Οικονομικό Πανεπιστήμιο Αθηνών
Τμήμα Πληροφορικής

Ευφυή Κινητά Δίκτυα: Ασύρματο Κανάλι και Διάδοση Σημάτων

Εαρινό Εξάμηνο 2024-25

Βασίλειος Σύρης

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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 phones)

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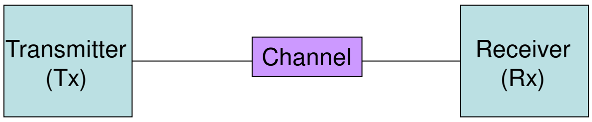
Basic communication system (single hop)

- Transmitter performs encoding, modulation, and multiplexing
- Receiver performs demodulation and demultiplexing



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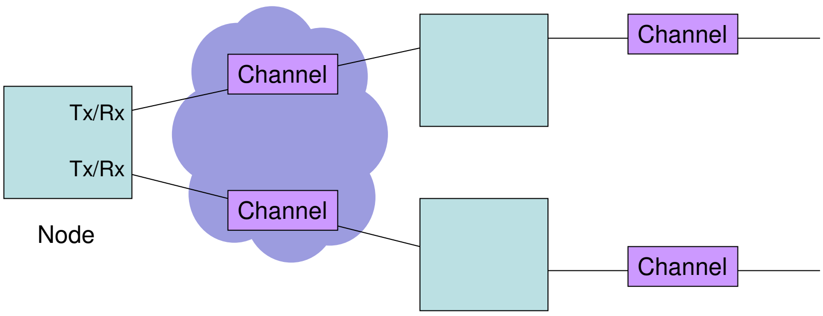
Basic communication network (multiple hops)

- Wired communication: channels independent (no interference)
- Wireless: channels interfere



- Same feature can be an advantage: broadcast

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Basic wireless terms

- Frequency
- Spectrum
- Bandwidth
- Capacity

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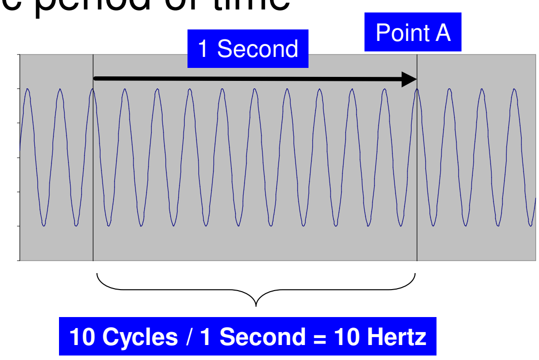
Frequency

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



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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

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Spectrum

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

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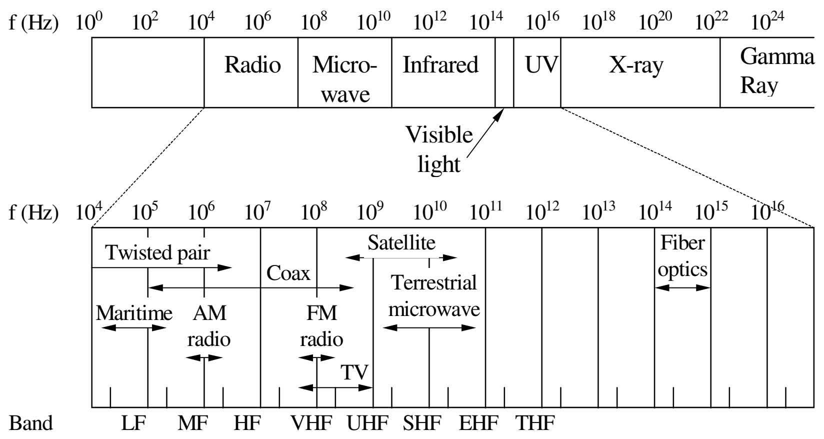
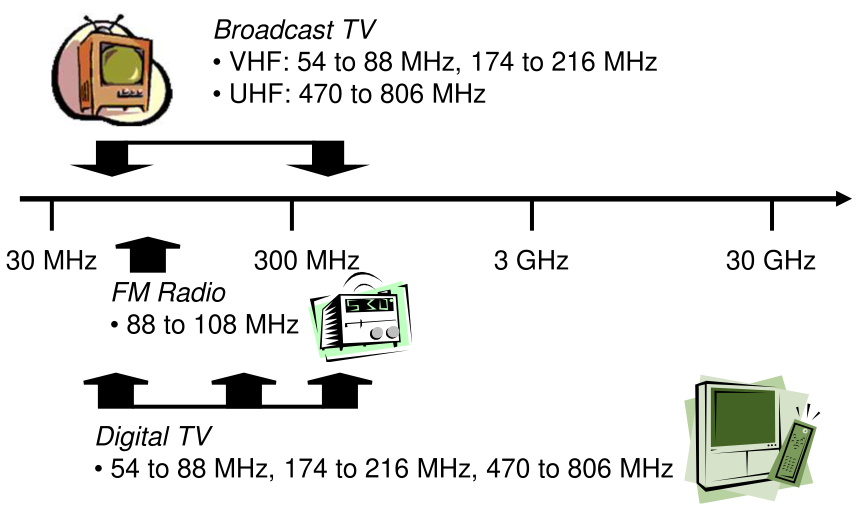
Electromagnetic spectrum

