251-0292: A Hand-on Introduction to Wireless Networks

Lectures 2 and 3: Physical Layer

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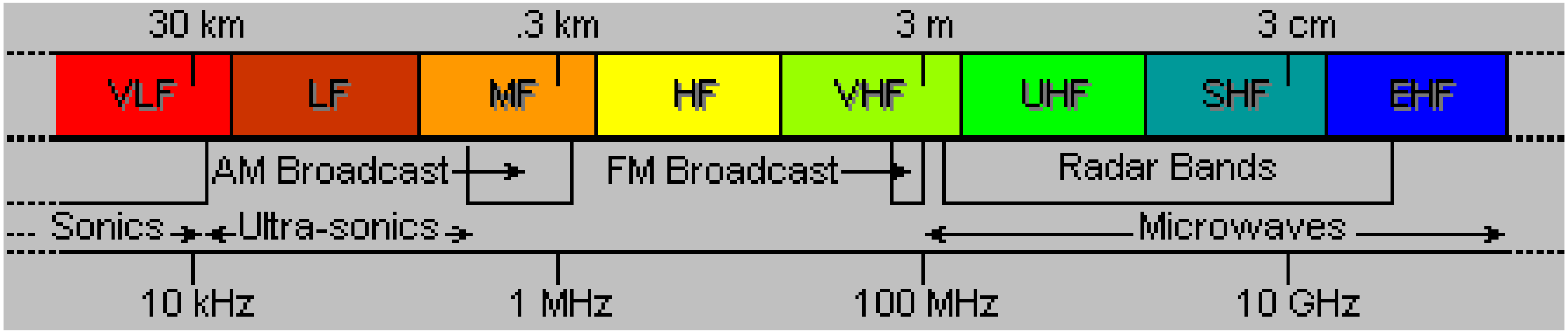
Outline

- RF introduction
  - » Time versus frequency view
  - » A cartoon view
- Modulation
- Spectrum and channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Channel coding

RF Introduction

- RF = Radio Frequency
  - » Electromagnetic signal that propagates through “ether”
  - » Ranges 3 KHz .. 300 GHz
  - » Or 100 km .. 0.1 cm (wavelength)



- Travels at the speed of light
- Can take both a time and a frequency view

Time-Domain View

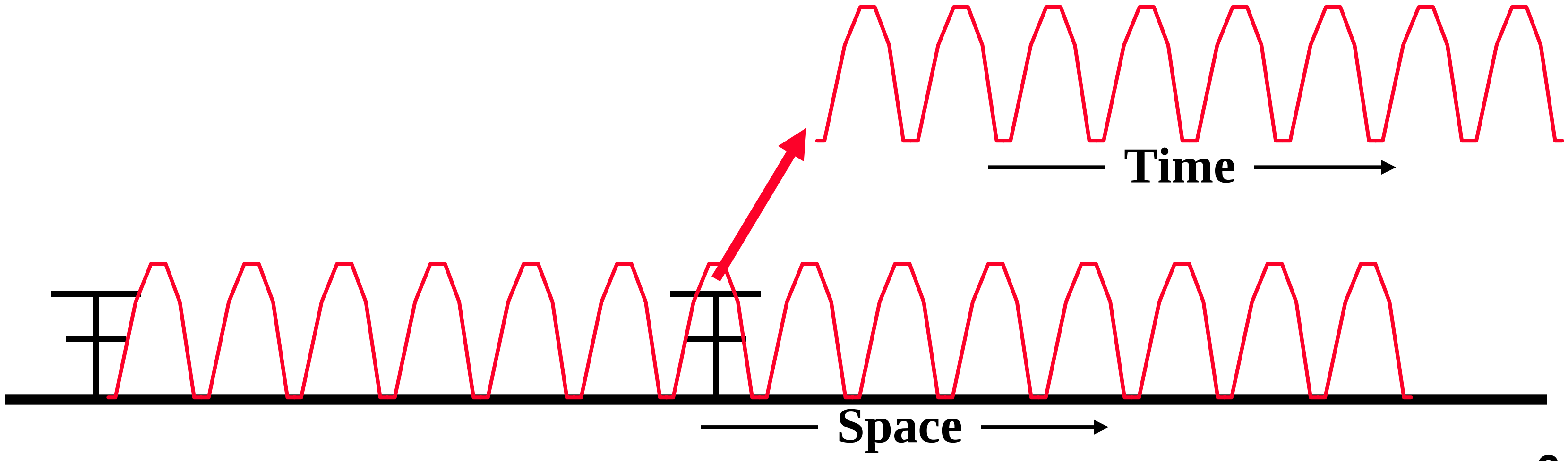
- Can be used to represent both an analog and a digital signal.
- Analog signal - signal intensity varies in a smooth fashion over time
  - » No breaks or discontinuities in the signal
  - » E.g. voice signal traveling over traditional phone line
- Digital signal - signal intensity maintains a constant level for some period of time and then changes to another constant level.
  - » E.g. stream of 1 and 0 values represented as “low” and “high” signal

Periodic versus Aperiodic Signals

- **Periodic signal - analog or digital signal pattern that repeats over time**
  - » $$s(t + T) = s(t)$$
    - – **where *T* is the period of the signal**
  - » **Allows us to take a frequency view**
- **Aperiodic signal - analog or digital signal pattern that doesn't repeat over time**
- **Can “make” an aperiodic signal periodic by taking a slice T and repeating it**
  - » **Often what we do implicitly**

Simple Example: sine wave

- RF signal travels at the speed of light
- Can look at a point in space: signal will change in time according to a sine function
- Can take a snapshot in time: signal will “look” like a sine function in space



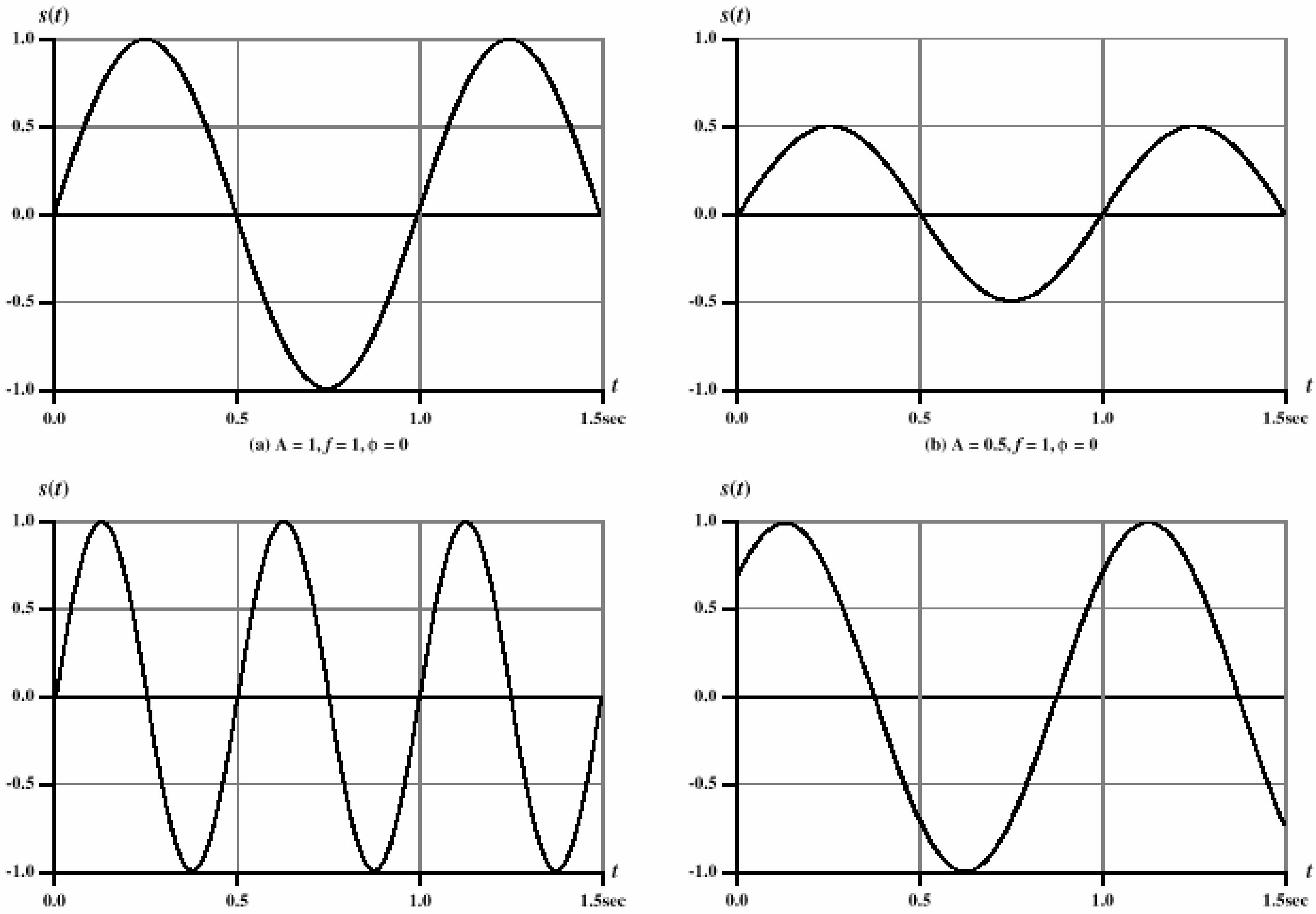
Key Parameters of (Periodic) Signal

- Peak amplitude (A) - maximum value or strength of the signal over time; typically measured in volts
- Frequency (f)
  - » Rate, in cycles per second, or Hertz (Hz) at which the signal repeats
- 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 a signal
- Wavelength (λ) - distance occupied by a single cycle of the signal
  - » Or, the distance between two points of corresponding phase of two consecutive cycles

