WIRELESS COMMUNICATIONS

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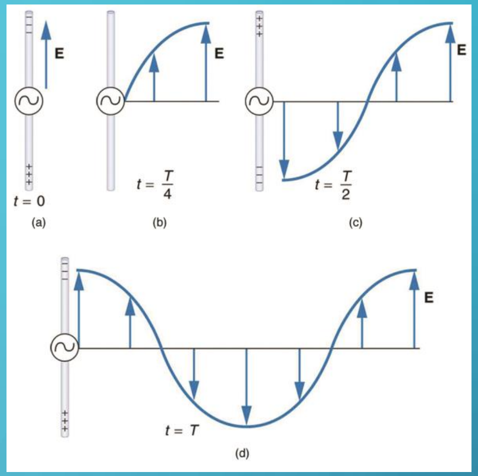
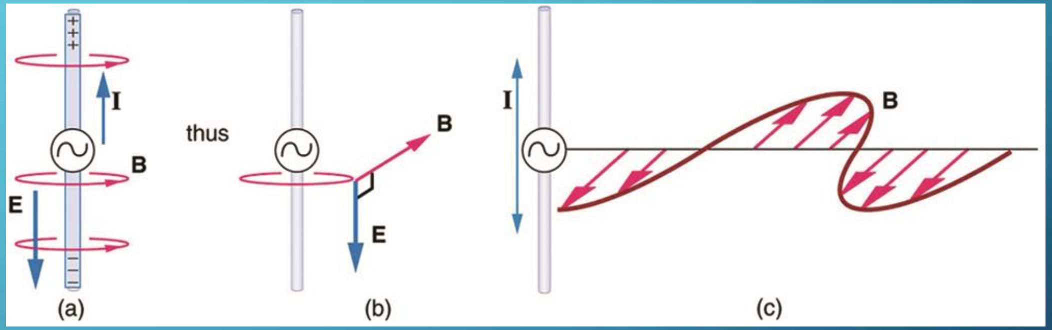
BASIC PHYSICS

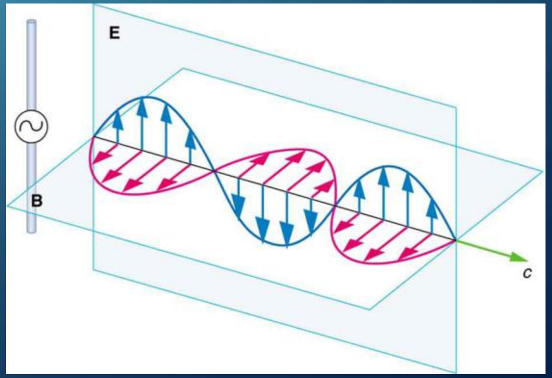
- Voltage is a potential; it pulls/pushes charged items
- Oscillating voltage makes electrons oscillate in conductors
- Oscillating electrons create an oscillating electric field



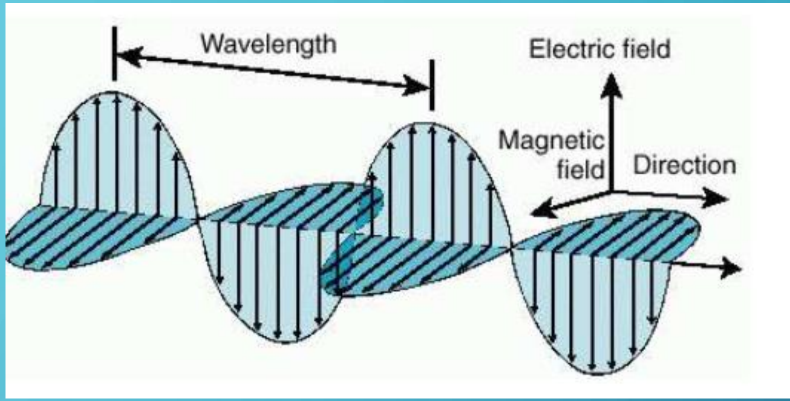
- Changing electric fields makes a changing perpendicular magnetic field



- These create an **electromagnetic wave**



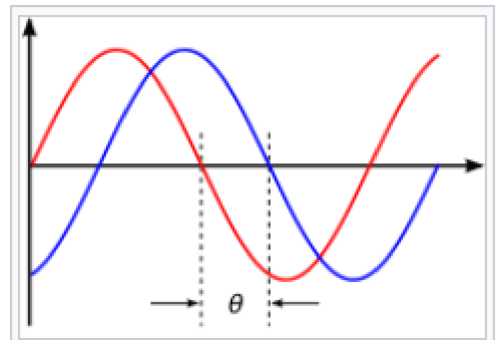
ELECTROMAGNETIC WAVES



- Wave propagates at the speed of light
  - Speed $c \approx 3 \times 10^8$ m/s $= 300$ m/us
  - **Wavelength** λ is distance between humps
  - **Frequency** f is how many times per second hump passes
  - $\lambda f = c$
  - **Amplitide** is height (strength) of the wave
- Inverse square law for static electric field: $E(x_0) = \frac{1}{4\pi\epsilon_0} \frac{q_1}{(x_1 - x_0)^2}$
- Liénard–Wiechert potential for moving charge
  - Relativistically correct time-varying electromagnetic field for charge in motion
  - $E(r,t) = \frac{1}{4\pi\epsilon_0} \left(\frac{q(n-\beta)}{\gamma^2 (1-n\beta)^3 |r-r_s|^2} + \frac{qn \times \left((n-\beta) \times \dot{\beta}\right)}{c(1-n\beta)^3 |r-r_s|} \right)$
  - *Note last term is not inverse square! Without this radio would be useless!*

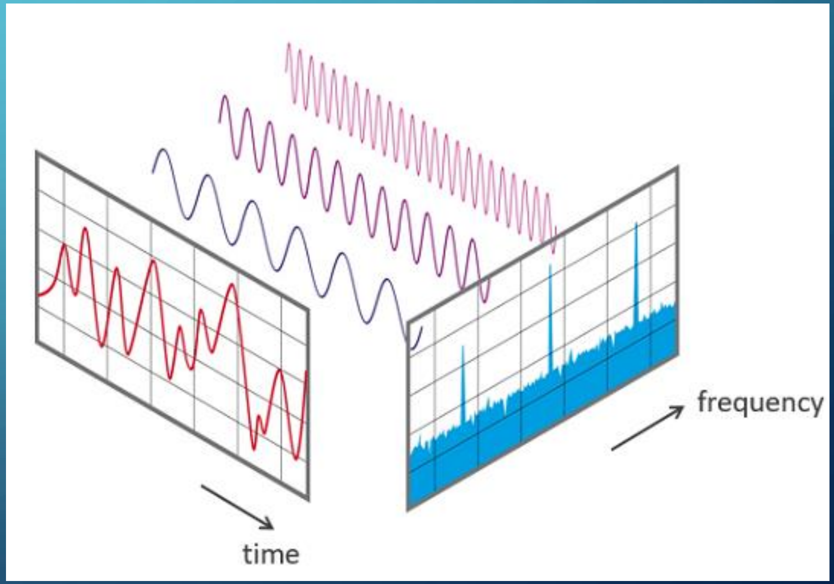
ELECTROMAGNETIC WAVES

- Fourier: A complex wave can be represented as a sum of (possibly shifted, called **phase**) sine waves



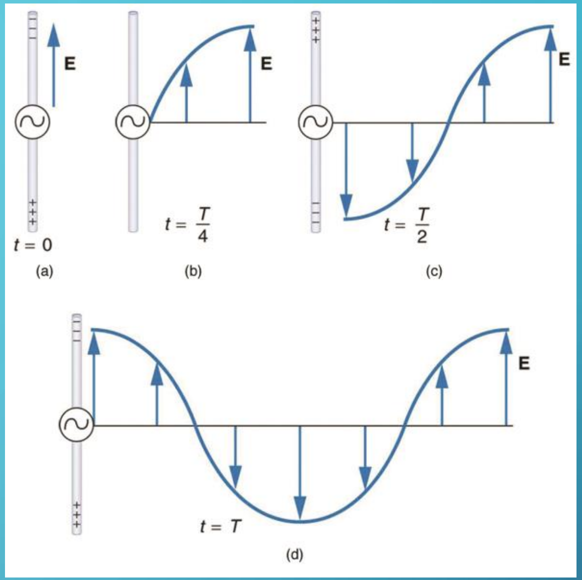
- Fourier Transform: wave => frequencies

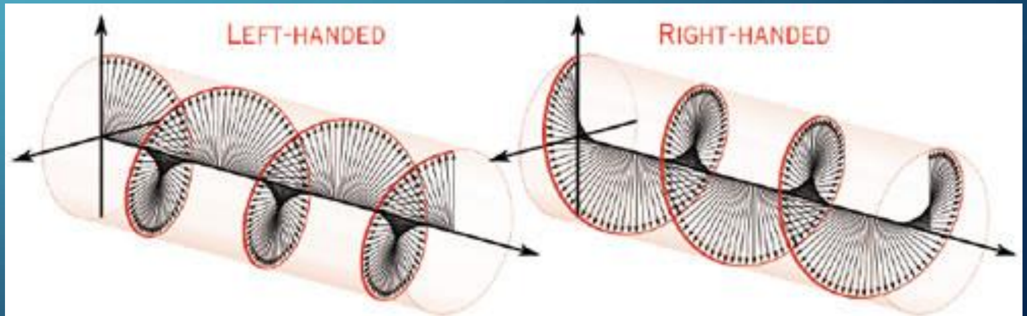
- A signal can be manipulated in the **frequency** or **time** domains



ELECTROMAGNETIC WAVES

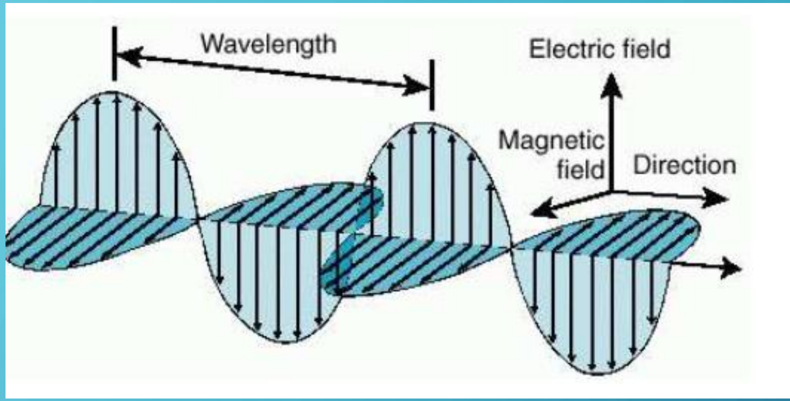
- **Polarization** – direction of electrical field
- Electric field parallel to the conductor
- What if the conductor turns 90 degrees?
- Changes **horizontal** to **vertical polarization**
- What if conductor spins?
    - **Left** or **right handed circular polarization**
- Can have two perpendicular antennas, driving them in/out of phase
    - **Elliptical polarization**, and/or all of above

