NTNU

Kunnskap for en bedre verden

Wireless Transmission

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The slides of this lecture are based on :

- *Mobile Communication*, Chapter 2, by J. Schiller
- *Wireless Communication Networks and Systems*, chap. 2, 5 by C. Beard & W. Stallings

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Outline

- Radio frequency (RF)
- Signal propagation and antennas
- Channel capacity
- Wireless channel impairments
  - Fading
- Modulation and demodulation

Radio Frequency (RF)

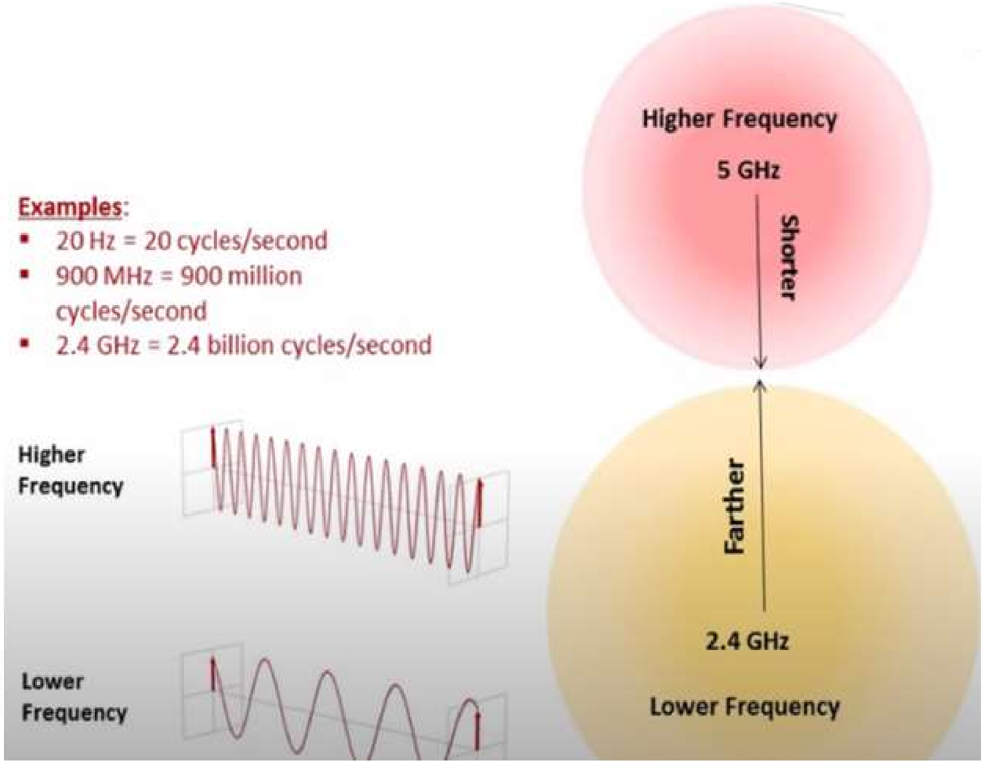
Electromagnetic signal that propagates through a medium

Three main usages:

1. Transfer information
   - Sound and images such as Radio and TV (broacast, cable)
   - Data transmission: WiFi, Bluetooth, Cellular, satellite/GPS
2. Sensing / detecting objects
   - Radar and body scanners use RF to detect objects
3. Heating objects
   - Microwave (frequency: 2.45GHz, about the same as WiFi)

About RF frequencies

- When we lower the frequency
  - the RF propagates longer distances
  - Higher object penetration, i.e. RF passes through objects more easily
- Broadcast AM and FM use MF to allow the signal to travel long distances and penetrate buildings.
- WiFi uses frequency of 2.4/5 GHz (ca. 25 to 50 x higher than AM) because we don't want WiFi signals to travel too far (to avoid interference between different AP)

