Οικονομικό Πανεπιστήμιο Αθηνών
Τμήμα Πληροφορικής

Ευφυή Κινητά Δίκτυα: Ασύρματο Κανάλι και Διάδοση Σημάτων

Εαρινό Εξάμηνο 2023-24

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(Διαφάνειες του Βασίλειου Σύρη)

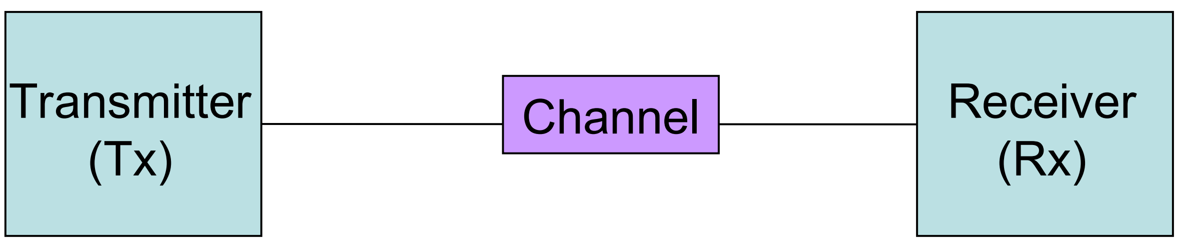
What is wireless networking

- Any form of communication that does not require the transmitter and receiver to be in physical contact
- Simplex: one-way communication (e.g., radio, TV)
- Half-duplex: two-way communication but not simultaneous (e.g., walkie-talkie, CB, Wi-Fi physical layer)
- Full-duplex: two-way communication (e.g., cellular

Basic communication system (single hop)

» Transmitter performs encoding, modulation, and multiplexing

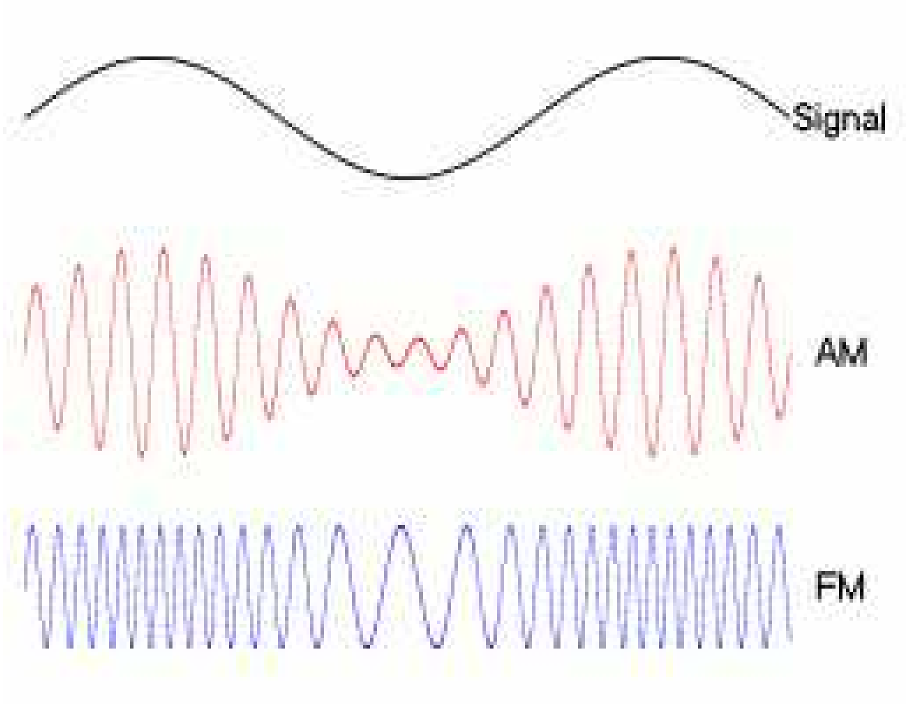
» Receiver performs demodulation and demultiplexing



Modulation

- Modulation is the general technique of shaping a signal to convey information.
- Digital Vs. Analog
  - D: Modulated signal has limited number of states (or values) commonly zero and one
    - depends on the number of symbols used
  - A: Modulated signal has infinite number of states (or values).

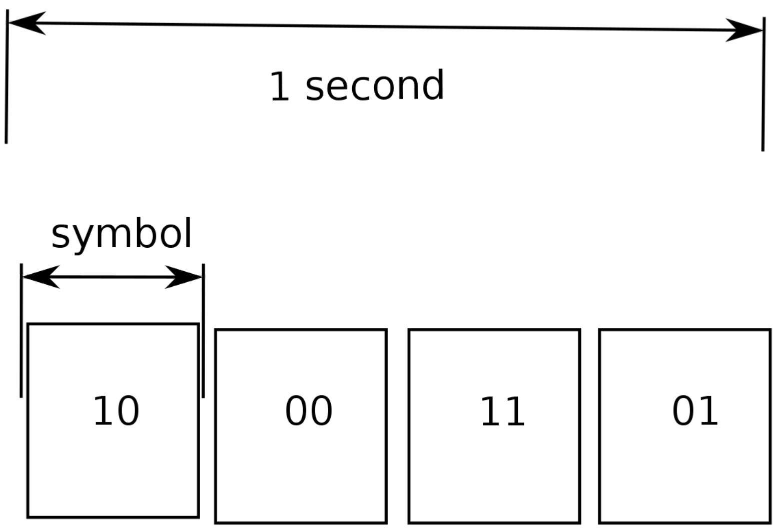
Analog Modulation



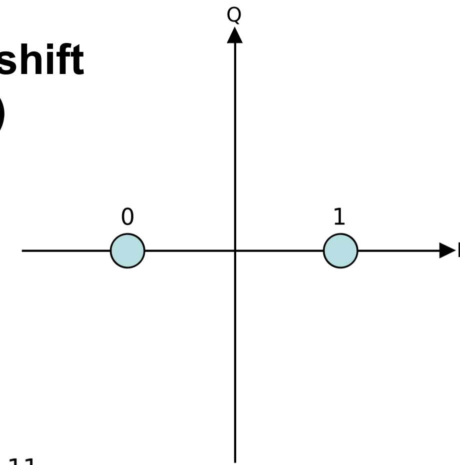
Src: https://en.wikipedia.org/wiki/Modulation#/media/File:Amfm3-en-de.gif

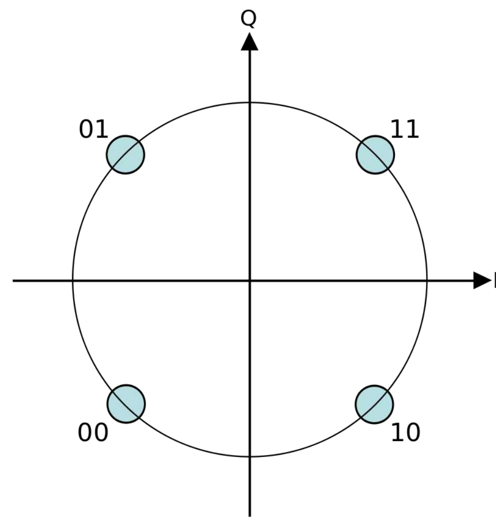
Digital Modulation

Schematic of 4 baud, 8 bit/s data link containing arbitrarily chosen values.



Binary phase-shift keying (BPSK)



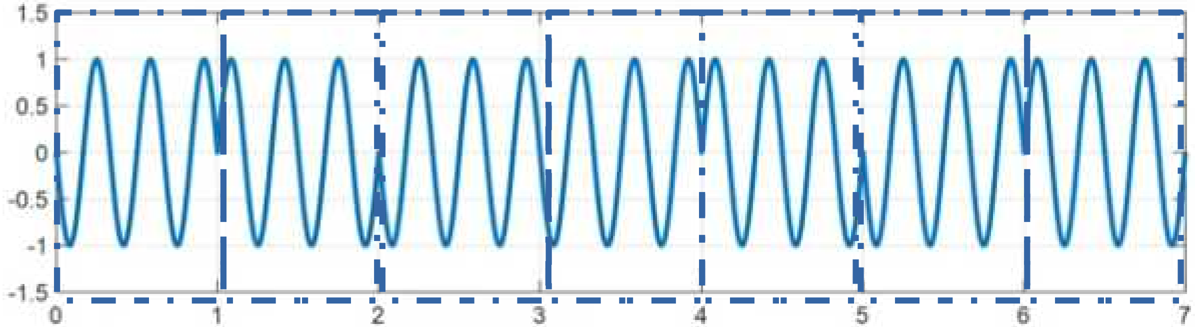


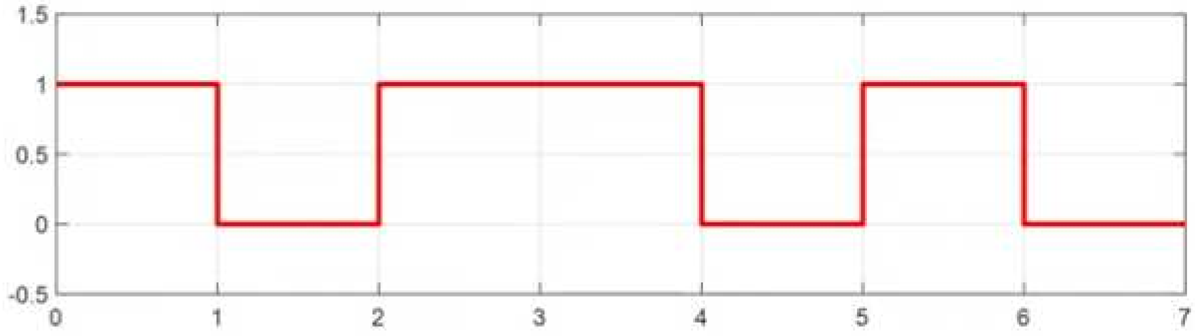
Quadrature phase-shift keying (QPSK)

Src: https://en.wikipedia.org/wiki/Modulation#/media/File:Baud.svg
https://en.wikipedia.org/wiki/Phase-shift_keying

Digital Modulation – Ex. BPSK

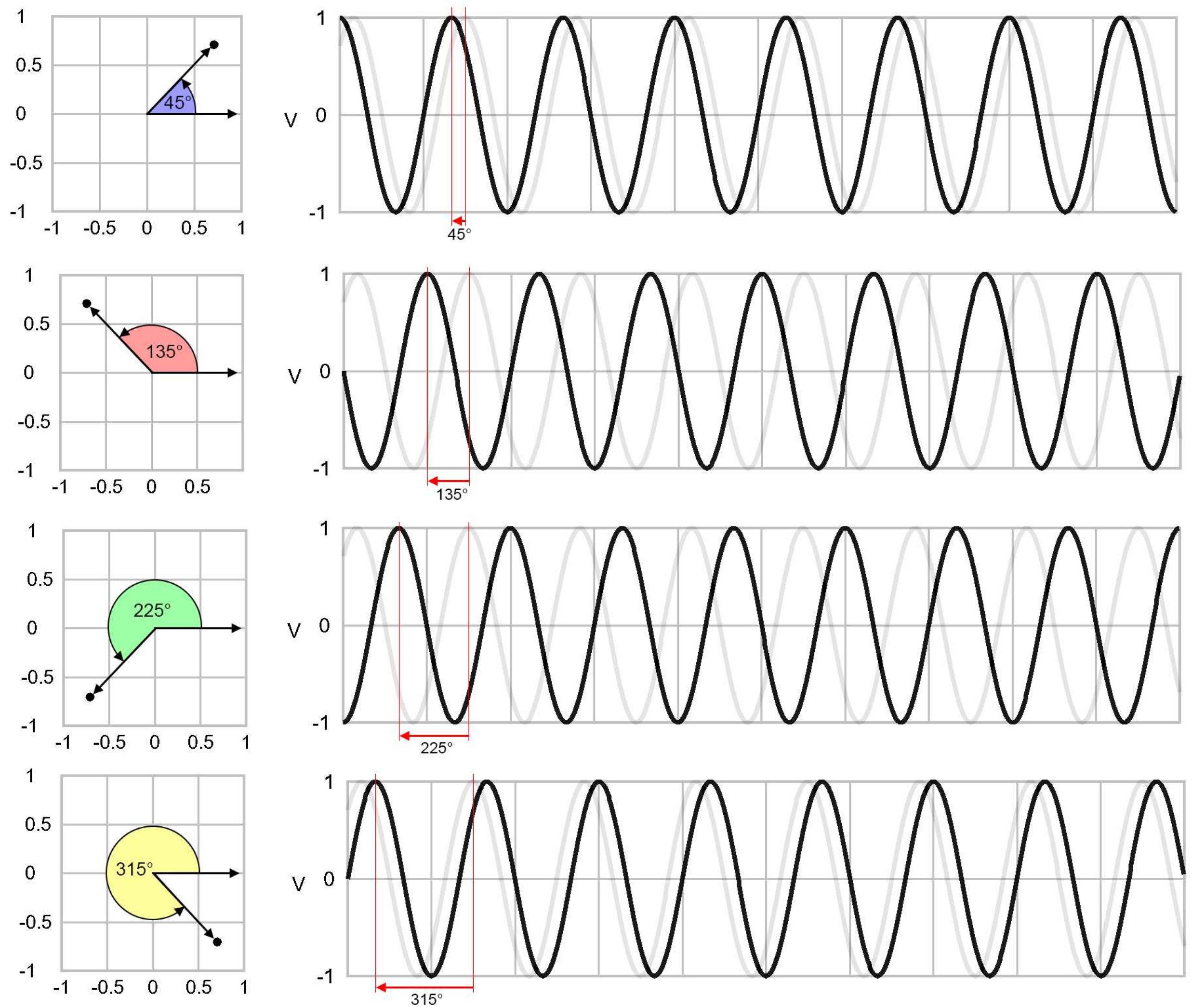
Carrier wave with fixed amplitude and frequency.





