CS263: Wireless Communications and Sensor Networks

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Lecture 2: RF Basics and Signal Encoding
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Today's Lecture

Basics of wireless communications

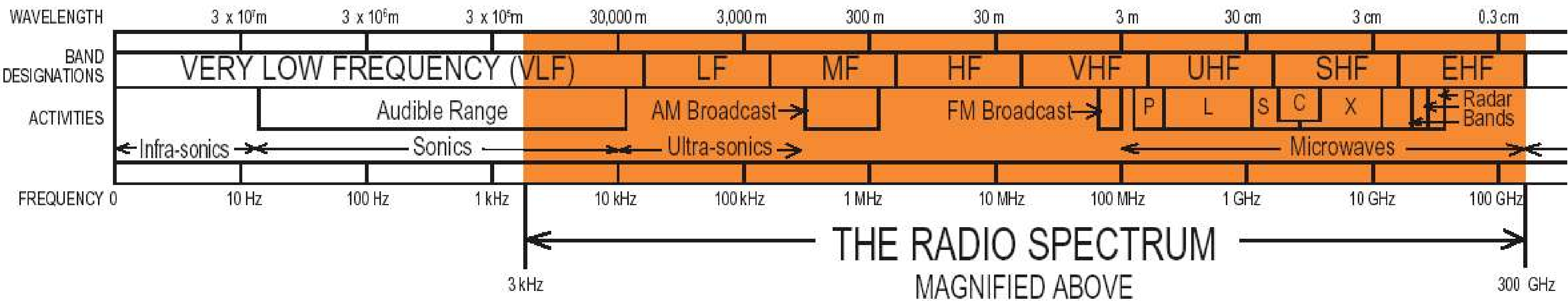
Analog and digital signals

Bandwidth and channel capacity

Signal encoding and modulation

What is RF?

Radio Frequency is an electromagnetic signal with a frequency between 3 kHz and 300 Ghz



RF signals carry analog or digital information

- Analog: Information content varies continuously over time
  - *Example: radio and TV stations*
- Digital: Information content consists of discrete units (e.g., 0s and 1s)
  - *Example: Cell phones and wireless networks*

Carrier Wave

How do we send *information* in a radio signal?

Carrier wave

- An RF signal – usually a sinusoid – that carries information
- Carrier is usually a much higher frequency than the information itself!
  - *Ex: 2.4 GHz 802.11b networks carry a lot less than 2.4 GBit/sec of data....*
  - *Rather, carry up to 11 MBit/sec of information*
- Why use a carrier??
  - *Easier to generate a sinusoid signal, and it will travel further.*

Carrier wave frequency

- The frequency of a radio transmission is the center frequency of the carrier
  - *Actual frequency of the carrier changes over time, e.g., with FM transmission*

Signal Modulation

How do we encode information in a carrier wave?

An information signal must be *modulated* onto the carrier wave

- That is, we must modify the carrier wave in some way...
- Receiver must *demodulate* the carrier to get back the original signal

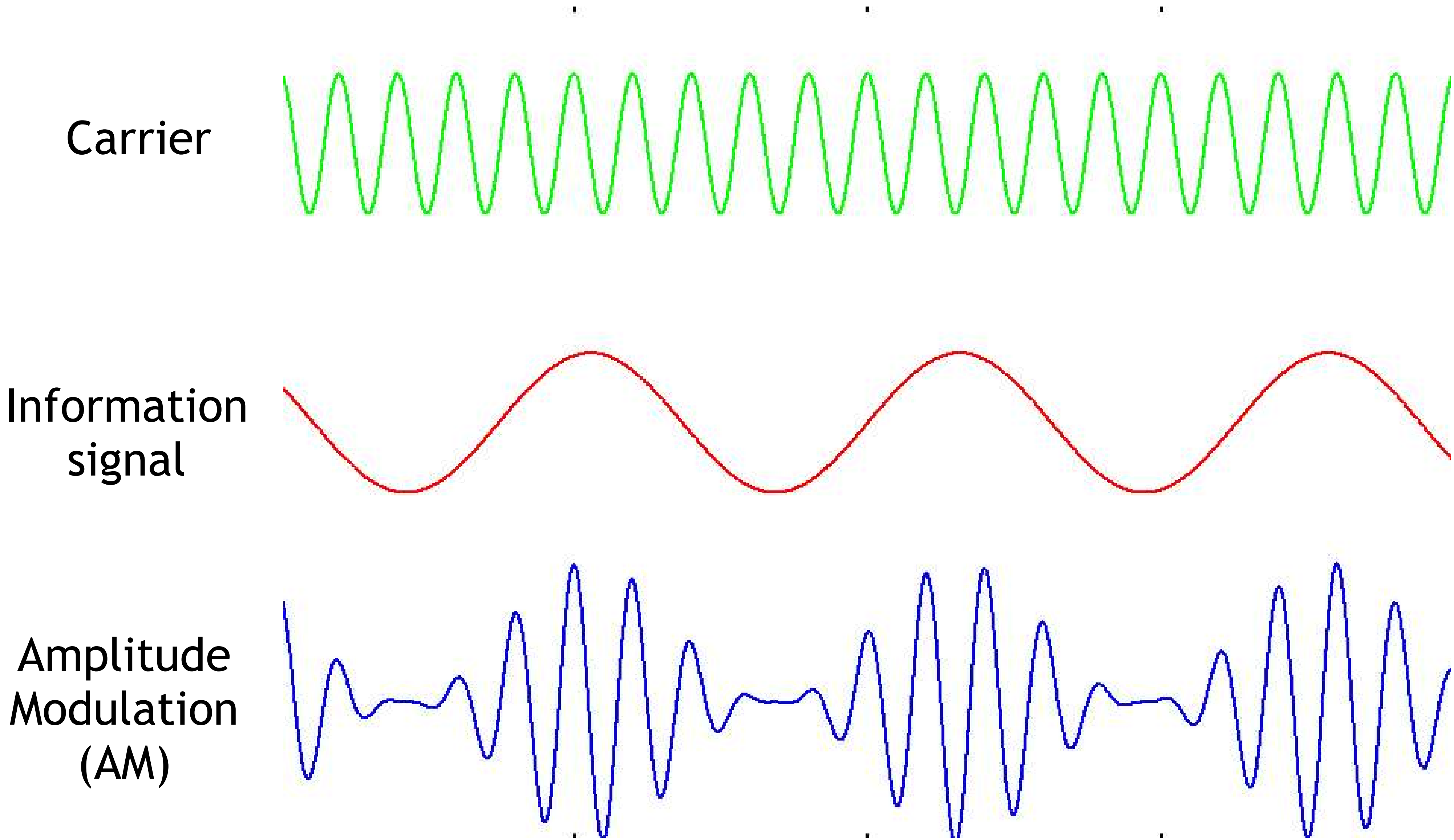
Amplitude Modulation (AM)