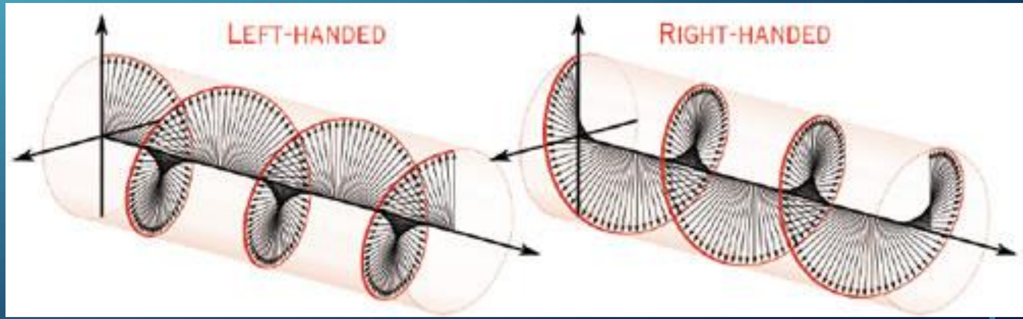




ELECTROMAGNETIC WAVES

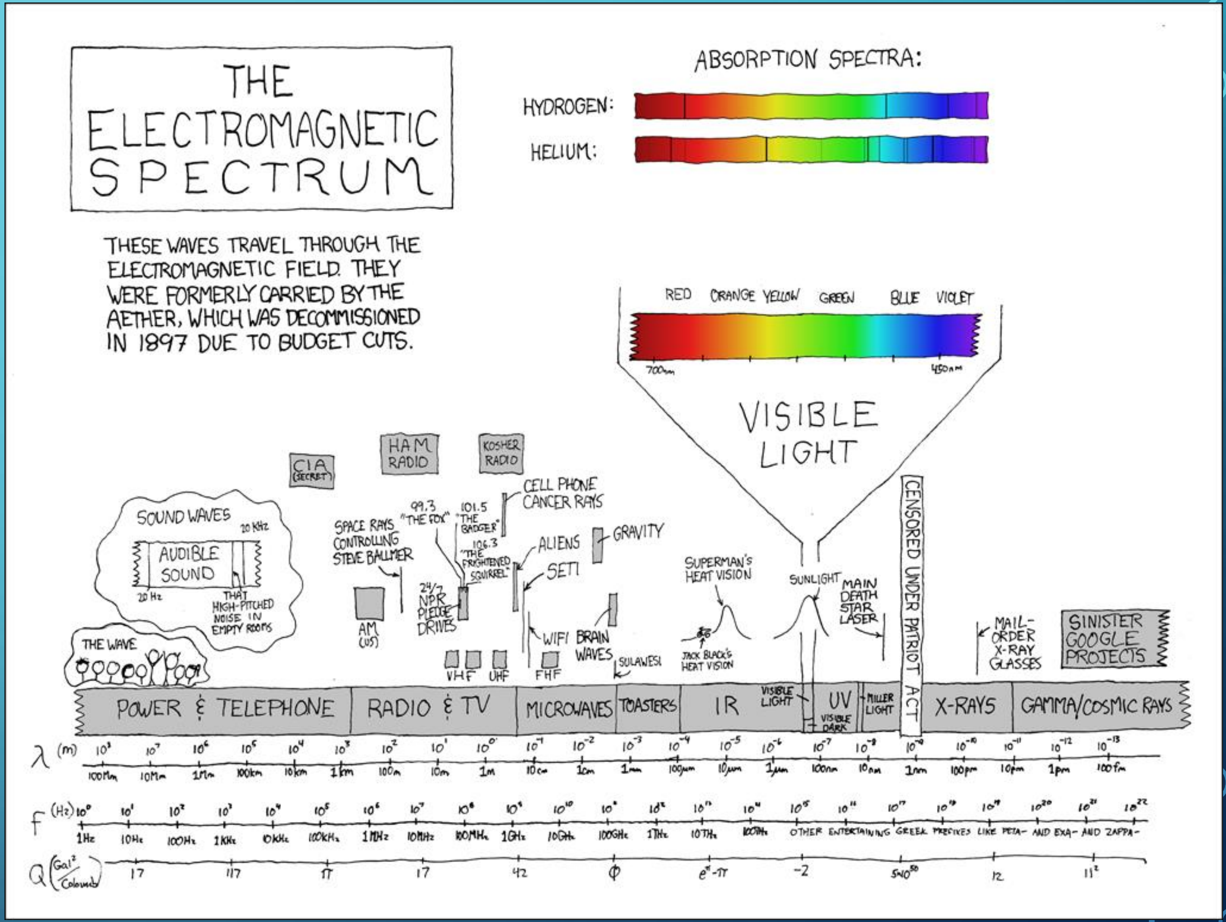
- Wave properties used to send data:
  - **Frequency**
  - **Amplitude**
  - **Phase**
  - **Polarization**





RADIO FREQUENCIES

- Wireless uses 100kHz to 60 GHz
- Three common unlicensed bands
  - 900 MHz: 902 to 928 MHz
  - 2.4 GHz band: 2.400 to 2.483 GHz (Japan extends to 2.495 GHz)
  - 5 GHZ: 5.150 to 5.350,
    5.725 to 5.825 MHz,
    (some countries + 5.350 – 5.825 GHz)



- Visible light 400-900 THz

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

- AERONAUTICAL MOBILE
- AERONAUTICAL MOBILE SATELLITE
- AERONAUTICAL RADIONAVIGATION
- AMATEUR
- AMATEUR SATELLITE
- BROADCASTING
- BROADCASTING SATELLITE
- EARTH EXPLORATION SATELLITE
- FIXED
- FIXED SATELLITE
- INTER-SATELLITE
- LAND MOBILE
- LAND MOBILE SATELLITE
- MARITIME MOBILE
- MARITIME MOBILE SATELLITE
- MARITIME RADIONAVIGATION
- METEOROLOGICAL
- METEOROLOGICAL SATELLITE
- MOBILE
- MOBILE SATELLITE
- RADIO ASTRONOMY
- RADIODETERMINATION SATELLITE
- RADIOLOCATION
- RADIOLOCATION SATELLITE
- RADIONAVIGATION
- RADIONAVIGATION SATELLITE
- SPACE OPERATION
- SPACE RESEARCH
- STANDARD FREQUENCY AND TIME SIGNAL
- STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

ACTIVITY CODE

- FEDERAL EXCLUSIVE
- FEDERAL/NON-FEDERAL SHARED
- NON-FEDERAL EXCLUSIVE

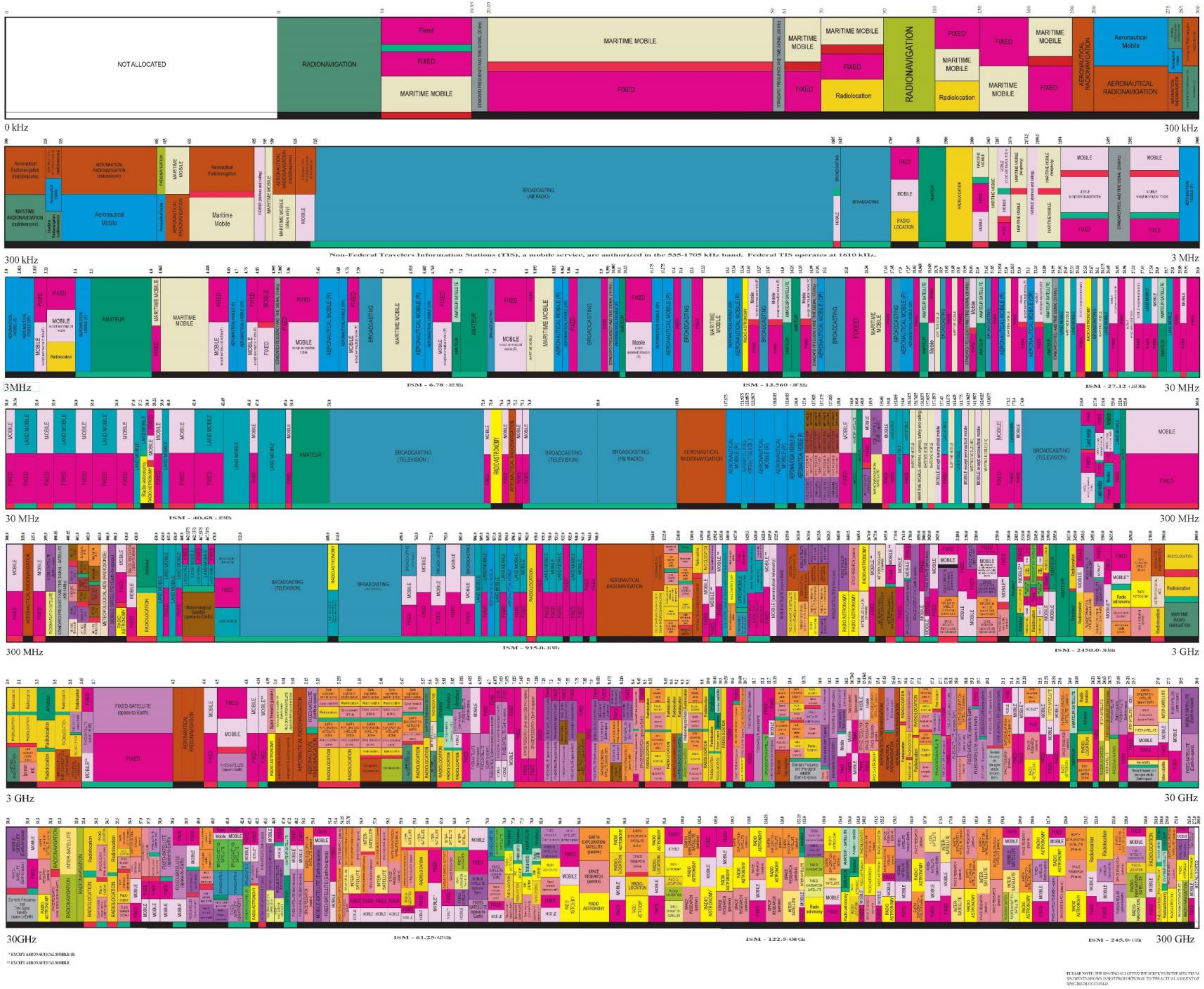
ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

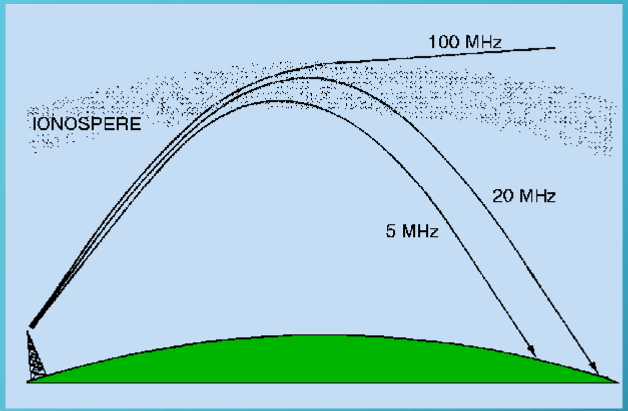
This chart is a graphic single-point-in-time portrayal of the Table of Frequency Allocations used by the FCC and NTIA. As such, it may not completely reflect all aspects, i.e. footnotes and recent changes made to the Table of Frequency Allocations. Therefore, for complete information, users should consult the Table to determine the current status of U.S. allocations.

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management

JANUARY 2016



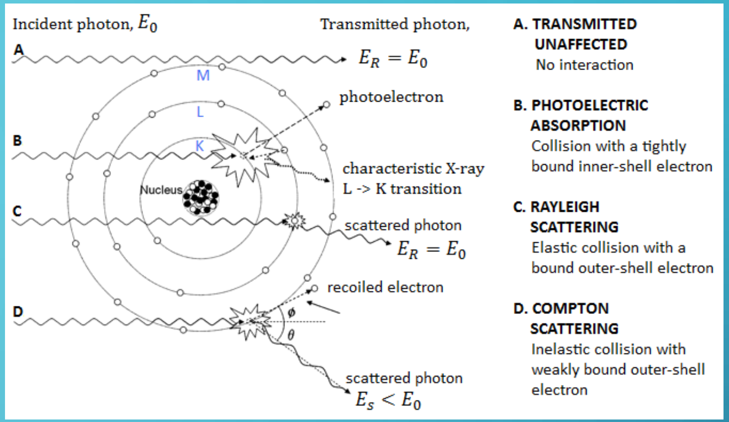
WIRELESS PROPAGATION

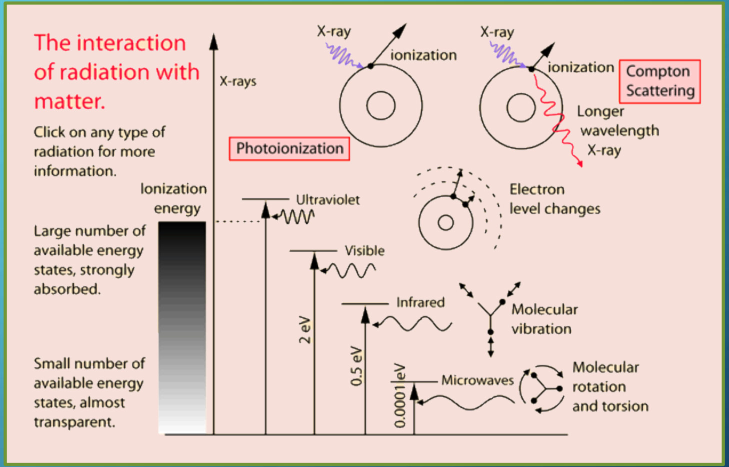


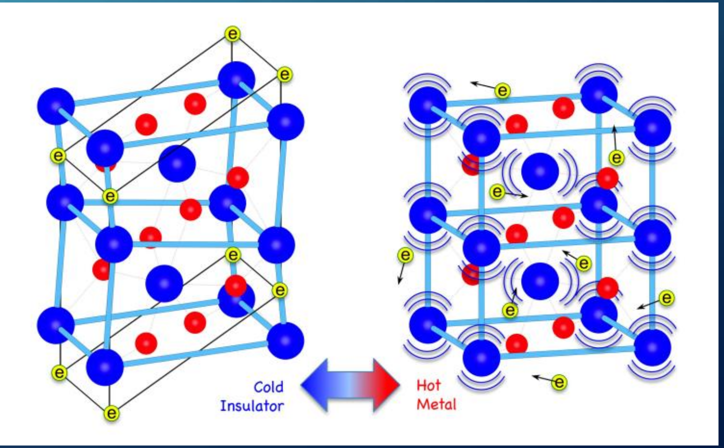
- Ground wave – follows earth contour, < 2MHz, AM radio
- Sky Wave: signal reflected/refracted from ionosphere
  - BBC world service, Voice of America
- Line of sight: > 30 MHz. Density of atmosphere decreases with height, results in waves bending towards earth
- Free space loss: signal disperses with distance
  - Greater for lower frequencies (longer wavelengths)
- Atmospheric absorption: water vapor and oxygen
  - Water greatest at 22 GHz, less below 15 GHz
  - Oxygen greater at 60 GHz, less below 0 GHz
  - Rain and fog scatter radio waves
  - Energy intensity in W/m^2 is $I_{avg} = c\ \epsilon_0 E_0^2/2$ where E_0 is max electric field of sin wave
- **Attenuation** the loss in signal amplitude due to distance, material, other reasons

INTERACTION WITH MATERIALS

- Wave causes electrons to vibrate
- These then re-emit radio waves
  - Causes refraction, reflection
- Some increases atomic lattice vibrations
  - Radio energy lost to heat
- Metals have a lot of free electrons
  - Absorb most
- Tightly bound electrons, no **resonance** near transmission, appears the most “clear”
- Radio waves deflect like light when changing media