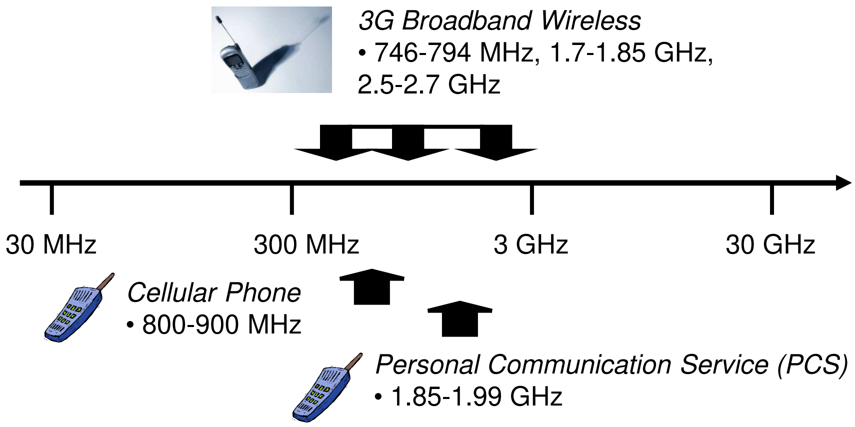
- Wireless communications: 100KHz-60GHz



Wireless Spectrum (1)



Wireless Spectrum (2)



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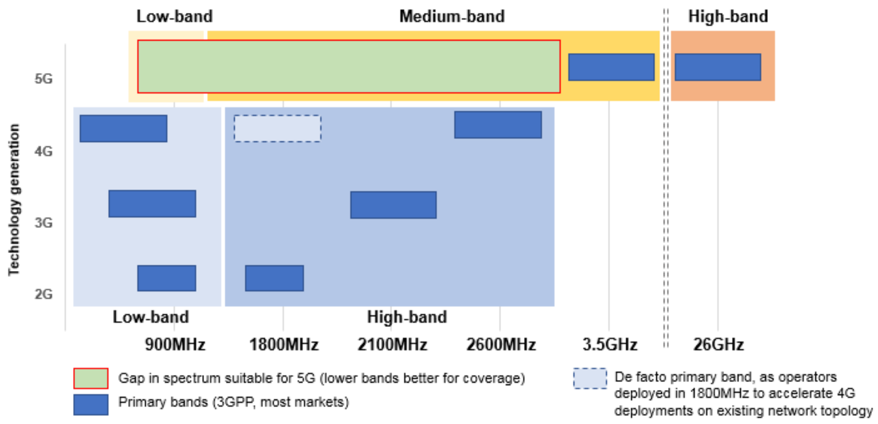
5G frequency bands



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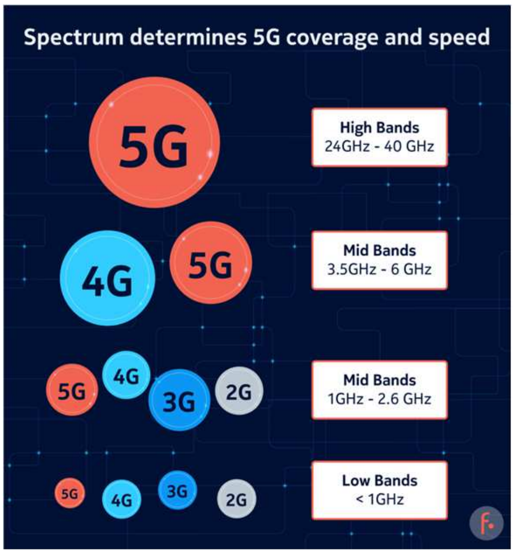
3-5G frequency bands