Sine Wave Parameters

- **General sine wave**
  - » $s(t) = A \sin(2\pi f t + \phi)$
- **Example on next slide shows the effect of varying each of the three parameters**
  - » **(a) $A = 1$, $f = 1$ Hz, $\phi = 0$; thus $T = 1$s**
  - » **(b) Reduced peak amplitude; A=0.5**
  - » **(c) Increased frequency; $f = 2$, thus $T = ½$**
  - » **(d) Phase shift; $\phi = \pi/4$ radians (45 degrees)**
- **note: 2π radians = 360° = 1 period**

Space and Time View Revisited



(a) A = 1, f = 1, ϕ = 0

(b) A = 0.5, f = 1, ϕ = 0

(c) A = 1, f = 2, ϕ = 0

(d) A = 1, f = 1, ϕ = π/4

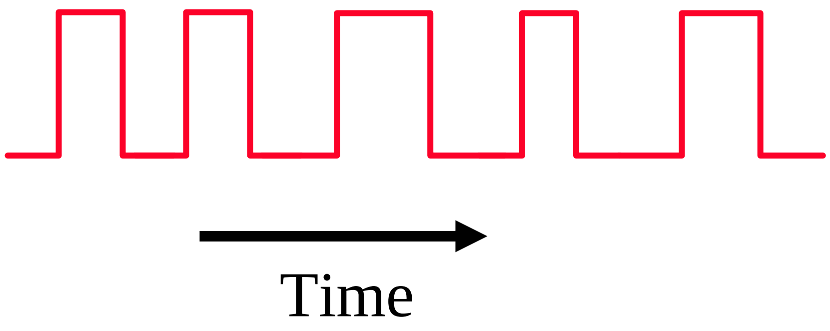
$$s(t) = A \sin(2\pi ft + \phi)$$

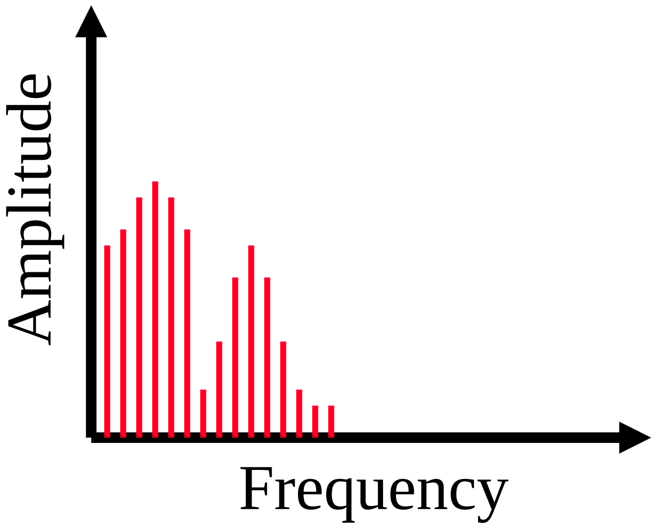
Frequency-Domain Concepts

- **Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases**
- **The period of the total signal is equal to the period of the fundamental frequency**
  - » **All other frequencies are an integer multiple of the fundamental frequency**

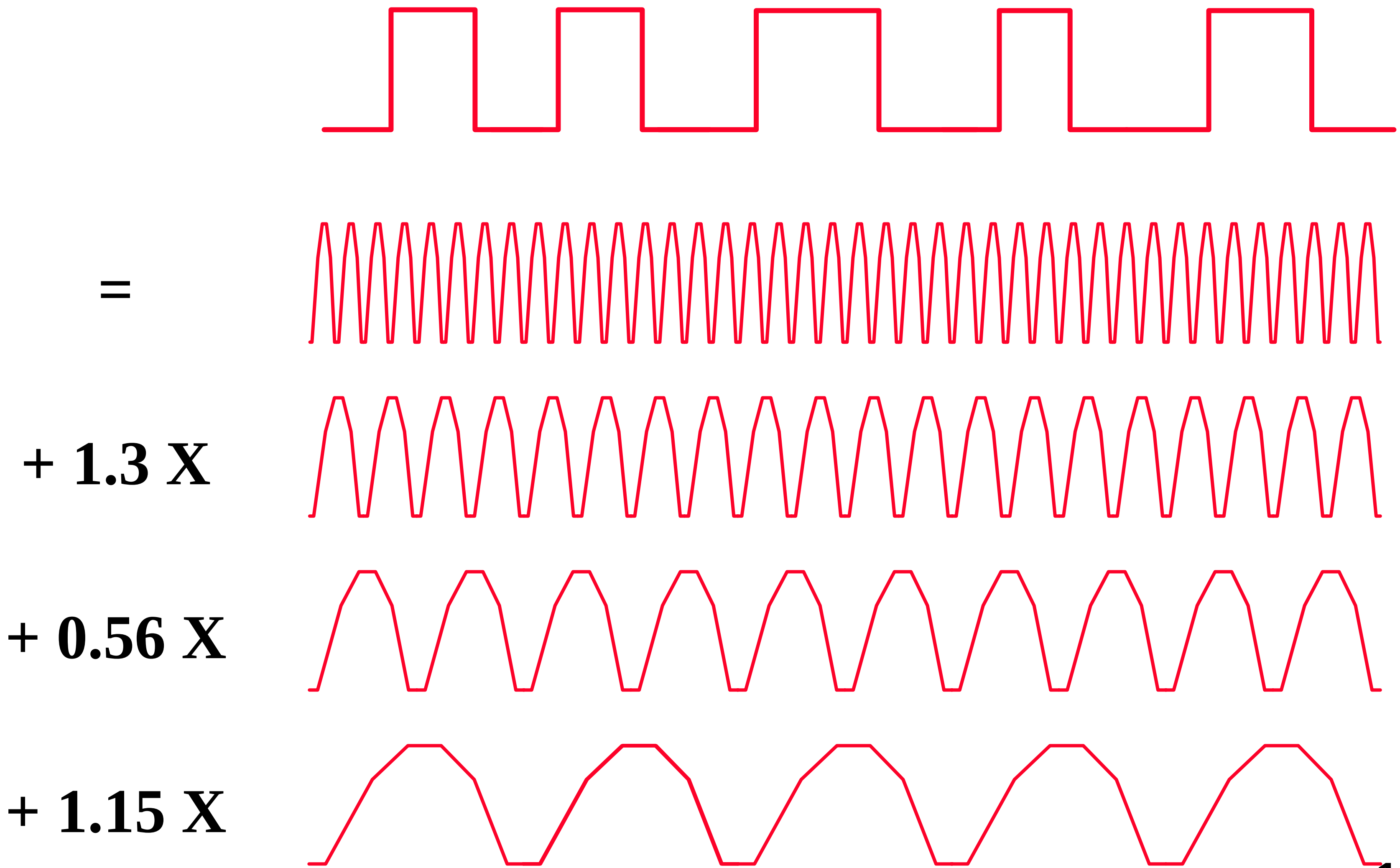
The Frequency Domain

- A (periodic) signal can be viewed as a sum of sine waves of different strengths.
  - » Corresponds to energy at a certain frequency
- Every signal has an equivalent representation in the frequency domain.
  - » What frequencies are present and what is their strength (energy)
- Again: Similar to radio and TV signals.





Signal = Sum of Sine Waves

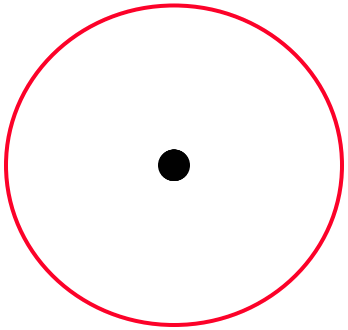


Frequency-Domain Concepts

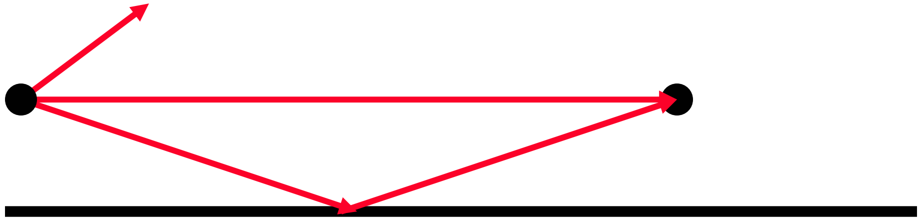
- Fundamental frequency - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- Spectrum - range of frequencies that a signal contains
- Absolute bandwidth - width of the spectrum of a signal
- Effective bandwidth (or just bandwidth) - narrow band of frequencies that most of the signal's energy is contained in