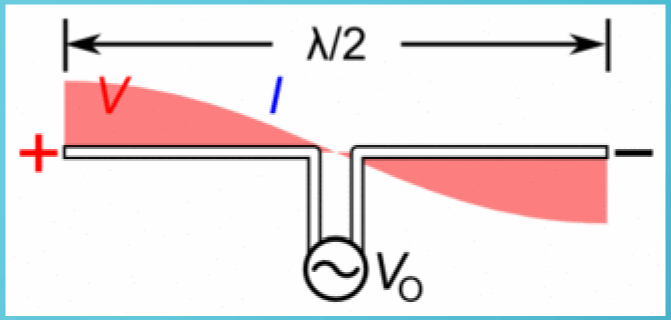






ANTENNAS - LENGTH

- Converts between electrical energy and electromagnetic waves
- Radio wavelength = length of antenna
  - Causes resonance, much better signal
  - Electrons absorb, some reemit, some of those absorb, …
- Half wave **dipole** antenna
  - ½ also works via reflection of half wave at end
- Quarter wave **monopole** antenna
  - ¼ works with reflective ground plane at powered end via another mechanism
  - Like a VHF antenna on a car or a metal plane on a PCB
  - Most popular in portable devices



Band	Freq	Wavelength	½ Length Antenna	¼ Length Antenna
AM	~1MHz	300m	150m	75m
FM	~100 MHz	3 m	150 cm	75 cm
Television	~75 MHz ~175MHz ~470-884 MHz	4 m 0.33 m	2m 0.15 m	1m 0.08 m
Cellular	~900 MHz	33 cm	15 cm	8 cm
GPS	~1.5 GHz	20 cm	10 cm	5 cm
Wireless	~2.4 GHz ~5 GHz	12 cm 6 cm	6 cm 3 cm	3 cm 1.5 cm
W band	~100 GHz	3 mm	1.5mm	0.75mm

DECIBELS

- **Decibels** measure a **ratio** of **power** between two things on a log scale

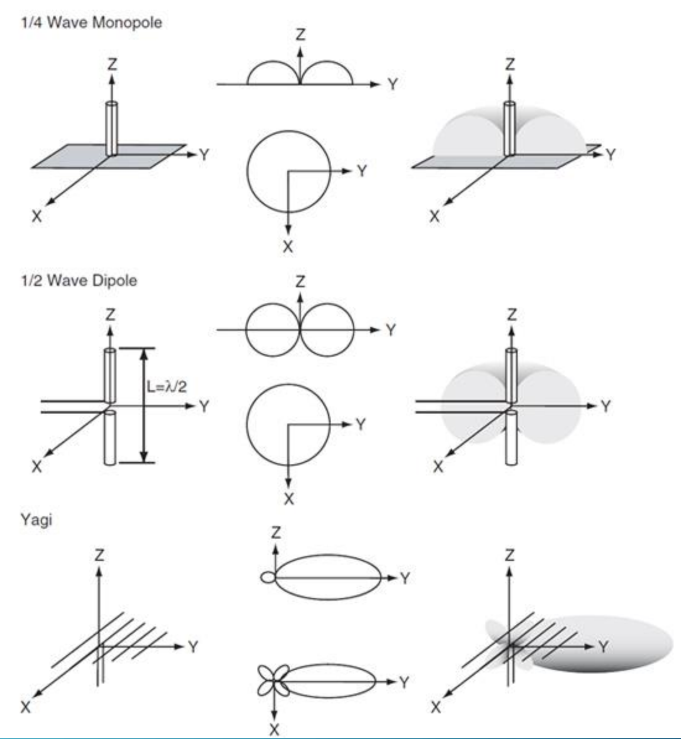
$$dB = 10 \times \log_{10} \frac{P_1}{P_0}$$

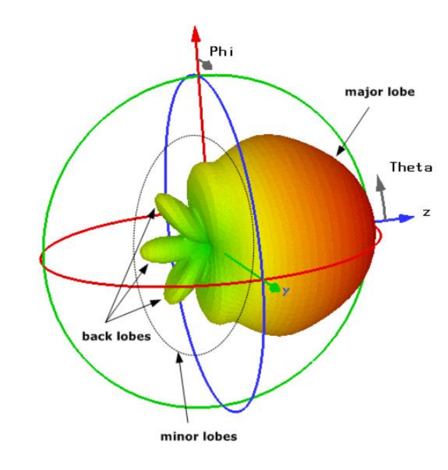
- Use log since numbers vary by many orders of magnitude
- Larger numbers are more power
- Each 3dB is approximately a doubling (or halving) of power
- For antennas and wireless, generally P_1 and P_0 measure power in Watts
- Often a suffix tells what P_0 is
  - **dBm** : P_0 = 1mW
  - **dBi** : antenna gain versus an isotropic (uniform) antenna
  - **dBd**: antenna gain versus a dipole antenna
- Can add to get total gain/loss (**attenuation**)

801.11 network loss	
Plasterboard	3dB
Glass wall with metal frame	6dB
Cinder block wall	4dB
Office window	3dB
Metal door	6dB
Metal door in brick wall	12dB

ANTENNAS - GEOMETRY

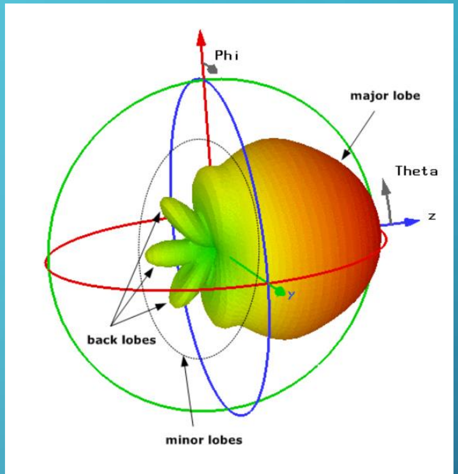
- **Isotropic** antenna
  - Ideal, uniform power spread in sphere
- Directional
  - Gains energy in some directions, loses in others
  - Dipole
  - Whip
  - Helical
  - Yagi
  - Ceramic loop
  - PCB trace
- Ex: out of 360 degree, Grid is 7 degrees, Yagi is 36 degrees, and the Panel is 34 degrees

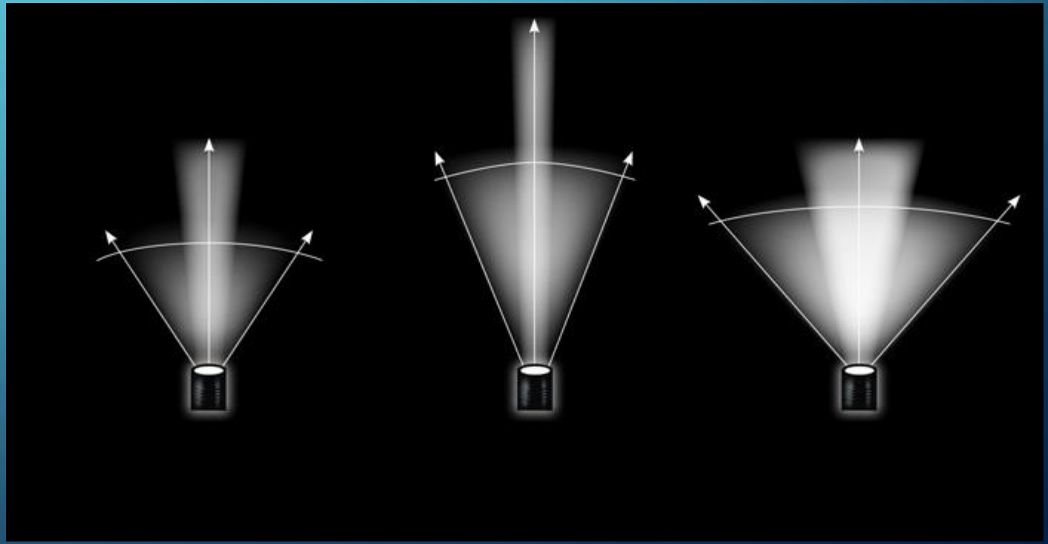




ANTENNAS - GAIN

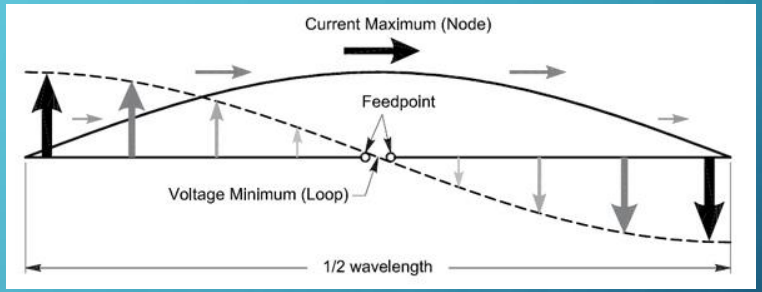
- **Gain** : apparent increase in power given by an antenna in a particular direction, often dBi
- Increased gain implies decreased **beamwidth**





ANTENNAS - IMPEDANCE

- **Impedance** – measure of opposition to current when voltage applied (ohms)
  - When voltage changes, current moves electrons, makes magnetic field, resists electron movement.
  - Capacitance also affects

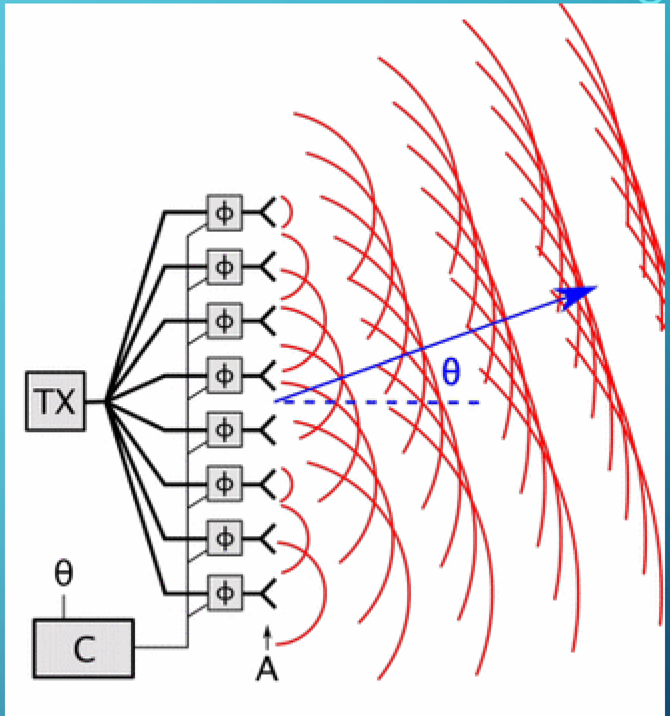


- Antenna: impedance mismatch causes power loss in transmission
  - Think: mismatch causes the wave to reflect before entering antenna
  - Called an **impedance mismatch**
- **Impedance matching** – antenna works like RC, need to balance

ANTENNAS

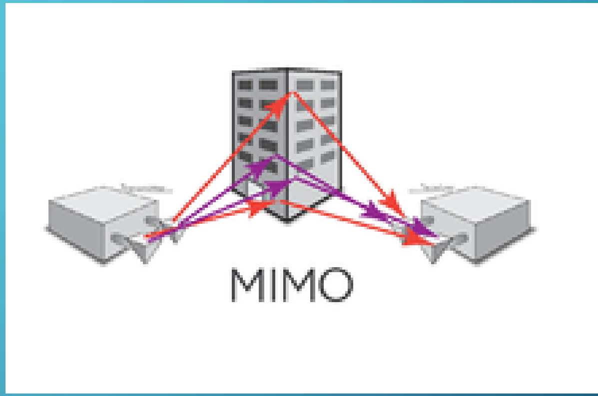
- **Beam shaping** via **phase array**

- **Reciprocity theorem**
  - The following are the same for a given antenna for transmitting and receiving
    - Gain
    - Radiation pattern
    - Impedance
    - Bandwidth
    - Resonant Frequency
    - Polarization

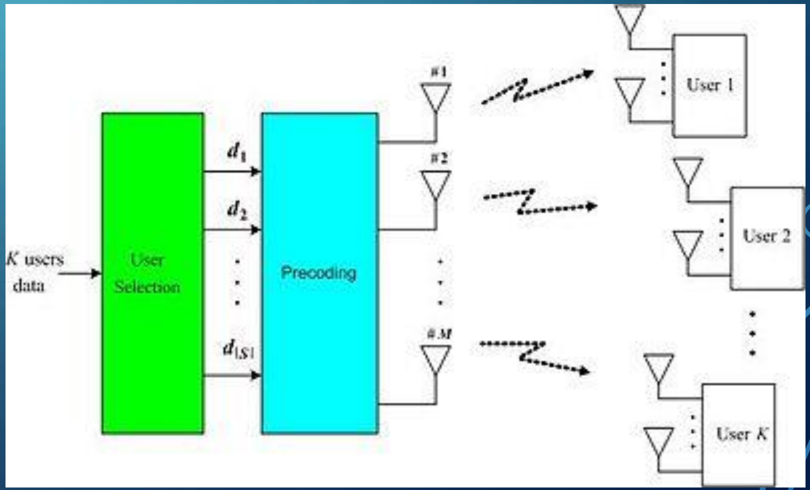


MIMO

- Multiple-Input and Multiple-Output (**MIMO**)
  - Exploit multipath propagation to multiply link capacity
  - 802.11n, WiMAX, LTE 4G, more

