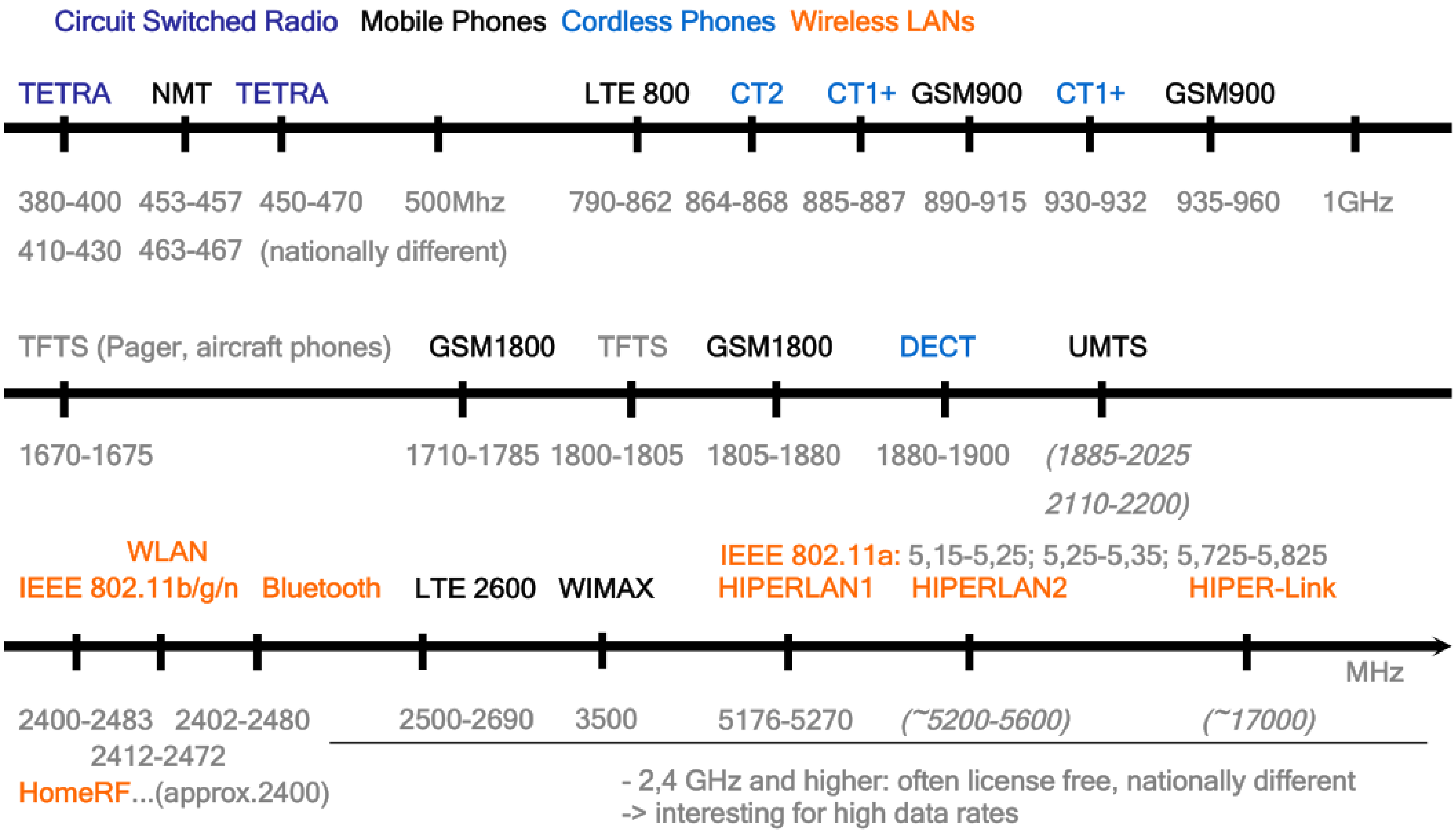
Introduction
Wireless Communication

Communication

- So far, we have talked about embedded systems, the OS, and potential applications
- What kind of communication technology should be used?
  - Wired vs wireless

- We will focus here on wireless communication through radio waves (=electromagnetic radiation with frequencies below 300 GHz)
- Other wireless technologies exist: Ultrasonic, visible light, infrared,...