Two Cartoon Views of an Electromagnetic Signal

- Both are real in some way
- Think of it as energy that radiates from an antenna and is picked up by another antenna.
  - » Helps explain properties such as attenuation



- Can also view it as a "ray" that propagates between two points.
  - » Helps explain properties such as reflection and multipath



Outline

- RF introduction
- Modulation
  - » Analog versus digital signals
  - » Forms of modulation
  - » Baseband versus carrier modulation
- Spectrum and channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Channel coding

Analog and Digital Information

- Initial RF use was for analog information
  - » Radio and TV stations
  - » The information that is sent is of a continuous nature
- In digital transmission, the transmitted information consists of discrete units (e.g. bits)
  - » Data networks, cell phones
  - » Focus of this course
- We can also send analog information as digital data
  - » Sample the signal, i.e. analog -> digital -> analog
  - » Cell phones, …
  - » Why?
  - » Also digital -> analog -> digital (e.g. modem)

Analog and Digital Signals

- Sender changes the signal, e.g. the amplitude, in a way that receiver can recognize
- Analog: a continuously varying electromagnetic wave that may be propagated over a variety of media, depending on frequency
  - » Copper wire media (twisted pair and coaxial cable)
  - » Fiber optic cable
  - » Atmosphere or space propagation
- Digital: a sequence of pulses representing bits sent over a copper transmission medium
  - » Optical fiber or wireless a bit trickier since they inherently only transfer higher frequencies – see later
  - » Less susceptible to noise but can suffer other effects such as attenuation

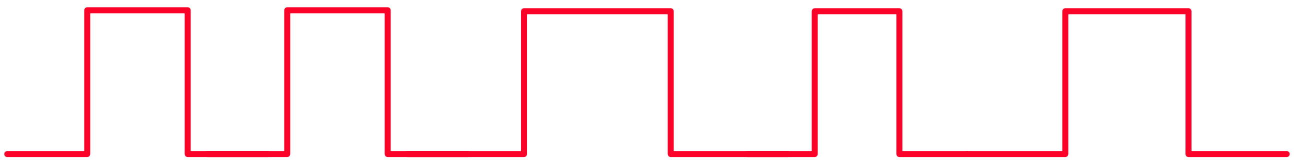
Analog versus Digital Transmission

- **Analog: transmit analog signals without regard to content**
  - » **Attenuation limits length of transmission link**
  - » **Cascaded amplifiers boost signal's energy for longer distances but cause distortion**
    - – **Analog data can tolerate (some) distortion**
    - – **But introduces errors in digital data**
- **Digital: can recognize the content of signal**
  - » **Attenuation endangers integrity of data**
  - » **Repeaters can recover the signal and retransmit**
    - – **Also true of analog signal that carries digital data: repeater can recover signal and generate new clean analog signal**

Digital Signal Modulation

- Sender changes the nature of the signal in a way that the receiver can recognize
- Amplitude modulation (AM): change the strength of the carrier based on information
  - » High values -> stronger signal
- Frequency (FM) and phase modulation (PM): change the frequency or phase of the signal
  - » Frequency or Phase shift keying
- Digital versions are sometimes called “shift keying”
  - » Amplitude (ASK), Frequency (FSK), Phase (PSK) Shift Keying
- Discussed later in more detail

Amplitude and Frequency Modulation



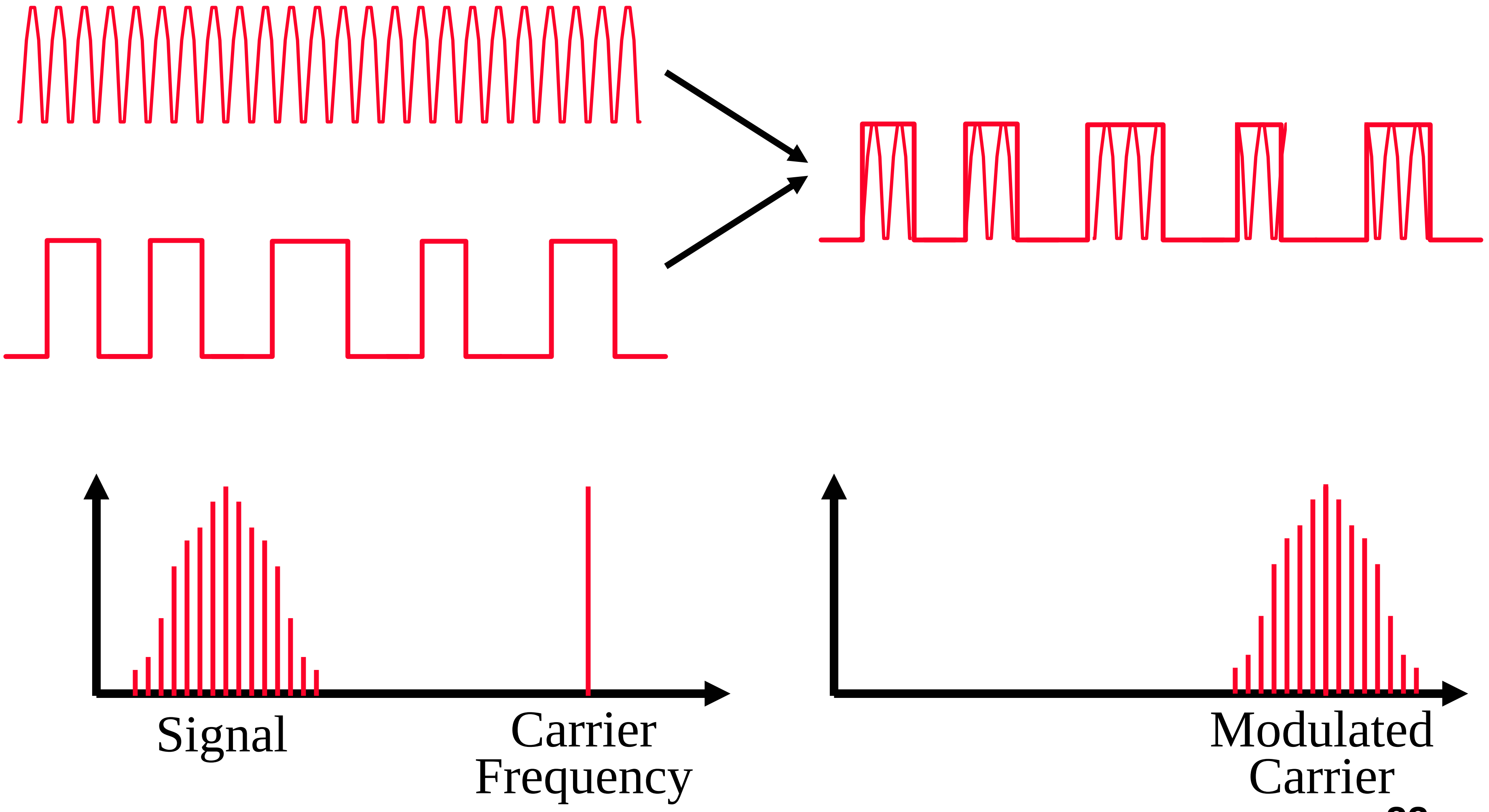
0 0 1 1 0 0 1 1 0 0 0 1 1 1 0 0 0 1 1 0 0 0 1 1 1 0