- Modify the *amplitude* of the carrier with respect to the amplitude of the signal

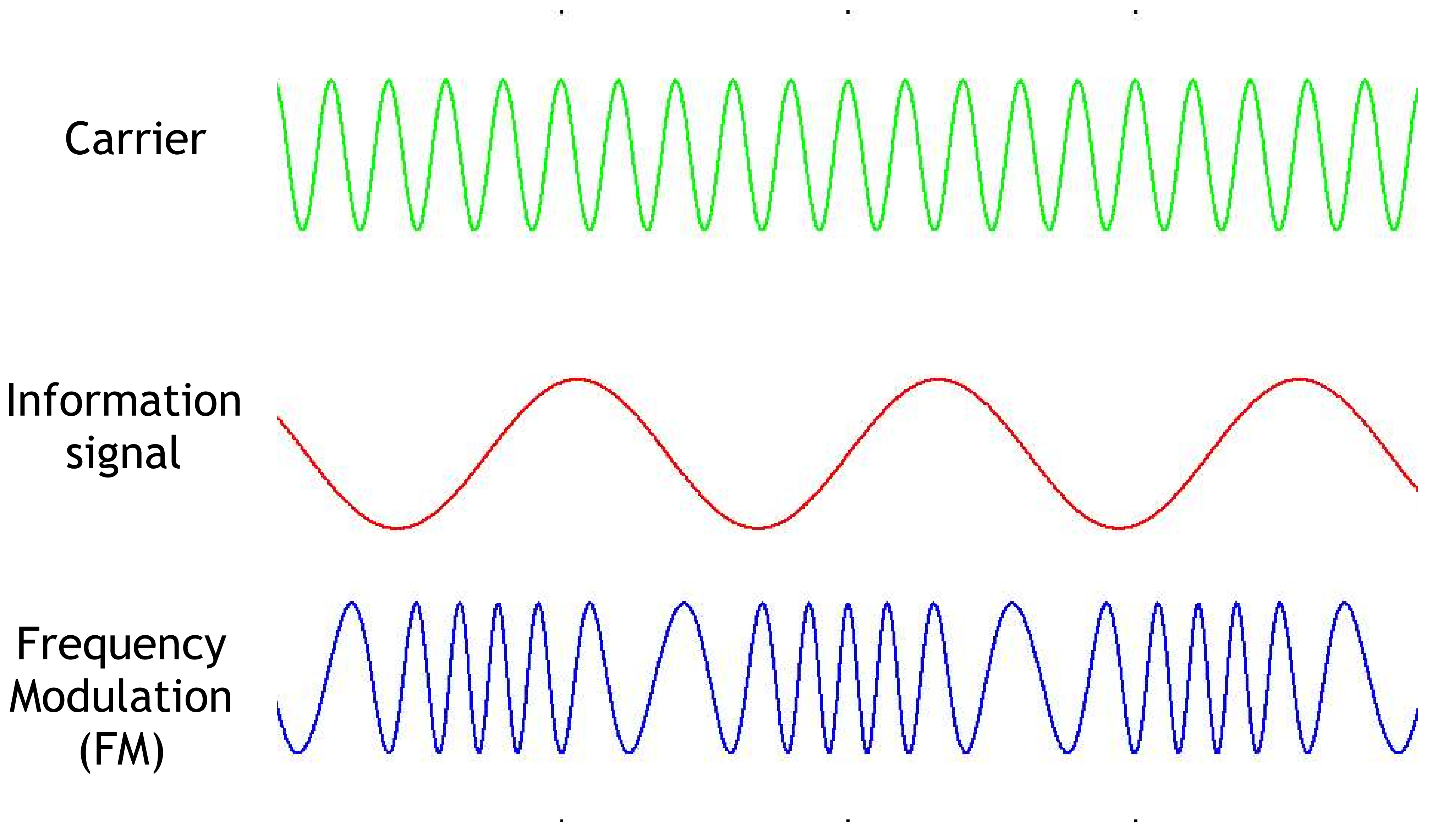
Frequency Modulation (FM)