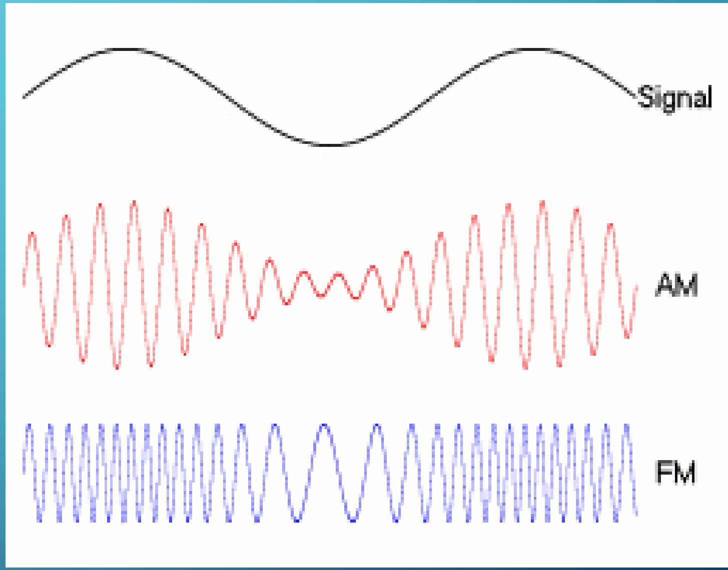


- Multi-user MIMO (**MU-MIMO**)
  - Complex signal processing handles multiple users
  - 3G, WiMAX



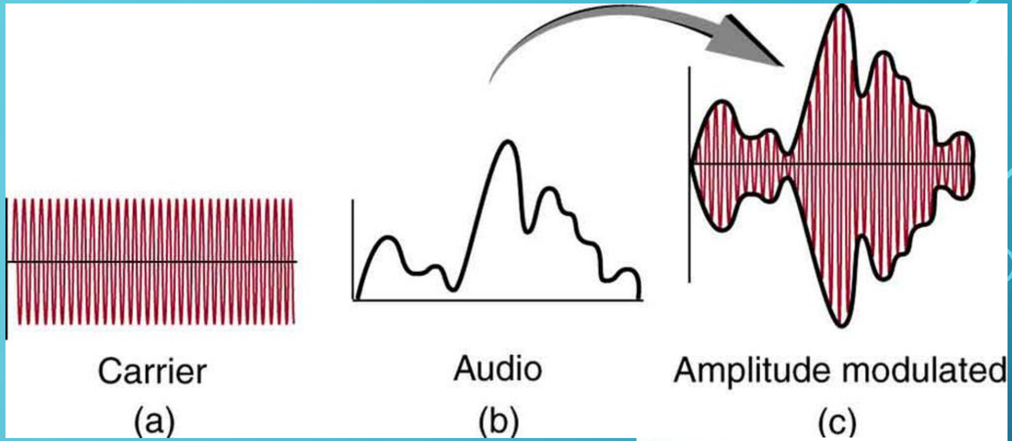
MODULATION

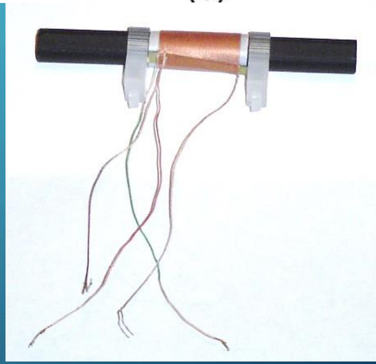
- **Modulation**: varying a periodic waveform called the **carrier signal** with another signal to encode information
- modem = modulator/demodulator
- AM = amplitude modulation
- FM = frequency modulation
- Data direction:
  - **Simplex** : one way (TV)
  - **Half duplex** : two way, alternate channel use (CB radio)
  - **Full duplex** : two way using two channels (mobile phone)



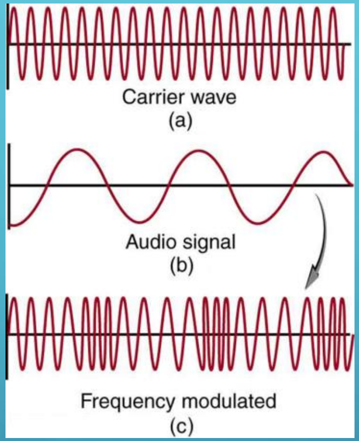
EX: RADIO SIGNALS

- AM – magnetic antenna
  - Wavelength 300m
  - ¼ monopole antenna would be 75m!

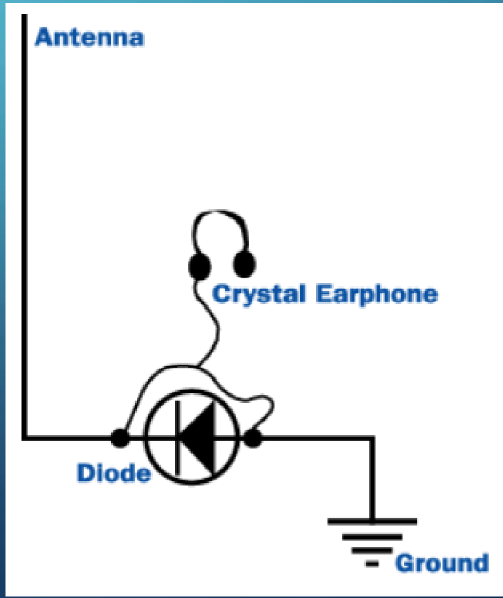




- FM – electric antenna
  - Wavelength 3 m
  - ¼ monopole antenna 75cm

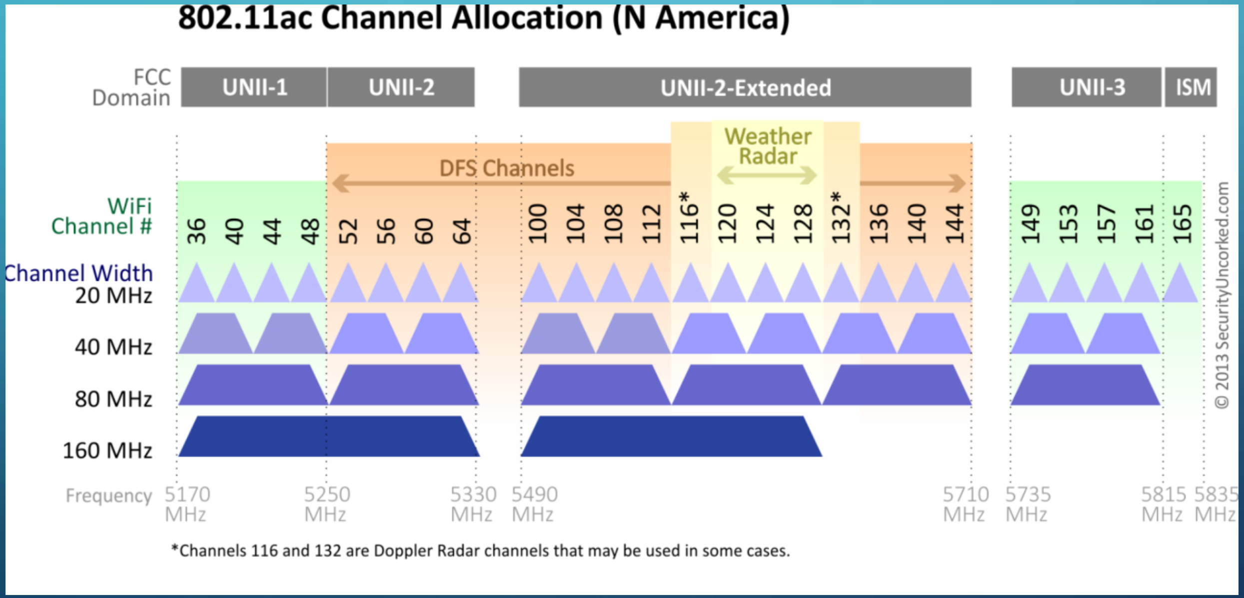


- Simple crystal radio – how works



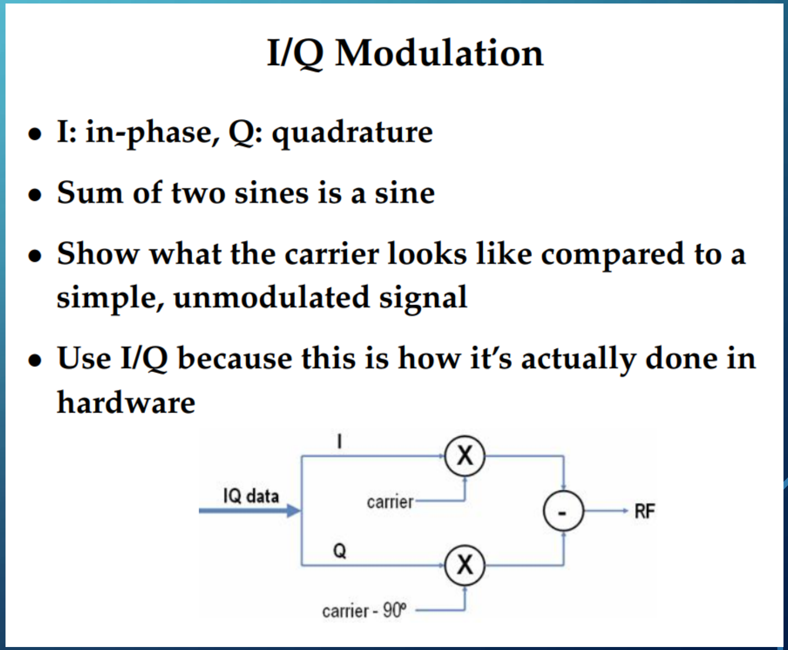
SPECTRUM

- Communication given a **frequency** and **bandwidth**
- Ex:
  - FM radio channels are separated by 200 kHz, so channels “odd”: 97.1, 103.5
  - 200 kHz is the **bandwidth**



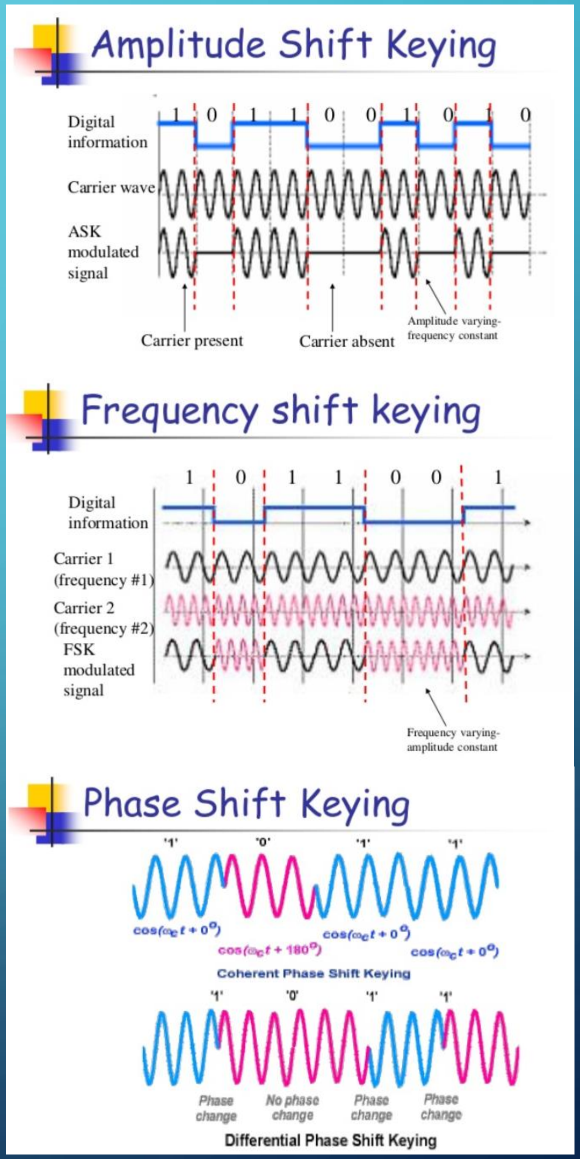
DIGITAL MODULATION

- In digital domain, modulation often called **keying**
- Wave parameters: frequency, amplitude, phase, polarization
- Some aspects susceptible to some errors while others not
  - Changes by use case, domain, power, cost, etc.
- In-phase (**I**) signal and quadrature (**Q**) signal
  - Q is 90 degrees out of phase with I



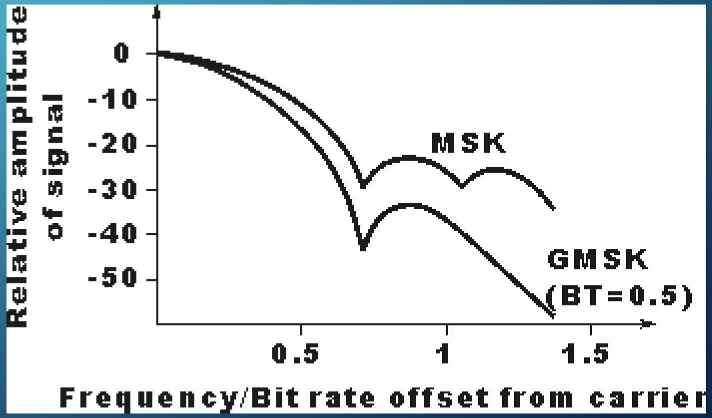
DIGITAL MODULATION

- Amplitude Shift Keying (**ASK**)
  - Amplitude denotes symbols
- Frequency Shift Keying (**FSK**)
  - Frequency denotes symbols
  - FSK less susceptible to errors than ASK (Keying)
  - Used in 300-1200 bps voice grade lines
- Phase-Shift Keying (**PSK**)
  - Phase denotes symbols
  - Exact phase requires clock syncing, so…
  - Differential (**DPSK**): change in phase is symbol
  - When 2 symbols, called Binary PSK (**BPSK**)
  - When 4 symbols, Quadrature PSK (**QPSK**)



DIGITAL MODULATION

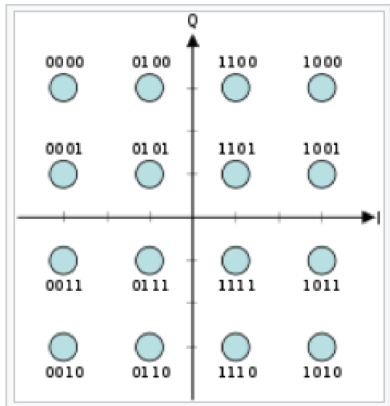
- Multi-level PSK (**MPSK**)
  - 9600 baud modems use PSK with 4 bits
- Offset quadrature phase-shift keying (**OQPSK**)
  - limited to 90 degree rotations
- Gaussian Minimum Shift Keying (**GMSK**)
  - Minimum shift for next symbol
  - Gaussian filtered to remove sideband noise (square edges "ring")
  - Used in GSM cellular systems
- Many, many more….