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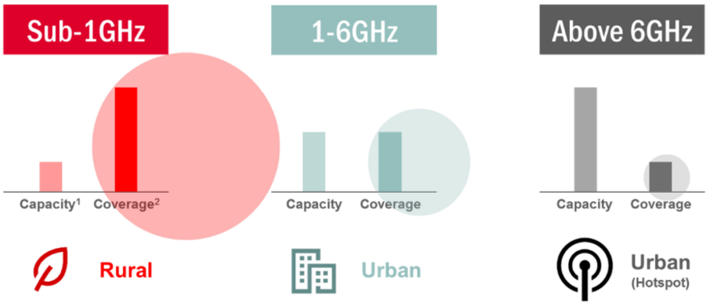
Sub/Mid/Hi 5G frequency bands



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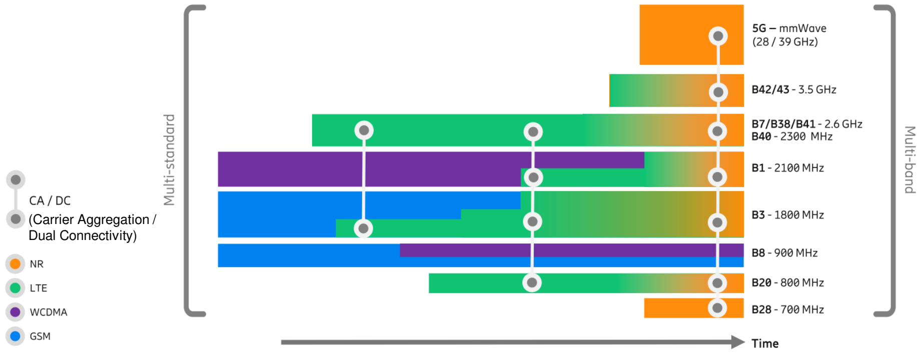
5G multi-standard & multi-band



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

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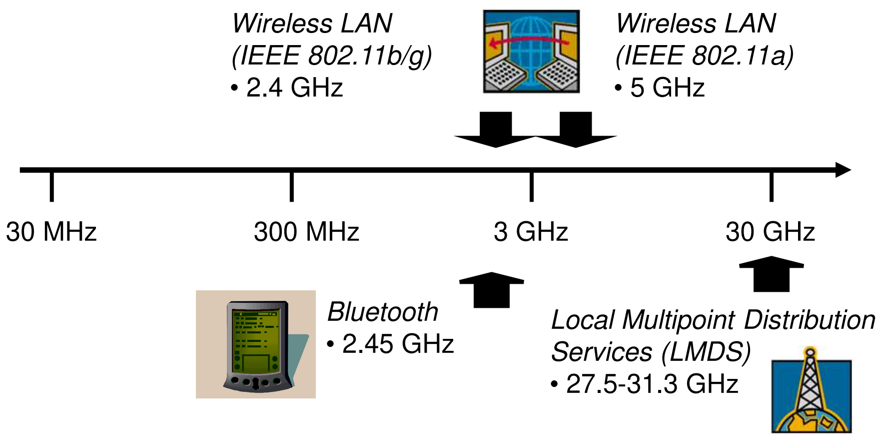
Wireless Spectrum (3)



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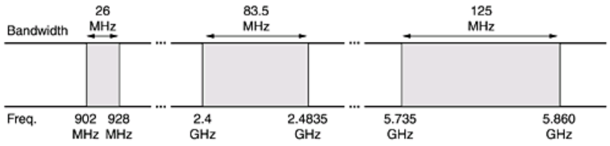
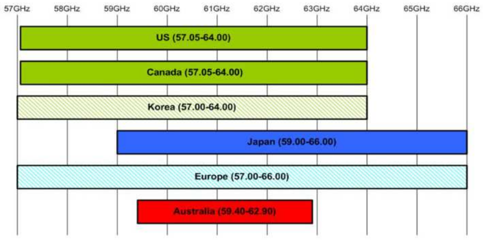
ISM Band (Industrial Scientific Medical)