- Modify the *frequency* of the carrier with respect to the amplitude of the signal

Signal Modulation



Signal Modulation



Digital Modulation

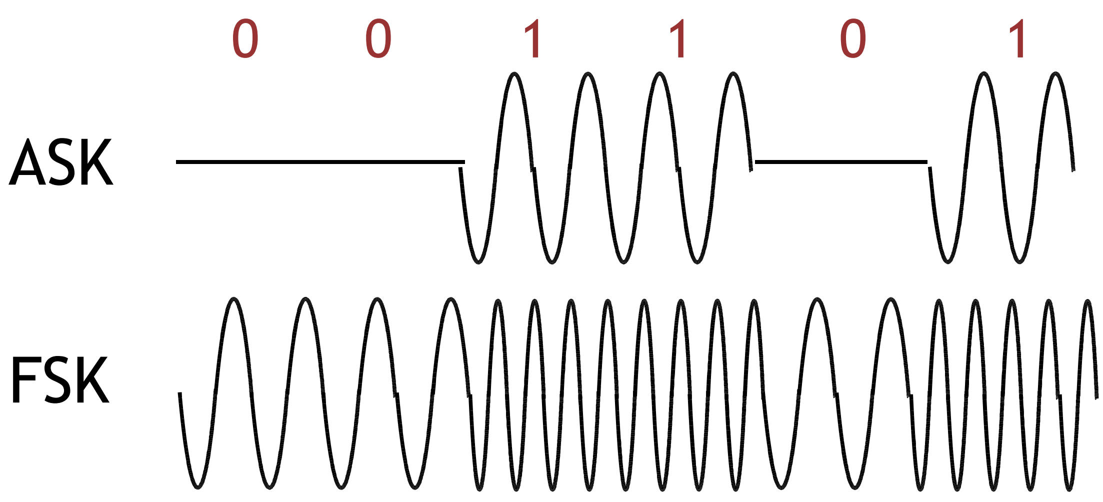
How do we modulate *digital* signals?

Amplitude shift keying (ASK)

- "0" bit is the absence of the carrier (flat signal)
- "1" bit is the presence of the carrier with some fixed amplitude

Frequency shift keying (FSK)

- "0" bit is carrier at frequency f_0 ; "1" bit is carrier at frequency f_1



Other modulation techniques

Lots of other modulation schemes are used in practice

- Each has different properties in terms of resiliency to noise, interference, multipath effects, etc.

Gaussian Frequency Shift Keying (GFSK)

- Binary 1 is a positive frequency shift from base frequency
- Binary 0 is negative frequency shift from base frequency
- Used in Bluetooth

Phase shift keying (PSK)

- The *phase* of the carrier is used to represent data
- “Differential quadrature phase shift keying” (DQPSK) used by 802.11b networks
  - *Four phase levels representing 00, 01, 10, and 11 bit sequences*

