

# 15-496 : A Hand-on Introduction to Wireless Networks

## Lectures 2: Physical Layer

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<http://www.cs.cmu.edu/~prs/wireless08/>

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## Outline

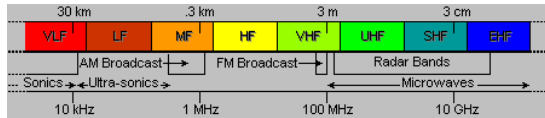
- RF introduction
  - » Time versus frequency view
  - » A cartoon view
- Modulation and multiplexing
- Spectrum and channel capacity
- Antennas and signal propagation
- Equalization and diversity
- Channel coding

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## 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

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## Time Domain View: Periodic versus Aperiodic Signals

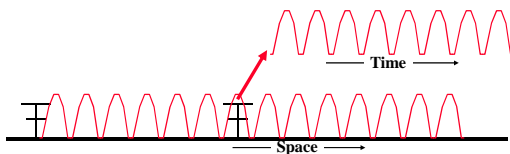
- Periodic signal - analog or digital signal pattern that repeats over time
  - »  $s(t+T) = s(t)$ 
    - where  $T$  is the period of the signal
  - » Allows us to take a frequency view
- Aperiodic signal - analog or digital signal pattern that doesn't repeat over time
- Can "make" an aperiodic signal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

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## 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



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## 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 ( $\phi$ ) - measure of the relative position in time within a single period of a signal
- Wavelength ( $\lambda$ ) - distance occupied by a single cycle of the signal
  - » Or, the distance between two points of corresponding phase of two consecutive cycles

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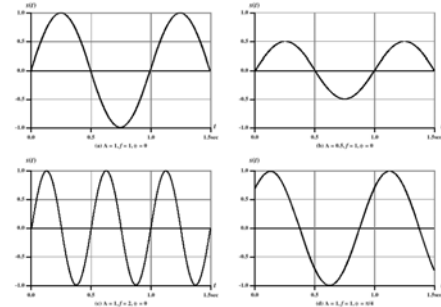
## Sine Wave Parameters

- **General sine wave**
  - ›  $s(t) = A \sin(2\pi ft + \phi)$
- **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  $T = \frac{1}{2}$
  - › (d) Phase shift;  $\phi = \pi/4$  radians (45 degrees)
- **note:  $2\pi$  radians =  $360^\circ = 1$  period**

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## Space and Time View Revisited



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

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## Frequency-Domain Concepts

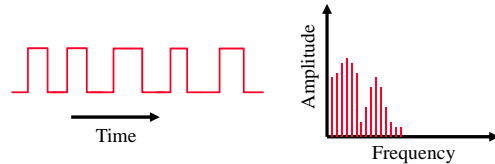
- Any electromagnetic signal can be shown to consist of a collection of periodic analog signals (sine waves) at different amplitudes, frequencies, and phases
- The period of the total signal is equal to the period of the fundamental frequency
  - › All other frequencies are an integer multiple of the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

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## The Frequency Domain

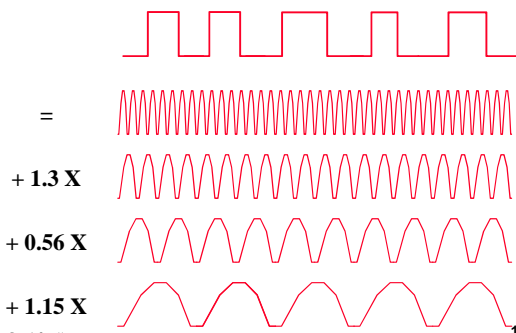
- A (periodic) signal can be viewed as a sum of sine waves of different strengths.
  - › Corresponds to energy at a certain frequency
- Every signal has an equivalent representation in the frequency domain.
  - › What frequencies are present and what is their strength (energy)
- Again: Similar to radio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



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## Signal = Sum of Sine Waves



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## Frequency-Domain Concepts

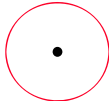
- **Fundamental frequency** - when all frequency components of a signal are integer multiples of one frequency, it's referred to as the fundamental frequency
- **Spectrum** - range of frequencies that a signal contains
- **Absolute bandwidth** - width of the spectrum of a signal
- **Effective bandwidth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