Src: https://www.youtube.com/watch?v=lDSzyEQKE6o

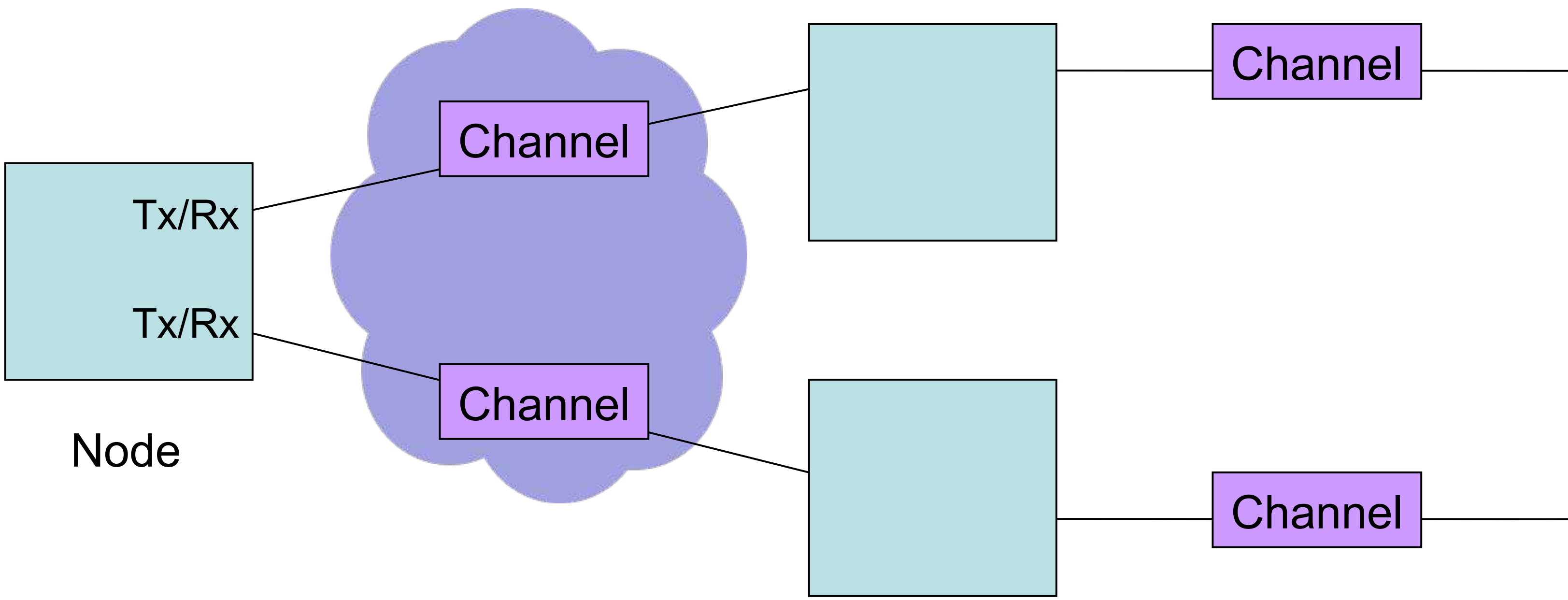
Digital Modulation – Ex. QPSK



Basic communication network (multiple hops)

» Wired communication: channels independent (no interference)

» Wireless: channels interfere



» Same feature can be an advantage: broadcast

Basic wireless terms

» Frequency

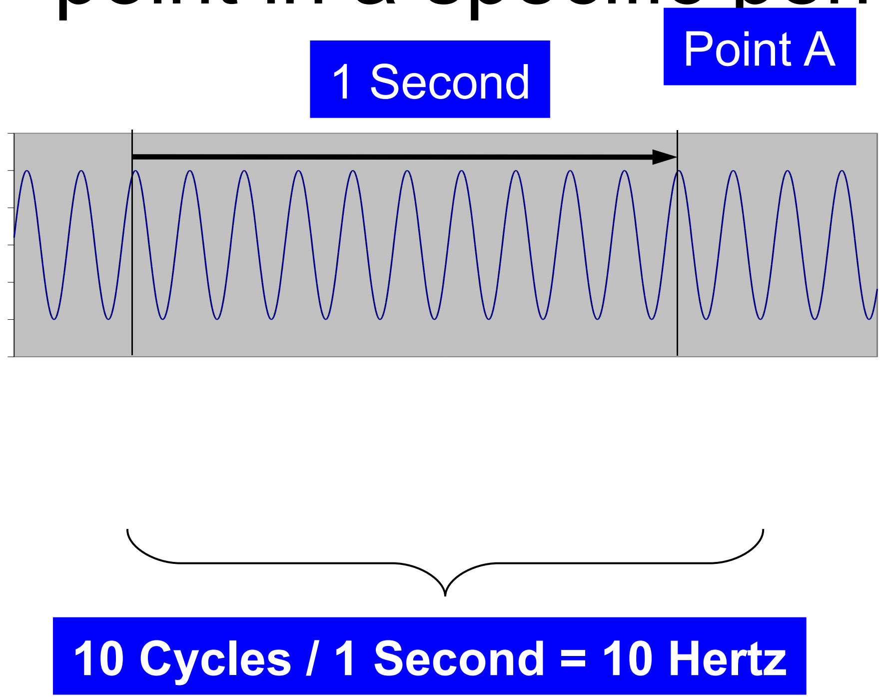
» Spectrum

» Bandwidth

» Capacity

Frequency

» Frequency is the number of times that a wave's peak passes a fixed point in a specific period of time



Frequency (cont)

- Frequency is measured in cycles per second, or Hertz (Hz)

1,000 Hz =	1 KiloHertz (kHz)
1,000,000 Hz =	1 MegaHertz (MHz)
1,000,000,000 Hz =	1 GigaHertz (GHz)

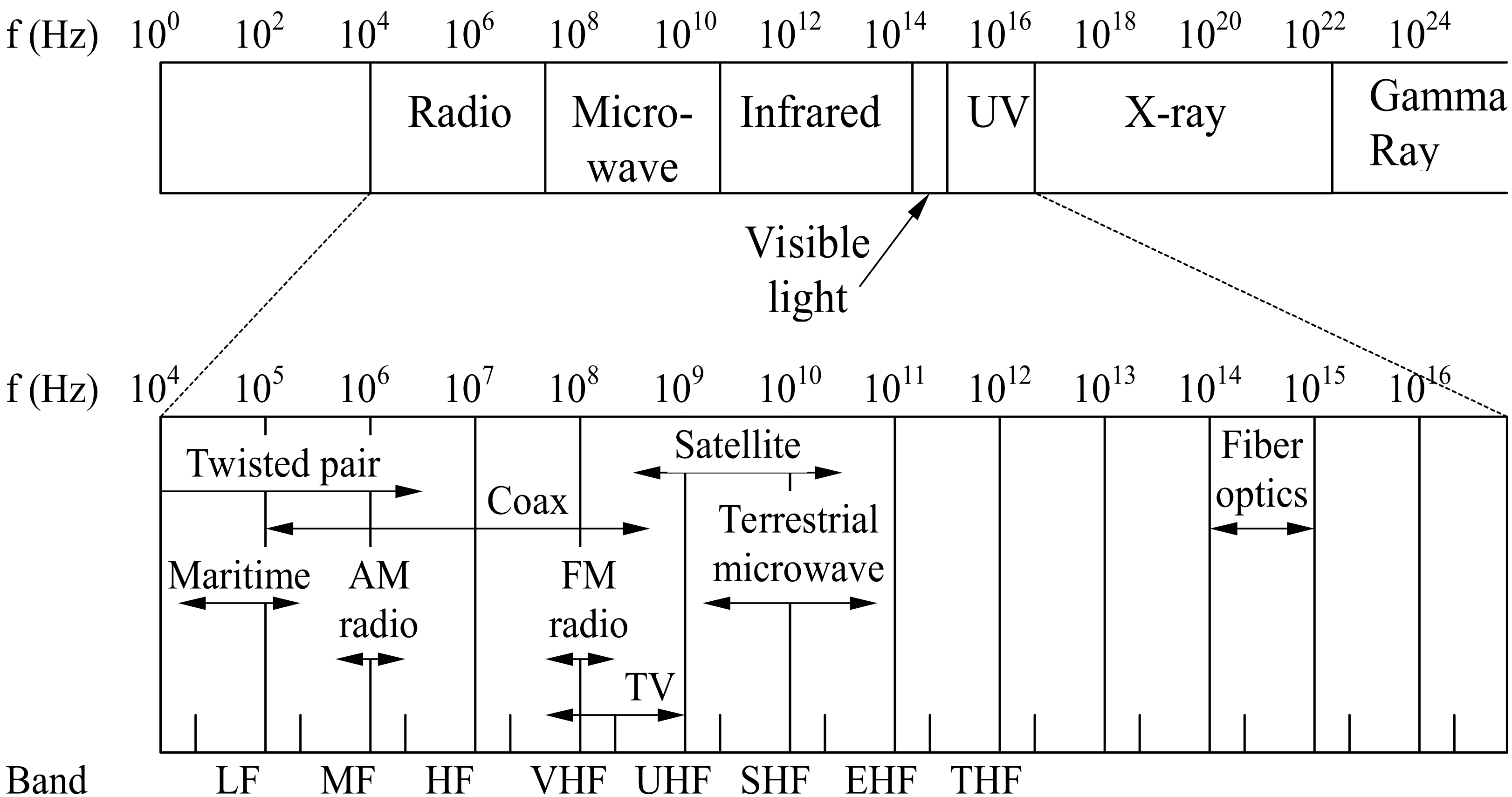
- Cellular phones, for example, produce radio waves with frequencies around 900 million Hz (900 MHz)
- Frequency f and wavelength λ: $f = c/\lambda$
  - c: speed of light

Spectrum

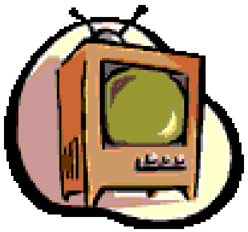
- For our purposes, spectrum is the term that describes a set of radio waves that can be used to transmit information

Electromagnetic spectrum

» Wireless communications: 100KHz-60GHz



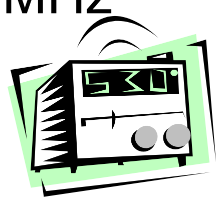
Wireless Spectrum (1)



Broadcast TV
- VHF: 54 to 88 MHz, 174 to 216 MHz
- UHF: 470 to 806 MHz

30 MHz   300 MHz   3 GHz   30 GHz

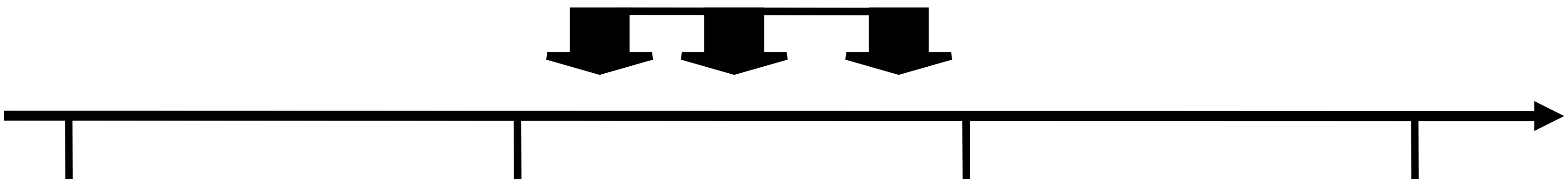
FM Radio
- 88 to 108 MHz



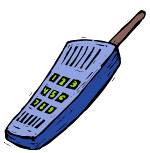
Digital TV
- 54 to 88 MHz, 174 to 216 MHz, 470 to 806 MHz

Wireless Spectrum (2)

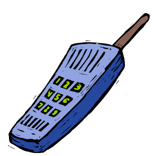
3G Broadband Wireless
• 746-794 MHz, 1.7-1.85 GHz, 2.5-2.7 GHz