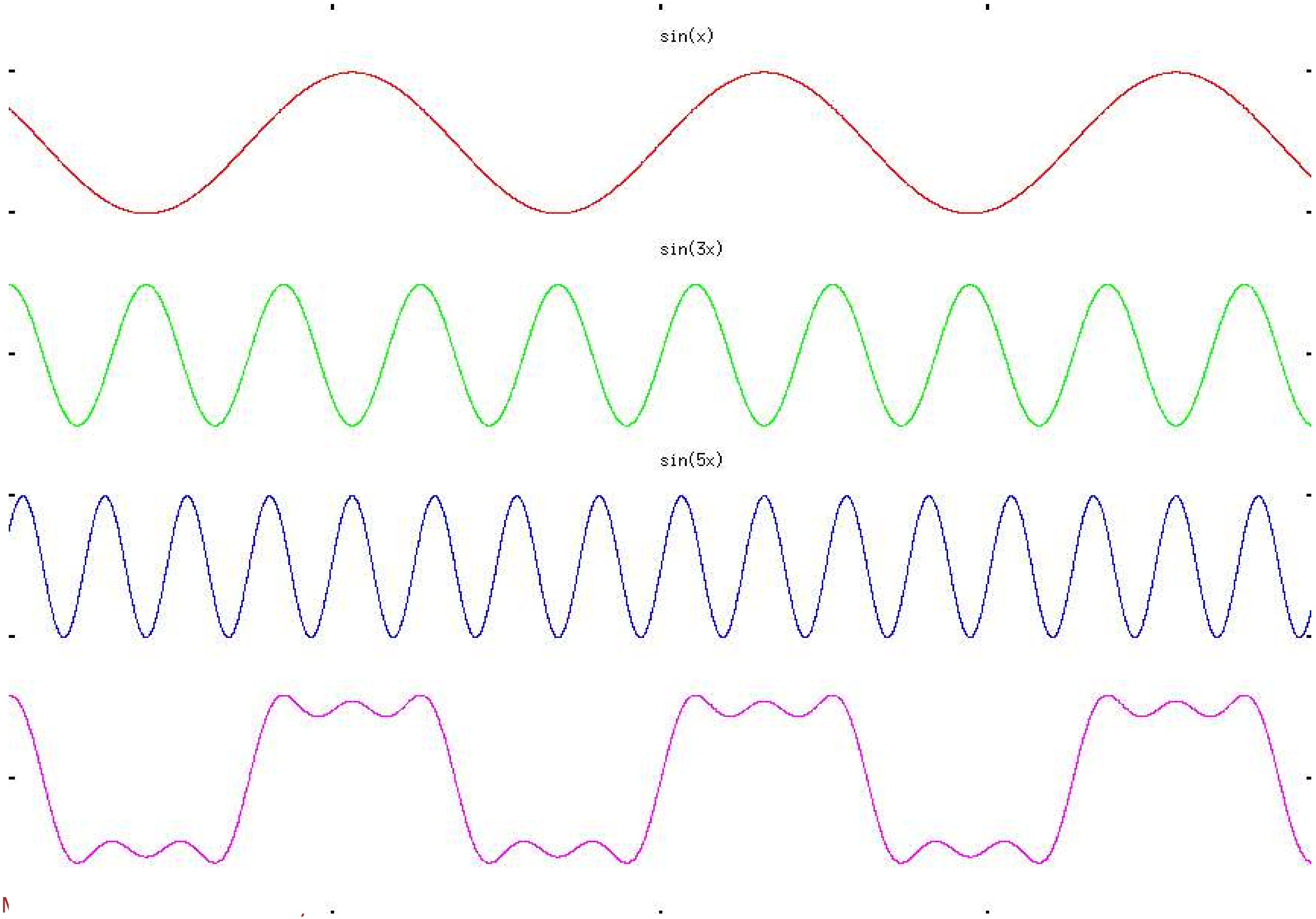
Quadrature Amplitude Modulation (QAM)

- Combination of AM + PSK
- Use two amplitudes and 4 phase levels to represent each sequence of 3 bits

Bandwidth

A typical signal will include many frequencies

- Fourier theorem: Any periodic signal is a combination of sinusoids



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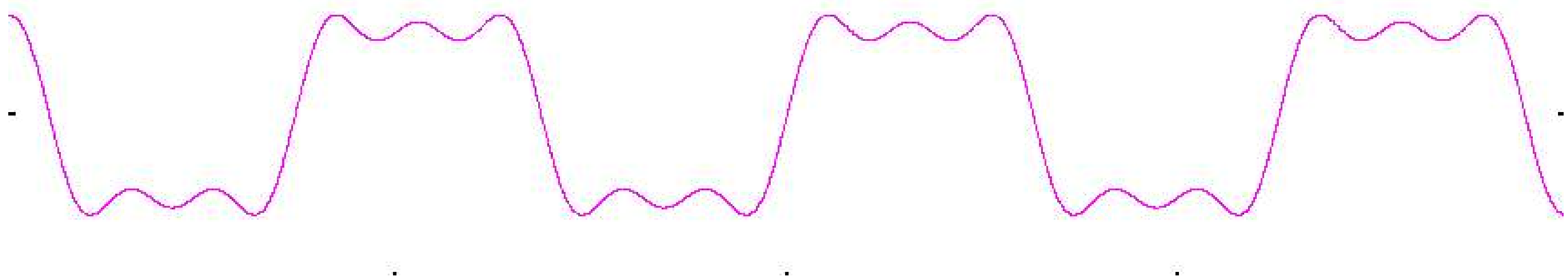


Spectrum: The range of frequencies in a signal

- In this case, [f ... $5f$]