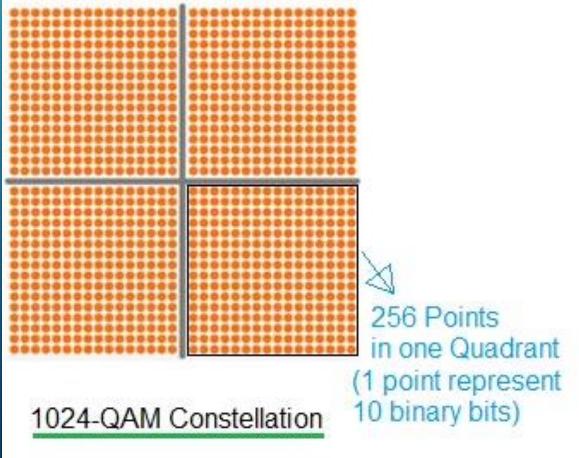
DIGITAL MODULATION

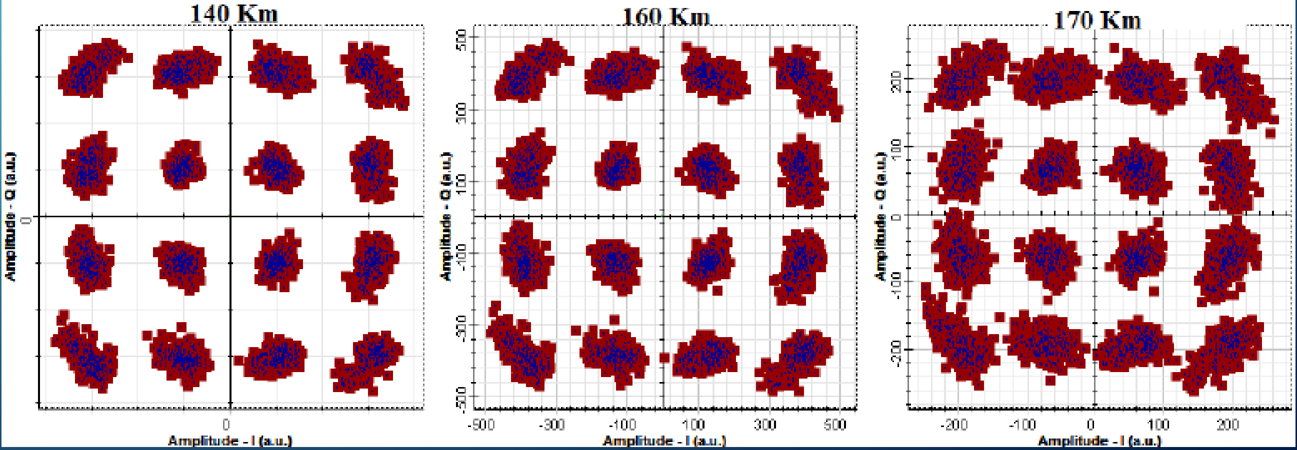
- Want more symbols: so mix **phase** and **amplitude**….
- Quadrature Amplitude Modulation (**QAM**)
  - QAM-4, QAM-16, QAM-64, QAM-256, …
  - DOCSIS up to QAM-16384, Digital Video 65536, more ?

    QAM-4: same performance, twice the bandwidth efficiency of BPSK
  - Used in DSL, wireless networks, many more



Constellation diagram for rectangular 16-QAM.



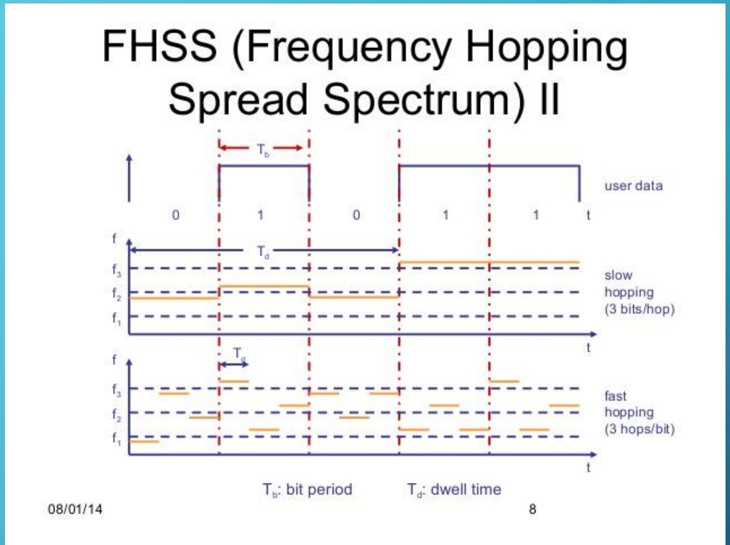


SPREAD SPECTRUM

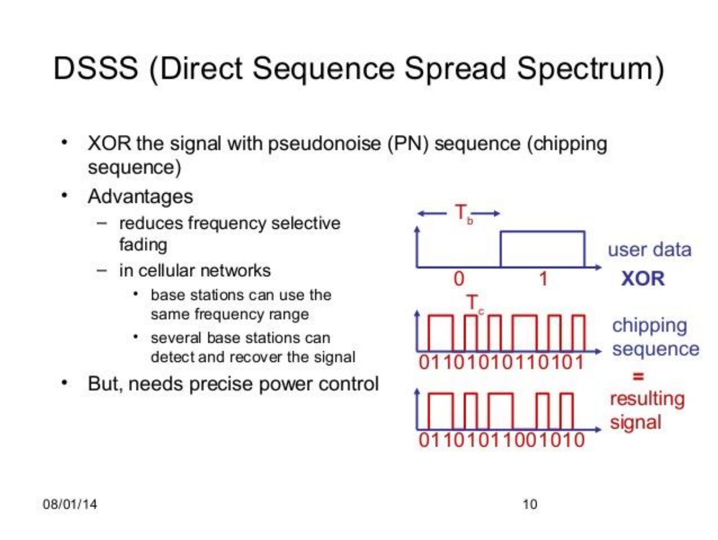
- Send data over wider bandwidth
  - Resistance it interference, noise jamming
  - Prevent detection
  - Limit flux density (satellite downlinks)
  - Security
  - Spreads power over wide spectrum -> spread spectrum
  - Narrowband interference cannot jam
  - Patented Hedy Lamarr

SPREAD SPECTRUM

- Frequency hopping spread spectrum (**FHSS**)
  - Pseudo random frequency hopping, known to transmitter and receiver
  - Bluetooth

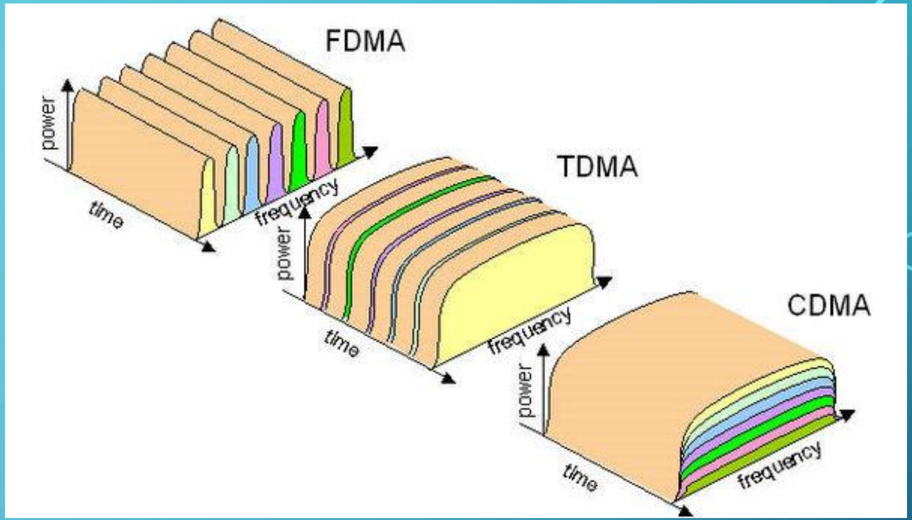


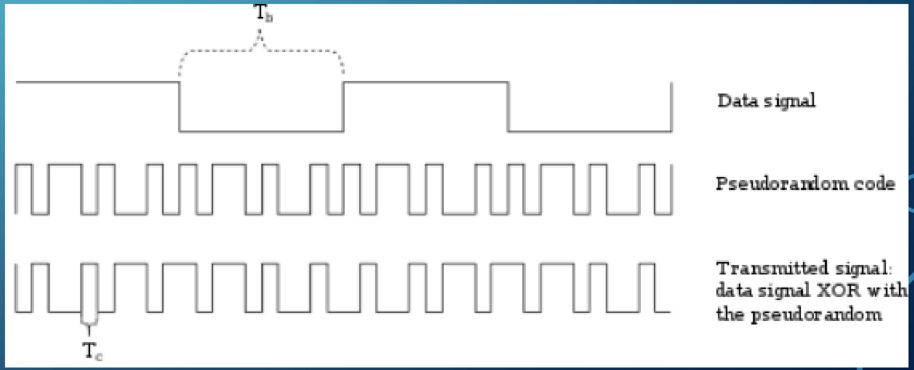
- Direct sequence spread spectrum (**DSSS**):
  - Spreading factor: code bits/databit = 10-100 commercial (FCC min 10), 10,000 for military
  - Signal bandwidth > 10x data bandwidth



DIVISION

- Frequency Division Multiple Access (**FDMA**)
  - Multiple users share channel bandwidth, each has very specific frequency
  - Requires high performance hardware filters
- Time Division Multiple Access (**TDMA**)
  - Users share same channel, take turns split in time
  - Used in 2G
- Time Division Duplex (**TDD**)
  - Allows duplex over single channel via time
  - Used in many LTE deployments
- Code Division Multiple Access (**CDMA**)
  - Each user data XORed with unique pseudorandom code, all users transmit, decoder pulls out each signal
  - 8-15 times capacity of analog
  - Spread spectrum single sideband



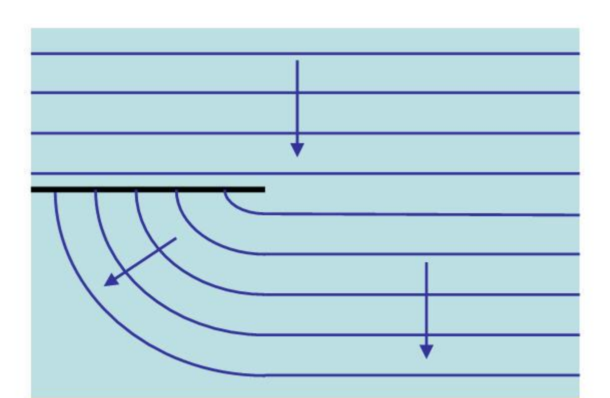


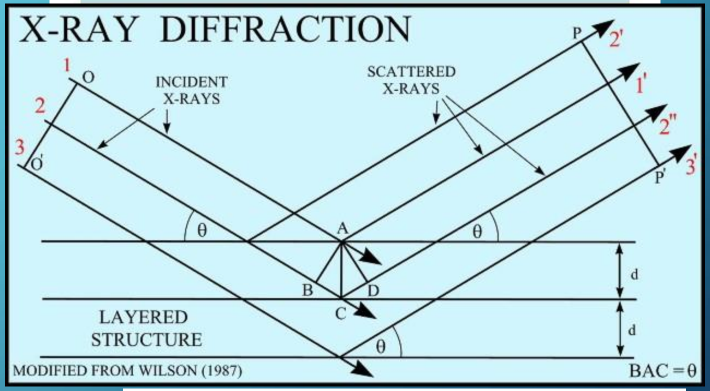
DIVISION

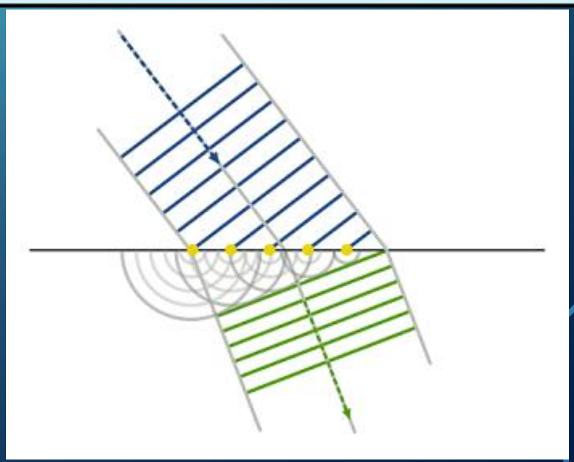
- Orthogonal Frequency Division Multiplexing (**OFDM**)
  - Splits channel into multiple frequencies
    - Nearby subchannels encoded using methods to avoid crosstalk, "orthogonal"
    - Orthogonal => peak of one is null of other
  - Better able to cope with severe channel conditions
  - Available band divided into 256 or more subbands
  - Each carrier modulated **BPSK**, **QPSK**, **16-QAM**, **256-QAM**, …
    - Selective frequency fading
  - Used in 802.11a/g, 802.16, HDTV, ADSL, DOCSIS, WLAN, 802.11ax, more