- Unlicensed
- Used mainly by WLANs
- 60 GHz ISM band:



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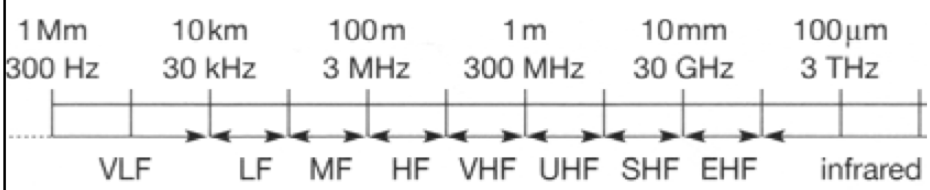
Basic properties



- Moving from left to right
  - higher bandwidth
  - more power
  - shorter range (higher attenuation, blocking)
  - more sophisticated electronics

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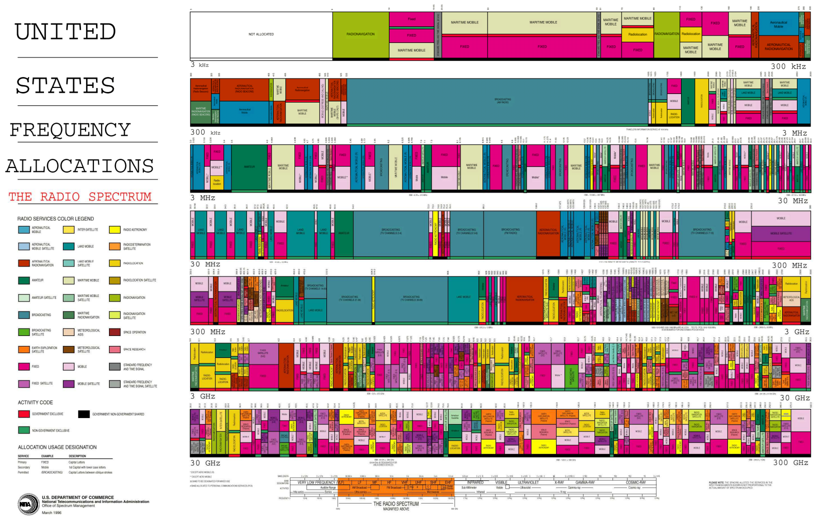
Radio Spectrum Allocation (USA)



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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

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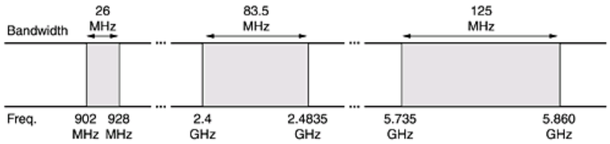
ISM Band (Industrial Scientific Medical)



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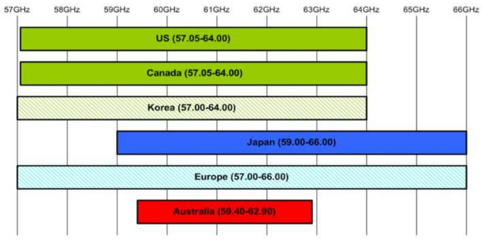

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Bandwidth vs. Capacity

- 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

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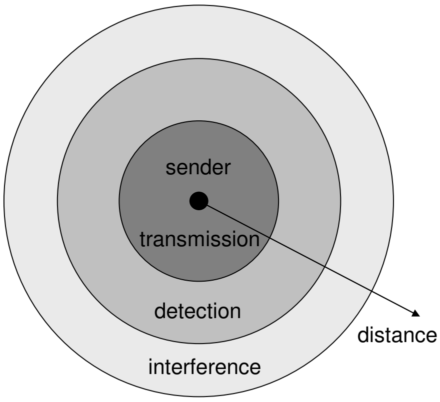
Signal strength (or power)

- 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)

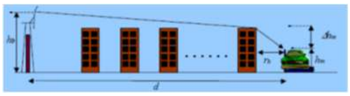
Signal propagation range

- 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

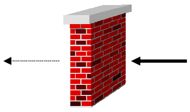


Electromagnetic wave propagation

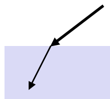
- shadowing (e.g. through a wall or a door)
- refraction depending on the density of a medium
- reflection at large obstacles
- scattering at small obstacles
- diffraction at edges