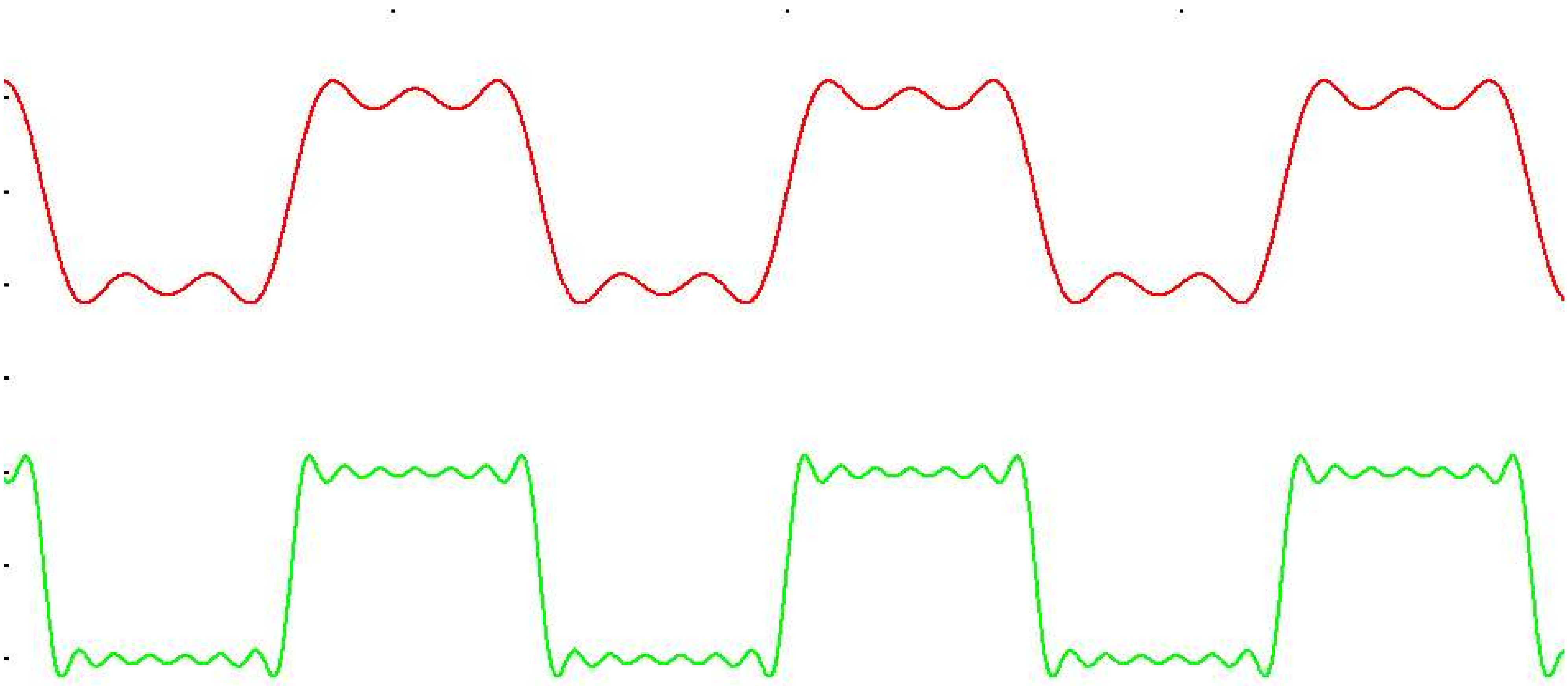
Bandwidth: The width of the spectrum

- In this case, $(5f - f) = 4f$

Bandwidth

What happens if we increase the bandwidth?

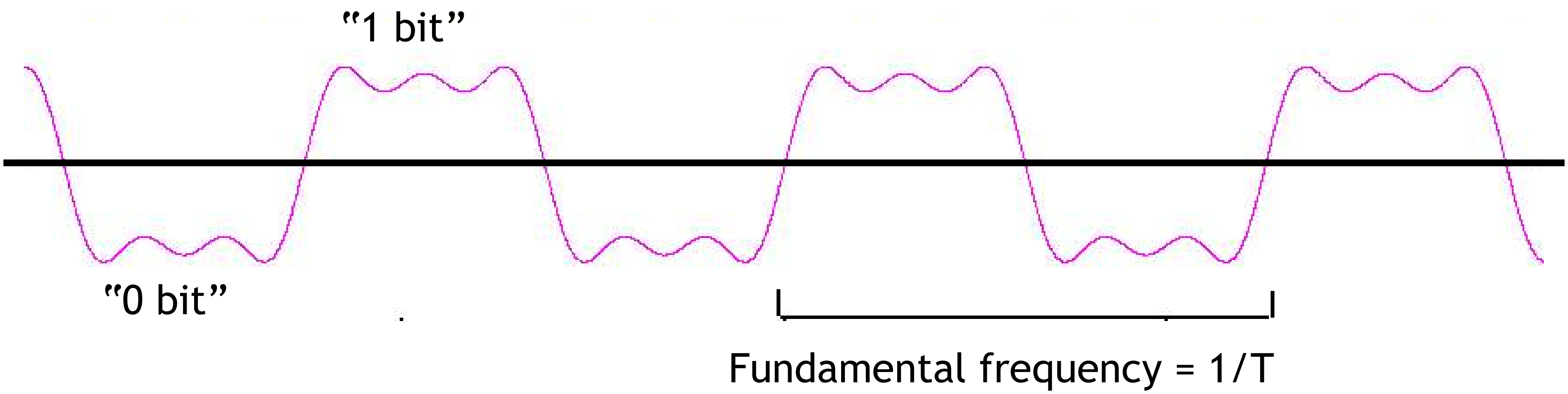
- Consider two waves, one with bandwidth 4*f*, the other with bandwidth 12*f*:



- As the bandwidth increases, the wave approximates a square wave.
- A perfect square wave (or any true digital signal) has *infinite bandwidth*

Data Rate and Bandwidth

What is the relationship between bandwidth of a signal and its information-carrying capacity?