30 MHz 300 MHz 3 GHz 30 GHz

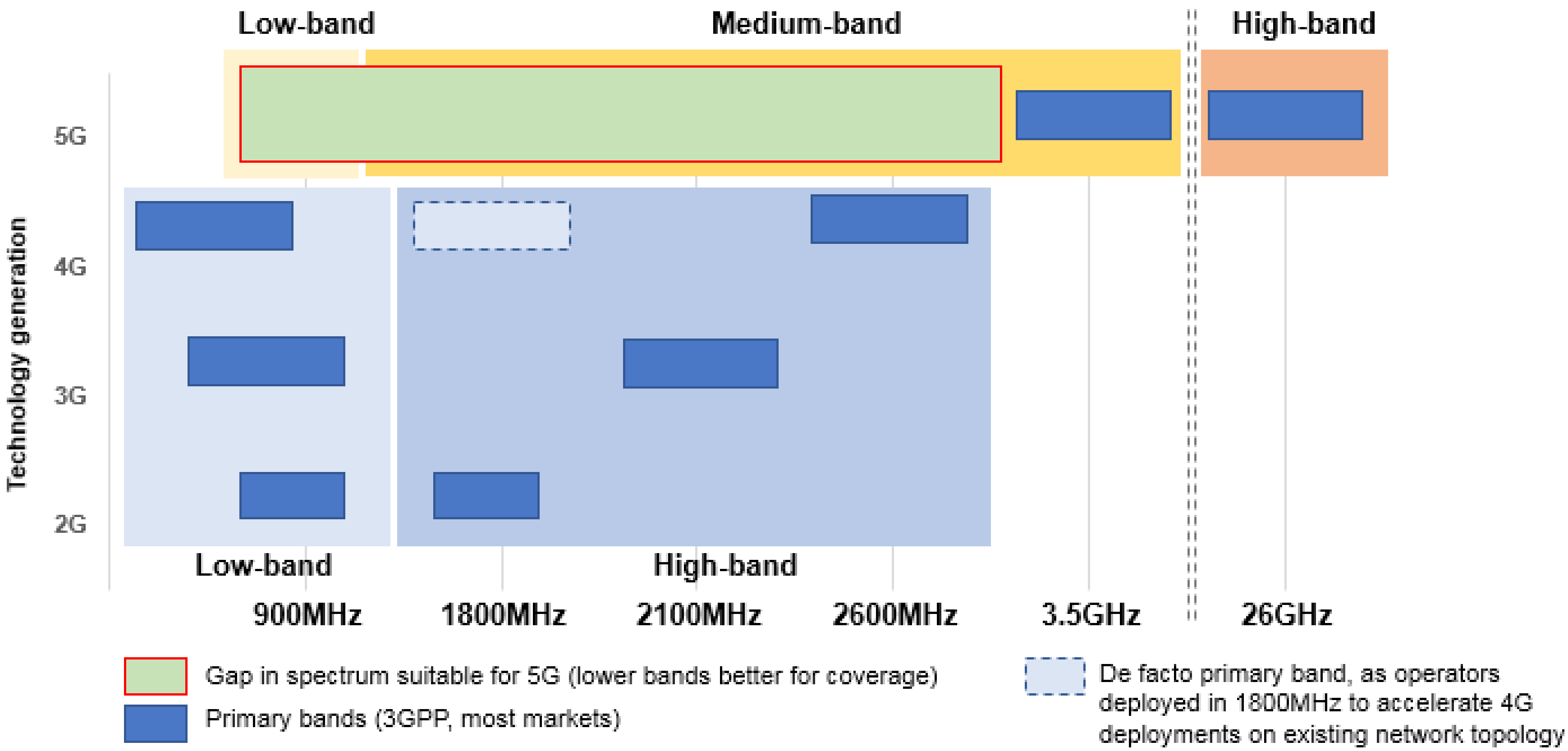


Cellular Phone
• 800-900 MHz

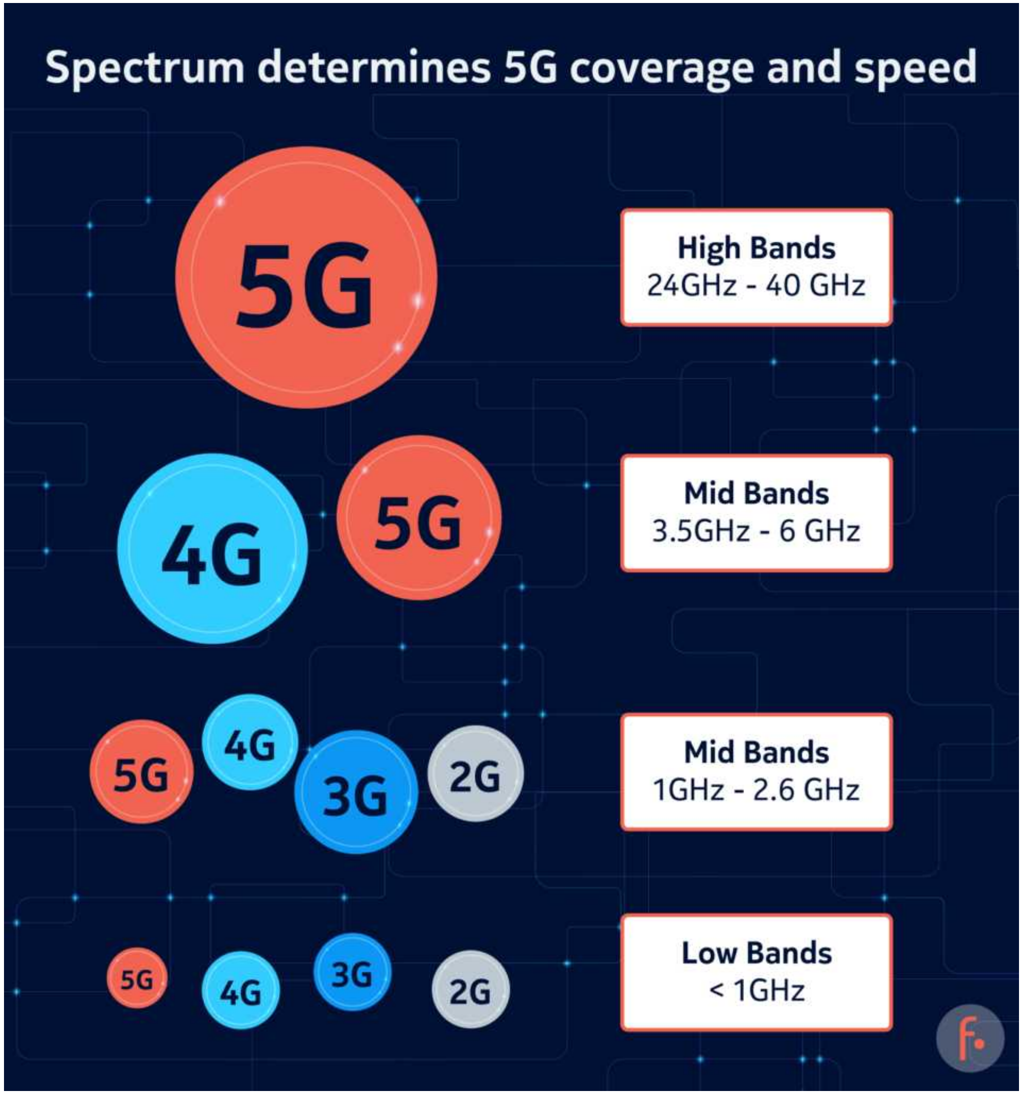


Personal Communication Service (PCS)
• 1.85-1.99 GHz

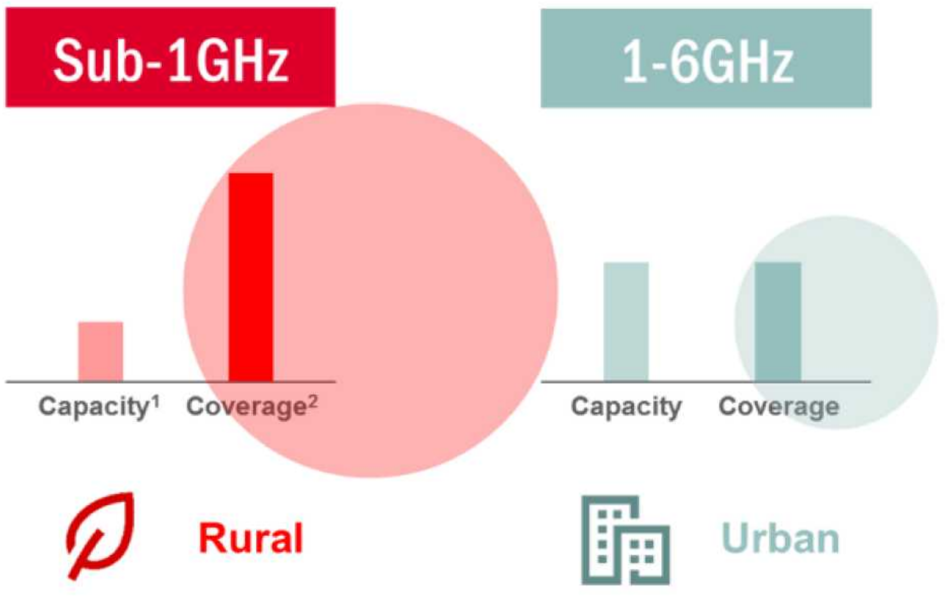
5G frequency bands



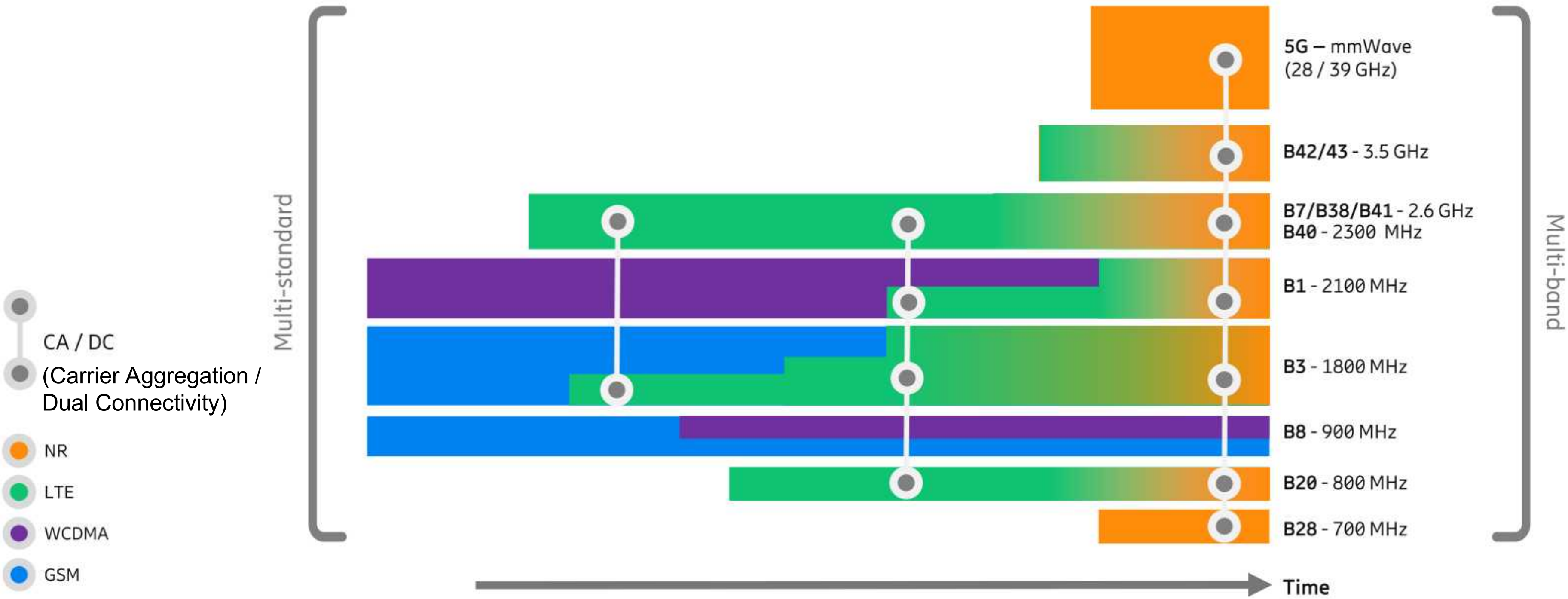
3-5G frequency bands



Sub/Mid/Hi 5G frequency bands

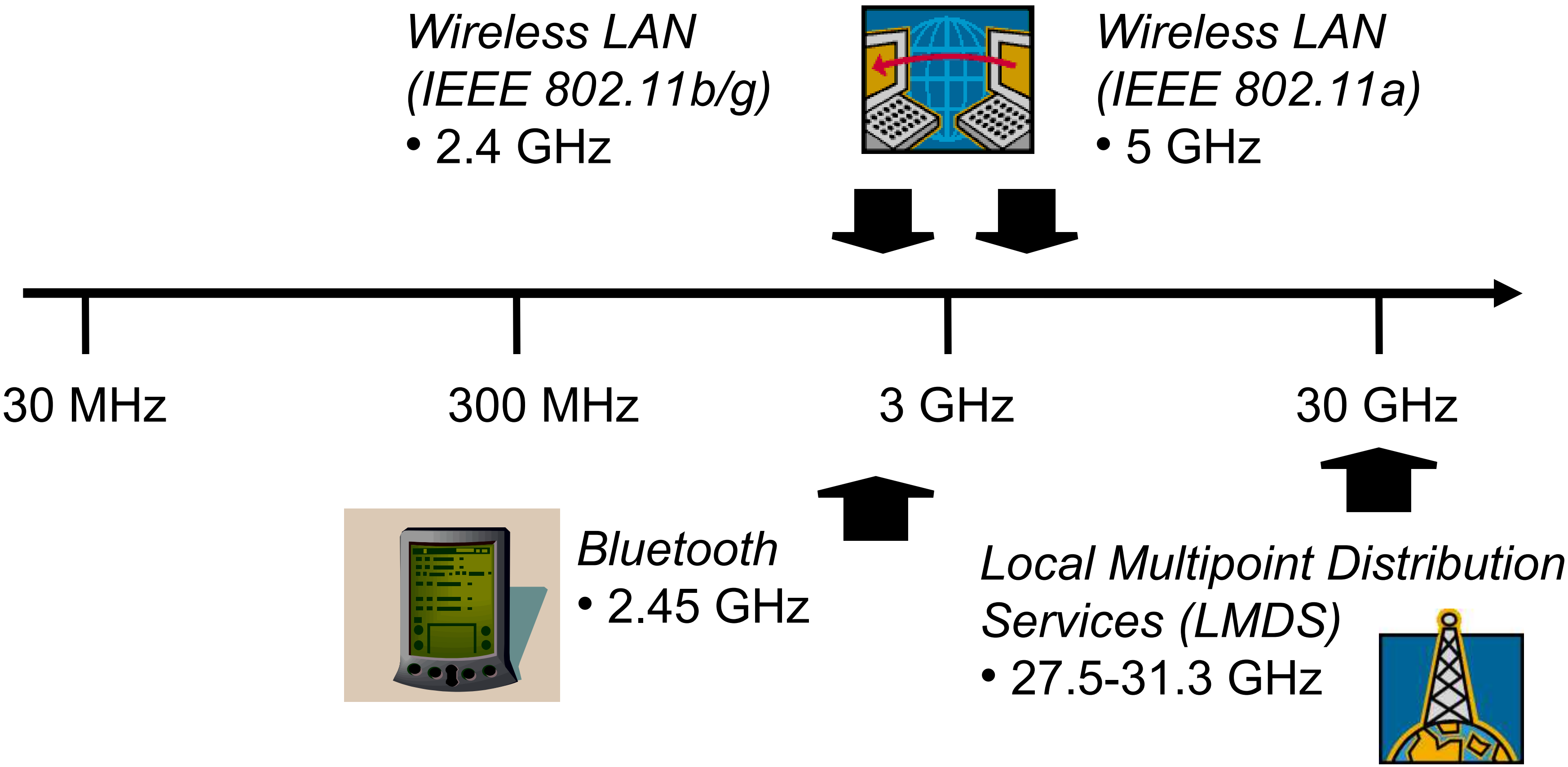


5G multi-standard & multi-band

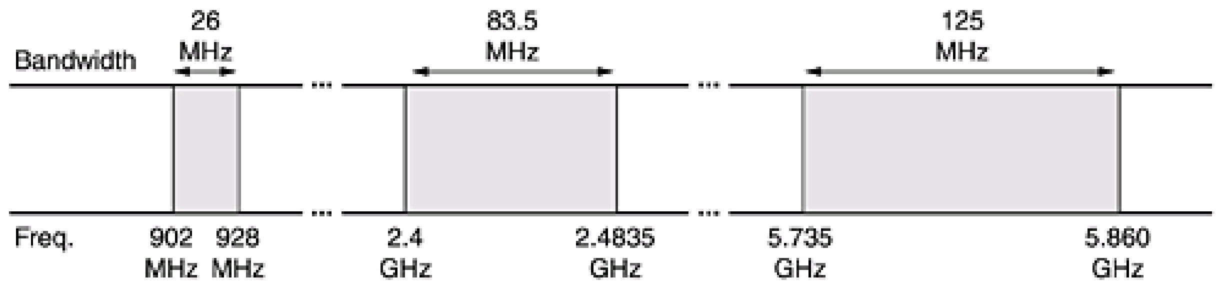


Source: 5G Today: Trends and Insights 2019-09-18

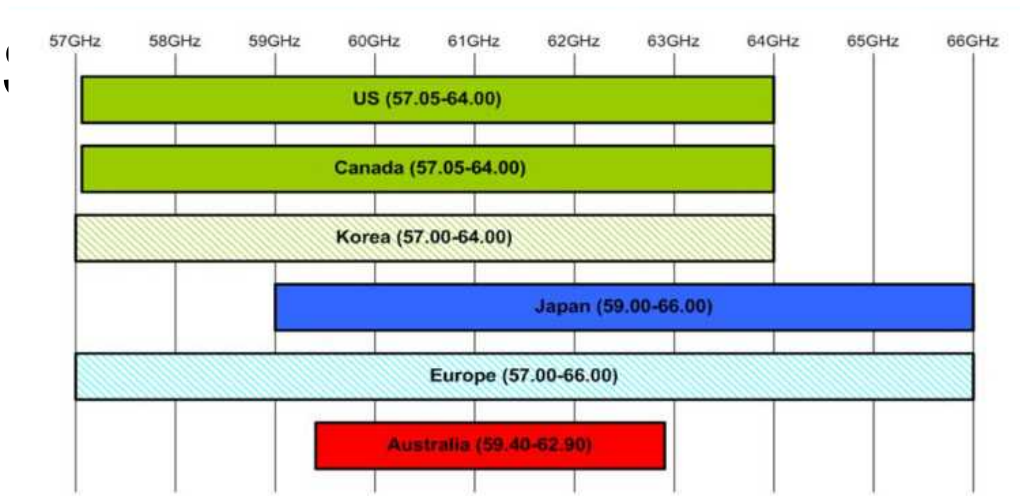
Wireless Spectrum (3)