Radio Spectrum

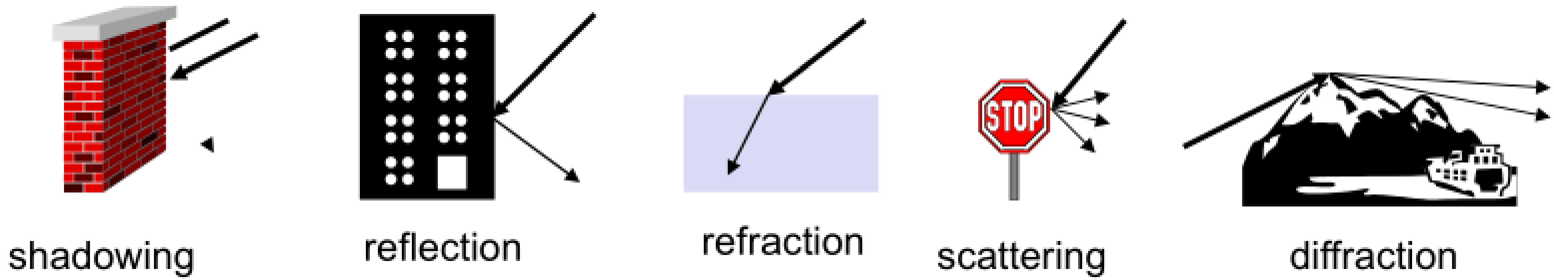


Radio Spectrum (2)

- Not all frequencies are equally suitable for all purposes
  - Some frequencies are reserved to specific uses and need a license: Cellular phones, police,…
  - Some frequencies are license free: ISM bands (“Industrial, Scientific, Medical”). Example: 2.4GHz-2.5GHz (Bluetooth, WiFi,…)
  - Allowed maximum power emission is regulated for the different frequencies!
  - Frequencies have different propagation properties (wall penetration, atmospheric attenuation,…): path loss

Path Loss

- Many reasons:
  - Free-space path loss: signal becomes weaker with distance
  - Shadowing (obstacles)
  - Reflection
  - Refraction
  - Scattering
  - Diffraction



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Free-Space Path Loss

- Signal becomes weaker even without obstacles, refraction etc.
- Attenuation depends on frequency and distance
- Friis transmission equation:

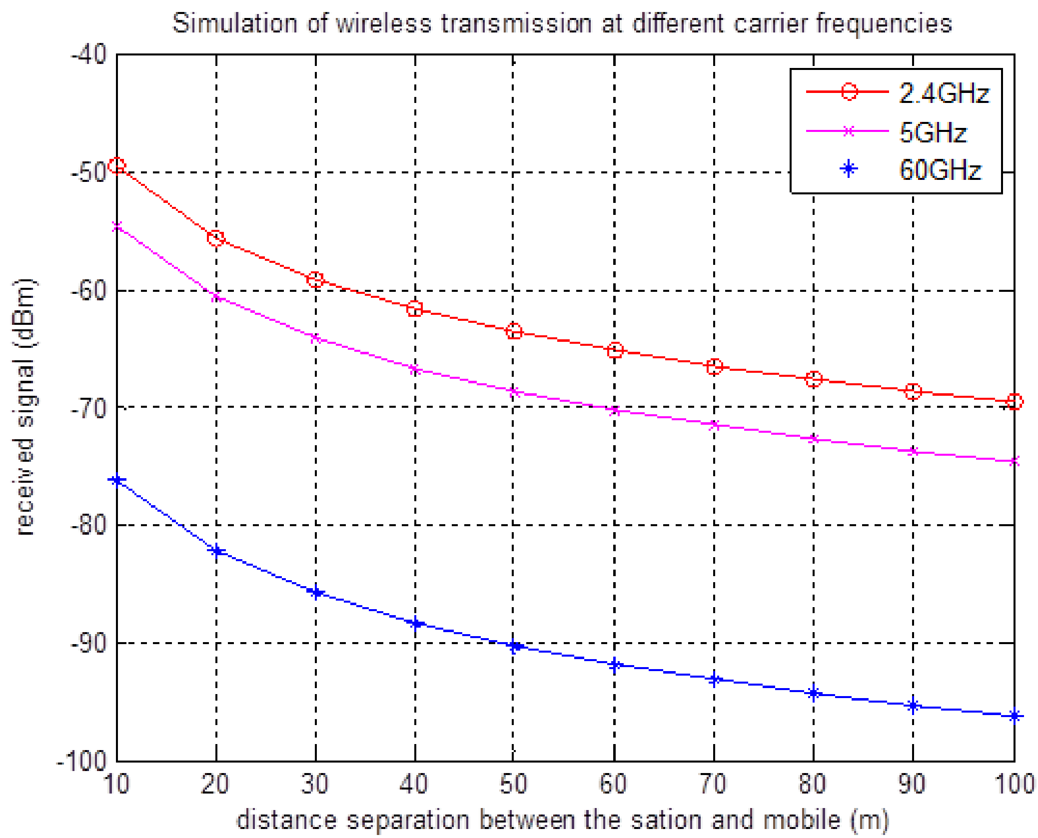
$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^2$$