0 1 1 0 1 1 0 0 0 1

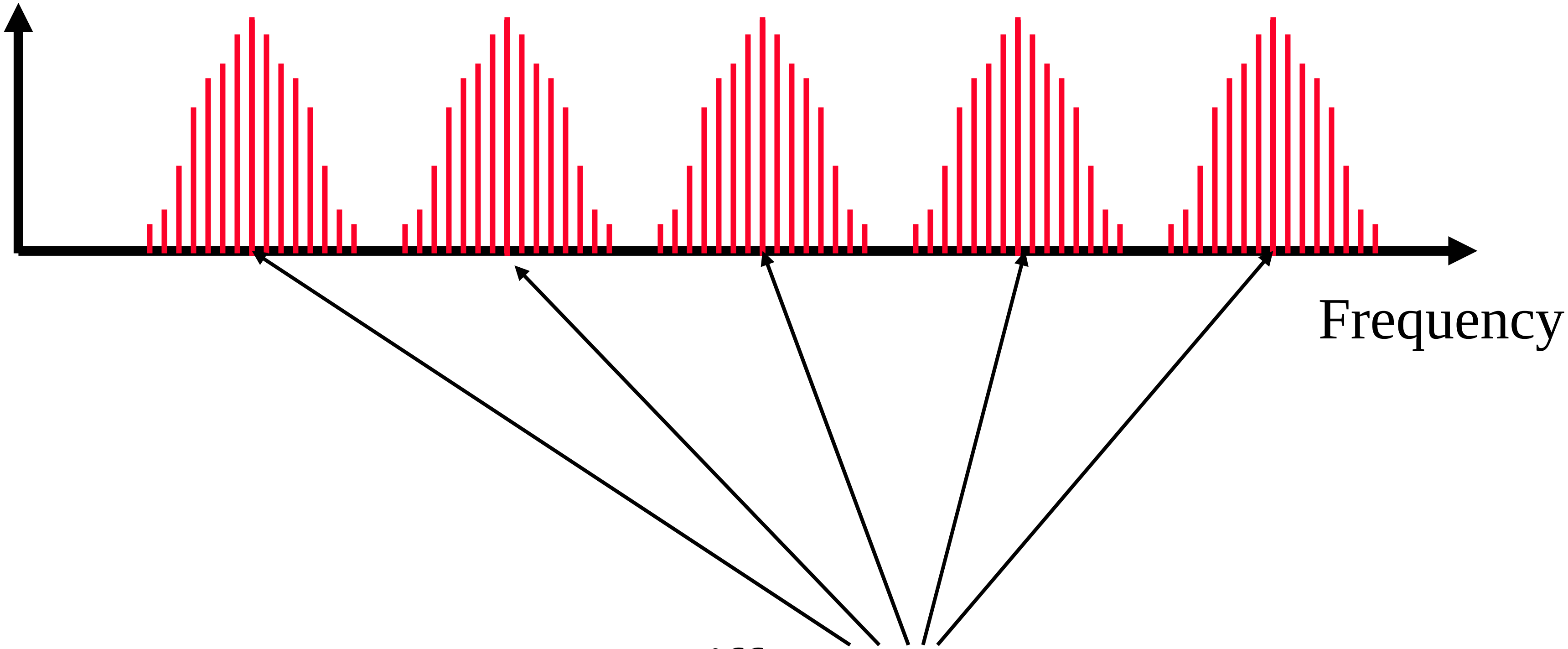
Baseband versus Carrier Modulation

- Baseband modulation: send the “bare” signal
  - » Use the lower part of the spectrum
- Baseband modulation has limited use
  - » Everybody competes – only makes sense for point-to-point links, but unattractive for wireless
  - » Use of higher frequencies requires transmission of a single high bandwidth signal
  - » Some media only transmit higher frequencies, e.g. optical
- Carrier modulation: use the (information) signal to modulate a higher frequency (carrier) signal
  - » Can be viewed as the product of the two signals
  - » Corresponds to a shift in the frequency domain
- Also applies to frequency and phase modulation
  - » E.g. change frequency of the carrier instead of its amplitude

Amplitude Carrier Modulation



Multiple Users Can Share the Ether



**Different users use
Different carrier frequencies**

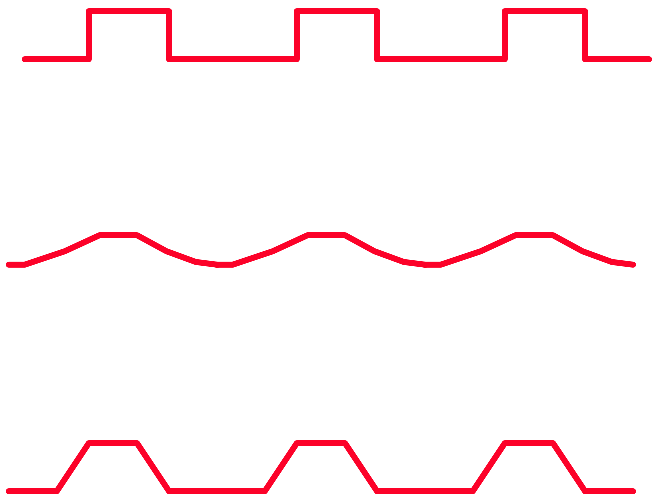
Outline

- RF introduction
- Modulation
- Spectrum and channel capacity
  - » Channel capacity
  - » Spectrum considerations
- Antennas and signal propagation
- Equalization and diversity
- Channel coding

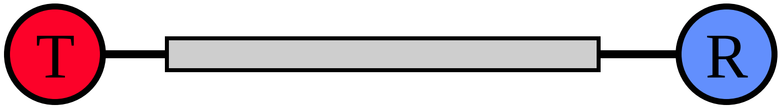
Relationship between Data Rate and Bandwidth

- 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 of convey a very interesting TV channel

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

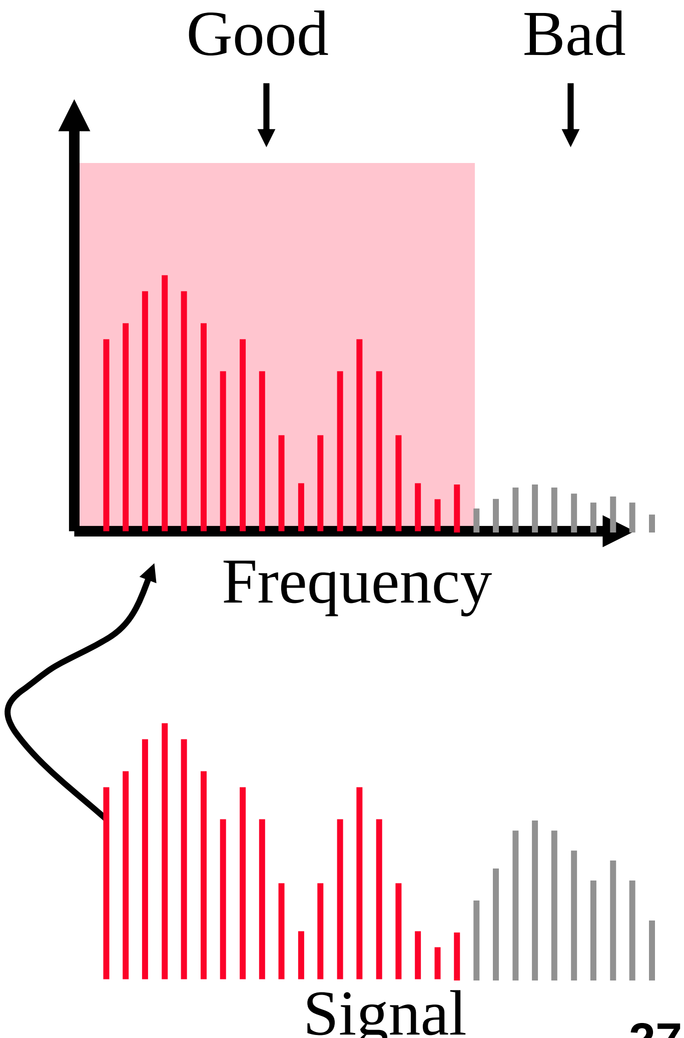


- Channels have a limit on the type of signals it can carry
  - » Good transmission of signals only in certain frequency range
  - » Signals outside of that range get distorted, e.g. attenuated
- Distortion can make it hard for receiver to extract the information
  - » It is beneficial to match the signal to the channel
  - » Limits the throughput of the channel



Transmission Channel Considerations

- Example: grey frequencies get attenuated significantly
- For wired networks, channel limits are an inherent property of the channel
  - » Different types of fiber and copper have different properties
- As technology improves, these parameters change, even for the same wire
  - » Thanks to our EE friends
- For wireless networks, limits are often imposed by policy
  - » Can only use certain part of the spectrum



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)**

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

- **A high SNR means a high-quality signal, low number of required intermediate repeaters**
- **SNR sets upper bound on achievable data rate**

Shannon Capacity Formula

- Equation: $$C = B\log_2\left(1+\mathrm{SNR}\right)$$
- Represents theoretical maximum that can be achieved
- In practice, only much lower rates achieved
  - » Formula assumes white noise (thermal noise)
  - » Impulse noise is not accounted for
  - » Attenuation distortion or delay distortion 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.