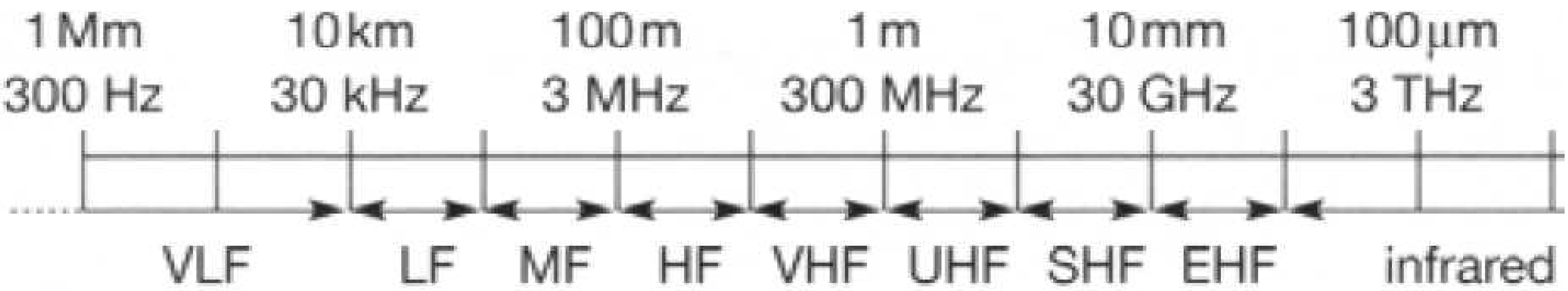
ISM Band (Industrial Scientific Medical)



- Unlicensed
- Used mainly by WLANs
- 60 GHz I



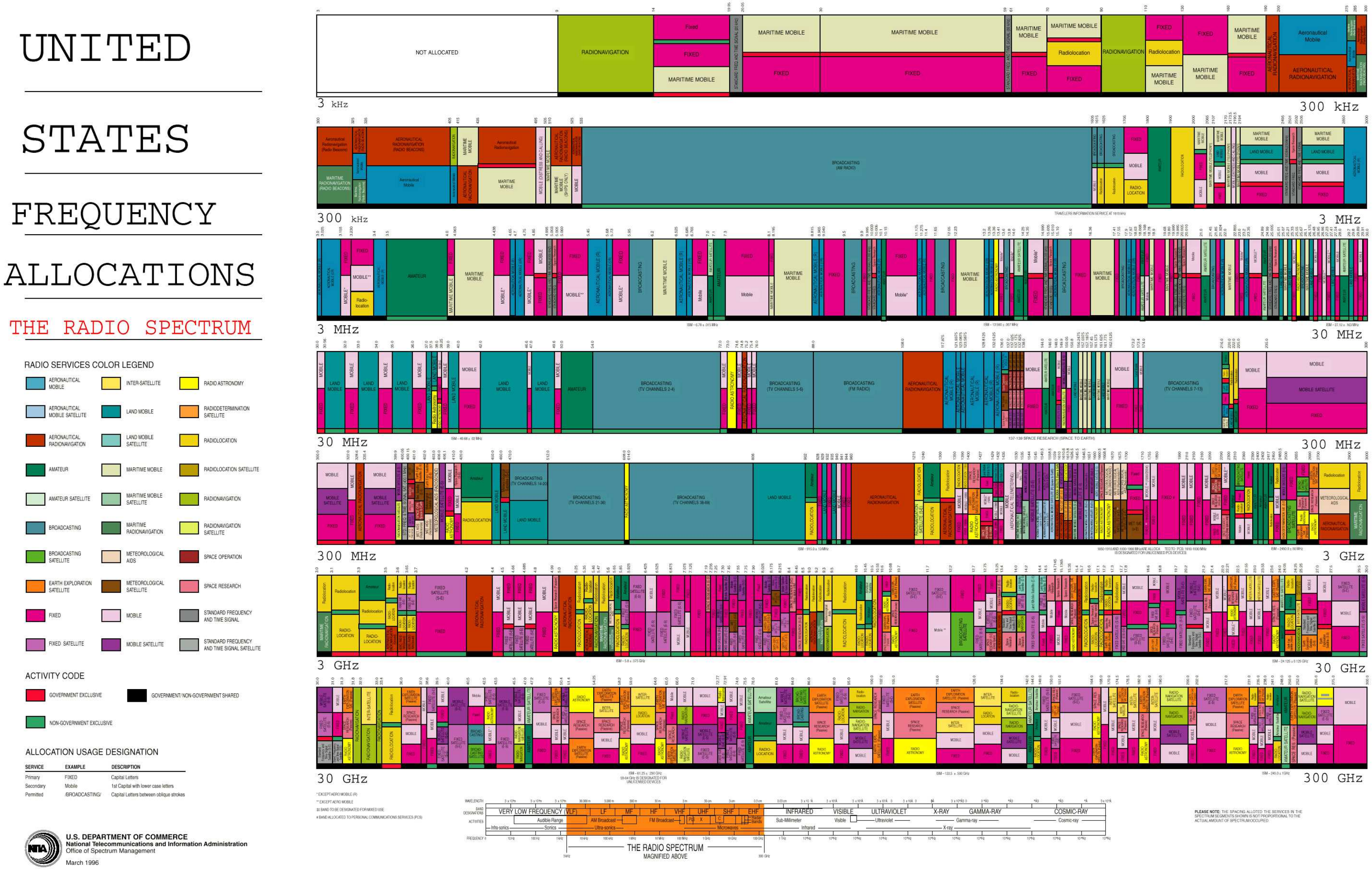
Basic properties



» Moving from left to right

- higher bandwidth
- more power
- shorter range (higher attenuation, blocking)
- more sophisticated electronics

Radio Spectrum Allocation (USA)

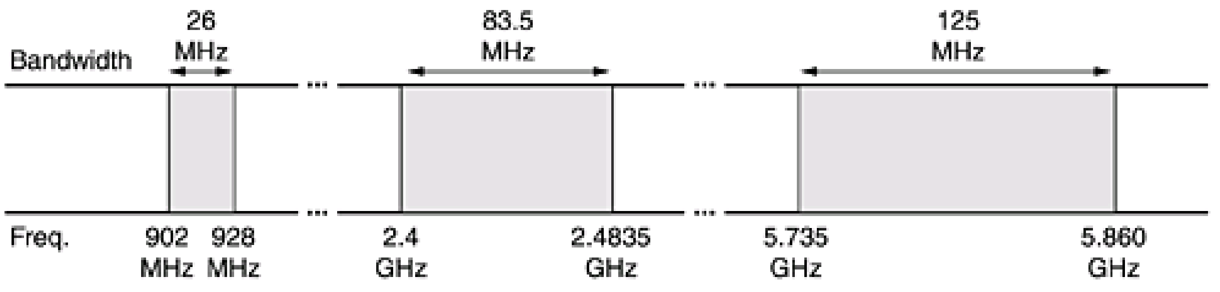


Frequency vs. Bandwidth

- » Frequency is a specific location on the electromagnetic spectrum
- » Bandwidth is the range between two frequencies

- Bandwidth is measured in Hertz
- A cellular operator may transmit signals between 924-949 MHz, for a total bandwidth of 25 MHz

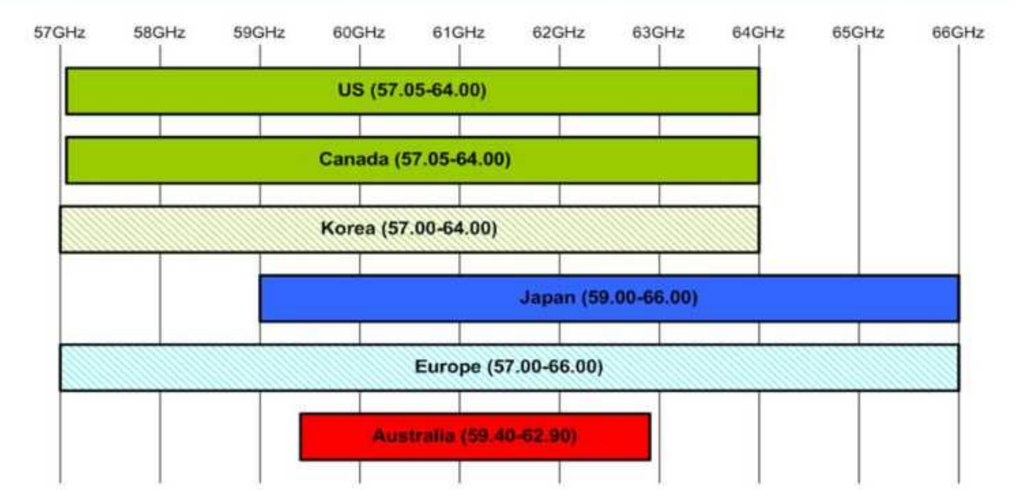
ISM Band (Industrial Scientific Medical)



» Unlicensed

» Used mainly by WLANs

» 60 GHz I



Bandwidth vs. Capacity

» Bandwidth for a particular service is fixed, but the number of calls and the rate of data transmission is not (capacity)

» The technology used determines the capacity of a particular bandwidth

» Shannon capacity fundamental limit

Signal strength (or power)

- The ability of an electromagnetic wave to persist as it radiates out from its transmitter
- Signal strength, or power, is measured in Watts, or more conveniently expressed relative to milliWatts in decibels (dBm)

Signal propagation range

» Transmission range

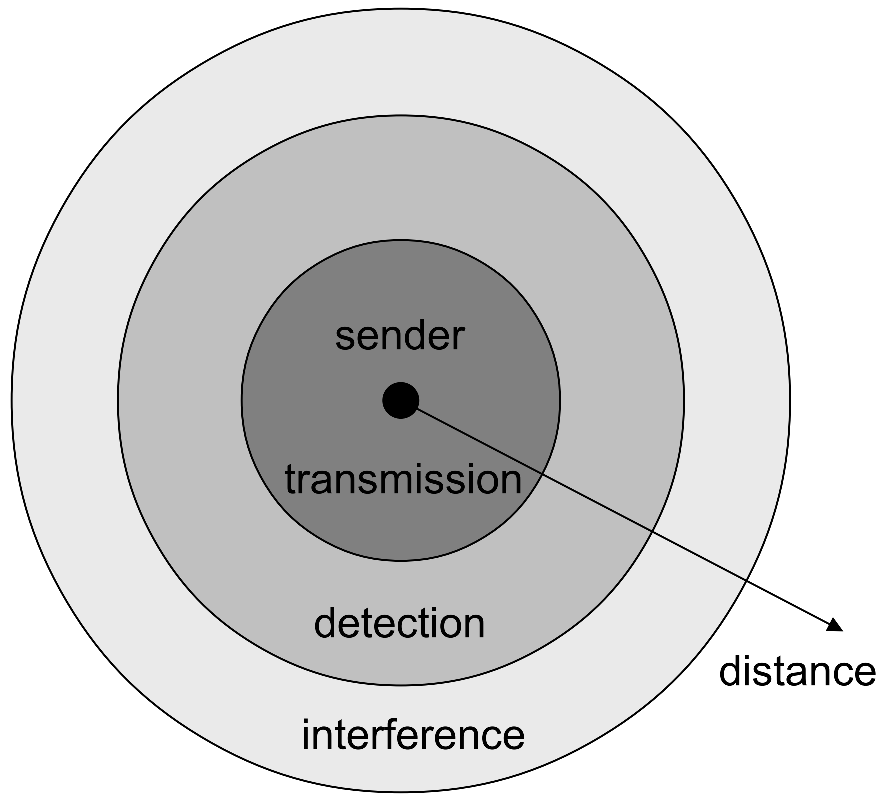
- communication possible
- low error rate

» Detection range

- detection of the signal possible
- no communication possible

» Interference range

- signal may not be detected
- signal adds to the background noise



Electromagnetic wave propagation

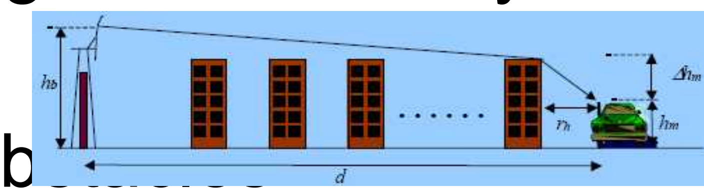
» shadowing (e.g. through a wall or a door)