$\frac{P_r}{P_t}$ = ratio received power vs transmitted power
G_r and G_t = receiver and transmitter antenna gain
R = distance between transmitter and receiver
λ = wavelength. Note: only works for $R \gg \lambda$!

- Free-space path loss typically specified in dB:

$$FSPL[dB] = 10\log_{10}\frac{P_t}{P_r} = 20\log_{10}\frac{4\pi R}{\lambda} \quad \text{for } G_t = G_r = 1$$

Free-Space Loss

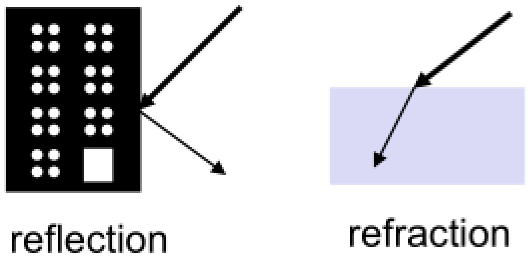


Source: www.essex.ac.uk

- Y-axis: received power when $P_t = 1mW$ in dBm:

$$dBm = 10\log_{10}\frac{P_r}{1mW}$$

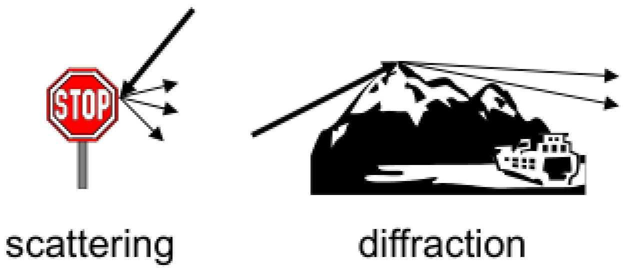
Reflection and Refraction



- Happens when signal wave hits a boundary between different types of material
  - Reflection: fraction of the wave is reflected by the surface
  - Refraction: fraction of the wave propagates through the boundary (with changed direction)