Example of Nyquist and Shannon Formulations

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

$$B = 4\,\text{MHz} - 3\,\text{MHz} = 1\,\text{MHz}$$

$$\text{SNR}_{\text{dB}} = 24\,\text{dB} = 10\log_{10}(\text{SNR})$$

$$\text{SNR} = 251$$

- **Using Shannon's formula**

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

Example of Nyquist and Shannon Formulations

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

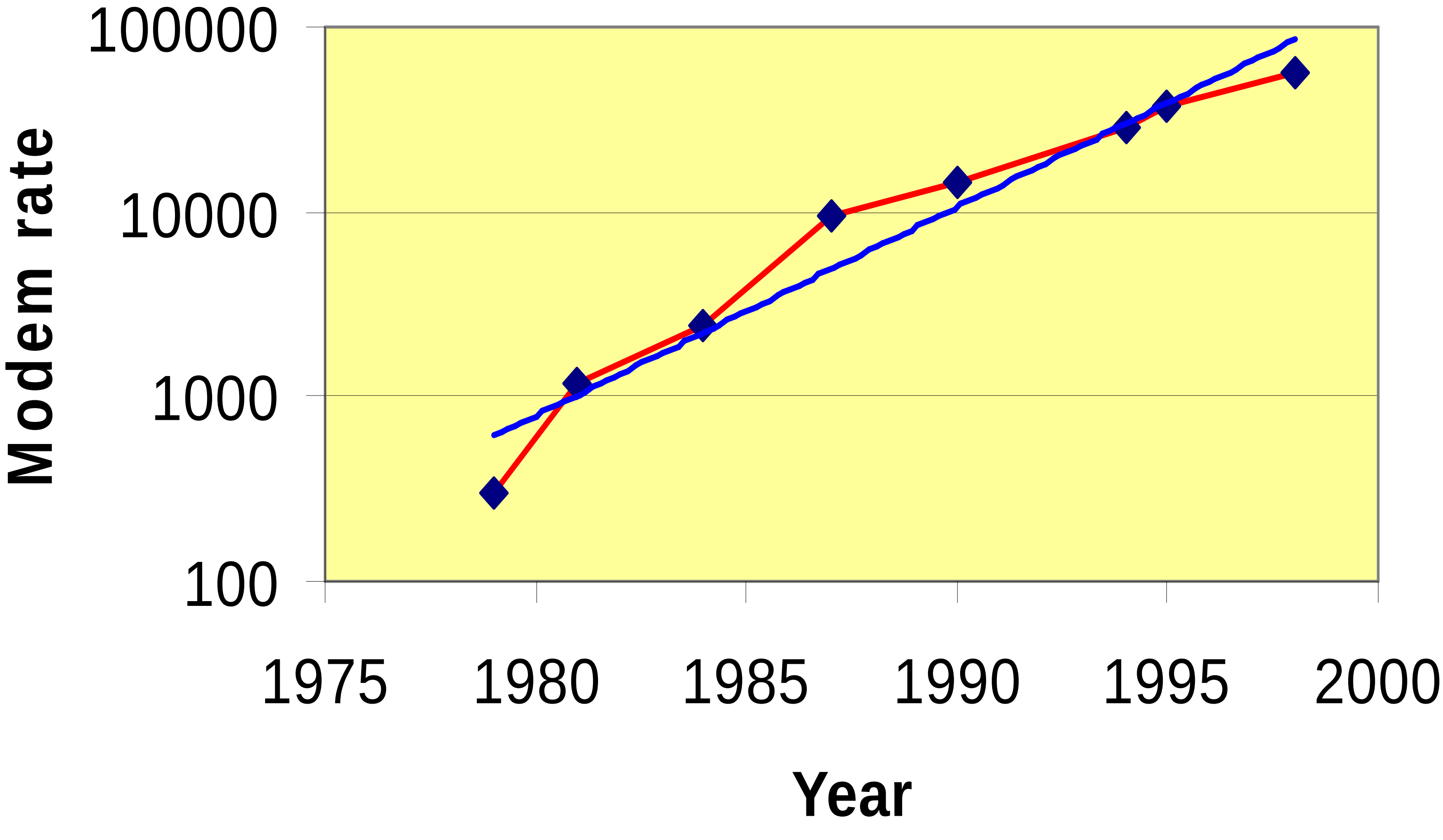
$$C = 2B\log_2 M$$

$$8\times10^6 = 2\times\left(10^6\right)\times\log_2 M$$

$$4 = \log_2 M$$

$$M = 16$$

Example Impact of Technology: Modem Rates



Classifications of Transmission Media

- **Copper: twisted pair versus coax cable**
  - » **Variety of modulation techniques are used**
- **Fiber: modulate an optical signal**
  - » **Lots of capacity available!**
  - » **Typically uses simple modulation schemes**
- **Wireless: no solid medium to guided signal**
  - » **Wide variety of distances: frequencies, distances, …**
  - » **Often uses very aggressive modulation techniques (later)**

General Frequency Ranges

- Microwave frequency range
  - » 1 GHz to 40 GHz and higher
  - » Directional beams possible
  - » Suitable for point-to-point transmission
  - » Used for satellite communications
- Radio frequency range
  - » 30 MHz to 1 GHz
  - » Suitable for omnidirectional applications
- Infrared frequency range
  - » Roughly, $3x10^{11}$ to $2x10^{14}$ Hz
  - » Useful in local point-to-point multipoint applications within confined areas

Wireless Communication Looks Pretty Easy?

- 300 GHz is huge amount of spectrum!
  - » Spectrum can also be reused in space
- Not quite that easy:
  - » Most of it is hard or expensive to use!
  - » Noise and interference limits efficiency
  - » Most of the spectrum is allocated by FCC
- FCC controls who can use the spectrum and how it can be used.
  - » Need a license for most of the spectrum
  - » Limits on power, placement of transmitters, coding, ..
  - » Need rules to optimize benefit: guarantee emergency services, simplify communication, return on capital investment, …

Spectrum Allocation

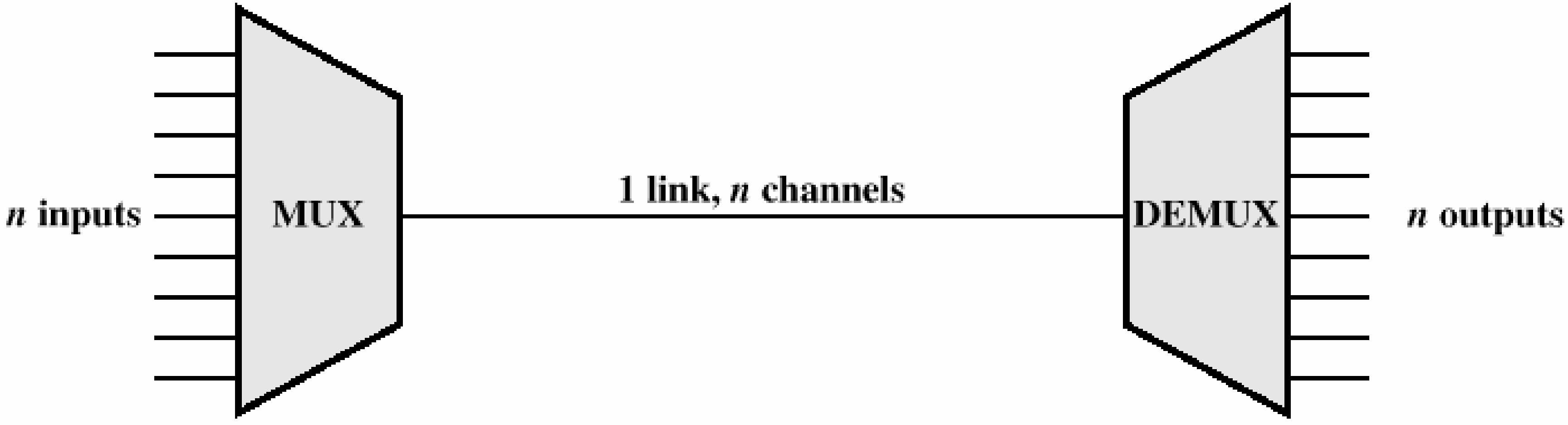
See:

http://www.ntia.doc.gov/osmhome/allochrt.html

- **Most bands are allocated.**
- **Industrial, Scientific, and Medical (ISM) bands are "unlicensed".**
  - **But still subject to various constraints on the operator, e.g. 1 W output**
  - **433-868 MHz (Europe)**
  - **902-928 MHz (US)**
  - **2.4000-2.4835 GHz**
  - **Unlicensed National Information Infrastructure (UNII) band is 5.725-5.875 GHz**

Multiplexing

- Capacity of transmission medium usually exceeds capacity required for transmission of a single signal
- Multiplexing - carrying multiple signals on a single medium
  - » More efficient use of transmission medium

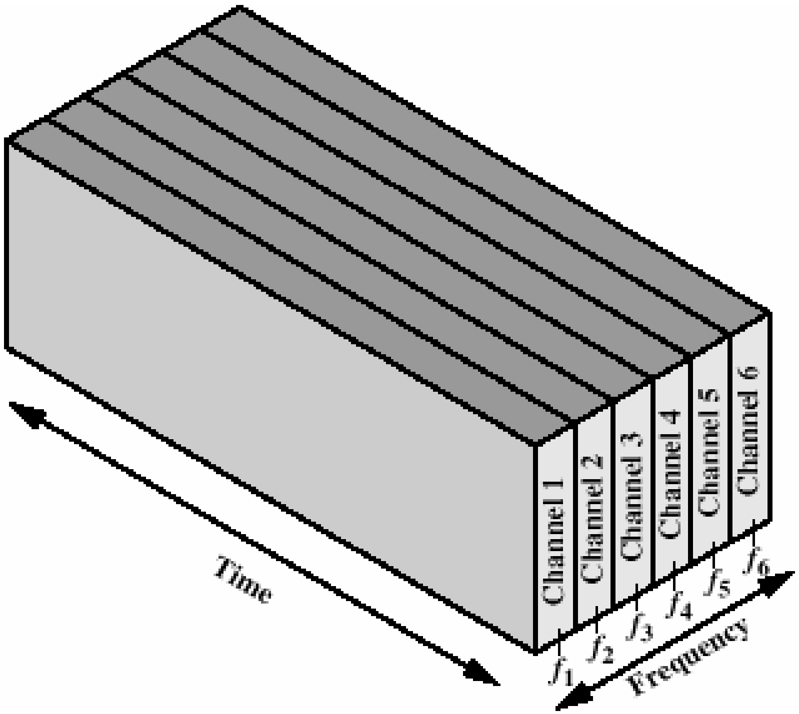


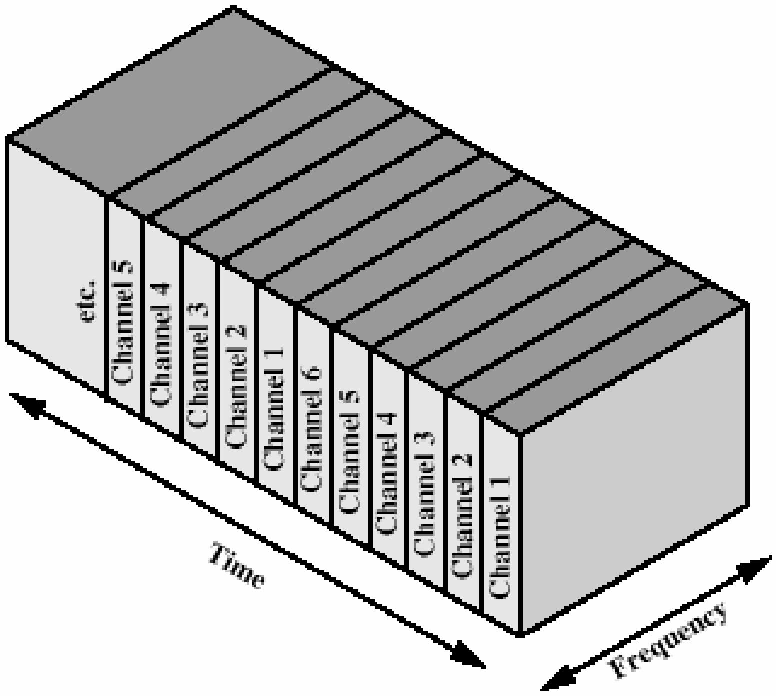
Reasons for Widespread Use of Multiplexing