» refraction depending on the density of a medium

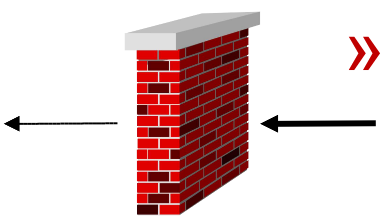
» reflection at large obstacles

» scattering at small obstacles

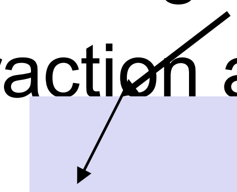
» diffraction at edges



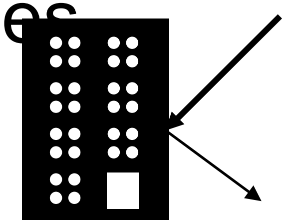
diffraction



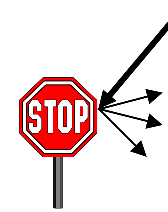
shadow fading



refraction



reflection

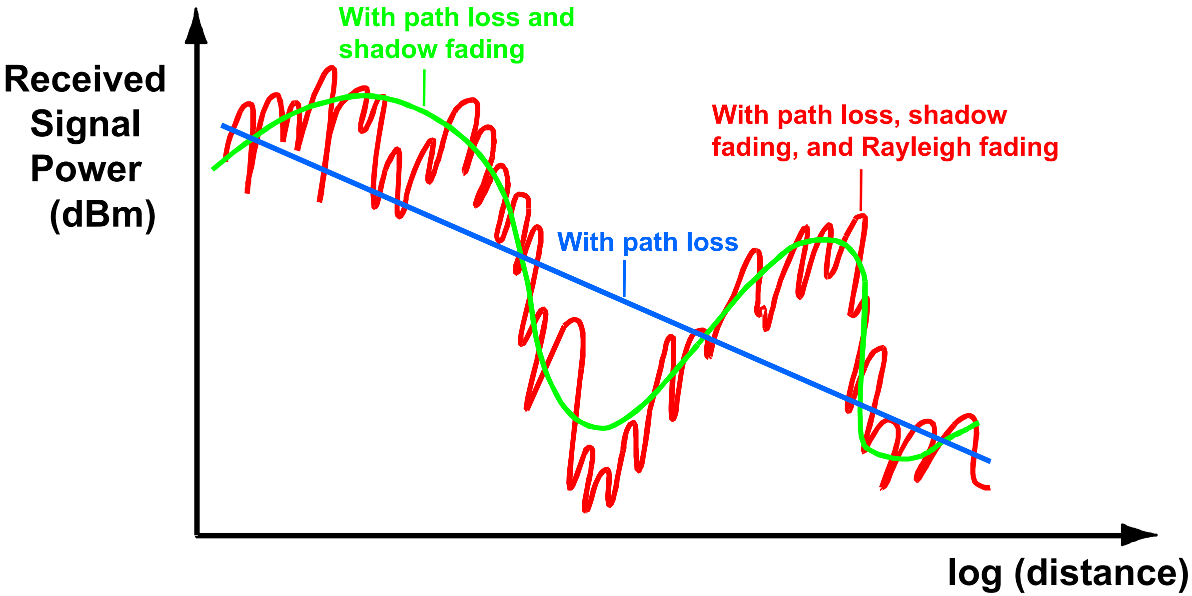


scattering

Fading

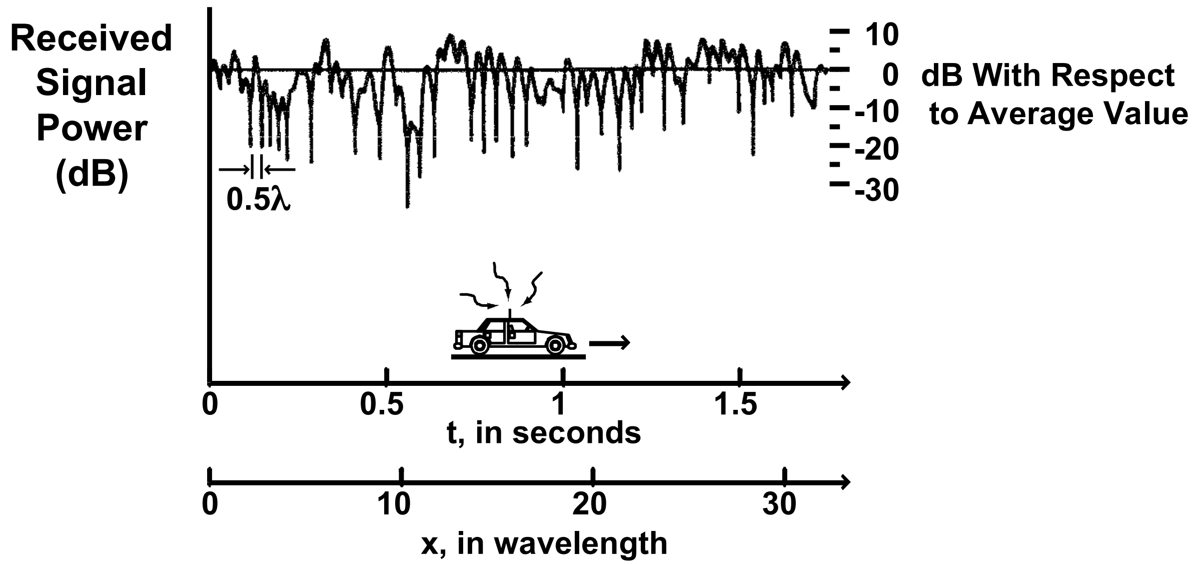
- Large-scale fading
- Small-scale fading
- Flat (frequency non-selective) fading

Fading (cont)



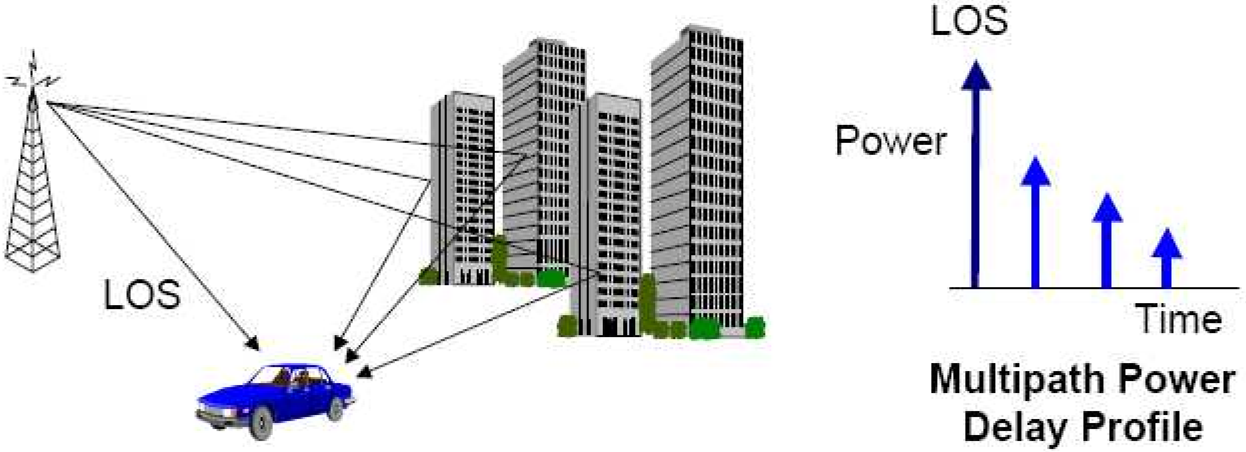
» path loss
» slow fading (also called long term, shadowing)
» fast fading (short term)

Fading (cont)

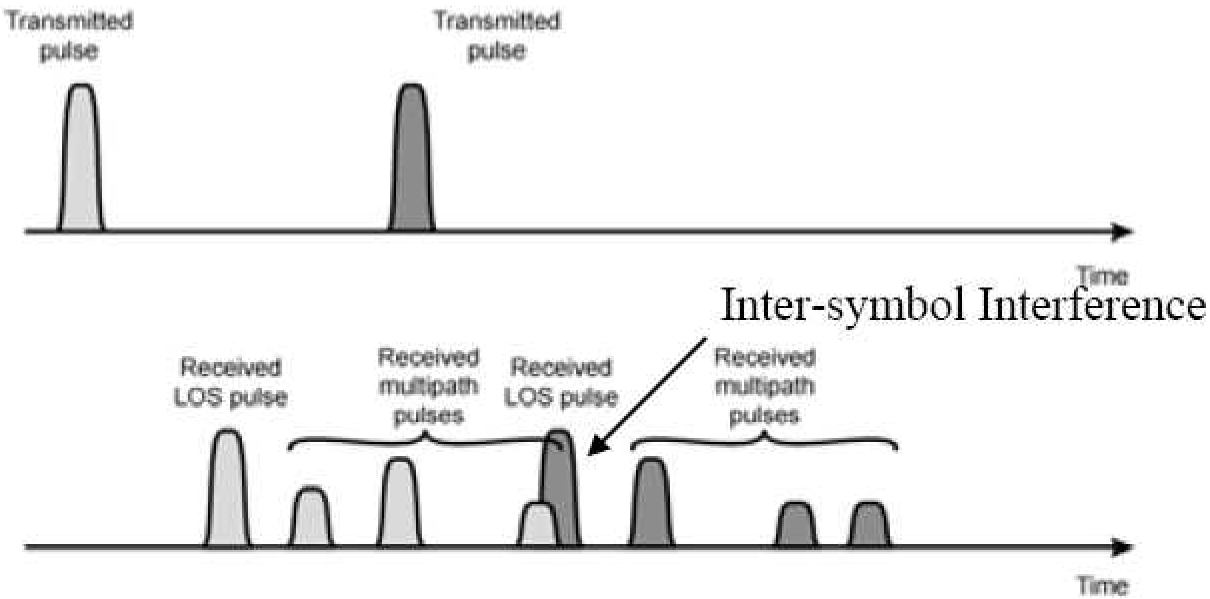


» fading due to multipath and mobility

Multipath



Multipath and delay spread



- Delay spread: time between first and last version of signal
- Multipath may add constructively or destructively => fast fading

Free space propagation model

» Power of wireless transmission reduces with square of distance (due to surface area increase)

» Reduction also depends on wavelength

- High wavelength/low frequency has less loss
- Small wavelength/high frequency has higher loss

- PT/R: transmitter/receiver power, d: distance, f: frequency, c: light speed, λ: wavelength

$$L = \frac{P_T}{P_R} = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi d f}{c}\right)^2$$

General propagation model

- L_{d_0} loss at reference distance d_0

$$L_d = L_{d_0}\left(\frac{d}{d_0}\right)^a$$

- Path loss exponent a depends on environment
  - Free space 2
  - Urban area cellular 2.7 to 3.5
  - Shadowed urban cell 3 to 5
  - In building LOS 1.6 to 1.8
  - Obstructed in building 4 to 6
  - Obstructed in factories 2 to 3

Indoor propagation

Path loss formula:

Path Loss = Unit Loss + 10 n log(d) = k F + l W

where:

Unit loss = power loss (dB) at 1m distance (30 dB)

n = power-delay index (between 3.5 and 4.0)

d = distance between transmitter and receiver

k = number of floors the signal traverses

F = loss per floor

l = number of walls the signal traverses

W = loss per wall

dB and dBm

» Decibel (dB): relative unit of measurement

$$dB = 10\log\frac{P_2}{P_1}$$

dBm (decibel-milliwatts)

» Signal strength or power measured in dBm: power relative to 1mW

$$P(\text{dBm}) = 10\log\frac{P(\text{mW})}{1\ \text{mW}}$$

- 1mW = 0dBm
- 100mW=20dBm
- 200mW=23dBm
- 1000mW=30dBm

Path loss in dB

» Path loss when power measured in Watt

$$L = \frac{P_T}{P_R}$$

» Path loss when power measured in dBm

$$L = P_T - P_R$$

» 3dB loss = power halved (3dB ≈ 10log2)

General propagation model

- L_{d_0} loss at reference distance d_0

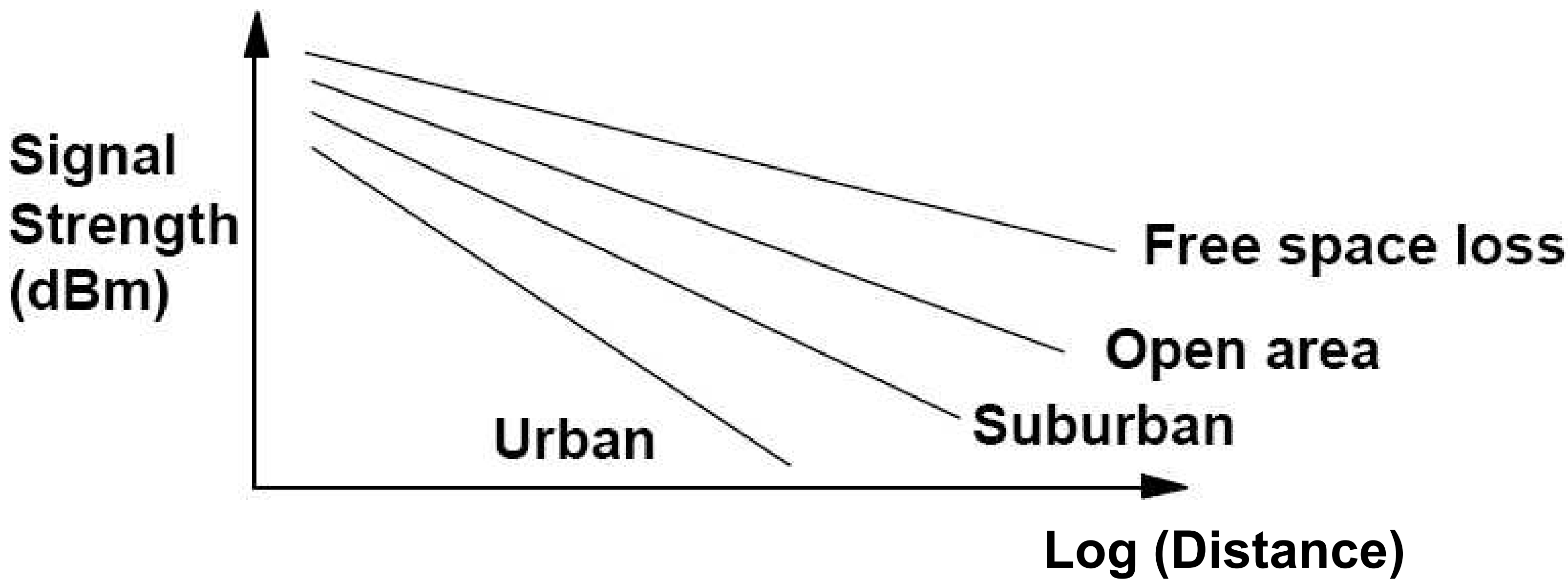
$$L_d = L_{d_0}\left(\frac{d}{d_0}\right)^a$$