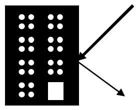
diffraction



shadow fading



refraction



reflection

scattering

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Fading

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

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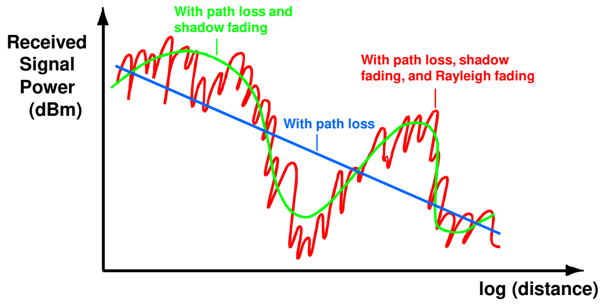
Fading (cont)



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

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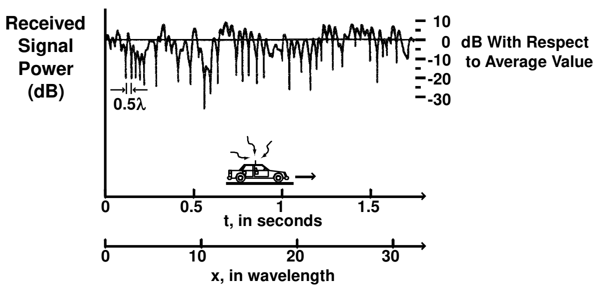
Fading (cont)



- fading due to multipath and mobility

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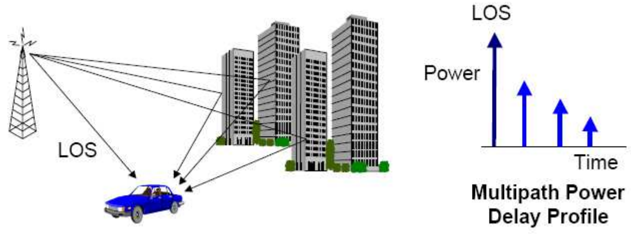
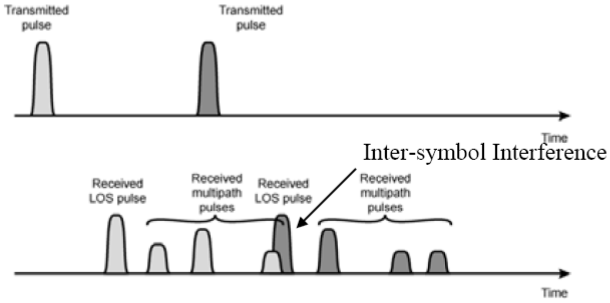
Multipath



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

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

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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

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Indoor propagation

Path loss formula:

Path Loss = Unit Loss + 10 n log(d) = k F + I 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
I = number of walls the signal traverses
W = loss per wall

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dB and dBm

- Decibel (dB): relative unit of measurement

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

- 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

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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)
- easier to do addition/subtraction compared to multiplication/division

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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

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

  - path loss increases linear to log of distance

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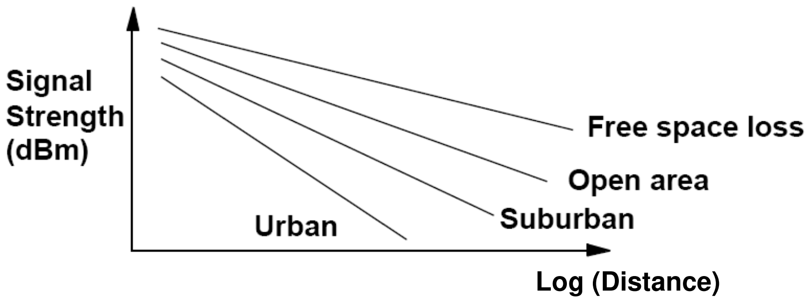
Path loss in different environments



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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