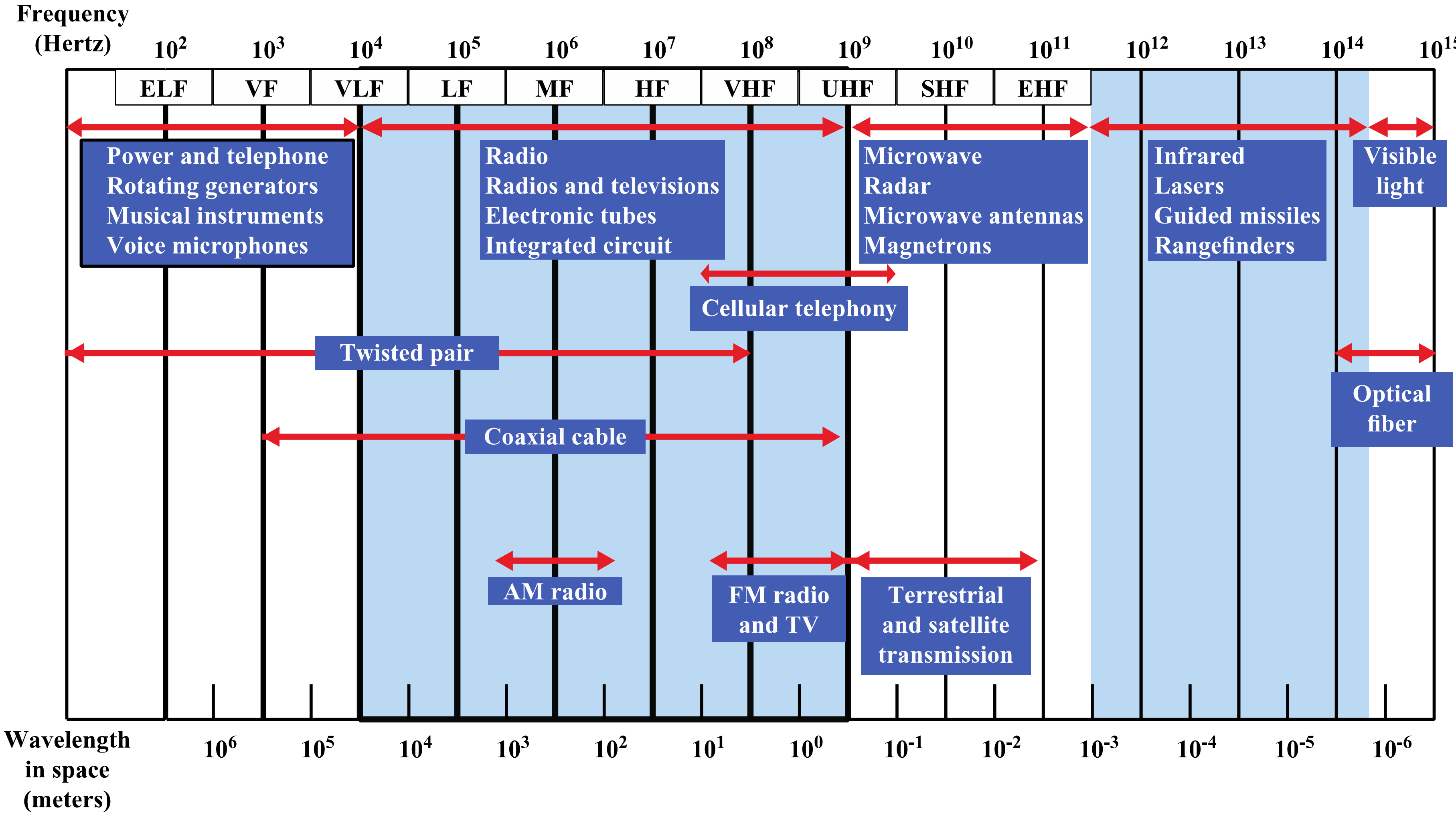


The frequency of an RF is chosen based on the application

What is a spectrum?

- Spectrum is a range of frequencies
- The RF frequency spectrum is not humanly perceivable, therefore spectrum analyzers are used to analyze spectrum
- A spectrum analyzer detects what kind of signals (power, modulation) are present at what frequencies

Electromagnetic spectrum of telecommunications



ELF = Extremely low frequency
VF = Voice frequency
VLF = Very low frequency
LF = Low frequency
MF = Medium frequency
HF = High frequency
VHF = Very high frequency
UHF = Ultrahigh frequency
SHF = Superhigh frequency
EHF = Extremely high frequency