- in dB

$$L_d(\mathrm{dB}) = 10\log L_{d_0} + a \times \log\left(\frac{d}{d_0}\right)$$

  - path loss increases linear to log of distance

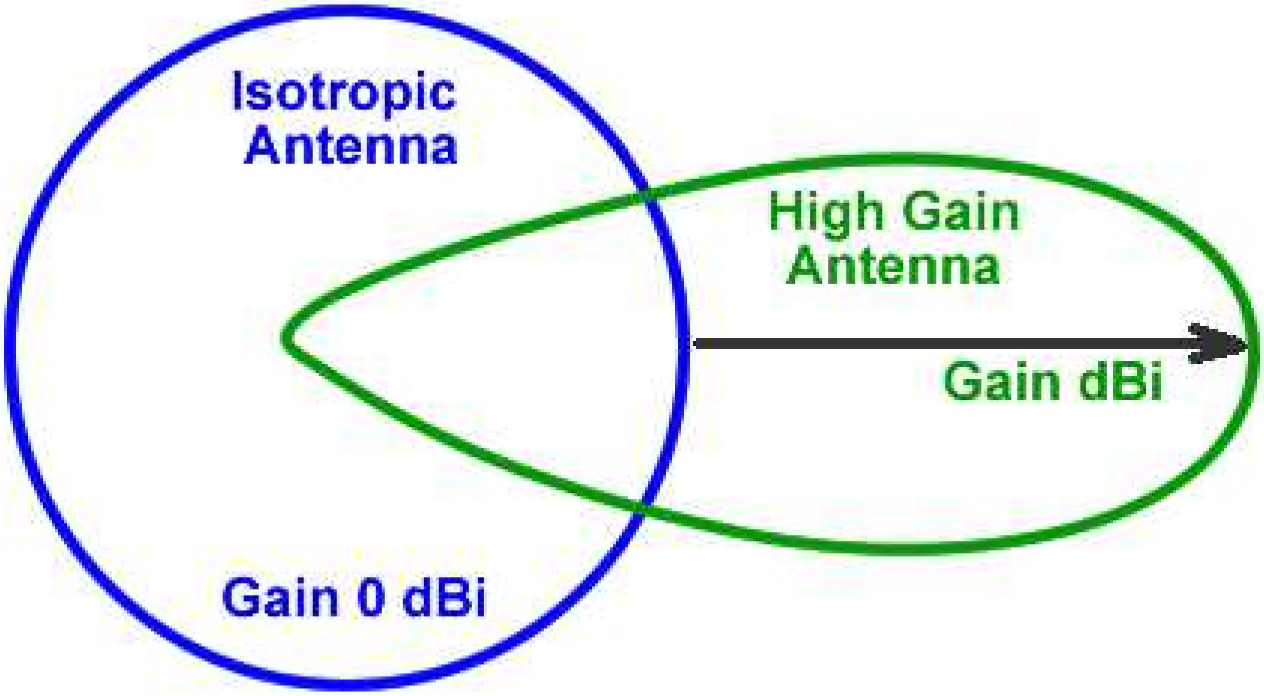
Path loss in different environments



Antenna radiation

- » Isotropic antenna (idealized) radiates power equally in all directions
- » Most practical antennas do not radiate power equally in all directions
- antenna’s radiation pattern shows energy it transmits/collects in each direction
  - » Antenna gain measured in dBi
- power output in preferred direction compared to perfect isotropic antenna

Antenna gain



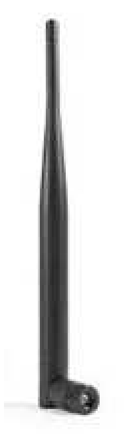
Src: https://www.ahsystems.com/articles/Understanding-antenna-gain-beamwidth-directivity.php

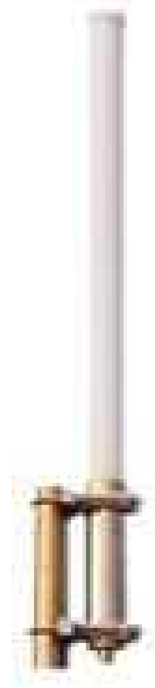
Antenna types

- Isotropic antenna (idealized)
  - Radiates power equally in all directions
- Omni-directional
- Dipole antennas
- Yagi
- Parabolic or dish
- Sector
- Panel

Omni-directional antennas

- Indoor and outdoor
- Typically 2-15 dBi



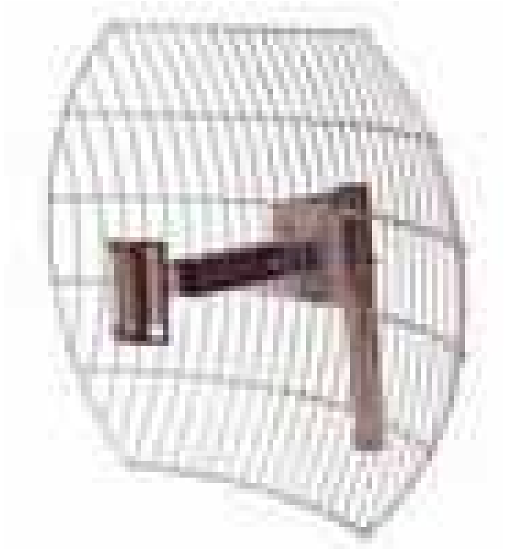


Yagi

- referred to as Yagi – Uda
- typically very directional
- Cantenna: built from Pringles box!

Parabolic

» grid/wiretype or satellite dish (solid)



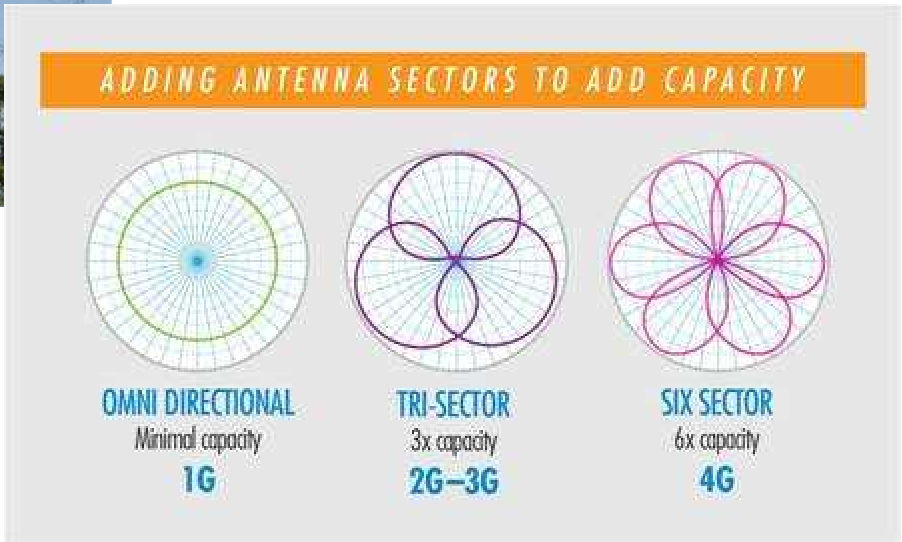
Panel and sector antennas

Panel:

Sector:

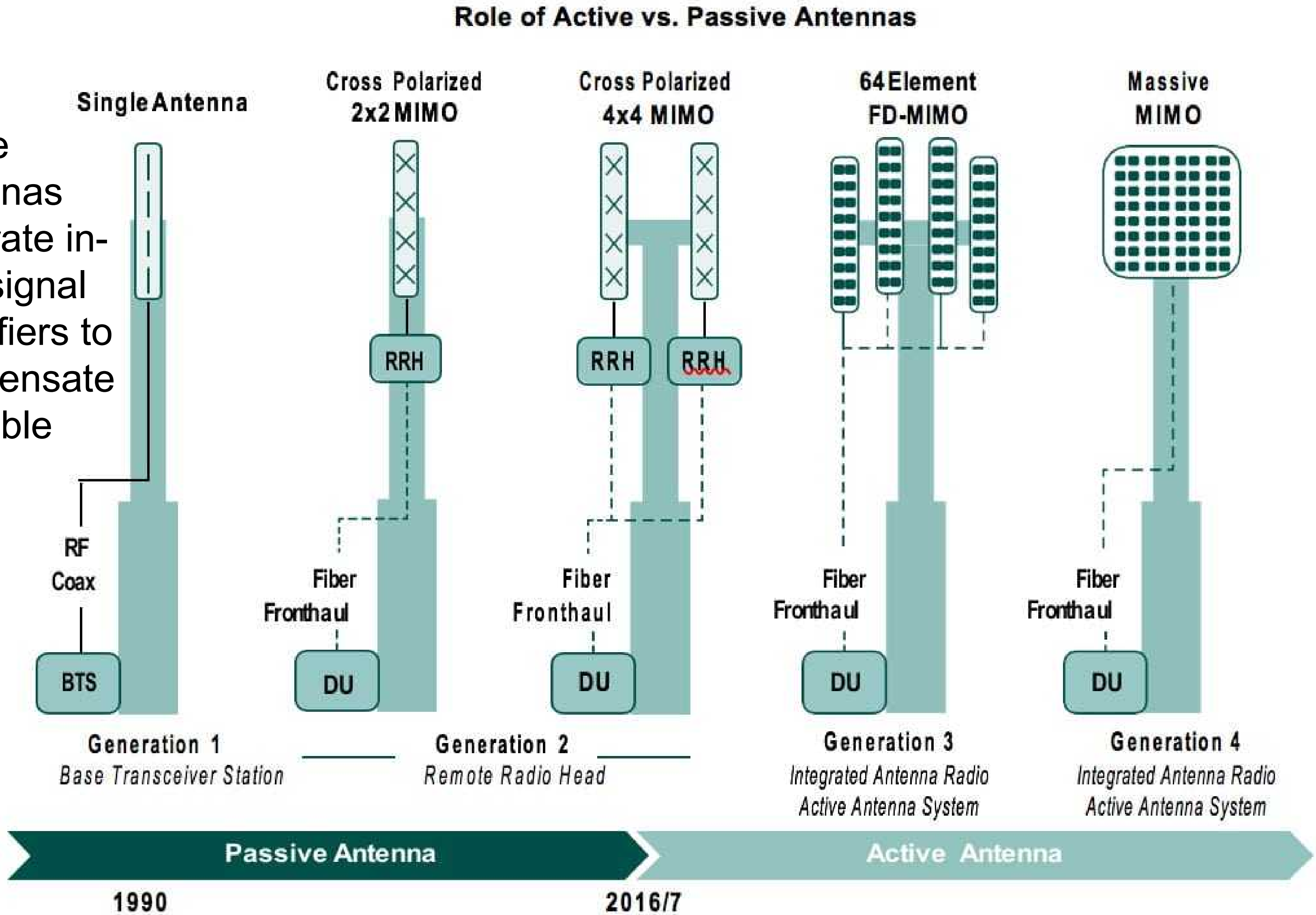
» Patch: smaller version of panel antenna

Tri-sector antennas



Antenna technologies

Active antennas integrate in-built signal amplifiers to compensate for cable loss.