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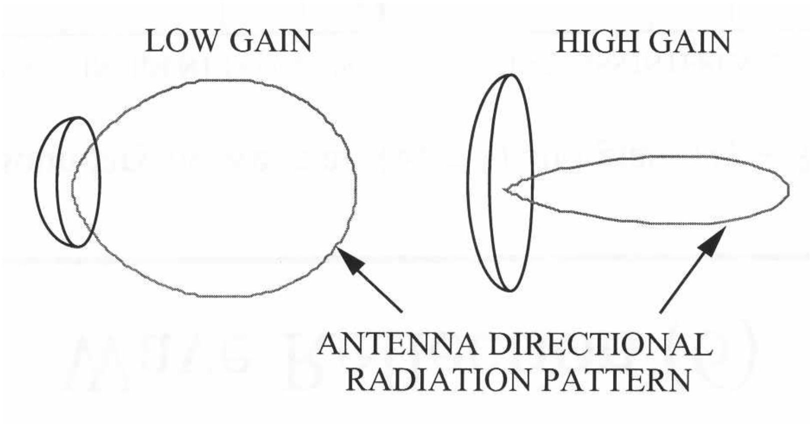
Antenna gain



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Antenna types

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

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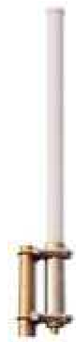
Omni-directional antennas

- Indoor and outdoor
- Typically 2-15 dBi



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Yagi

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


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Parabolic

- grid/wiretype or satellite dish (solid)

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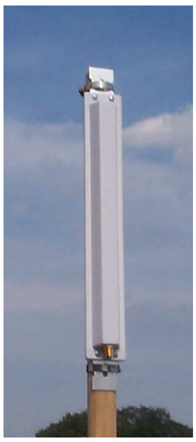
Panel and sector antennas

Panel:

Sector:



- Patch: smaller version of panel antenna

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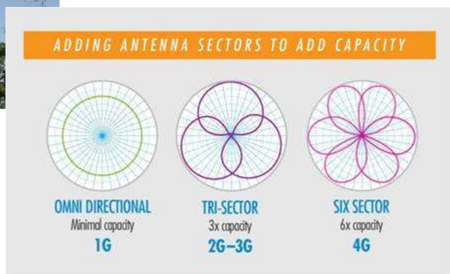
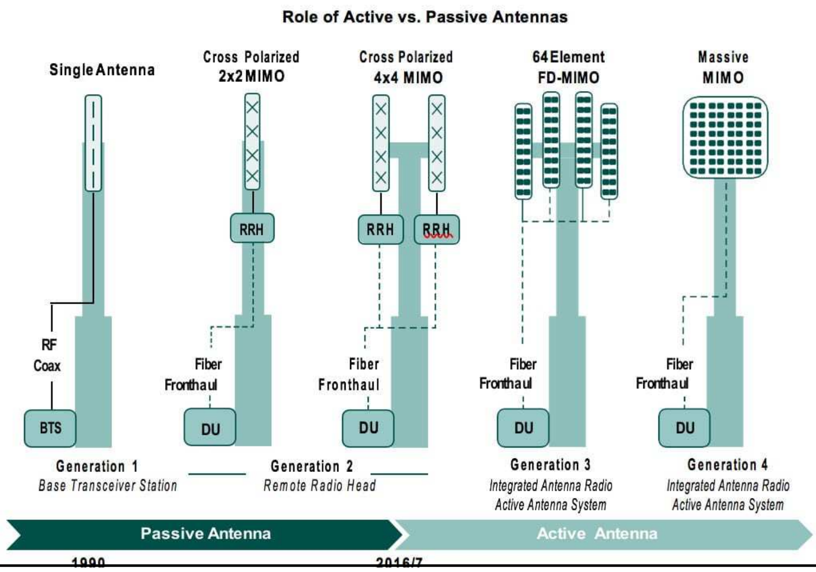
Tri-sector antennas