NOISE

- **Reflection**
  - Large surface relative to wavelength
  - May have phase shift
  - May cancel original or increase it
- **Diffraction** around edges
  - Edge of impenetrable body large relative to wavelength
- **Scattering**
  - Obstacle on order of wavelength, like a lightpost
- If no line of sight (LOS), diffraction and scattering are primary means of reception

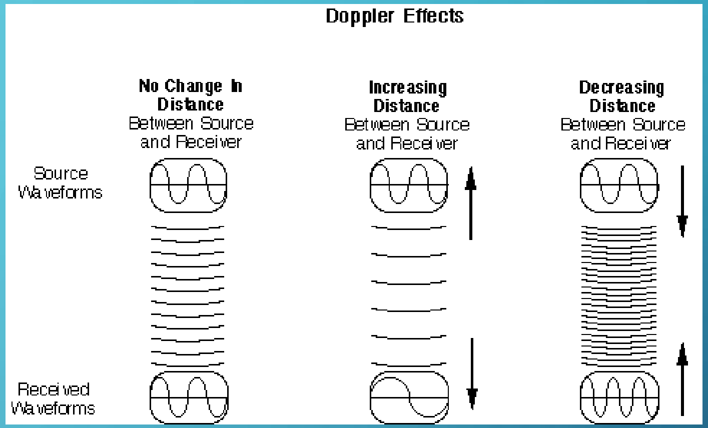


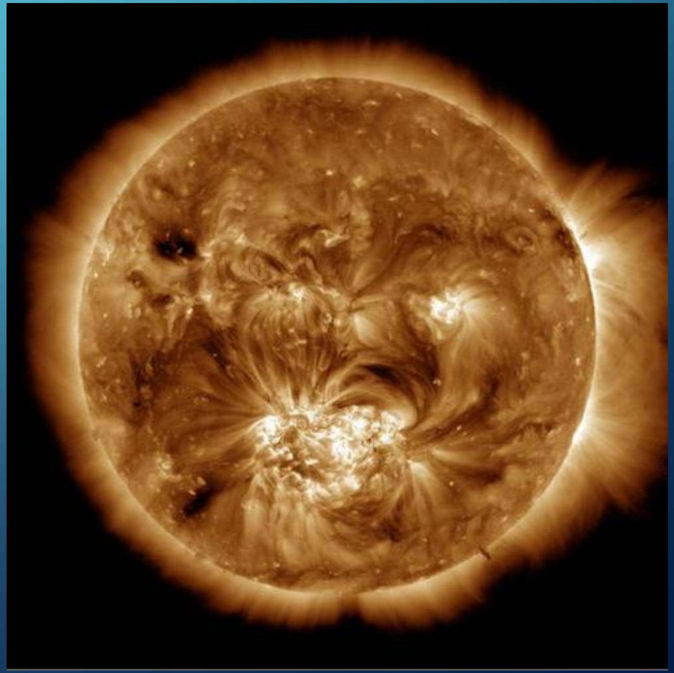




NOISE

- **Doppler** shift
  - 2.4 GHz, 120 km/hr => 267 hz difference
- Doppler if moving
  - 2.4 ghz, moving 120km/hr, 267 hz change)
- **Intermodulation**
- **Crosstalk**
- **Impulse** (spikes, short duration, high amplitude)
- **Sunspots** mostly affect lower frequencies (under GHz)
- Carrington event 1859
  - damaged telegraph lines world wide,
  - would cost US ~$1Trillion today



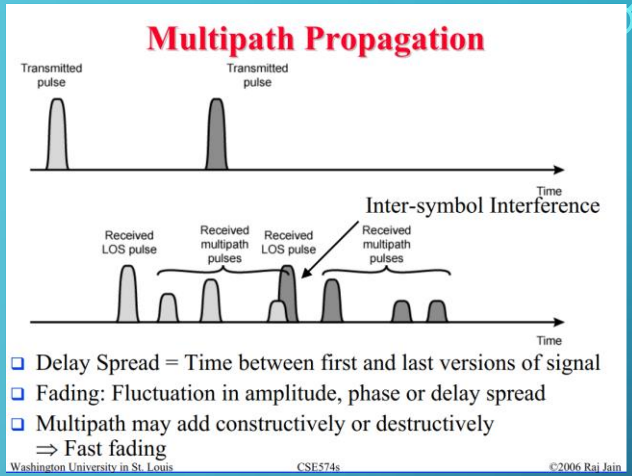


THERMAL NOISE

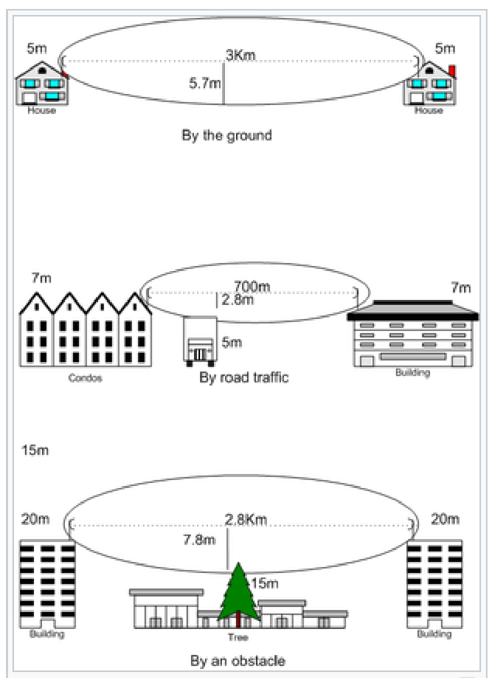
- **Thermal** – heat is vibrating atoms, vibrating atoms emit radio waves
    - antennas heat things, how microwave works
    - Uniformly distributed, white noise
- Thermal noise $= kT$ Watts/Hz
- $k =$ Boltzmann constant = 1.38 x 10^-23 Joules/Kelvin
- $T =$ absolute temperature in Kelvins
- **Ex:** 10 MHz receiver at 21 degrees C
    - Thermal noise = 1.38*10^-23 x (21+273.15) * (10*10^6)
    - In dBW = 10log_10 of above = -133.9 dBW

MULTIPATH

- **Multipath** issues



- **Fresnel zone**
  - Infinitely many
  - Out of phase reduce signal, in phase reinforce
  - Odd in phase, even out of phase
  - First 3 most important
  - Don't block first when placing antennas
  - Radius $F_n = \sqrt{\frac{n\lambda d_1 d_2}{d_1+d_2}}$ where d_i are distances to end, λ is wavelength



Several examples of how Fresnel zones can be disrupted

CHANNEL CAPACITY

- **Channel capacity**: tight upper bound on rate at which information can be transmitted over a communication channel. Symbol is **C**
- **Nyquist rate**: upper limit on symbol transfer rate, ≤ 2* bandwidth B
  - If symbol is a bit (bi-level encoding), then bit rate $\leq 2B$
  - Multi-level encoding: bit rate $\leq 2B \log_2 M$
- **Shannon-Hartley Theorem**:
  - Signal to noise S/N
  - Capacity $C = B \log_2(1 + S/N)$

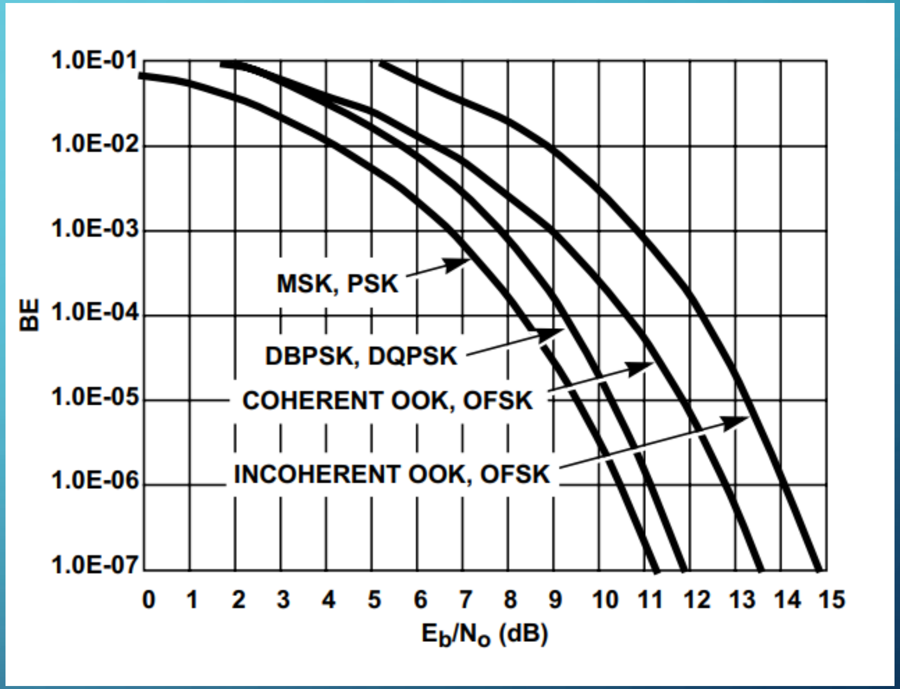
CHANNEL CAPACITY

- Shannon Hartley Theorem:
  - Example old wired phones::
    - Wire bandwidth 3100 hz, S/N = 30dB,
      10 log_10 S/N = 30 => S/N=1000
    - Capacity = 3100 log_2(1+1000) = 30,894 bps
- **Spectral efficiency** : bits/s/Hz
  - Link spectral efficiency: Bit rate per hertz of bandwidth, net after error correction, etc.
  - Modulation spectral efficiency: including error correction and other requirements
- Ex: V.92 phone modem: phone 300-3400Hz, 56,000 bps down, 56000/3100=18.1 bps/Hz

Technology	Spectral efficiency
2G cellular	0.5-1.3
3G	0.07-2.5
4G	2.7-7.3
WiFi a/g	2.7
WiFi ac	5-43

ERROR CORRECTION

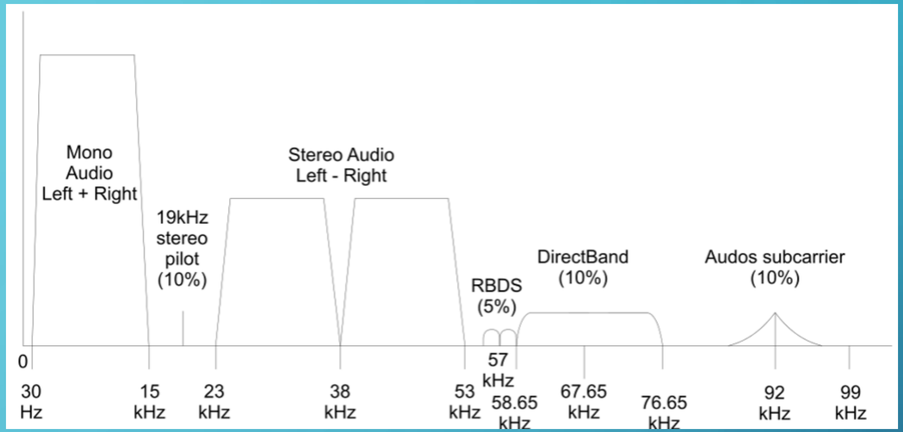
- Bit error rate
- Error detection – checksums: CRC, MD5, etc.
- **Forward Error Correction** (FEC)
  - Add redundancy, allows bit correction at receiver
  - Hamming distance: number of bits incorrect
- **Convolutional** codes: k bit in, k+r out,
  - designed for long bit streams
- **Classical FEC codes**: 3dB below Shannon limit
- **Turbo codes** : 0.5 dB below Shannon limit
  - Developed in 1993
  - 2 codes with interleaver
  - 3rd gen cellular uses



HIGHER LAYERS

- Above physical layer are many more layers
  - OSI model is a good reference
- Error correction
- Most advanced designs are packet networks, like IP
- Security