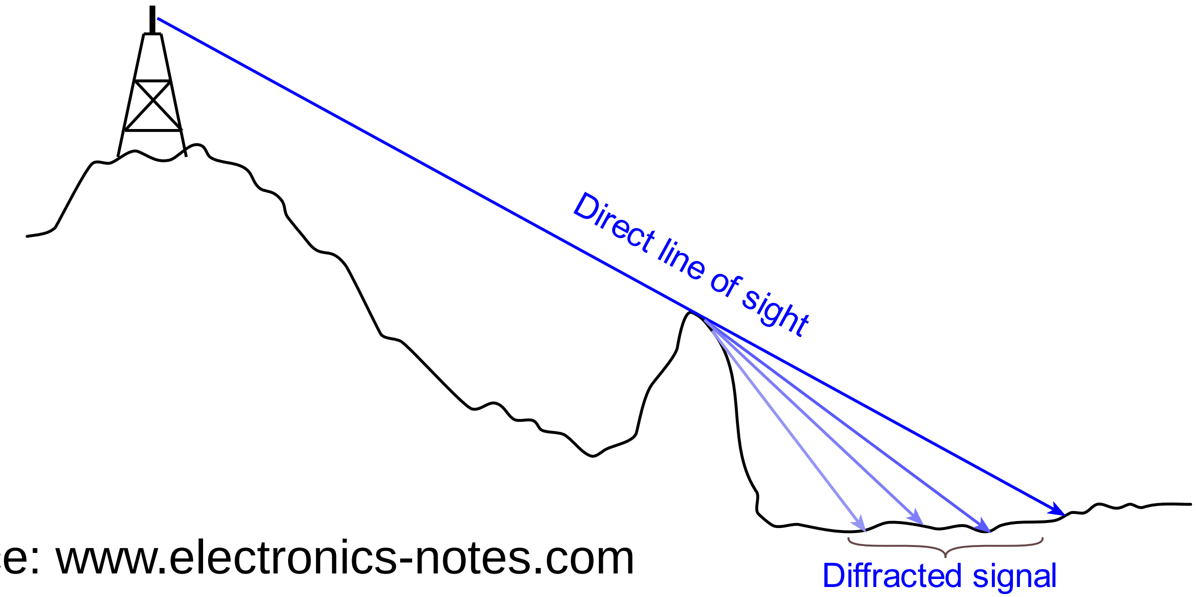
- Reflection and refraction depend on material and wavelength

Scattering and Diffraction



- Signal waves are diffracted at edges and scattered due to non-uniformities in the medium

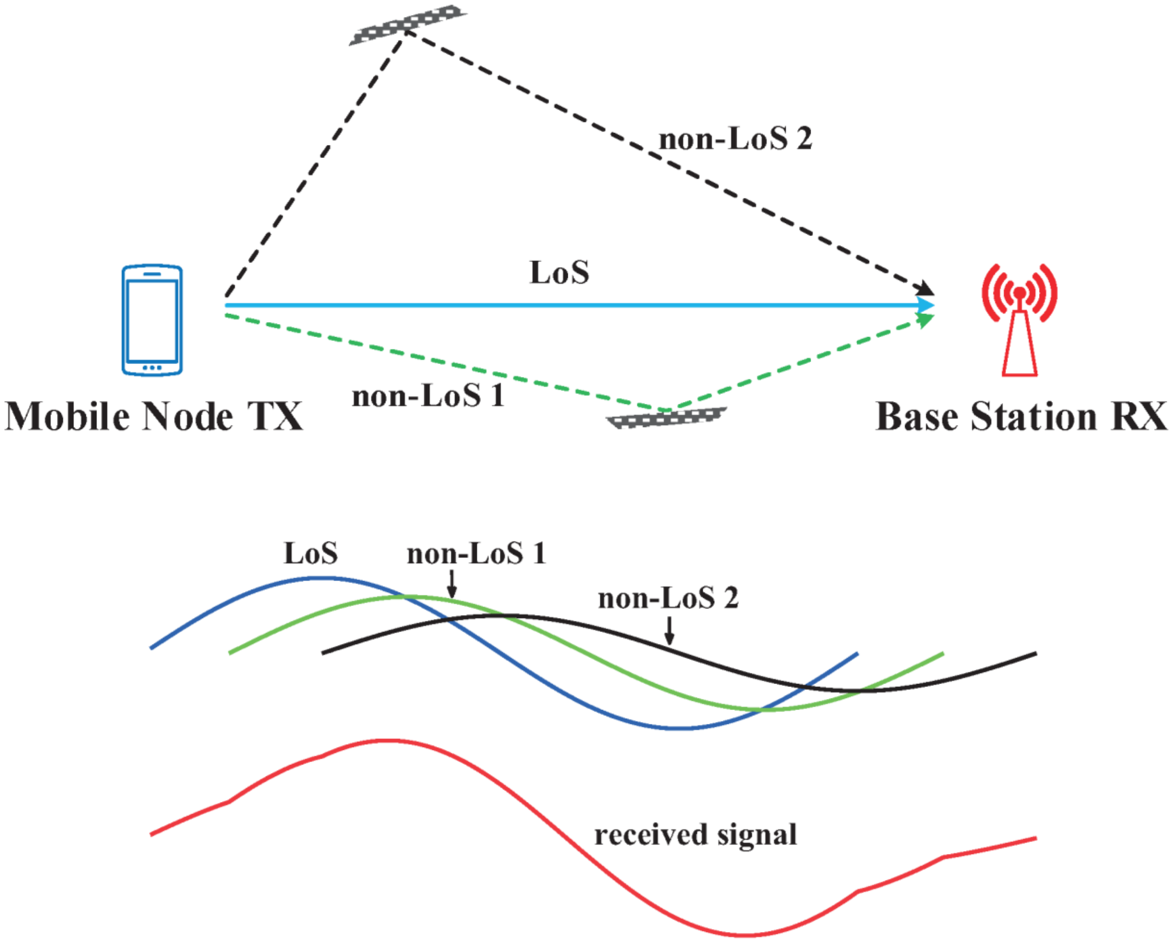
→ Signal strength is distributed over the new waves