Antenna technologies

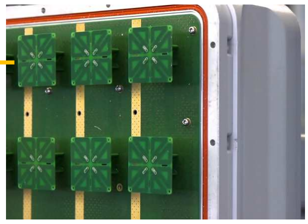


Massive MIMO antennas

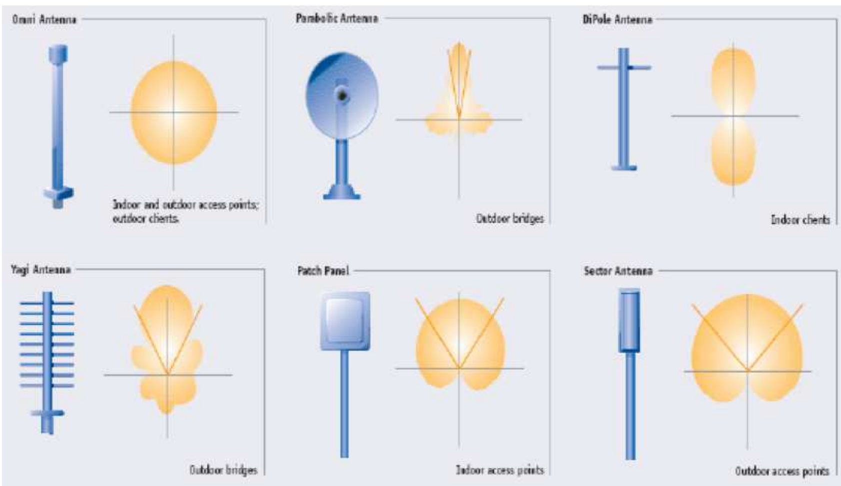
10-port sector antenna, 2x 790–960 MHz, 4x 1695-2690 MHz, 4x 1695-2180 MHz

2300M Hz LTE Massive MIMO panel

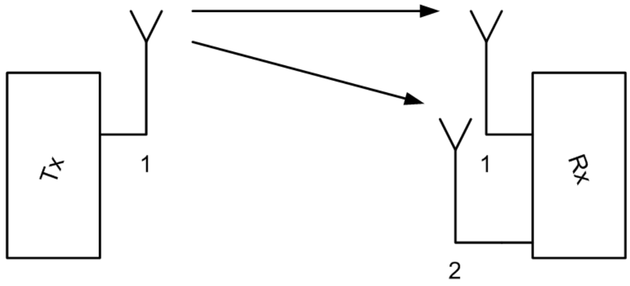
Each of the small squares is one of the 128 antennas



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

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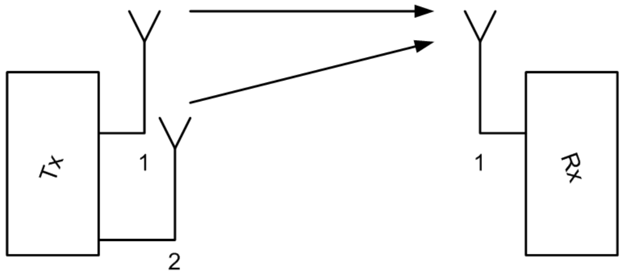
Multiple Input Single Output (MISO)



- Increases channel redundancy

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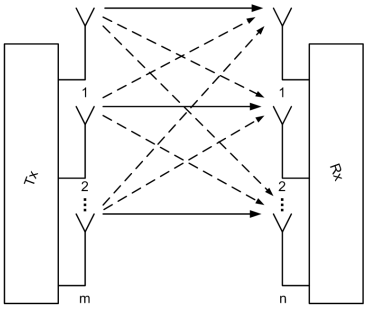
Multiple Input Multiple Output (MIMO)



- 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)

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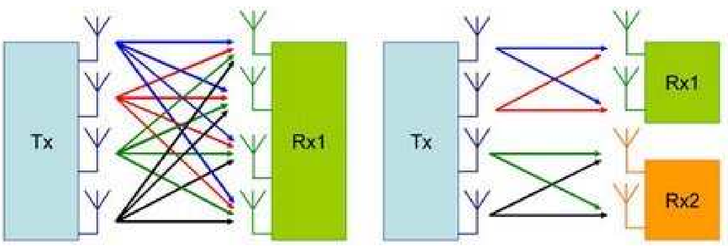
Single vs Multiuser MIMO



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

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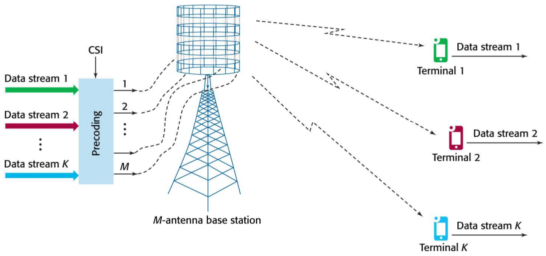
Massive MIMO