AM Radio: Around 10MHz
FM Radio: Around 100MHz
Television: Many frequencies from 470MHz to 800MHz, and others
Cellular phones: 850MHz, 1900MHz, and others

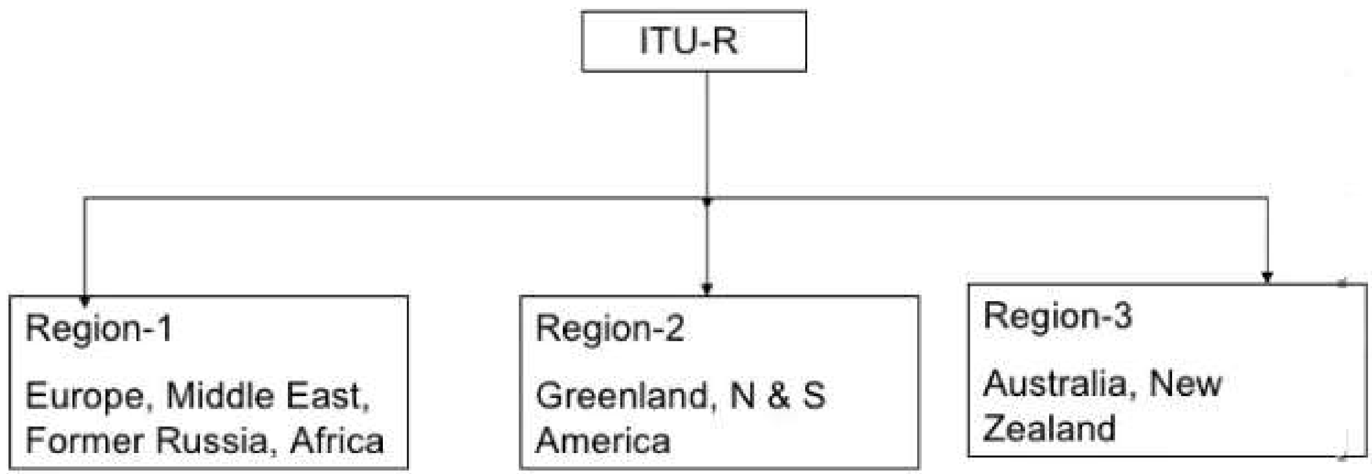
Wi-Fi: 2.4GHz
Satellite: 3.5GHz
Wi-Fi: 5GHz

Frequencies for radio transmission

- **LF** are used by submarins
  - Can penetrate water, follow earth’s surface, propagate long distances
- **MF** and **HF**: radio communications (AM and FM radio)
  - enabled by reflection at the ionosphere
  - transmit power: up to 500kW
- **VHF** and **UHF**: analog/digital tv, DAB, GSM
  - small antennas and low transmit power
- **SHF**: directed microwave and fixed satellite
  - small antennas and beamforming
  - large bandwidth available
- **EHF**: Infra red (IR) direct transmission
  - very short wavelength and transmission distance

Frequencies regulations

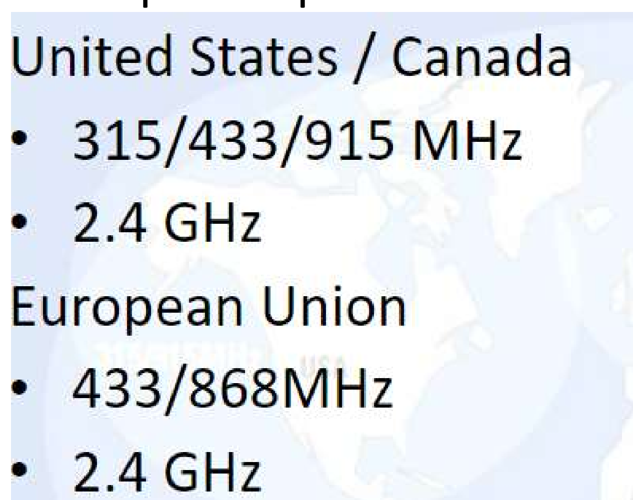
- Radio frequencies are scarce resources
- The International Telecommunications Union (ITU) is responsible for worldwide coordination of telecommunications activities (wired and wireless)
- The ITU Radio Communication Sector (ITU-R) holds auctions for new frequencies and manages frequency bands worldwide