Source: www.electronics-notes.com

Multi Path

- Reflection, scattering etc. make things much more complex
  → Signal reaches receiver through different paths



Indirect path
("non-line-of-sight" NLoS)

Direct path
("line-of-sight" LoS)

Source: Xie et al., 2019

Multi Path (2)

- Different paths have different lengths
  - Result: Not the entire signal power reaches the receiver at the same time → Signal is weakened and distorted
- Even more complex when the devices are moving

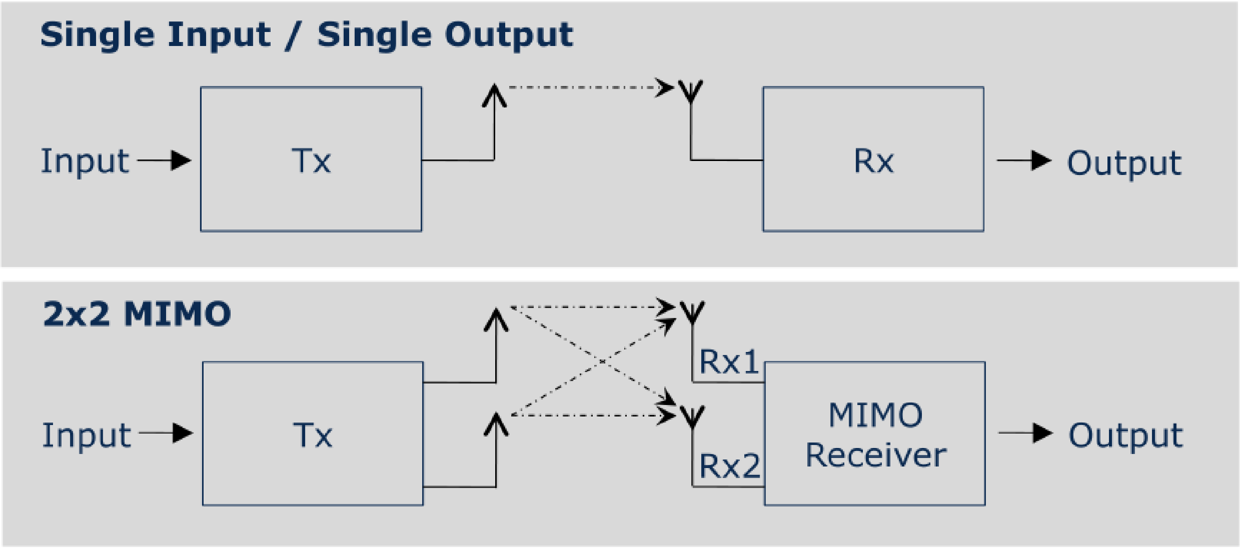
- Friis’ equation does not work well indoor or in cities because of shadowing, reflections, etc.
- Empirical adjustment:

$$\frac{P_r}{P_t} = G_t G_r \left(\frac{\lambda}{4\pi R}\right)^{\gamma}$$

with $\gamma \approx 3 - 5$ in cities, $\gamma \approx 4 - 6$ in buildings, etc.