- **Cost per kbps of transmission facility declines with an increase in the data rate**
- **Cost of transmission and receiving equipment declines with increased data rate**
- **Most individual data communicating devices require relatively modest data rate support**

Multiplexing Techniques

- **Frequency-division multiplexing (FDM)**
  - » **divide the capacity in the frequency domain**
- **Time-division multiplexing (TDM)**
  - » **Divide the capacity in the time domain**
  - » **Fixed or variable length time slices**





Outline

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

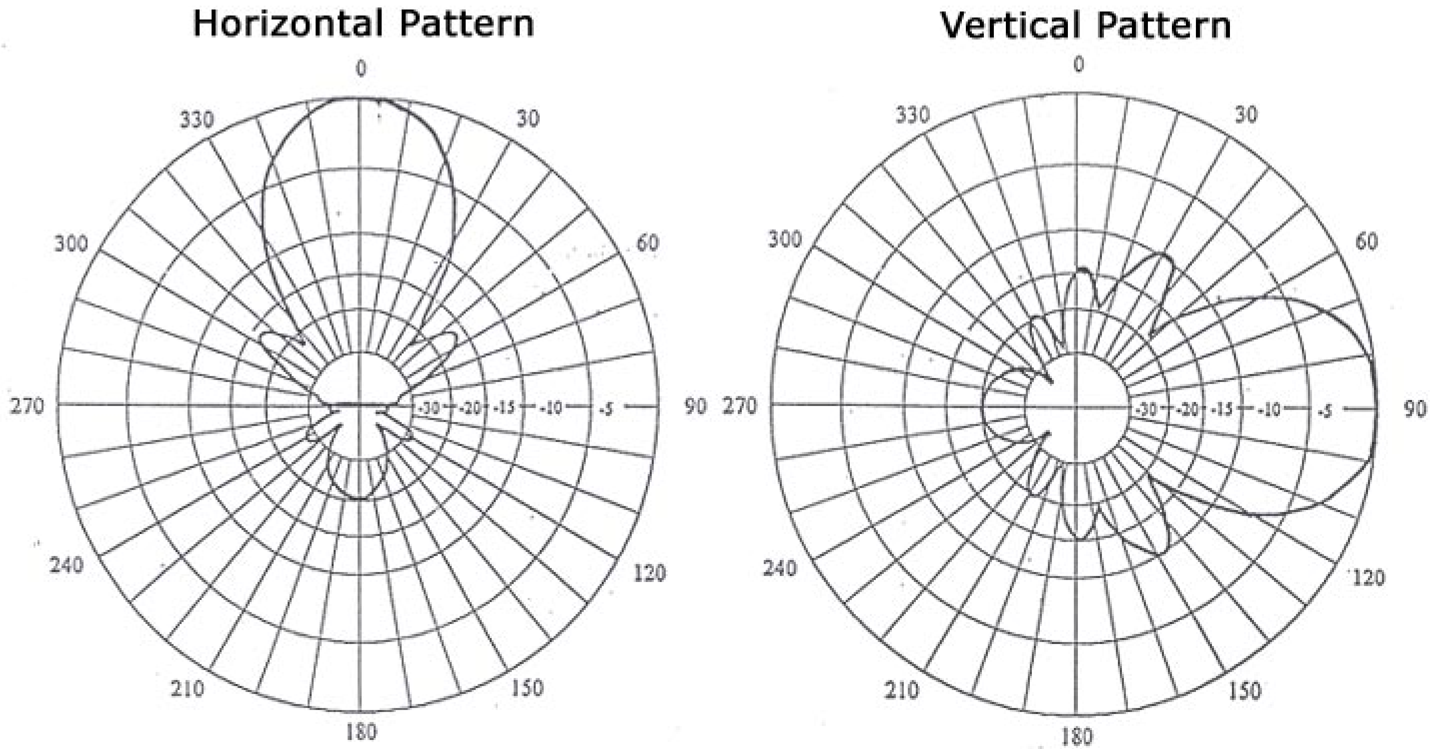
What is an Antenna?

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

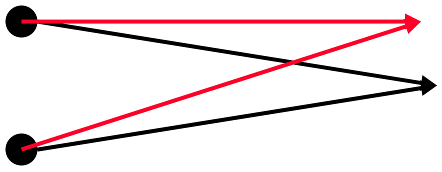
Directional Antenna Properties

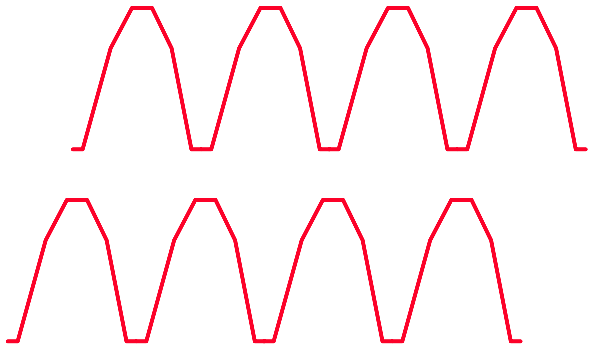


- **dBi: antenna gain in dB relative to an isotropic antenna with the same power.**
  - » **Example: an 8 dBi Yagi antenna has a gain of a factor of 6.3 (8 db = 10 log 6.3)**

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, …





Propagation Modes

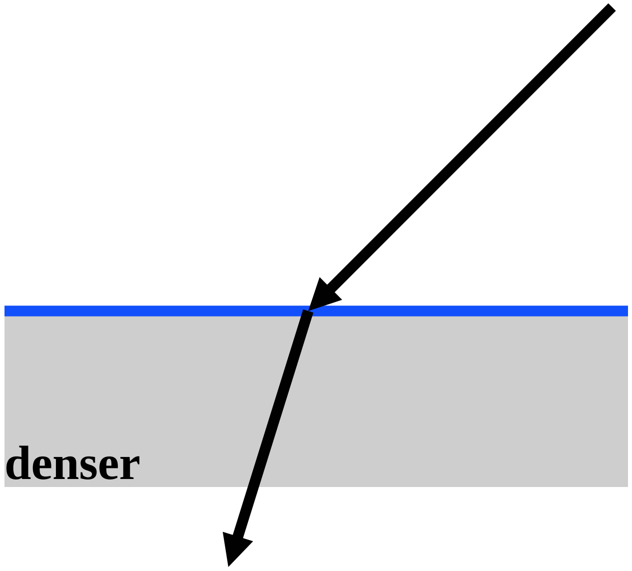
- **Line-of-sight (LOS) propagation.**
  - » **Most common form of propagation**
  - » **Happens above ~ 30 MHz**
  - » **Subject to many forms of degradation (next set of slides)**
- **Ground-wave propagation.**
  - » **More or less follows the contour of the earth**
  - » **For frequencies up to about 2 MHz, e.g. AM radio**
- **Sky wave propagation.**
  - » **Signal "bounces" off the ionosphere back to earth – can go multiple hops**
  - » **Used for amateur radio and international broadcasts**

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.
  - » Part of the signal is redirected
- Multi-path effects: multiple copies of the signal interfere with each other.
  - » Similar to an unplanned directional antenna
- Mobility: moving receiver causes another form of self interference.
  - » Node moves ½ wavelength -> big change in signal strength

Refraction

- Speed of EM signals depends on the density of the material
  - » Vacuum: 3 x 10^8 m/sec
  - » Denser: slower
- Density is captured by refractive index
- Explains "bending" of signals in some environments
  - » E.g. sky wave propagation
  - » But also local, small scale differences in the air



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 depends on frequency: higher loss with higher frequency.**
  - » **But careful: antenna gain depends on frequency too**
    - – **For fixed antenna area, loss decreases with frequency**
  - » **Can cause distortion of signal for wide-band signals**