- This wave can carry 2 bits every period, or 1 bit per T/2 sec
- If T = 1 μsec, the *fundamental frequency* *f* = 1 MHz
- *Data rate* is 2 * 10^6 = 2 Mbps

Data Rate and Bandwidth

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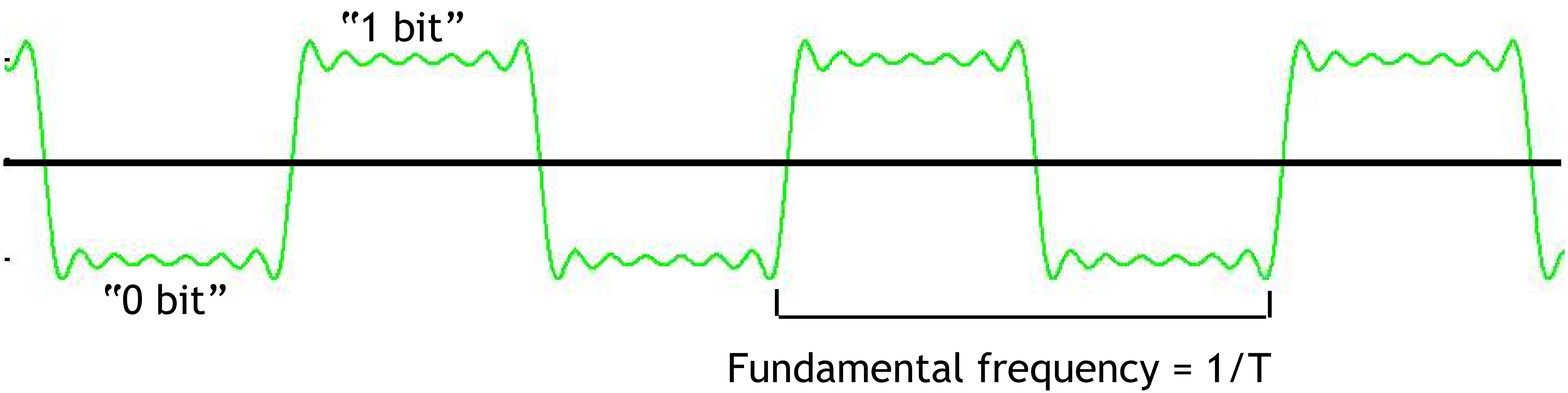


- What if we double the bandwidth?
- If the fundamental frequency is the same, data rate is identical!
  - *But ... this is a "cleaner" signal.*
  - *A receiver will be much more likely to discern 0 and 1 bits from this waveform.*
- In general: the greater the bandwidth, the less distortion in the signal.

Gain, loss, and decibels

Ratio between two signal power levels is often measured in *decibels (dB)*:

- gain(dB) = 10 $\log_{10}(P_{out} / P_{in})$
- loss(dB) = –10 $\log_{10}(P_{out} / P_{in})$ = 10 $\log_{10}(P_{in} / P_{out})$
- Where P_{out} is the output power level, and P_{in} is the input power level

Example

- Signal with power level 10mW transmitted over a wireless channel.
- Receiver gets a signal of 2mW.

$$\text{Loss} = 10 \log (10/2) = 10(0.698) = 6.98 \text{ dB}$$

mW and dBm

Decibels refers to relative *changes* in magnitude, not absolute values

So ... we define the *dBW (decibel-Watt)* as a reference

- 1 Watt of transmission power == 0 dBW
- Example: WGBH, 89.7FM in Boston transmits at 100,000 Watts
- Power in dBW = 10 * log(100,000W / 1W) = 10 * 5 = 50 dBW

For wireless networks, the *dBm (decibel-milliwatt)* is more useful

- 1 mW transmission power == 0 dBm
- 10 mW == 10 dBm
- 0.1 mW == -10 dBm
- 802.11b networks have a max transmit power of 100 mW == 20 dBm

Channel capacity

How do we get the most out of a signal of limited bandwidth?

- Want to minimize *noise.*

Nyquist Bandwidth:

- Given bandwidth B, highest signal rate that can be carried is 2B log M
  - *Where M is the number of discrete voltage levels (usually 2)*
- Simplest form: low-to-high transition is a “1”, high-to-low is a “0”

What about in the presence of noise??

- Shannon Capacity Theorem
- The maximum data rate of an analog channel in the presence of noise is:

$$C \leq B \log_2 (1 + S/N)$$

- Where C is the channel capacity, B is the bandwidth, and S/N is the *signal-to-noise ratio* (SNR)
- Here, S/N is just the ratio of the power levels – not the decibel value

Shannon Capacity

Example:

- Say we have a radio channel with bandwidth 10 MHz.
- Say the received signal level is 2 mW, and the noise level is 0.04 mW
- What is the Shannon Capacity of the channel?

SNR = 2mW / 0.04 mW = 50

$C = (10 * 10^6) \log_2 (1 + 50) = (10^7) (5.67) = 56.7$ Mbit/sec

- Note that this is more than the Nyquist bandwidth of the channel!!
- So .... how is it possible to approach the Shannon capacity????
  - *Answer: Must use more than 2 voltage levels to represent bits.*
  - *In practice this is rarely done.*

Shannon Capacity

How much noise can we tolerate on a channel?

- Say we have a radio bandwidth of 30 MHz (e.g., one 802.11b channel)
- We want to transmit data at 11 Mbit/sec.

$$SNR = 2^\wedge(C/B) - 1$$

$$SNR = 2^\wedge(11*10^6 / 30 *10^6) - 1$$

$$SNR = 1.28 - 1 = 0.28$$

This corresponds to a signal *loss* of 5.38 dB!

- So ... the signal power can actually be *less than* the channel noise level.

What limits bandwidth?

Sounds like higher bandwidth signals are a good idea.

So ... Why not transmit at the highest bandwidth possible?