National agencies are responsible for further regulations

Bands

- Specific ranges of frequencies in which signals are used for a specific purpose are called **«bands»**
- Examples:
  - The AM broadcast band covers 550 – 1700 KHz
  - The FM broadcast band covers 88 – 108 MHz
- Unlicensed bands:
  - Known as Industrial, Scientific, and Medical (ISM) bands
  - Can be used without a license (as long as power and spread spectrum regulations are followed)
  - ISM bands are used for
    - WLANs
    - Wireless Personal Area networks
    - Internet of Things



ISM bands

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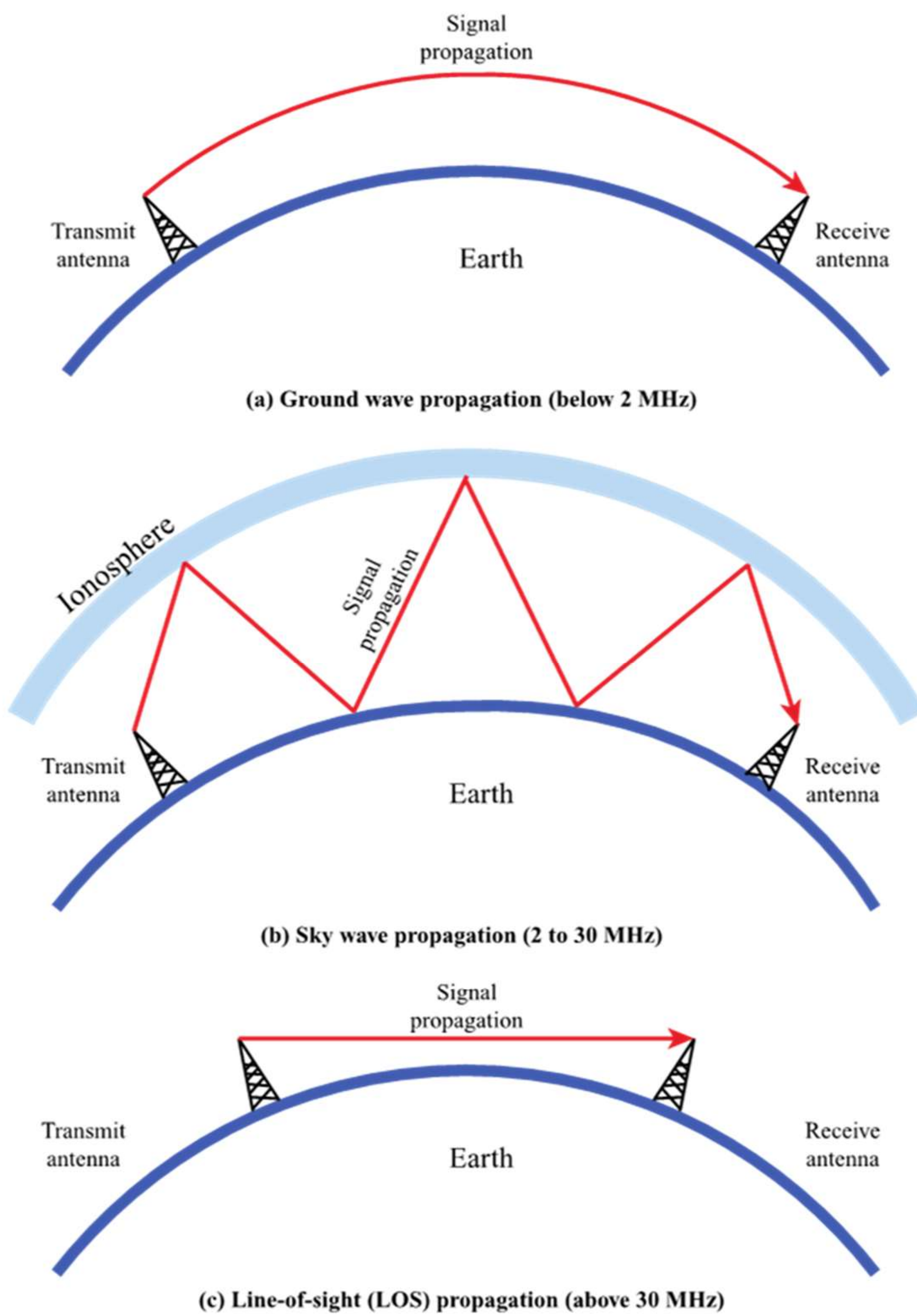
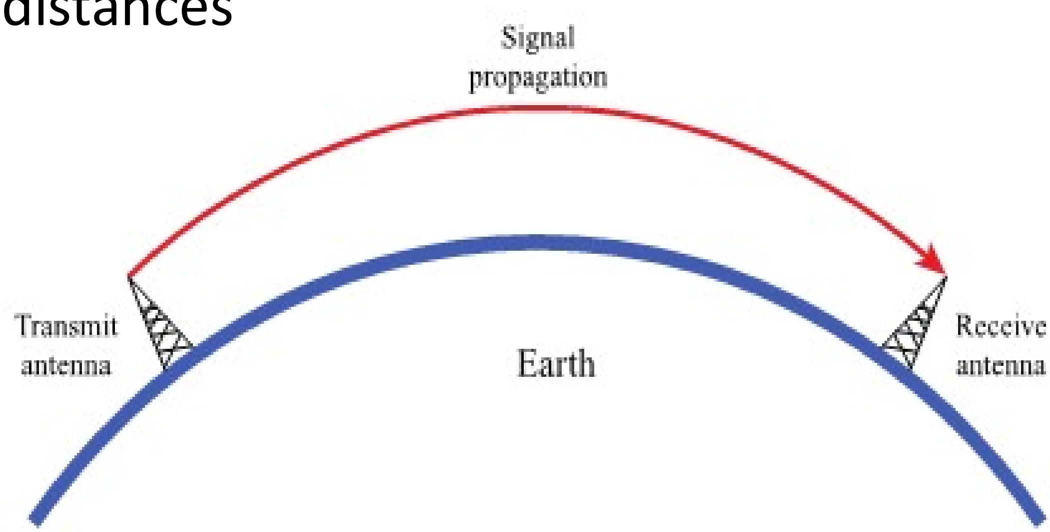
Wireless Propagation Modes