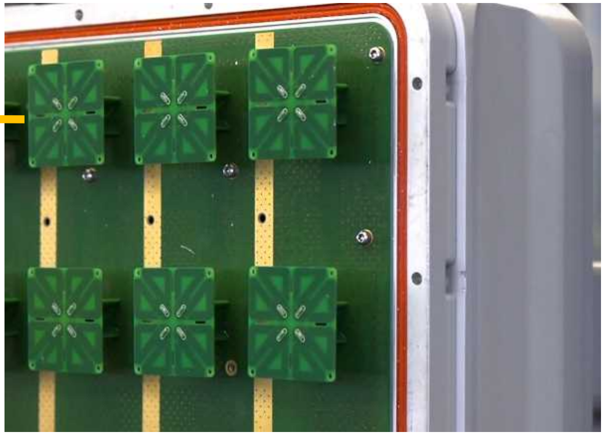


Massive MIMO antennas

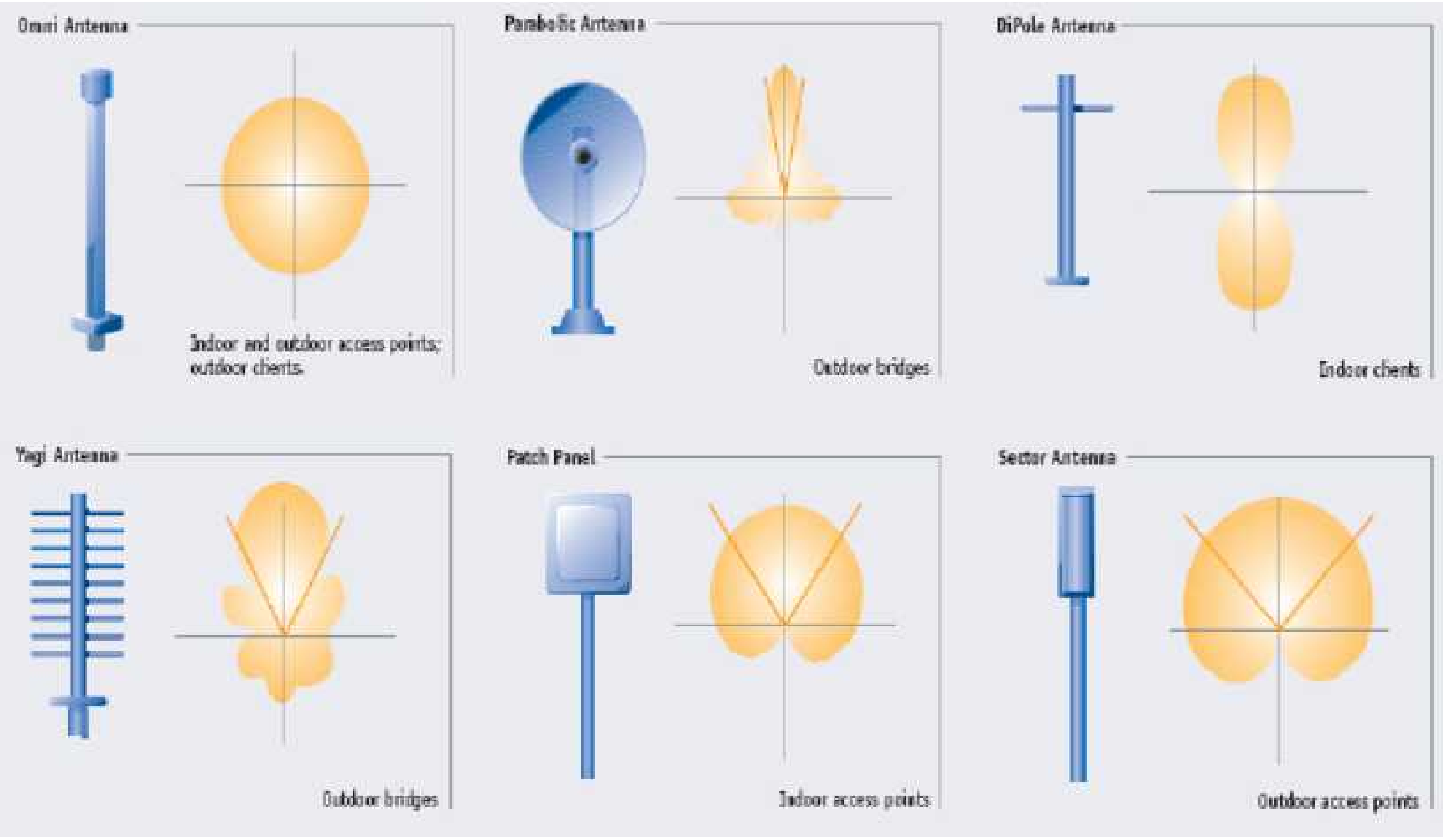
10-port sector antenna, 2x 790–960 MHz, 4x 1695-2690 MHz, 4x 1695-2180 MHz

2300M Hz LTE Massive MIMO panel

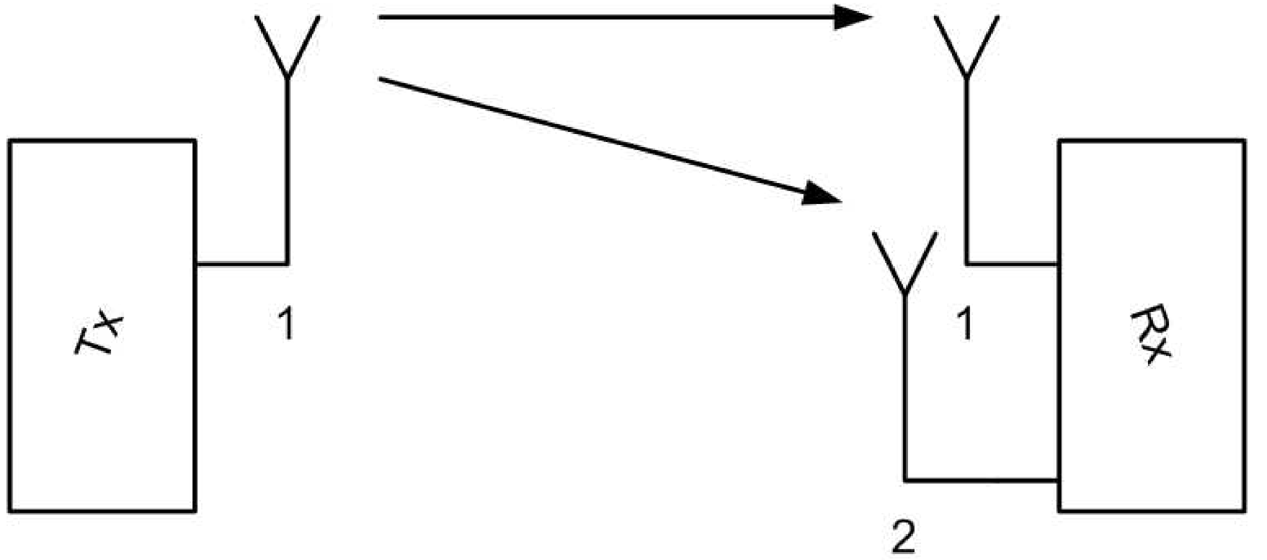
Each of the small squares is one of the 128 antennas



Antenna radiation patterns



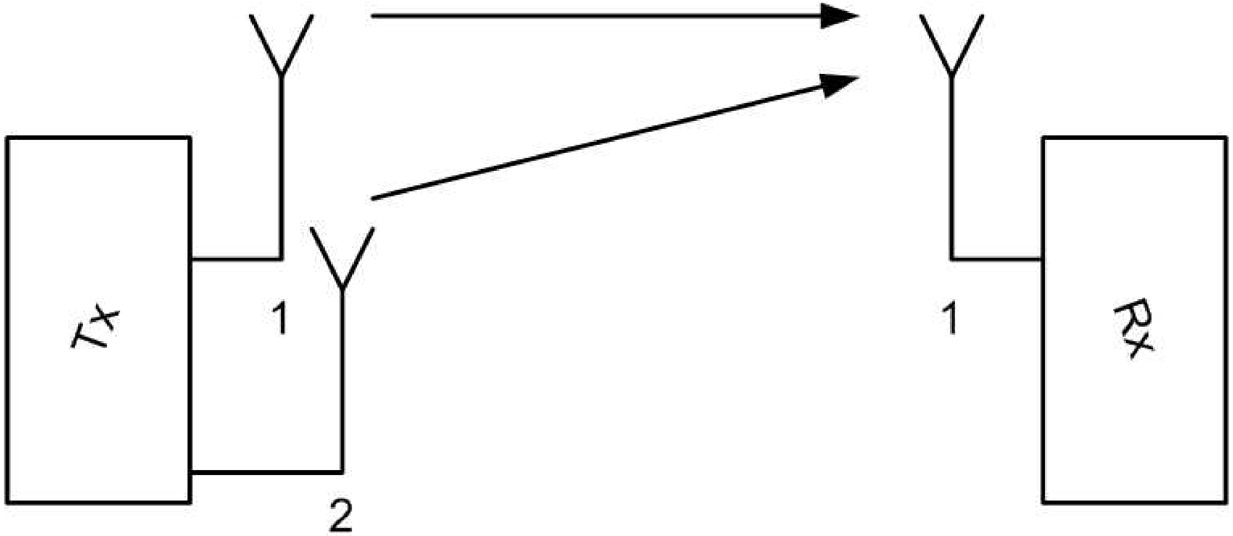
Single Input Multiple Output (SIMO)



» Receiver diversity: exploits multipath

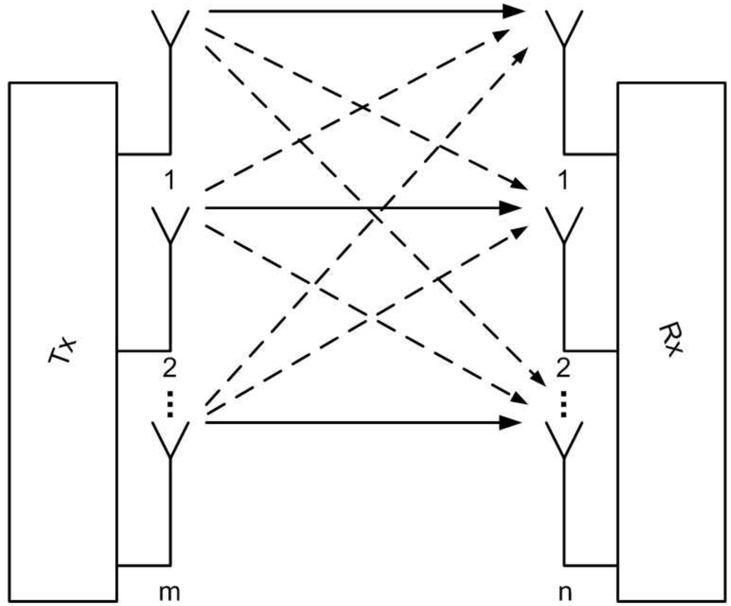
- Switched diversity: signal with better SNR is chosen
- Combining signals to improve SNR

Multiple Input Single Output (MISO)



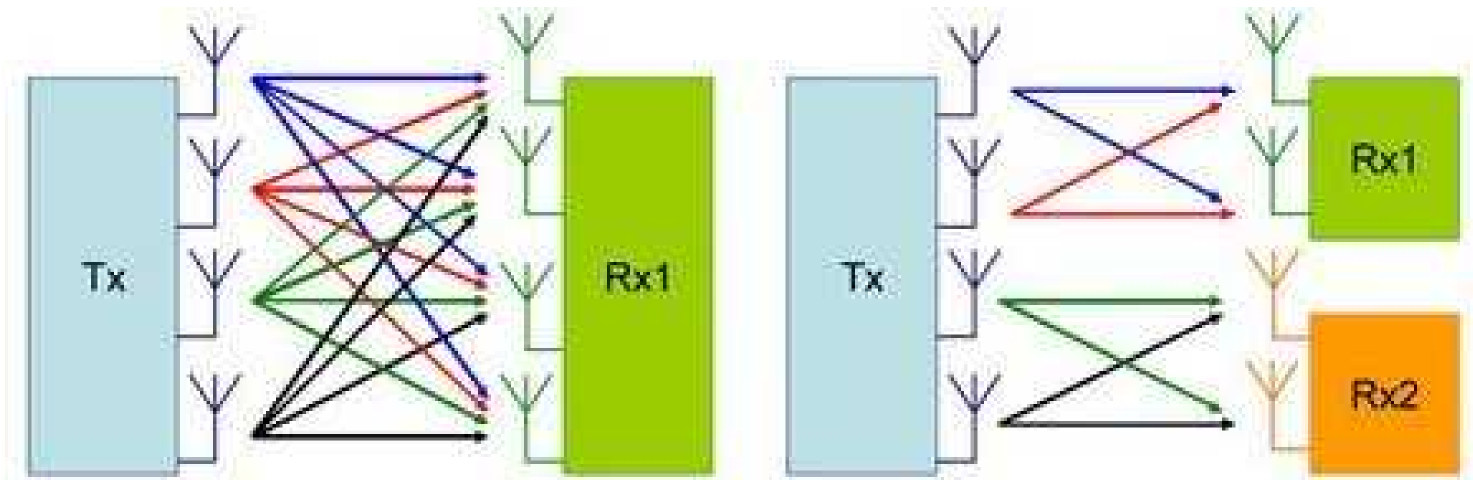
» Increases channel redundancy

Multiple Input Multiple Output (MIMO)



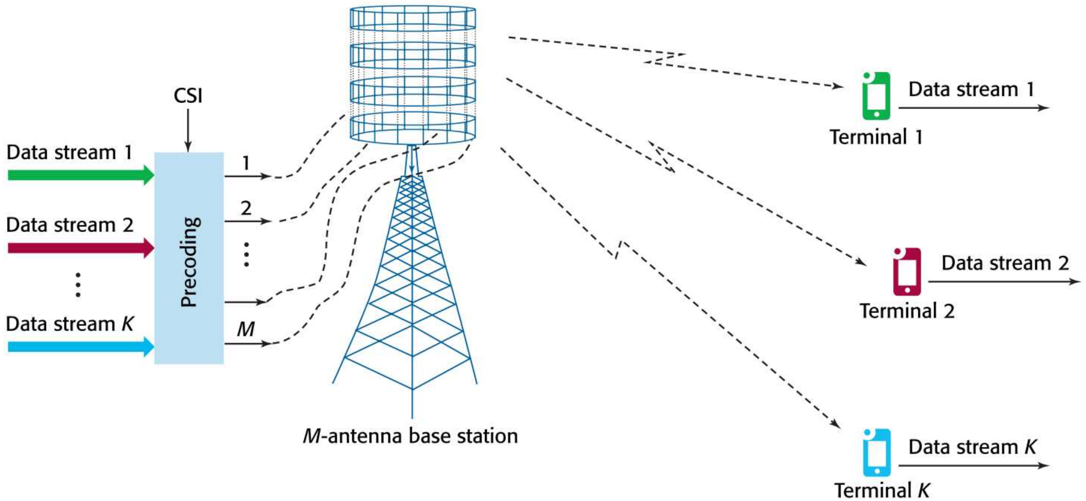
- Number of data streams that can be transmitted simultaneously: K=min(m, n)
- C = K·B·log2(1 + S/N)
- Each receiver antenna gets all radio signals (dash lines) not only signal addressed to a given antenna (solid line)
- If channel matrix is known signals addressed to other antennas can be removed from received signal (signal processing)