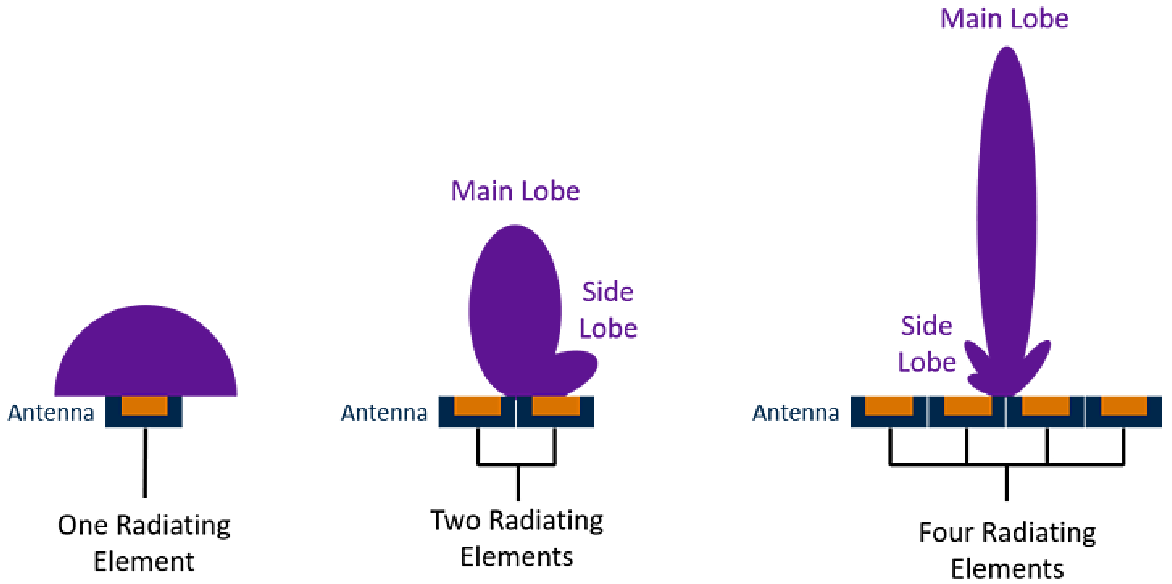
MIMO Antennas

- Modern radio interfaces (as used in LTE, 802.11ac) try to reduce the impact of multipath propagation by using multiple sender and receiver antennas