- 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

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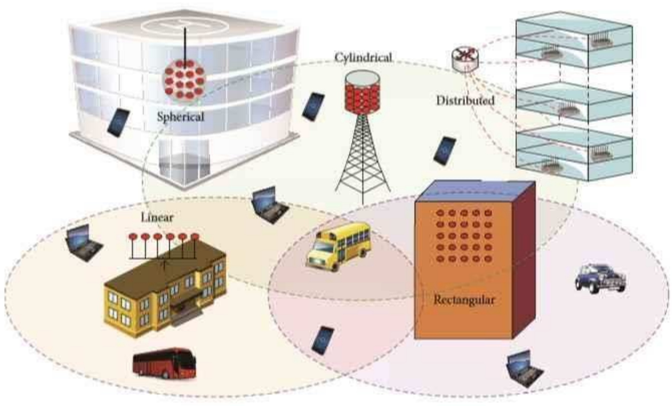
Massive MIMO antenna configurations



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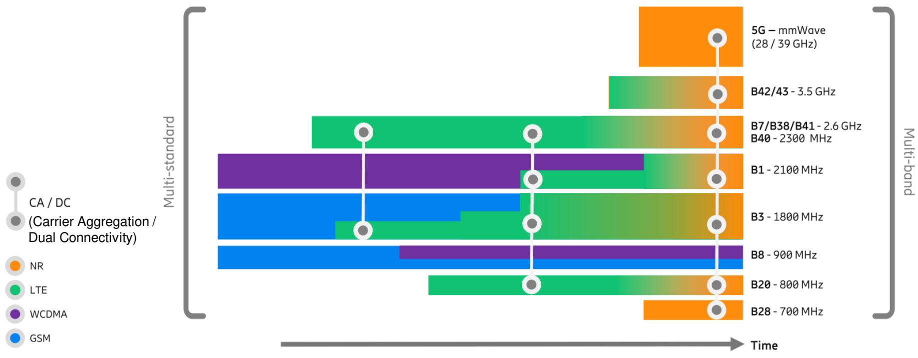
5G multi-standard & multi-band



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

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EIRP

- EIRP: Effective Isotropic Radiated Power
- 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

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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
  - Baud ≠ Bits per second!

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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

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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

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Shannon's Theorem (cont.)

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

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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:

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

  - N0 = noise power density in watts per 1 Hz of bandwidth
  - k = Boltzmann's constant = 1.3803×10^{-23} J/K
  - T = temperature, in kelvins (absolute temperature)
- Noise is assumed to be independent of frequency
- Thermal noise in bandwidth B Hertz

$$N = kTB = N_o B$$

Example

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

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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:

$$C = 2B\log_2 M$$

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

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

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Eb/N0 and BER

- Ratio of signal energy per bit to noise power density per Hertz

$$\frac{E_b}{N_0} = \frac{S/R_b}{N_0} = \frac{S}{kTR_b}$$

- 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

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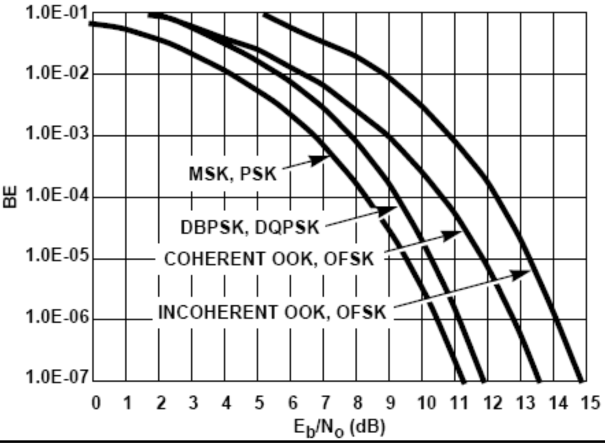
Eb/N0 and BER (cont.)

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



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Receiver sensitivity

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

E_b/N_o = 14.2dB = 26.3

SNR = (E_b/N_o) * (R/B_T)

= 26.3 * (40kbps / 80kHz) =13.15

= 11dB

Prx = Receiver Noise Floor + SNR

= -111dBm + 11dB

= -100dBm

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Noise floor

- Thermal noise power (80KHz bandwidth):

N = kTB

= 1.38×10^{-23} J/K x 290K x 80,000 s^{-1}

= 2.4×10^{-13}mW

= -126dBm

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

Receiver Noise Floor = -126dBm + 15dB

= -111dBm

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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)