Ground Wave Propagation

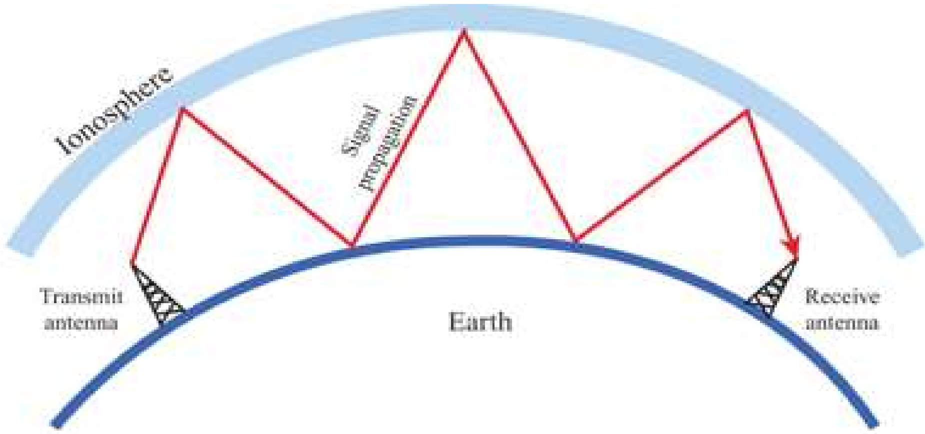
- Follows contour of the earth
- Can propagate considerable distances
- Frequencies up to 2 MHz
- Example: AM radio



(a) Ground wave propagation (below 2 MHz)