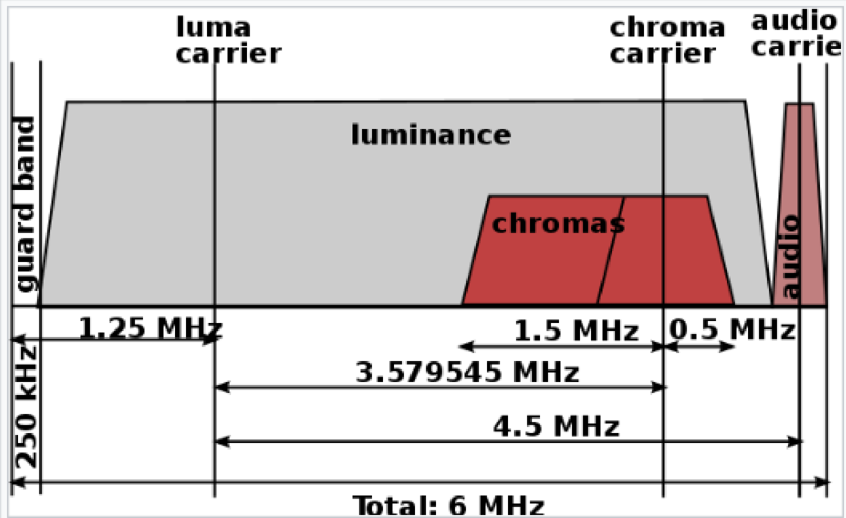
EXAMPLE: FM RADIO (US)



- 88-108 MHz
- Each channel gets 200 kHz bandwidth
- Digital : FM in-band on-channel (IBOC)
  - Digital in sidebands of usual FM stations
  - Increases interference for many older receivers
  - 57kHz subcarrier gives station name, GPS data for commercial receivers, radio text, at 1187.5 bps
  - OFDM and proprietary compressed
  - Gives 100, 112, 125, or 150 kbits/s data depending on power.
  - Can split into multiple channels

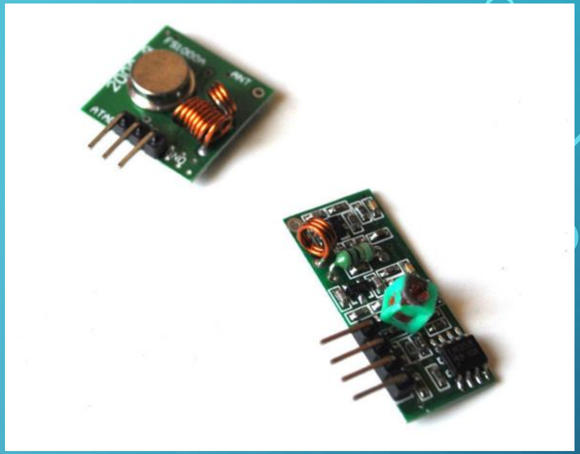
EXAMPLE: NTSC TELEVISION

- Channels 2-6 (54-88 MHz), 7-13 (174-216 MHz), 14-51 (470-698MHz)
- Each channel gets 6 MHz bandwidth
- 30/1.001 (~29.97) interlaced frames per second
  - Audio and video "beats"
    rate scaled down 1.001 to remove the aliasing
- 262.5 scan lines per frame, total of 525 lines, 483 visible
  - Vertical blanking lines allow synchronization and retrace
- Luma (brightness) and chrominance (color) => RGB at TV
  - Color subcarrier at 315/88 MHz
    uses QAM (I and Q) to encode chrominance
- Audio FM modulated 4.5 MHz higher than base freq

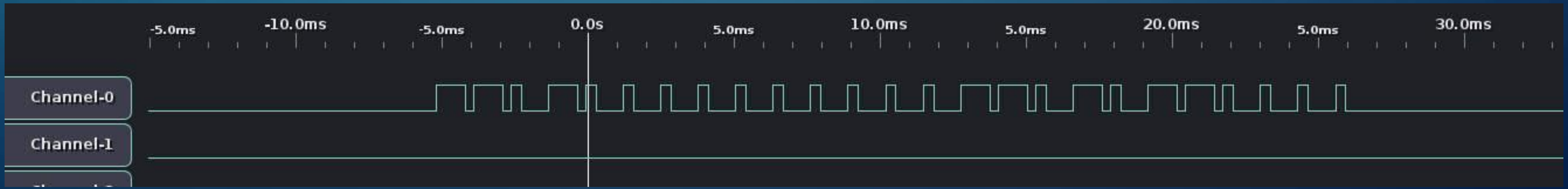


Spectrum of a System M television channel with NTSC color

EXAMPLE: RF REMOTES



- 433 MHz
  - 69 cm wavelength, antenna usually ¼ length at 17 cm, requires reflection plane
- On-off keying (OOK), also called Amplitude (ASK)
- **No formal data format**
- Usually something like:
  - 0 bit = on for T, off for T; 1 bit = on got T, off for 5T; SYNC = on for T, off for 10T
  - Sometimes short and long high pulses for 0,1
  - Sometimes other symbols also encoded
- Remote button press sends some number N of packets
- Packet usually around 50 bits, often manufacturer prefix, then data for key pressed

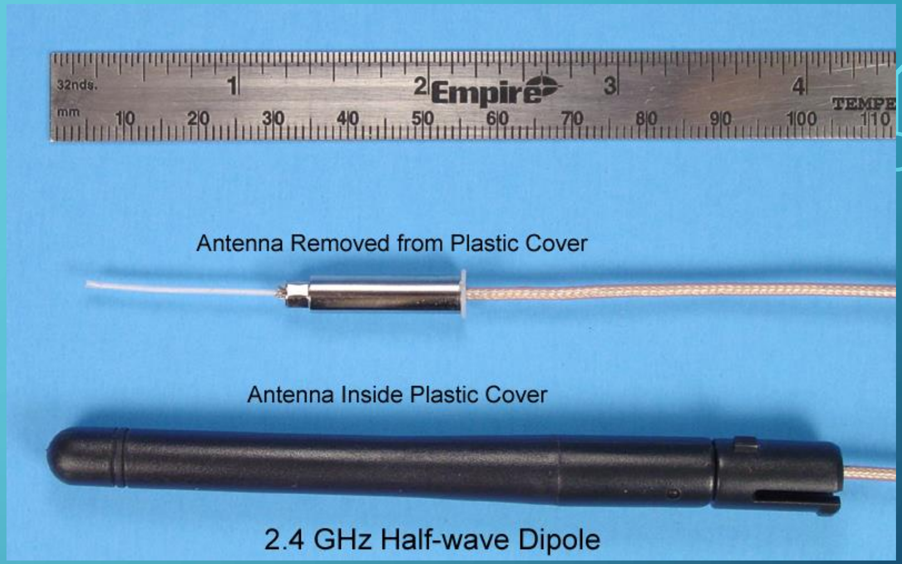


EXAMPLE: WIFI

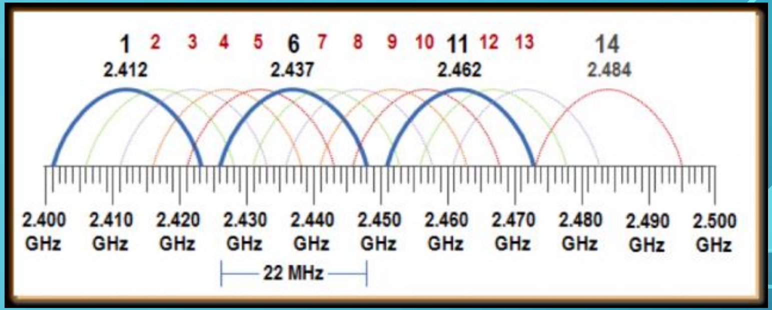
Standard	Year	GHz	Bandwidth (MHz)	Modulation	Antenna		Range m indoor/ outdoor
802.11	1997	2.4	20	DSSS,FHSS		2 Mb/s	20/100
802.11b	1999	2.4	20	DSSS		11 Mb/s	35/140
802.11a	1999	5	20	OFDM		4 Mb/s	35/120
802.11g	2003	2.4	20	DSSS,OFDM		54 Mb/s	38/140
802.11n	2009	2.5, 5	20,40	OFDM	MIMO	900 Mb/s	70/250
802.11ad	2010	60	2160	DSSS,OFDM, BPSK	Beamforming	7.2 Gb/s	3/120
802.11ac	2013	5	40,80,160	OFDM	(MU-)MIMO	2 Gb/s	35/120
802.11ax	2019	2.4, 5	20,40,80,160	OFDMA, 1024 QAM	(MU-)MIMO	14 Gb/s	35/120

EXAMPLE: WIFI

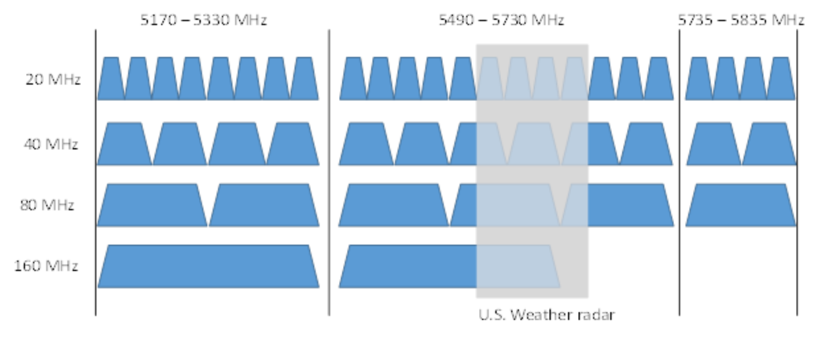
- 2.4 GHz used by microwave, Bluetooth, ZigBee
- 5 GHz used by satellites and radar
- Most wireless cards 32 mW output (+15dBm)
  - ~ high power Light Emitting Diode
  - Max power output 100 mW
- 3 dBi antenna common, 50 ohm impedance



EXAMPLE: WIFI

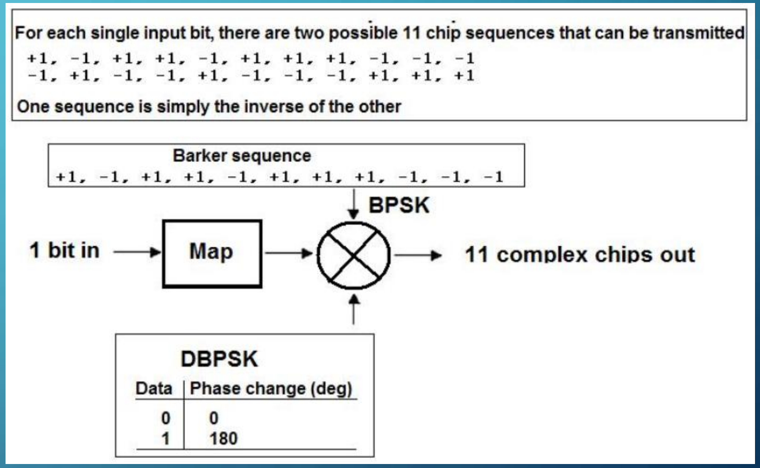


- 2.4 band is channels each 22MHz wide.
  - North America 11 channels, Europe 13, Japan 14.
  - Only two non-overlapping
- 5 GHZ band 3 bands, each split into 4 channels, total 12 channels
- 802.11 a and g use OFDM
  - Each 20 MHz wide carrier split into 52 subchannels, each 300 kHz wide.
  - OFDM uses 48 for data and 4 for error correction
  - BPSK for 125 kbps per channel = 6 Mbps
  - QPSK doubles to 12 Mbps
  - 16-QAM for 24 Mbps
  - 64-QAM gives 54 Mbps



EXAMPLE: WIFI

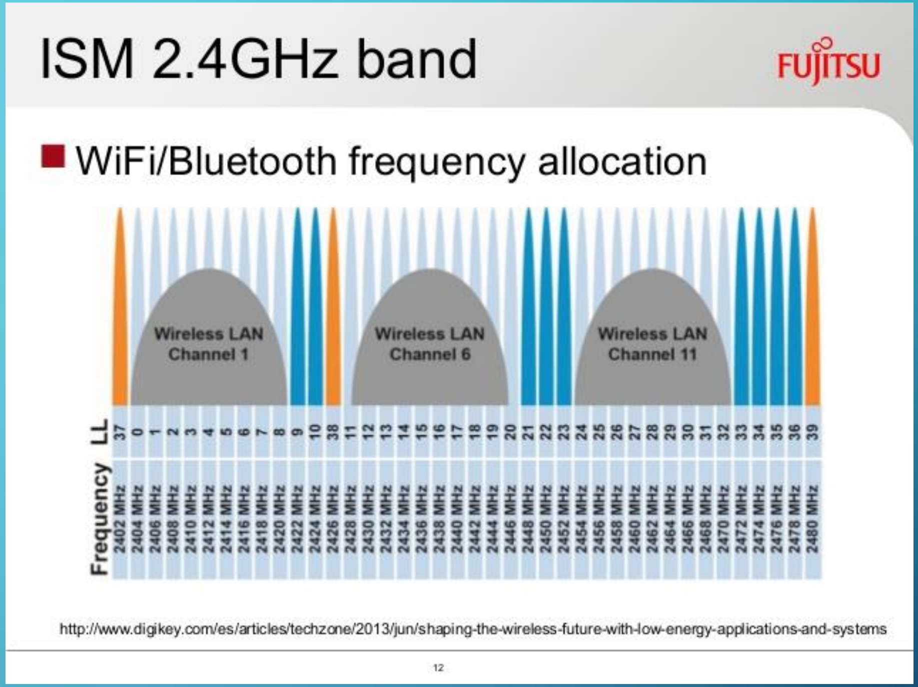
- 802.11b uses Direct Sequence Spread Spectrum (DSSS)
  - BPSK at 1 Mbps, QPSK for 2 Mbps, Complementary Code Keying (CCK) for 5.5 and 11 Mbps
  - 11 bit **Barker code** 1-2 Mbps
    - unaligned auto correlations are -1 and 0, aligned is +11
  - complementary code keying 5.5-11 Mbps