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## 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



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## Outline

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

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## 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
  - » Wired: Twisted pair, coaxial cable, fiber
  - » Wireless: Atmosphere or space propagation
  - » Cannot recover from distortions
- Digital: discrete changes in the signal that correspond to a digital signal
  - » Less susceptible to noise but can suffer, e.g., attenuation
  - » Can regenerate signal along the path (repeater versus amplifier)

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## 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

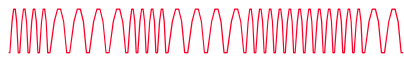
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## Amplitude and Frequency Modulation



0 0 1 1 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

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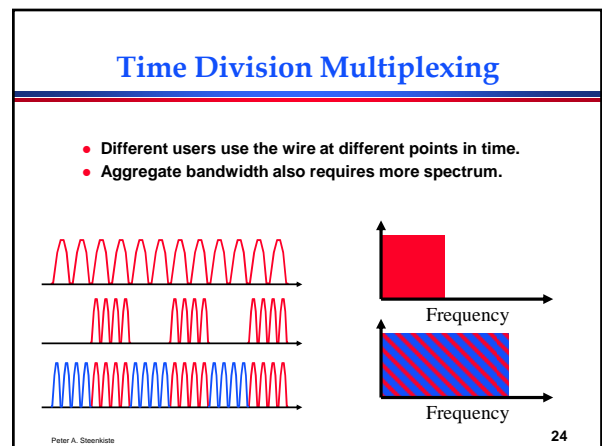
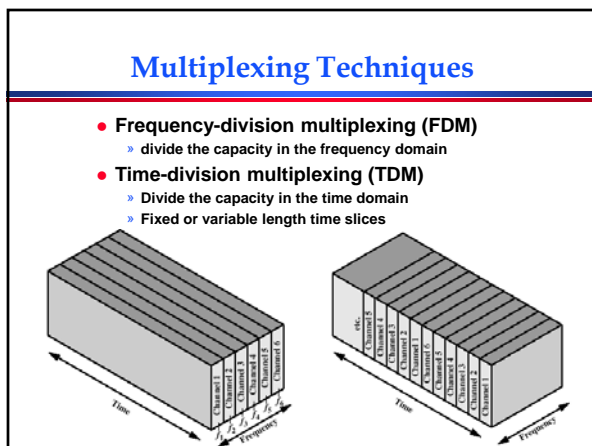
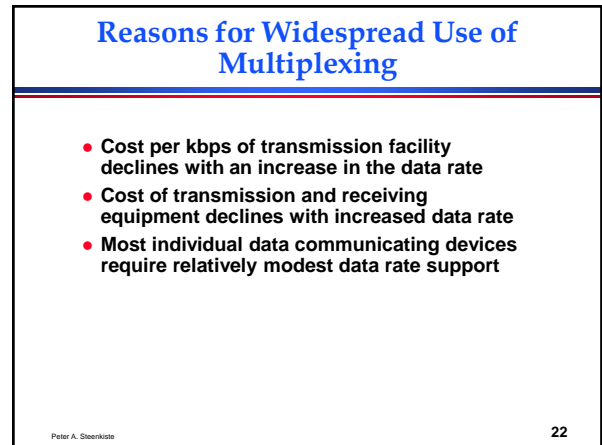
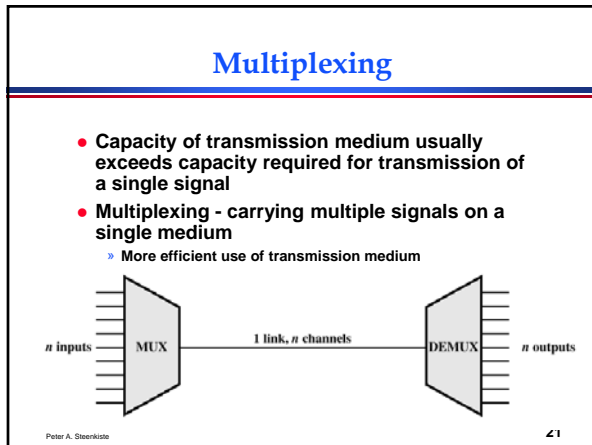
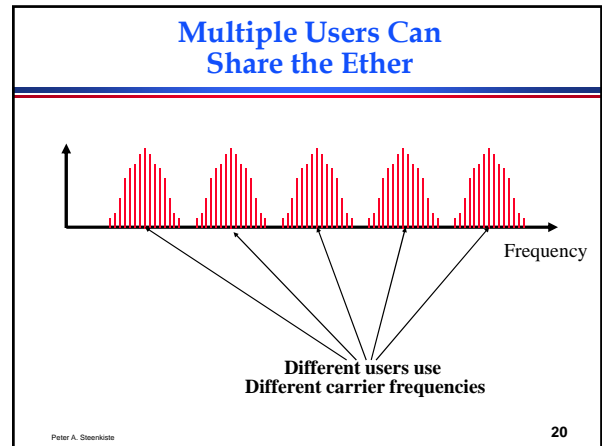
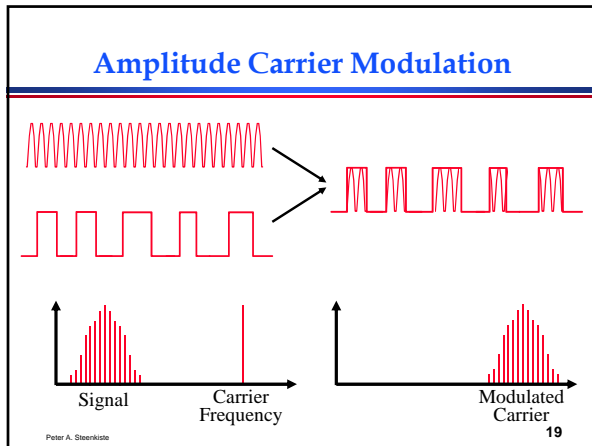
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## Baseband versus Carrier Modulation