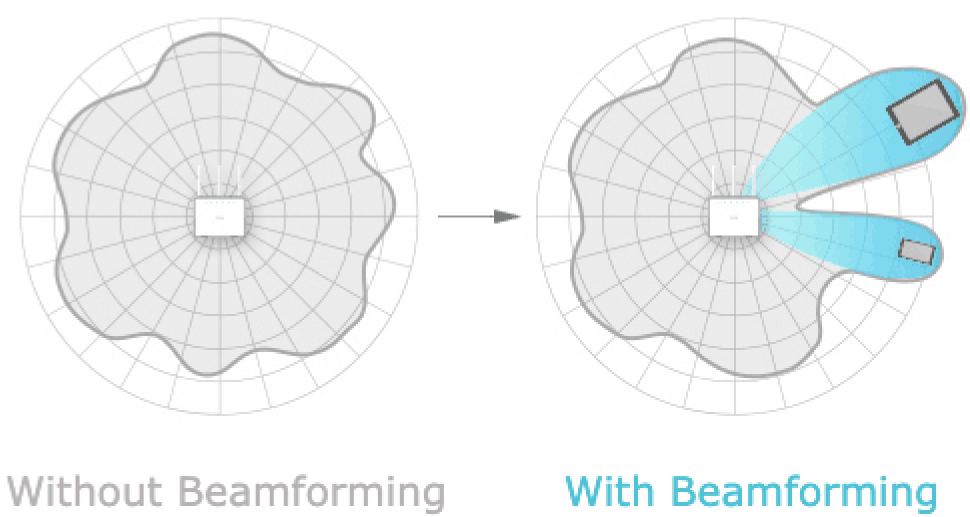


- If there is multipath propagation, the signals arrive at different times at the different antennas of the receiver. The receiver can reconstruct the original signal.
- Also other tricks (beam forming etc.) possible with MIMO to increase signal quality and bandwidth

Beam forming



Source: metaswitch.com



Source: 7labs.io

Noise and Multiple Senders

- So far, we have considered only <u>one</u> sender
- But there are other signal sources:
  - Two senders might try to send at the same time
  - Nearby networks or electronic devices “pollute” the wireless channel
  - Another sender uses another channel (=transmission frequency), but the receiver’s frequency filters are not good enough
  - Thermal noise from the electronics

SNIR

- The stronger the interference, the harder for the receiver to interpret the received signal as a symbol (e.g., “0” or “1”)
- Expressed as Signal-To-Noise and Interference Ratio (SNIR):

$$SNIR[dB] = 10 \log \left(\frac{P_r}{N_0 + \sum_j I_j} \right)$$

P_r = received signal power

N_0 = "background" noise power from various sources

(not only thermal noise)

$I_j =$ influence of interfering neighbor j

SNR

- With an appropriate *Medium Access protocol*, interference can be reduced. For example, the protocol could prevent that two devices send at the same time
- In that case SNIR simplifies to SNR (Signal-Noise-Ratio):

$$SNR[dB] = 10\log\left(\frac{P_r}{P_N}\right)$$

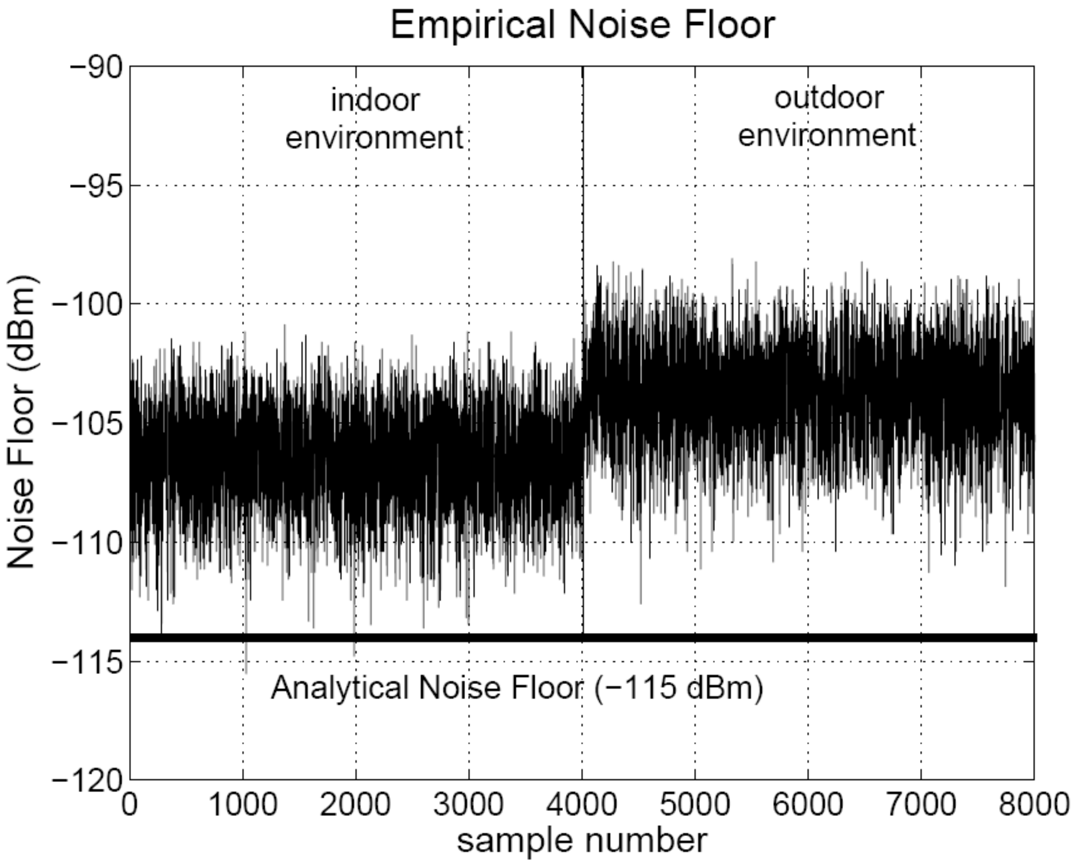
P_r = received signal power
P_N = noise power (“noise floor”)