Single vs Multiuser MIMO



(a) Single User MIMO, 4 streams (b) Multi User MIMO, 2 users, 2 streams each

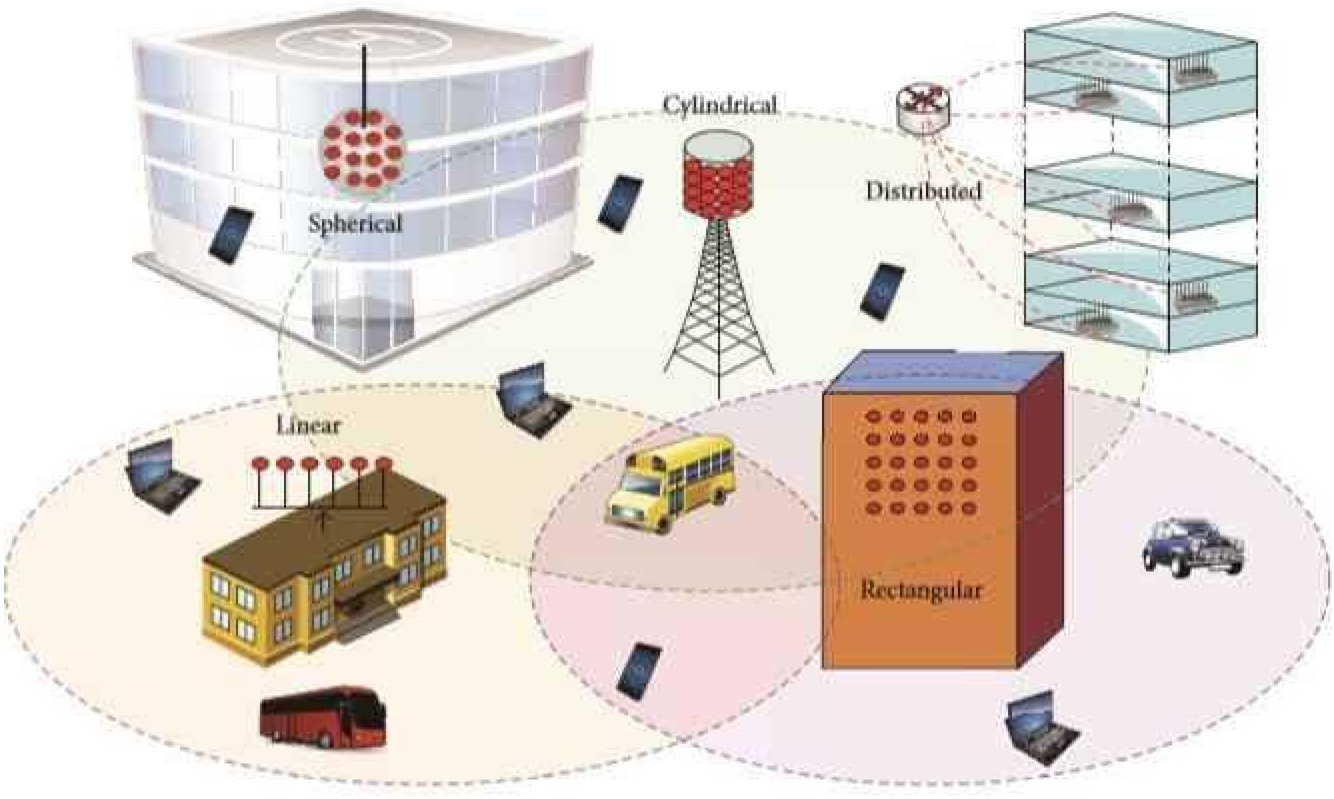
Massive MIMO



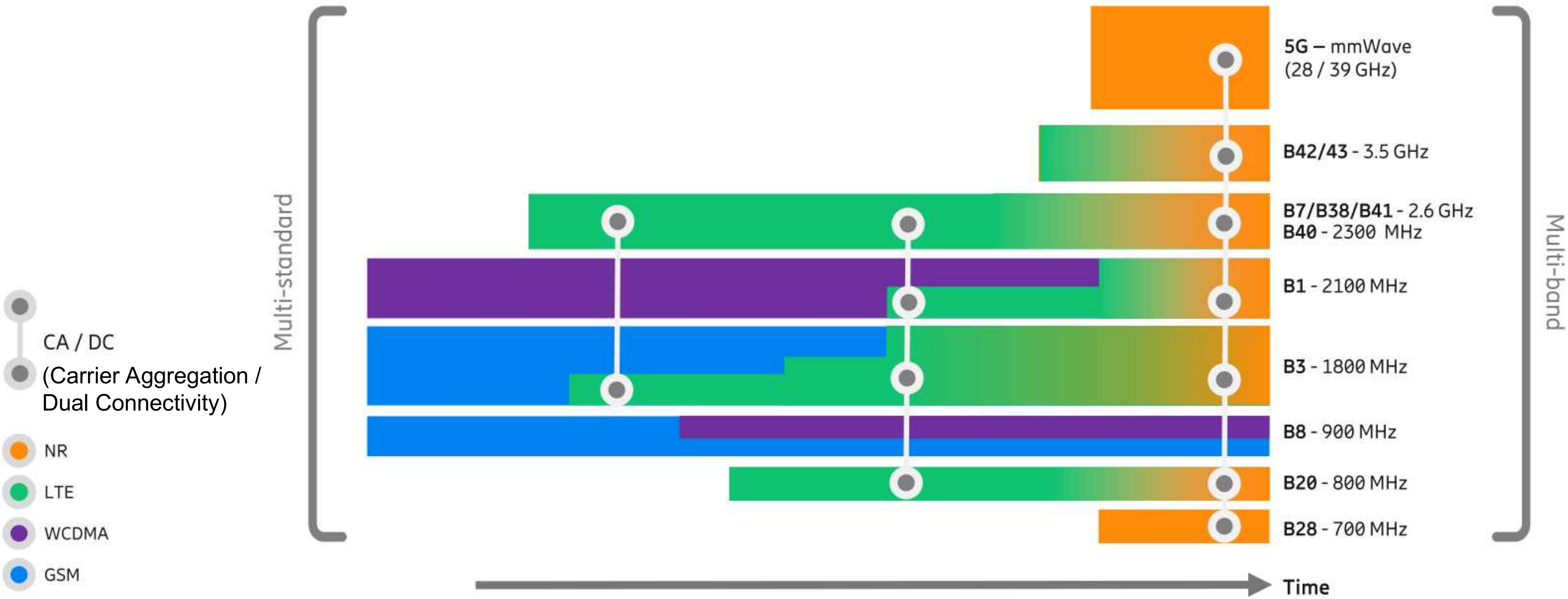
» Large scale antenna system

- M~100/1000 antennas, K~10s of terminals, M>>K
- 3G/UMTS: 3 sectors x 20 element-arrays = 60 antennas, 4G/LTE-A: 8-MIMO x 30 = 240 antennas
- BS can focus energy to spatial directions where users are located
  - » Spatial division multiplexing: different streams occupy same frequency and time
  - » BS selectively transmits multiple streams to different terminals

Massive MIMO antenna configurations



5G multi-standard & multi-band



Source: 5G Today: Trends and Insights 2019-09-18

EIRP: Effective Isotropic Radiated Power

- Estimates the radiated output power of an isotropic antenna
- EIRP=Transmitter Power + Transmitter Gain – Cable Loss
- European Radiocommunications Committee (ERC) sets max average EIRP (FCC in US)
- max EIRP
  - 2.4GHz: max EIRP=100mW (20dBm)
    - US: 36 dBm (9dBi omni), 48dBm (24dBi directional)
  - 5.150-5.350GHz (indoor use): 200mW (23dBm)
  - 5.470-5.725GHz: 1W (30dBm)
    - US: 5.25-5.35: 30dBm, 5.725-5.825: 36dBm, higher for p2p

Channel capacity

- Transmission rate or Capacity
  - » In bits per second
  - » Rate at which data can be communicated
- Bandwidth
  - » In cycles per second or Hertz (Hz)
  - » Constrained by transmitter and medium
- Baud: symbols/second rate – derives by modulation scheme
  - Basic symbols: 2 (0,1) , 4 (0, 0.25, 0.5, 1)

Nyquist Bandwidth

- Noise-free channel
- Limiting factor on transmission is channel bandwidth, and intersymbol interference
- If bandwidth is B, highest signal rate is $2B$
  - M different symbols encoded in $\log_2 M$ bits
    - Multi-level signaling:

$$C = 2B\log_2 M$$

C is the data rate
B is the bandwidth
M is the number of levels

Shannon's Theorem

- Noise creates errors
- Each transmission channel corresponds to some maximum capacity C
- Rate $R<C$ can be transmitted with arbitrarily small bit error probability

$$C = B \log_2 \left\{ 1 + \frac{S}{N} \right\}$$

B is channel bandwidth in Hz

S/N is signal to noise ratio at receiver

Shannon’s Theorem (cont.)

- Gives theoretical maximum that can be achieved
- Does not indicate how it can be achieved

Thermal noise

- Thermal noise due to agitation of electrons
- Present in all electronic devices and transmission media
- Cannot be eliminated
- Function of temperature

Thermal noise (cont.)

- Amount of thermal noise found in a bandwidth of 1Hz in any device is:

$$N_0 = kT \left(\mathrm{W/Hz} \right)$$

  - N_0 = noise power density in watts per 1 Hz of bandwidth
  - k = Boltzmann's constant = 1.3803 x 10^{-23} J/K
  - T = temperature, in kelvins (absolute temperature)
- Noise is considered independent of frequency
- Thermal noise in bandwidth B Hertz

$$N = k\,TB = N_o\,B$$

Example

- Spectrum of a channel between 3 MHz and 4 MHz; SNR = 24 dB; what is the capacity? How many signaling levels are required?

Solution

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

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

  $$\text{SNR} = 251$$

- Shannon capacity:

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

- Signaling levels required:

  $$C = 2B\log_2 M$$

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

  $$4 = \log_2 M \Rightarrow M = 16$$

Eb/N0 and BER

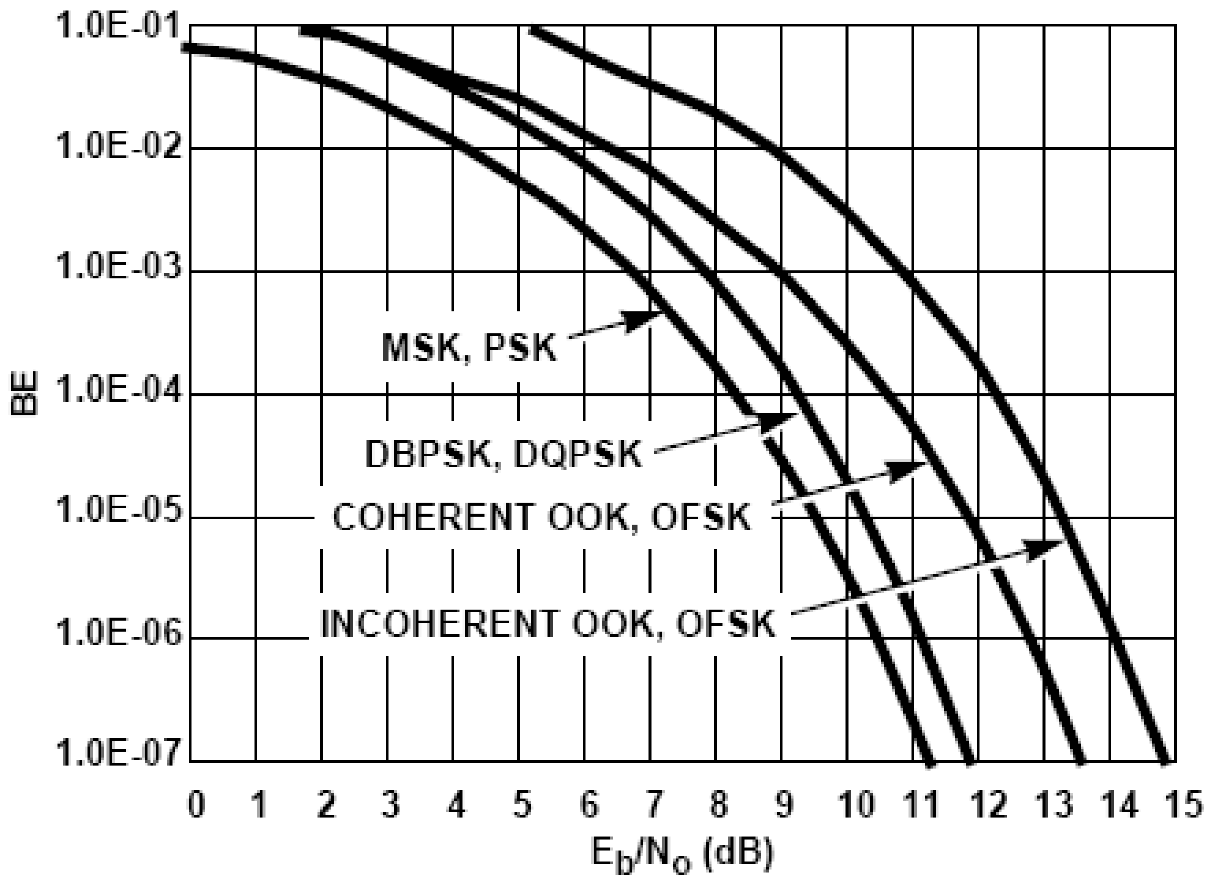
- Ratio of signal energy per bit to noise power density per Hertz (also known as "SNR per bit")

$$\frac{E_b}{N_0} = \frac{S/R_b}{N_0} = \frac{S}{k\,TR_b}$$

- Bit Error Rate (BER) for digital data is a function of Eb/N0
  - Given a value for Eb/N0 to achieve a desired error rate, parameters of this formula can be selected
  - As bit rate Rb increases, transmitted signal power S must increase to maintain required Eb/N0

Eb/N0 and BER (cont.)

» BER as function of Eb/N0 depends on modulation scheme



Receiver sensitivity

- Receiver sensitivity (Prx): minimum signal strength to achieve given BER
- Prx=ReceiverNoiseFloor+SNR

$E_b/N_o = 14.2\text{dB} = 26.3$

$\text{SNR} = (E_b/N_o) * (R/B_T)$

$= 26.3 * (40\text{kbps} / 80\text{kHz})$ =13.15

$= 11\text{dB}$

Prx = Receiver Noise Floor + SNR

$= -111\text{dBm} + 11\text{dB}$

$= -100\text{dBm}$

Noise floor

- Thermal noise power (80KHz bandwidth):

$$
\begin{aligned}
N &= kTB \\
&= 1.38 \times 10^{-23}\ J/K \times 290K \times 80{,}000\ s^{-1} \\
&= 2.4 \times 10^{-13} mW \\
&= -126dBm
\end{aligned}
$$

- Above is noise floor for ideal receiver
- Practical receiver:

$$
\begin{aligned}
\text{Receiver Noise Floor} &= -126dBm + 15dB \\
&= -111dBm
\end{aligned}
$$

Link budget calculation

- Link budget equation:

$$\text{Link Margin} = P_T - CL_T + G_T - P_L - CL_R + G_R - P_{rx}$$

  - » P_T: power at transmitter in dBm
  - » CL_T: cable and connector losses at transmitter in dB
  - » G_T: transmitter antenna gain in dBi
  - » P_L: propagation loss in dB
  - » CL_R: cable and connector losses at receiver in dB
  - » G_R: receiver antenna gain in dBi
  - » P_{rx}: receiver sensitivity in dBm
- To achieve communication, Link Margin>Min Margin (=10-20 db in practice)

Θα ξεκινήσουμε στις 12:10

Επιστρέφουμε 2:10