- 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

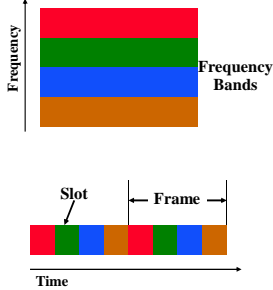
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## Frequency versus Time-division Multiplexing

- With frequency-division multiplexing different users use different parts of the frequency spectrum.
  - › I.e. each user can send all the time at reduced rate
  - › Example: roommates
  - › Hardware is slightly more expensive and is less efficient use of spectrum
- With time-division multiplexing different users send at different times.
  - › I.e. each user can send at full speed some of the time
  - › Example: a time-share condo
  - › Drawback is that there is some transition time between slots; becomes more of an issue with longer propagation times
- The two solutions can be combined.



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## FDM Example: AMPS

- US analog cellular system in early 80's.
- Each call uses an up and down link channel.
  - › Channels are 30 KHz
- About 12.5 + 12.5 MHz available for up and down link channels per operator.
  - › Supports 416 channels in each direction
  - › 21 of the channels are used for data/control
  - › Total capacity (across operators) is double of this

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## TDM Example: GSM

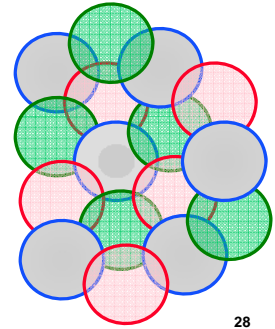
- Global System for Mobile communication.
  - › First introduced in Europe in early 90s
- Uses a combination of TDM and FDM.
- 25 MHz each for up and down links.
- Broken up in 200 KHz channels
  - › 125 channels in each direction
  - › Each channel can carry about 270 kbs
- Each channel is broken up in 8 time slots
  - › Slots are 0.577 msec long
  - › Results in 1000 channels, each with about 25 kbs of useful data; can be used for voice, data, control
- General Packet Radio Service (GPRS).
  - › Data service for GSM, e.g. 4 down and 1 up channel

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## Frequency Reuse in Space

- Frequencies can be reused in space
  - › Distance must be large enough
  - › Example: radio stations
- Basis for "cellular" network architecture
- Set of "base stations" connected to the wired network support set of nearby clients
  - › Star topology in each circle
  - › Cell phones, 802.11, ...