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

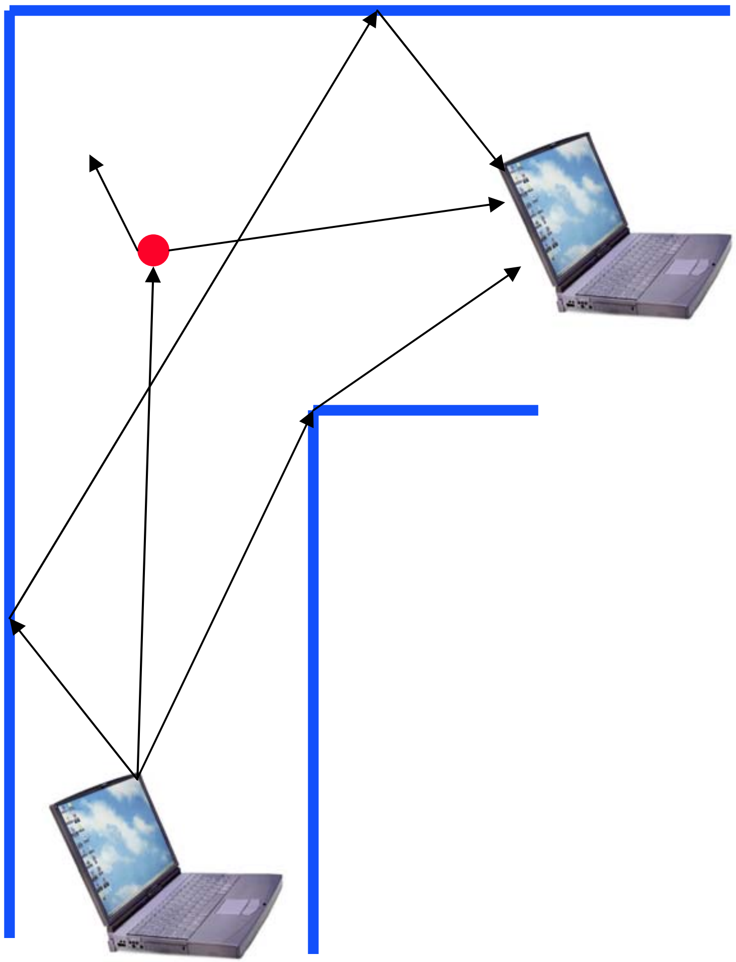
Fairly Predictable
➢Can be planned for or avoided

Other LOS Factors

- **Absorption of energy in the atmosphere.**
  - » **Very serious at specific frequencies, e.g. water vapor (22 GHz) and oxygen (60 GHz)**
  - » **Obviously objects also absorb energy**