Answer: The FCC!

Bandwidth Allocation

In the U.S., the FCC is responsible for allocating radio frequencies.

Why allocate the radio spectrum?

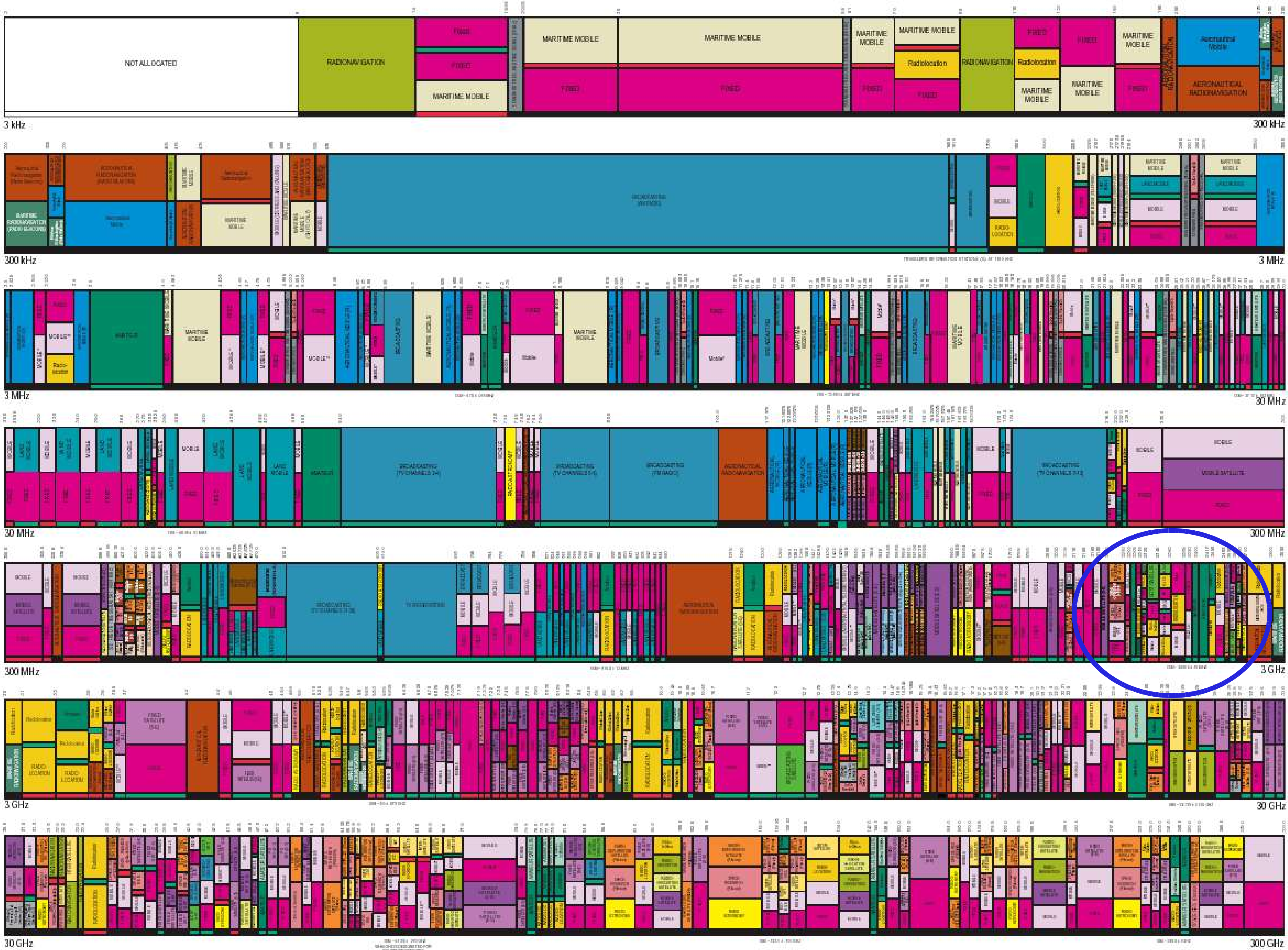
- Prevent interference between different devices
- It would be unfortunate if the local TV station interfered with police radio...