- 802.11n
  - **Channel bonding** aggregates two 20 MHz channels into one 40 MHz channel
  - MIMO (Multiple input/output) – uses multipath signals to the advantage of the receiver

EXAMPLE: BLUETOOTH

- 2.4 GHz bands, Antenna
- 80 Channels, 1MHz spacing.
  - Each channel shared by 8 devices
- GFSK at first, DQPSK added later
- **Frequency Hopping Spread Spectrum**
  - 800 hops per second,
- Duplex via time division (TDD)
- 1/3 or 2/3 rate Forward Error Correction, or Automatic Repeat Request (ARQ)
- Packets exchanged on master clock
  - 312.5 us/tick



Class	mW	dBm	Range m
1	100	20	~100
2	2.5	4	~10
3	1	0	~1
4	0.5	-3	~0.5

EXAMPLE: ZIGBEE

- 10-20 m
- 250 kbit/s
- 2.4 GHz (+ other in some countries)
  - 16 channels, 5 MHz apart, 2MHz bandwidth
  - Direct Sequence Spread Spectrum coding
  - BPSK in 868 and 915 MHz bands
  - OQPSK (2 bits per symbol) in 2.4 GHz band
  - ¼ length antenna is 3.125 cm long
- 0-20 dbm (1-100 mW) transmit
- Duty cycle for power savings
- 128 bit key for security

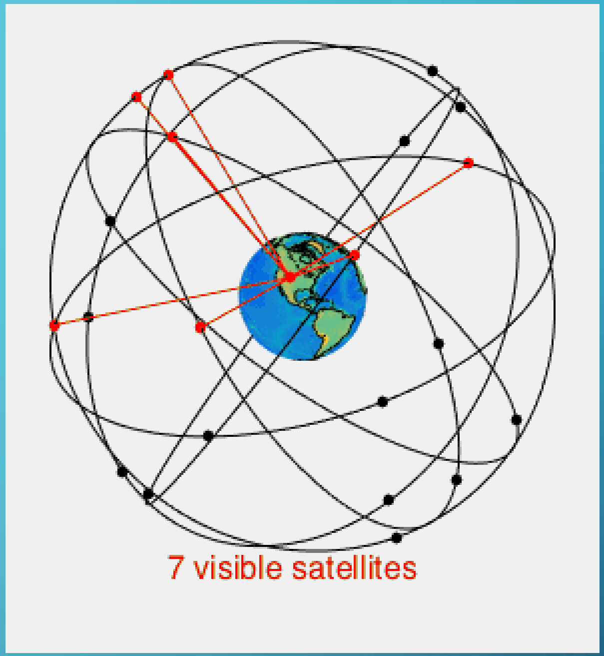
ZigBee®

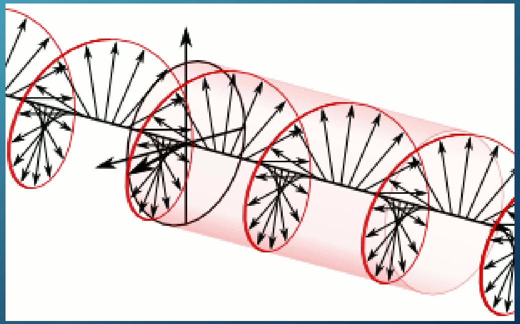
EXAMPLE: SATELLITE RADIO

- Sirius XM uses 2.3200-2.3325 GHz
  - Three 4MHz carriers, all decoded
- XM radio uses 2.3325-2.3450 GHz
  - Six 2MHz carriers, three decode by receiver
- User level antennas ~40dB gain
- OFDM QPSK signals
- Each two-carrier group broadcasts ~100 8-kilobit-per-second streams in approximately 4 MHz of radio spectrum
  - Audio compressed by proprietary methods

EXAMPLE: GPS

- 1.57542 GHz (L1 signal), 1.2276 GHz (L2 signal)
  - L3 at 1.38105 GHz used to report detected nuclear explosions to US
  - L4 at 1.379913 GHz is for studying ionosphere
  - L5 at 1.17645 is part of GPS modernization
- 24+ satellites, 20,000 km altitude, 4-12 visible at a time
  - 25.6 W transmitter, antenna gain 13 dBi gives 27 dbW
  - free space loss 182 dBW, leaves -155 dBW
  - Each has atomic clock with 1 nanosecond tick rate
  - Want 20-30 ns accuracy on clock ticks at earth
- GPS signals are **Right Hand Circularly Polarized**
  - Less vulnerable to destructive interference due to reflections
  - Difficult to read in small devices, which are usually vertically polarized





EXAMPLE: GPS

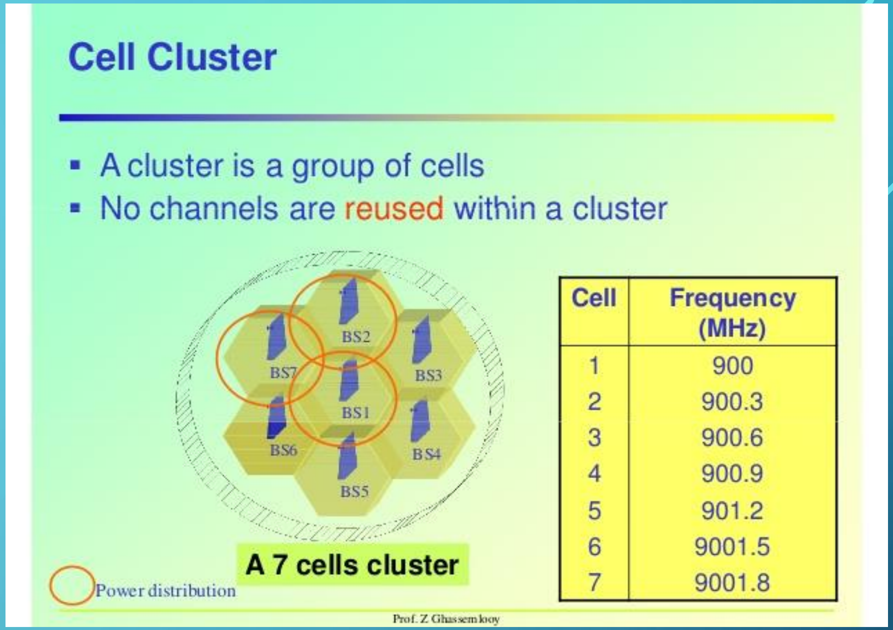
- Sends code known to receiver, alignment determines epoch
  - Sends Time of Transmission
  - Receiver measures 4 satellites, and from difference in times, computes receiver location
  - Modern receivers can track 12-20 satellites at once for more accuracy
- Transmits on L1 an L2 freqs, 50 bps, each message takes 750 seconds to complete (12.5 minutes)
- **Relativity** – Special and General both apply
  - Special relativity: Orbital speed 14,000 km/hr. Ground sees satellite clock as slower, adds about 7 ms per day.
  - General relativity: Earth mass curves space, satellites tick faster than ground by 45 ms per day.
  - Net is 45-7=38 ms per day needs added at ground, else off by 10km/day

EXAMPLE: CELLULAR

- 2G: 800 MHz, 850MHz, 1900 MHz
- 3G: 850, 1700, 1900, 2100 MHz
- 4G LTE : 600, 700, 850, 1700, 1800, 1900, 2100, 2300, 2600, 3600, 5200 MHz

Mobile 1G 1980s	Mobile 2G 1990s	Mobile 3G 2000s	Mobile 4G LTE 2010s
AMPS, NMT, TACS	D-AMPS, GSM/GPRS, cdmaOne	CMDA2000/EV-DO, WCDMA/HSPA+, TD-SCDMA	LTE, LTE Advanced
N/A	<0.5 Mbps	63 Mbps	300+ Mbps
Analog voice	Digital voice + Simple data	Mobile Broadband	Faster and better
Large freq gap between users	> 1 user per channel via TDMA	~14x user capacity per channel	1st global standard

EXAMPLE: CELLULAR



- Modulation formats:
  - FDMA, CDMA, TDMA, TDD (LTE), GMSK (GSM)
- Cellular tower structure
  - **Cell** –basic geographic unit of a cellular system
    - Channels
    - Coverage area called a footprint
  - **Cluster** – group of cells, no channels reused in cluster
  - Frequency reuse – each cell assigned some subset of channels different from neighbors
- Cell splitting – as cell gets too many users, needs split and more cells added
- Handoff – mobile, moving between cells. Cell network hands cell new channels as it moves
- Channels, antenna

EXAMPLE: CELLULAR

- Components:
  - Public Switched Telephone Network (PSTN)
    - Global backbone, wiring, local networks long-haul networks
  - Mobile Telephone Switching Office (MTSO)
    - Controls calls, tracks billing, locates subscribers
  - Cell site and antenna

  - Mobile Subscriber Unit (MSU). 3 types:
    - Mobile telephone (trunk of car style): typical transmit power 4.0 watts
    - Portable (hand held): 0.6 watts
    - Transportable: (1.6 watts)

EXAMPLE: CELLULAR 3G

- 1998
- 384 kbs – 21.6 Mbps (“3.5G”)
- Evolving encoding: UMTS, CMDA2000 and revisions…
- CMDA2000 Rev C
  - QPSK, 8-PSK, 16-QAM
  - SNR required -12 to 9.7 (slow to fast)

EXAMPLE: CELLULAR 4G

- 2009
- MIMO, MU-MIMO
- OFDM, OFDMA, Single Carrier FDMA (SC-FMDA)
- Turbo codes for error correction
- Adaptive modulation and error correction
- All IP packet switched network
- 100 Mbps high mobility, 1 Gbps low mobility
- Link spectral efficiency 15 bit/s/Hz downlink, 6.75 uplink
- LTE peak download 1Gbps, upload 500 Mbps

EXAMPLE: CELLULAR 5G

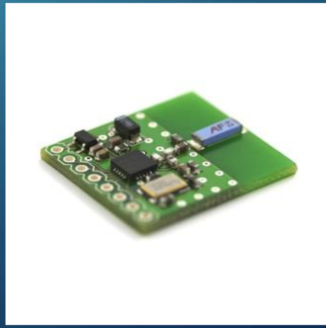
- First wave ~2021, trials 2018-2019
- 9 GHz of unlicensed spectrum at 60 GHz (current cellular has ~800 MHz of spectrum). Some current testing at 15 GHz
- Want
  - 10-100x data rate,
  - 1000x network capacity (10^6 devices / km^2) using smaller cells
  - 10x energy efficiency,
  - 10-20x lower latency (1ms)
- 20 Gbps throughput

EXAMPLE: EMBEDDED DESIGN

- Process for PCB antenna
  1. Build PCB
  2. Test with spectrum analyzer
  3. GOTO 1 until works
  4. FCC testing, fail
  5. GOTO 1 again

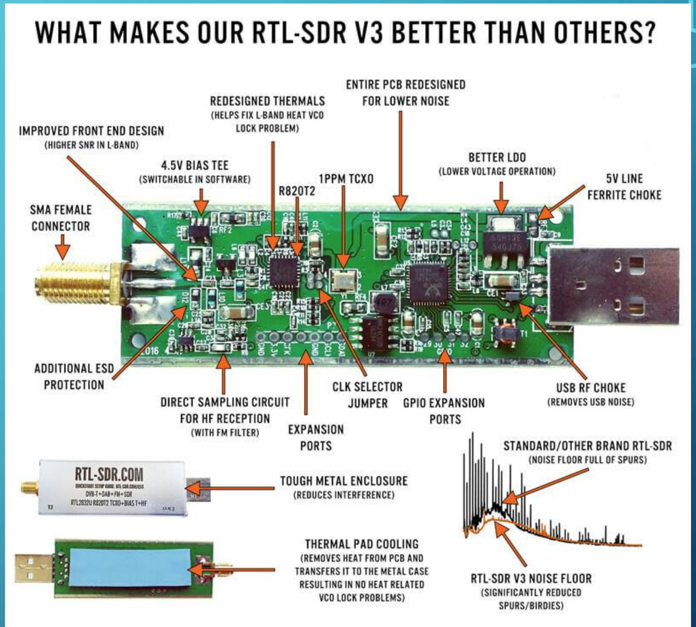
- External antennas

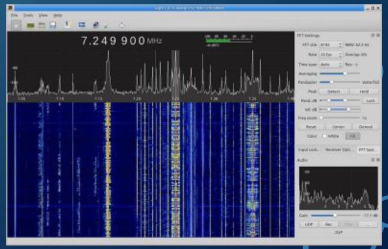
- **Chip antenna** – blue chip at right
  - High permittivity constant sets up standing wave in tiny space
  - Smaller than traditional antenna



EXPERIMENT: SOFTWARE DEFINED RADIO

- Cheap RTL-SDR dongle ~$25
  - Receive 500kHz - 28.8MHz signals
- HackRF One ~ $300
  - Transmit/receive 1MHz – 6 GHz
  - TX/RX not simultaneous (?)
- Open source GNU Radio, gqrx
- Know laws to transmit





SECURITY ISSUES

- Protocol holes
- Snooping
- Leaks
- Blocking
- Physical layer (def of hardware, encoding and signaling, transmission and reception, topology)

- Breaks galore!

QUESTIONS ?

THE END