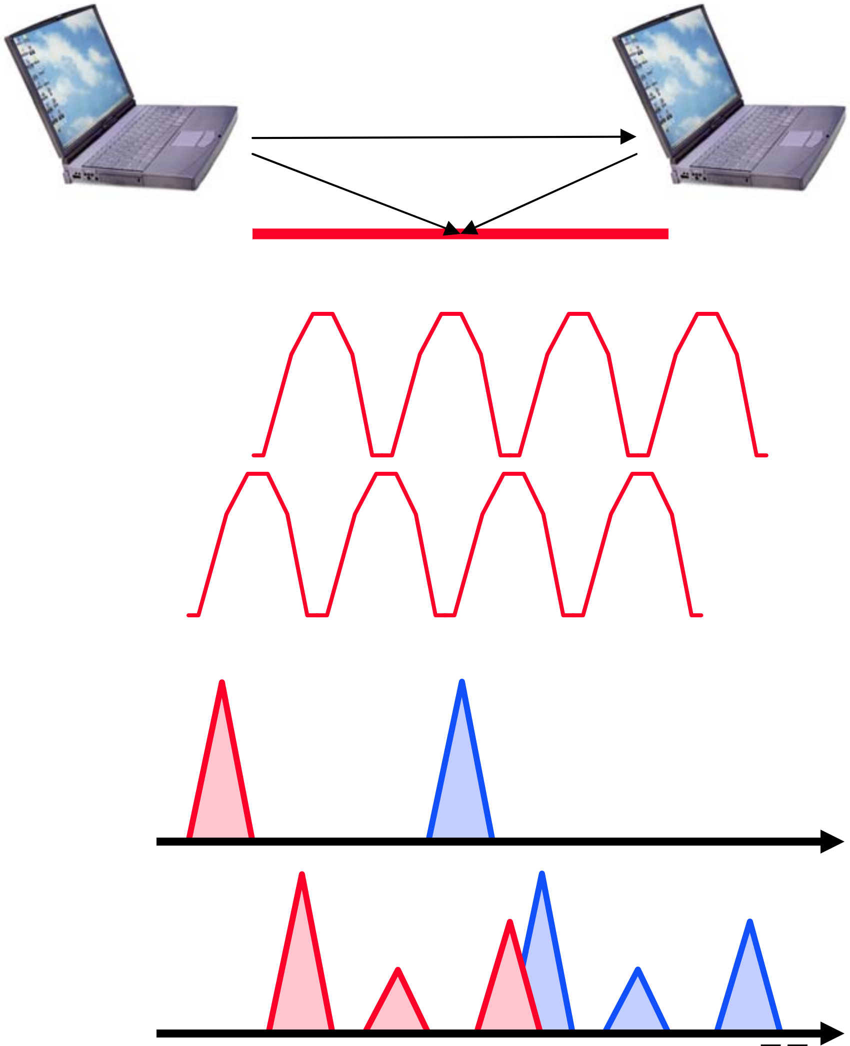
Propagation Mechanisms

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

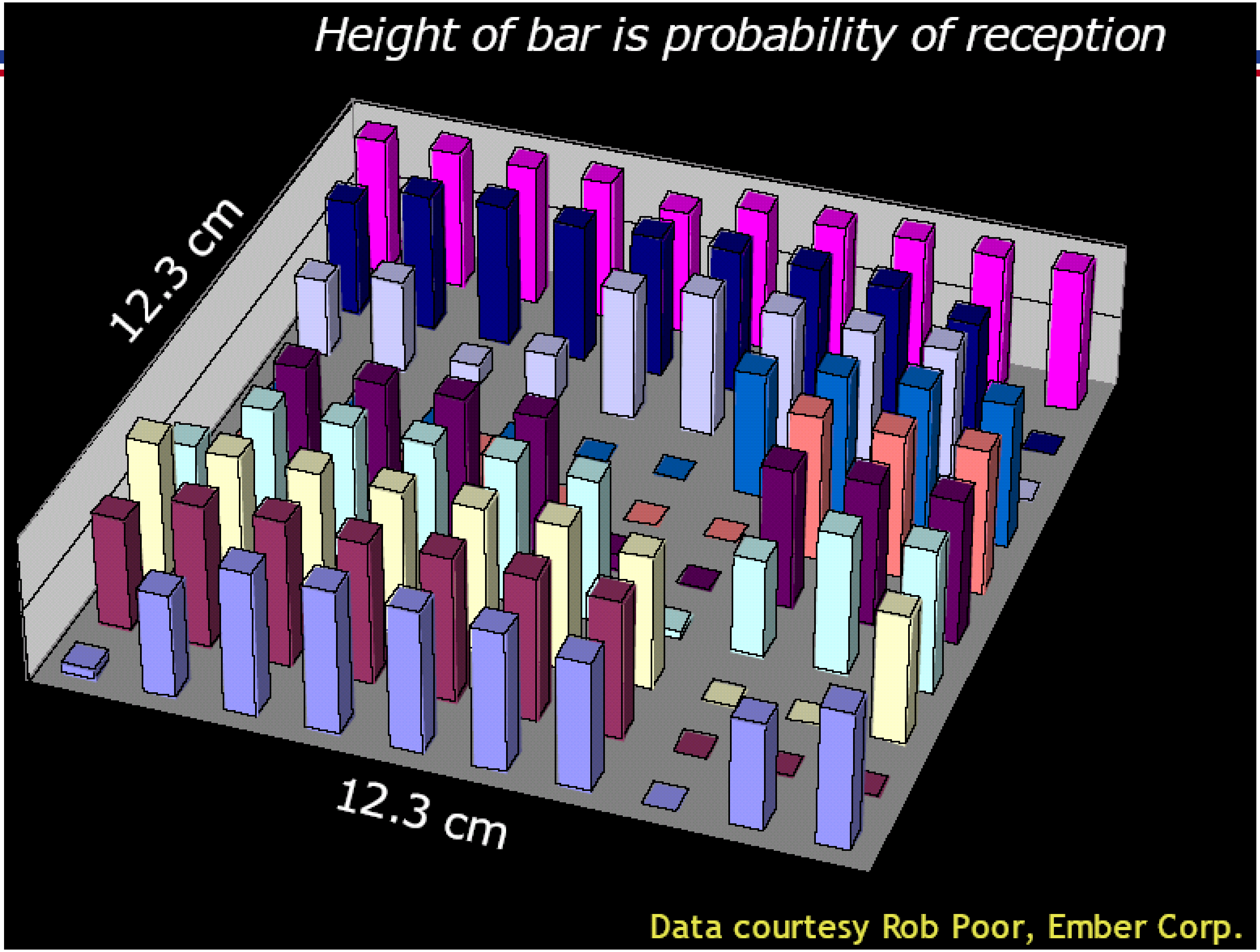


Multipath Effects

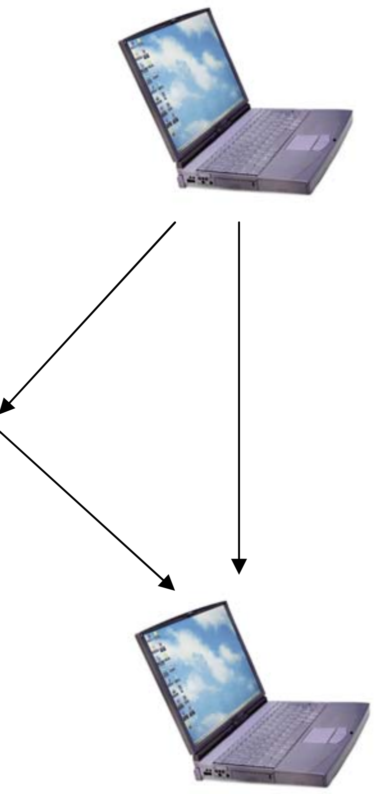
- Receiver receives multiple copies of the signal, each following a different path.
- Copies can either strengthen or weaken each other.
  - » Depends on whether they are in our out of phase
- Small changes in location can result in big changes in signal strength.
  - » Short wavelengths, e.g. 2.4 GHz -> 12 cm
- Difference in path length can cause intersymbol interference (ISI).

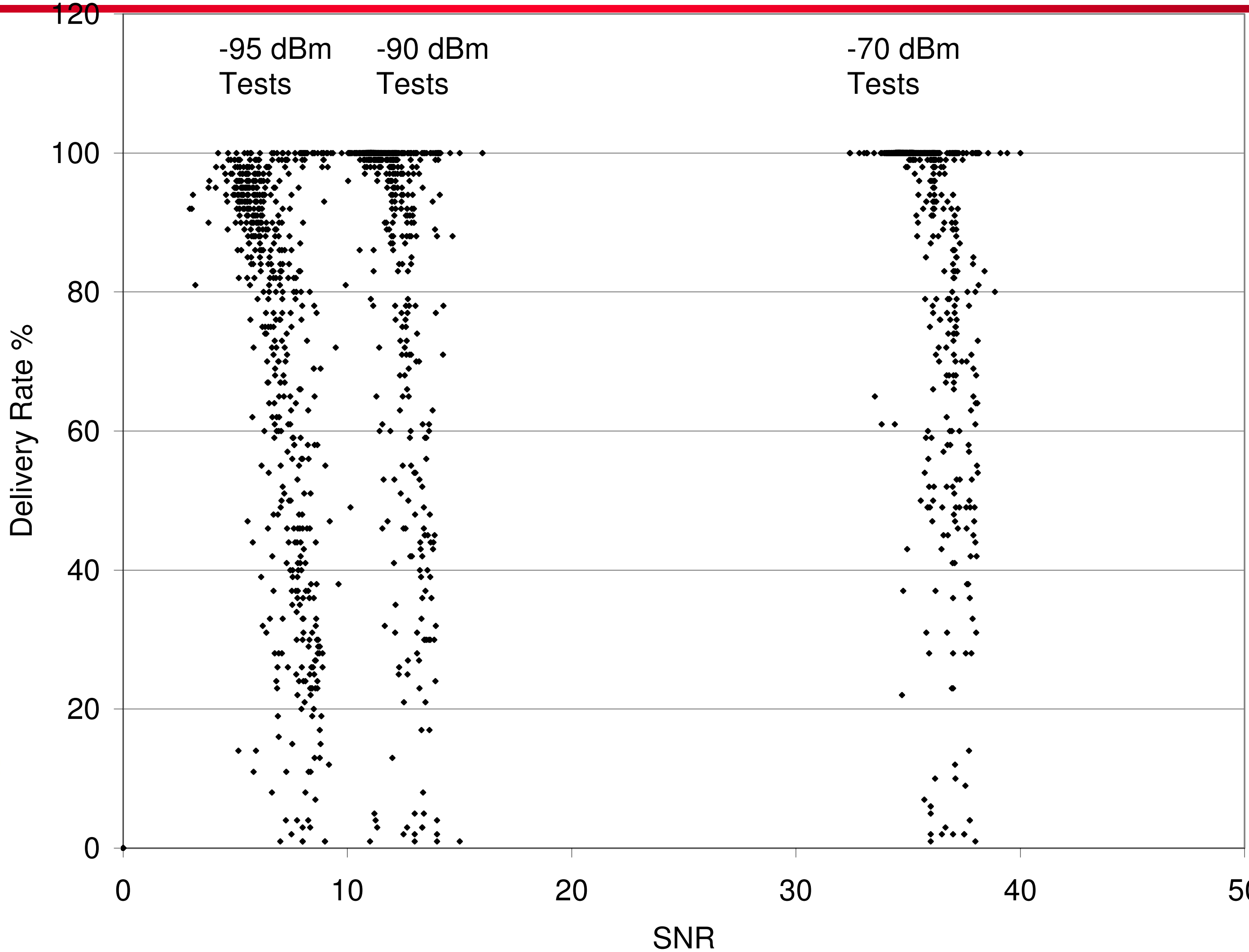


Example


Height of bar is probability of reception
12.3 cm
12.3 cm
Data courtesy Rob Poor, Ember Corp.

Multipath: “Random” Delivery Rates

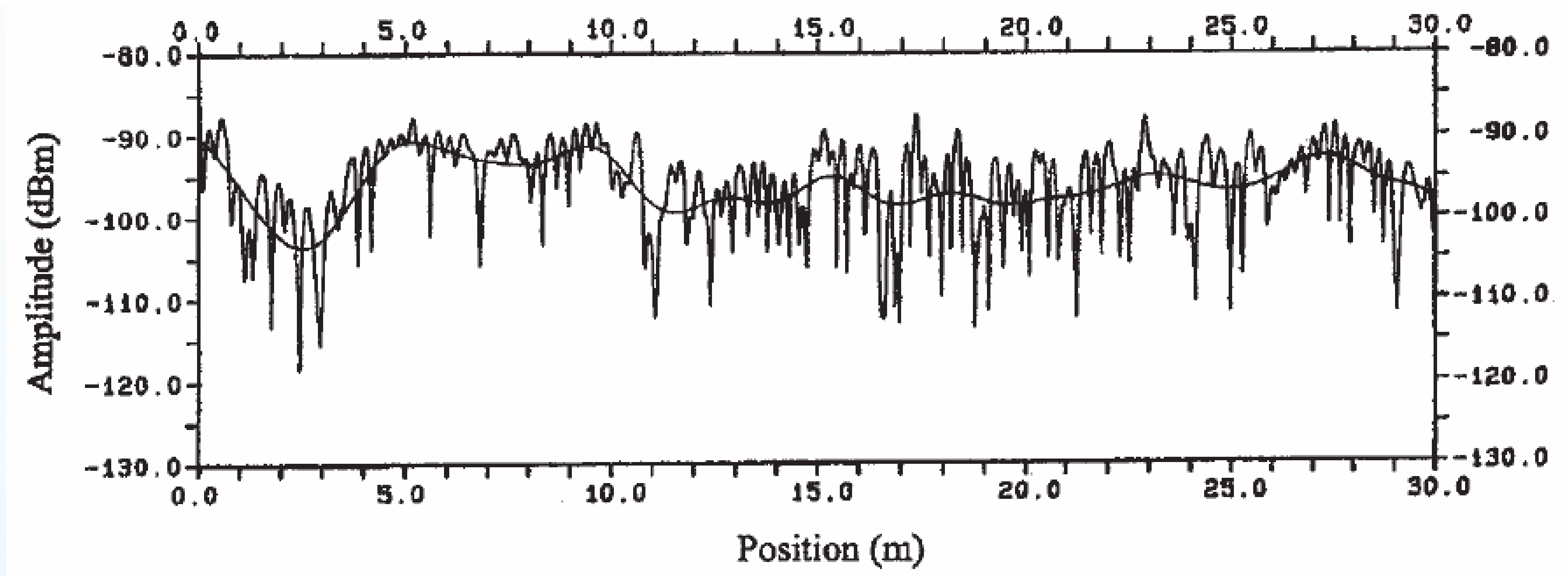




Fading in the Mobile Environment

- Fading: time variation of the received signal strength caused by changes in the transmission medium or paths.
  - » Rain, moving objects, moving sender/receiver, …
- Fast versus slow fading.
  - » Fast: changes in distance of about half a wavelength – result in big fluctuations in the instantaneous power
  - » Slow: changes in larger distances affects the paths – result in a change in the average power levels around which the fast fading takes place
- Selective versus non-selective (flat) fading.
  - » Does the fading affect all frequency components equally
  - » Region of interest is the spectrum used by the channel

Fading - Example



- Frequency of 910 MHz or wavelength of about 33 cm

Fading Channel Models

- **Statistical distribution that captures the properties of classes of fading channels.**
- **Raleigh distribution: multiple indirect paths but no dominating, direct LOS path.**
  - » **E.g. urban environment with large cells, in buildings**
- **Ricean distribution: LOS path plus indirect paths.**
  - » **Open space or small cells**