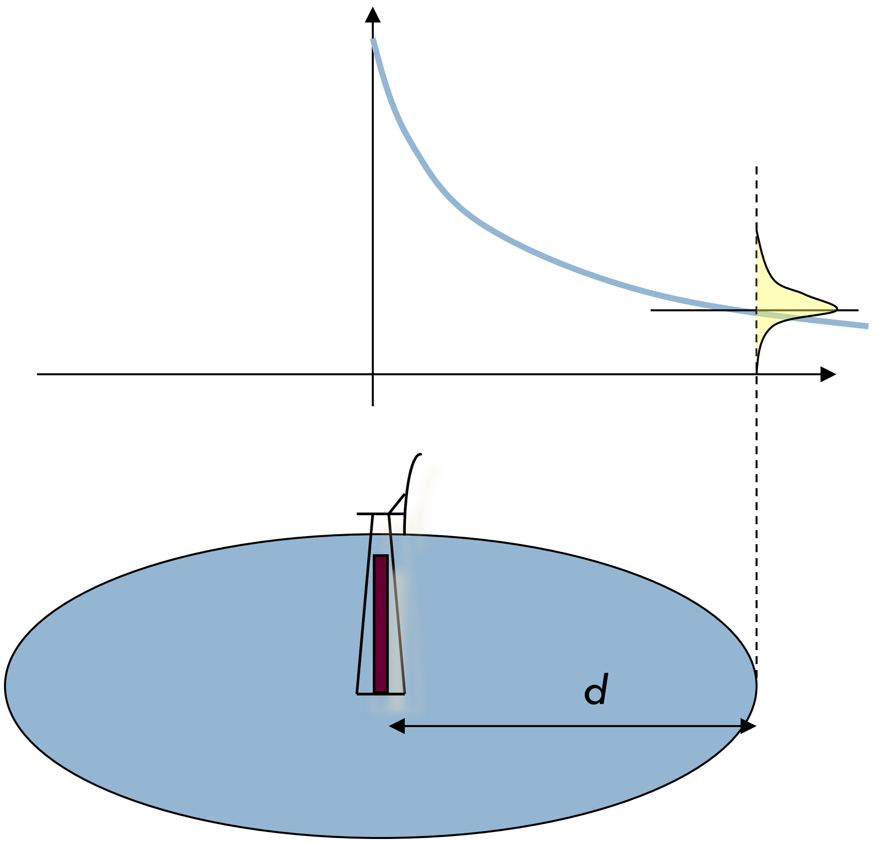
Environment Based Path Loss

- Basic characterization: $L_p = L_0 + 10\alpha \log_{10}(d)$
  - L_0 is frequency dependent component (often path loss at 1m)
  - The parameter α is called the "path loss gradient" or exponent
  - The value of α determines how quickly the RSS falls with d
- α determined by measurements in typical environment
  - For example
    - $\alpha = 2.5$ might be used for rural area
    - $\alpha = 4.8$ might be used for dense urban area

Shadow Fading

- Shadowing occurs when line of site is blocked
- Modeled by a random signal component X_σ
- $P_r = P_t - L_p + X_\sigma$

- Measurement studies show that X_σ can be modeled with a lognormal distribution ➔ normal in dB with mean = zero and standard deviation σ dB
- Thus at the "designed cell edge" only 50% of the locations have adequate RSS
- Since X_σ can be modeled in dB as normally distributed with mean = zero and standard deviation σ dB, σ determines the behavior



How shadow fading affects system design

- Typical values for σare
  - rural 3 dB, Suburban 6 dB, urban 8 dB, dense urban 10 dB
- Since X is normal in dB Pr is normal
  - $P_r = P_t - L_p + X_\sigma$
- Prob $\{P_r(d) > T\}$ can be found from a normal distribution table with mean P_r and σ
- In order to make at least Y% of the locations have adequate RSS
  - Reduce cell size
  - Increase transmit power
  - Make the receiver more sensitive

Cell Coverage modeling

- Simple path loss model based on environment used as first cut for planning cell locations
- Refine with measurements to parameterize model
- Alternately use ray tracing: approximate the radio propagation by means of geometrical optics- consider line of sight path, reflection effects, diffraction etc.
- CAD deployment tools widely used to provide prediction of coverage and plan/tune the network