- You will also see often the term *Bit Error Rate (BER):*

  BER = number of bit errors per time unit

Noise Floor

- Noise floor P_N changes over time
  $\rightarrow$ SNR varies even for constant signal strength P_r



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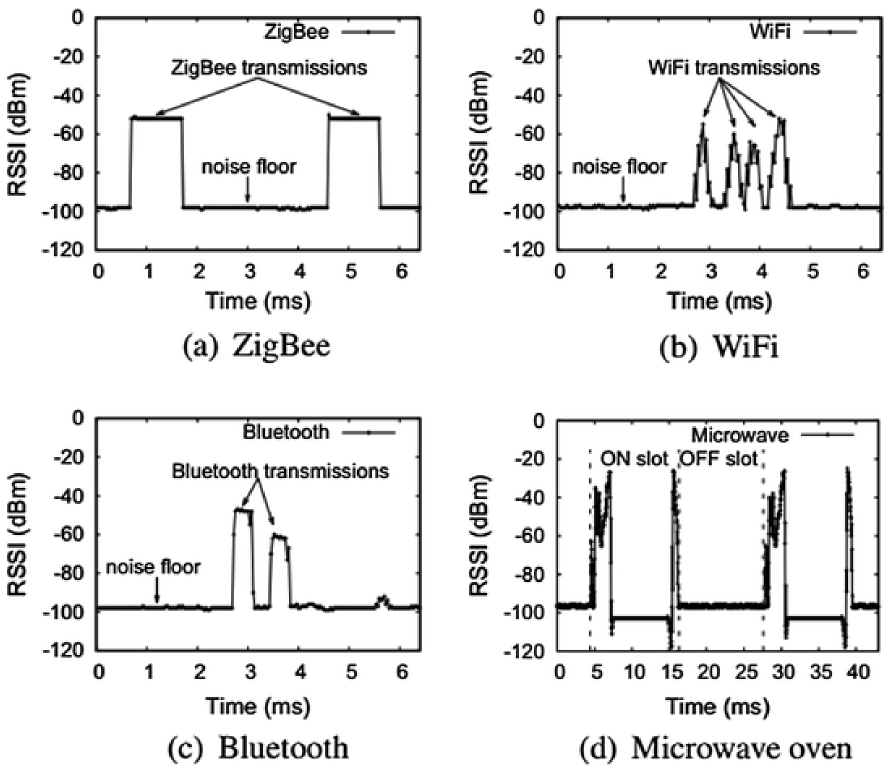
RSSI

- RSSI = Received Signal Strength Indicator
  - A number indicating the “usable strength” of the signal
  - Definition depends on the device manufacturers
  - Often an abstract number between 0 and 100 (sometimes you see also a scale like -100..0 or -127..0)



(a) ZigBee (b) WiFi

(c) Bluetooth (d) Microwave oven

RSSI seen by a CC2420 radio chip
Source: Shi et al., 2016

Conclusions

- Physical layer and medium access layer need to be carefully designed to cope with the wireless-specific problems
- But even with perfect hardware or software:

  We have to expect higher error rates than in wired networks due to interferences, reflections, etc.

  $\rightarrow$ Efficient error detection/correction needed
- In general, lower transmission rates than in wired networks