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## Outline

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

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## Relationship between Data Rate and Bandwidth

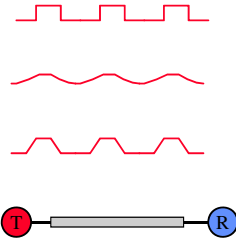
- The greater the (spectral) bandwidth, the higher the information-carrying capacity of the signal
- Intuition: if a signal can change faster, it can be modulated in a more detailed way and can carry more data
  - › E.g. more bits or higher fidelity music
- Extreme example: a signal that only changes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

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## 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

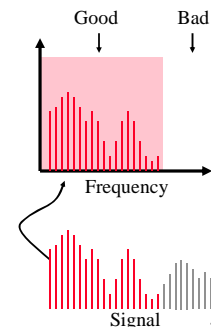


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## Transmission Channel Considerations

- 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

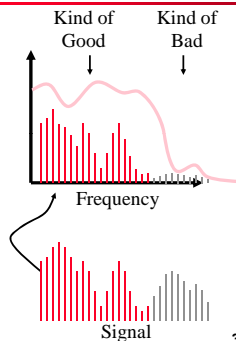


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## In Reality ...

- Attenuation is variable across the spectrum
  - › No discrete cutoff
- Signal in the "good" band gets distorted
- Some signal in the "bad" band gets through



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## 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

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## 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

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## 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

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## 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)
$$(SNR)_{dB} = 10 \log_{10} \frac{\text{signal power}}{\text{noise power}}$$
- A high SNR means a high-quality signal, low number of required intermediate repeaters
- SNR sets upper bound on achievable data rate

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## Shannon Capacity Formula

- Equation:  $C = B \log_2(1 + SNR)$
- 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

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## Example of Nyquist and Shannon Formulations

- Spectrum of a channel between 3 MHz and 4 MHz ;  $SNR_{dB} = 24$  dB
$$B = 4 \text{ MHz} - 3 \text{ MHz} = 1 \text{ MHz}$$
$$SNR_{dB} = 24 \text{ dB} = 10 \log_{10}(SNR)$$
$$SNR = 251$$
- Using Shannon's formula
$$C = 10^6 \times \log_2(1 + 251) \approx 10^6 \times 8 = 8 \text{ Mbps}$$

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## Example of Nyquist and Shannon Formulations

- How many signaling levels are required?
$$C = 2B \log_2 M$$
$$8 \times 10^6 = 2 \times (10^6) \times \log_2 M$$
$$4 = \log_2 M$$
$$M = 16$$

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## 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,  $3 \times 10^{11}$  to  $2 \times 10^{14}$  Hz
  - › Useful in local point-to-point multipoint applications within confined areas

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## 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, ...

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## Spectrum Allocation

See:

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

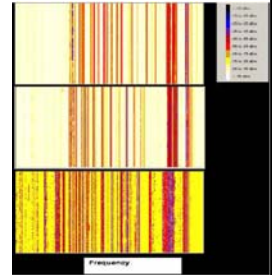
- Most bands are allocated.
- Industrial, Scientific, and Medical (ISM) bands are “uncensored”.
  - » But still subject to various constraints on the operator, e.g. 1 W output
  - » 433-868 MHz (Europe)
  - » 902-928 MHz (US)
  - » 2.4000-2.4835 GHz
  - » Uncensored National Information Infrastructure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

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## Spectrum Use is Limited

- Most of the spectrum is mostly unused most of the time
  - » E.g. 17% of spectrum used below 2 GHz in Manhattan during republican convention
  - » Only a few frequencies see heavy use regularly, e.g. uncensored, cellular
- Efforts to make spectrum use more dynamic and efficient
  - » Opportunistic users, secondary markets, etc.



Snapshot of utilization of 700 MHz slice of spectrum below 1 GHz

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