Generally, any transmitter is limited to a certain bandwidth

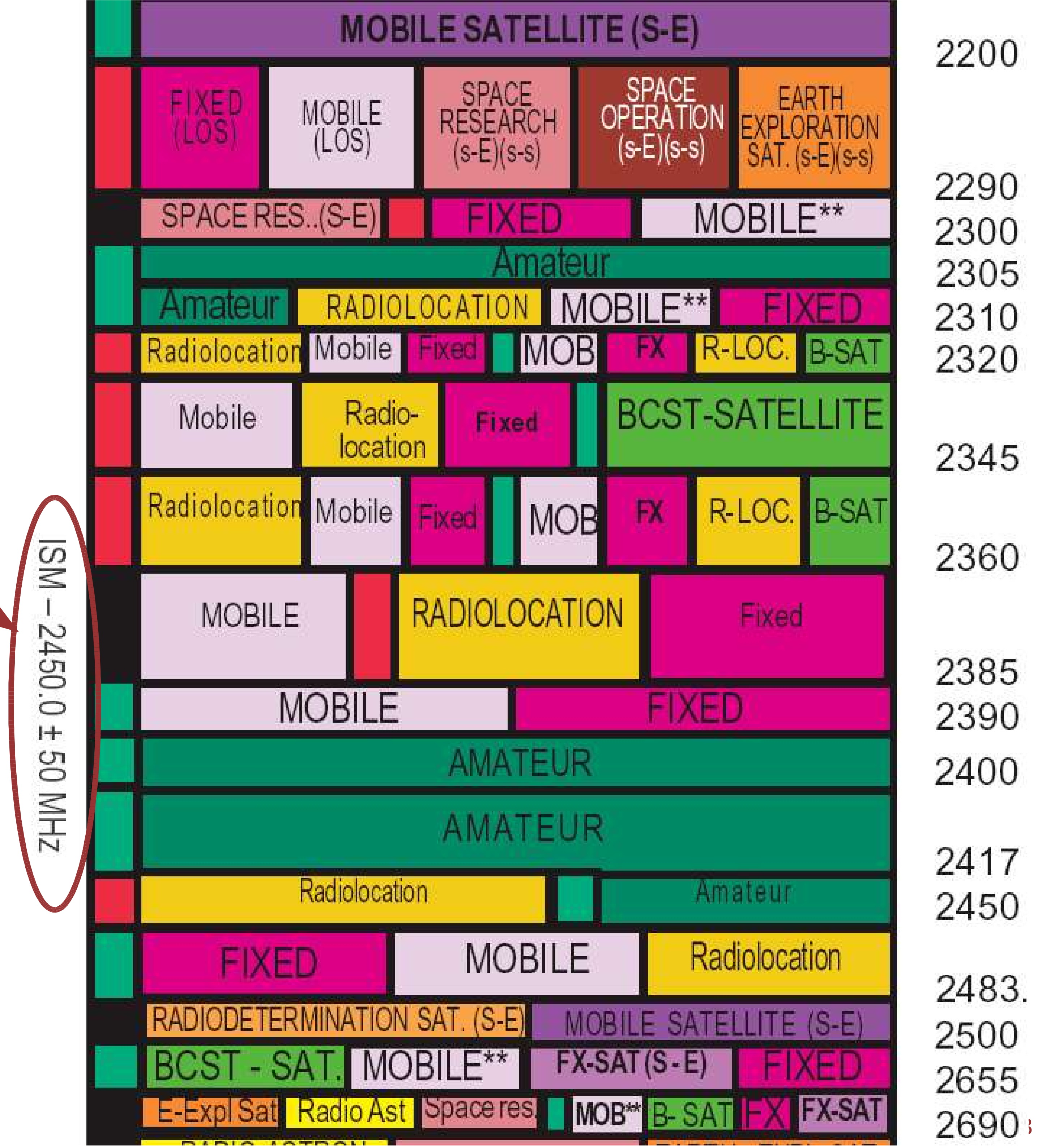
- e.g., a single 802.11 channel is 30 MHz “wide”

FCC also regulates the *power* and *placement* of transmitters

- Consumer devices generally limited to transmitting < 1 W of power
- Can't have two TV stations on channel 5 next to each other


3 kHz
300 kHz
NOT ALLOCATED
RADIONAVIGATION
FIXED
MARITIME MOBILE
Radiolocation
MARITIME MOBILE
FIXED
AERONAUTICAL RADIONAVIGATION
300 kHz
3 MHz
3 MHz
30 MHz
30 MHz
300 MHz
300 MHz
3 GHz
3 GHz
30 GHz
30 GHz
300 GHz

ISM:
Industrial,
Scientific,
and Medical



ISM and UNII bands

FCC Part 15 Rules regulate transmissions in U.S.

- ITU is worldwide governing body; individual countries regulate based on their recommendations
- Most consumer products operate in “unlicensed” bands set aside by FCC
- Rules allow devices to transmit up to some power limit

Industrial, Scientific, and Medical (ISM) bands

- 433 MHz and 868 MHz in Europe
- 902-928 MHz in US
- 2.4000 – 2.4835 Ghz worldwide
- Peak output: 1 W (30 dBm)
    - *However, most devices operate at much lower transmission powers, e.g., 100 mW or less*

Unlicensed National Information Infrastructure (UNII) bands

- 5.725 – 5.875 GHz

Wireless Medical Telemetry Service (WMTS)

Established by FCC and FDA in response to concerns about crowding in in TV/HDTV bands

- Feb '98: Incident at Baylor Medical Center in Dallas where HDTV test knocked out 50% of telemetry on one floor
- WMTS: 608-614 MHz, 1395-1400 MHz, 1429-1432 MHz
- Few interference sources
- May require coordination with radio astronomy in remote areas of country!

Requires hospitals to register equipment operating in these bands

- Perform a frequency search to ensure other devices are not interfering
- Depending on regulation to avoid interference, rather than market/technologies
- May only use in hospitals, not for home use

Tradeoffs with respect to ISM:

- ISM band still allowed for medical equipment
- WMTS solutions expected to be more expensive
- ISM requires use of spread spectrum, WMTS does not...

Next Lecture

Antennas, RF propagation, and fading

Spread Spectrum techniques

Reading: Stallings Ch. 5 and Ch. 7