Sky Wave Propagation

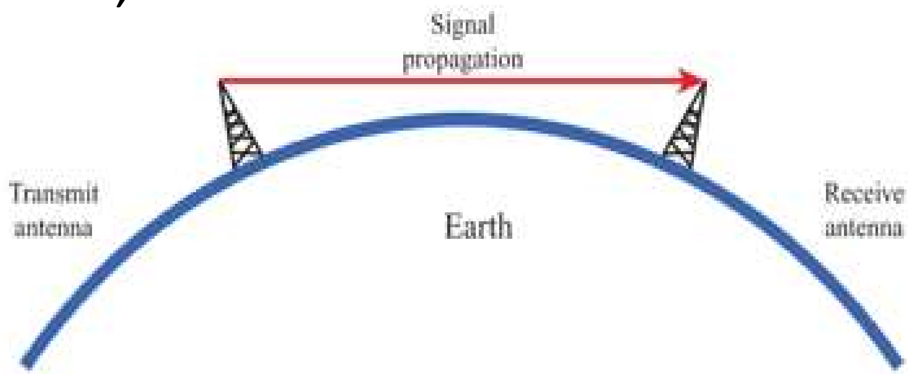
- Signal reflected from ionized layer of atmosphere back down to earth
- Signal can travel a number of hops, back and forth between ionosphere and earth's surface
- Reflection effect caused by refraction
- Example: CB radio (operates near 27 MHz)
  - Citizens band radio CB: a system allowing short-distance person-to-many persons bidirectional voice communication



(b) Sky wave propagation (2 to 30 MHz)

Line-of-sight Propagation

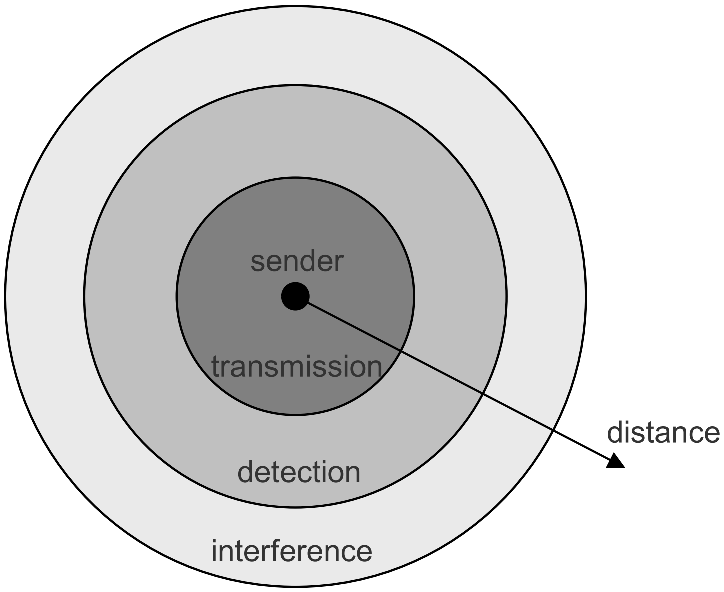
- Transmitting and receiving antennas must be within line of sight
  - Satellite communication – signal above 30 MHz not reflected by ionosphere
  - Ground communication – antennas within *effective* line of site due to refraction
- Mobile phones use a modified line-of-sight transmission, which is made possible through a combination of effects like diffraction, multipath reflection, local repeaters and rapid handoff
- Examples: FM radio, microwave and satellite transmission



(c) Line-of-sight (LOS) propagation (above 30 MHz)

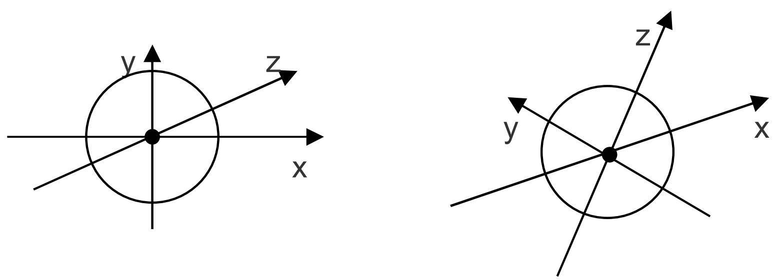
Signal propagation ranges

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - Communication not possible, but the signal can be detected
- Interference range
  - signal may not be detected
  - signal adds to the background noise



Antennas

- An antenna is an electrical conductor or system of conductors
  - Transmission - radiates electromagnetic energy into space
  - Reception - collects electromagnetic energy from space
- In two-way communication, the same antenna can be used for transmission and reception
- Isotropic radiator: equal radiation in all directions
  - only a theoretical reference antenna
  - Real antennas always have directive effects (vertically and/or horizontally)



ideal isotropic radiator

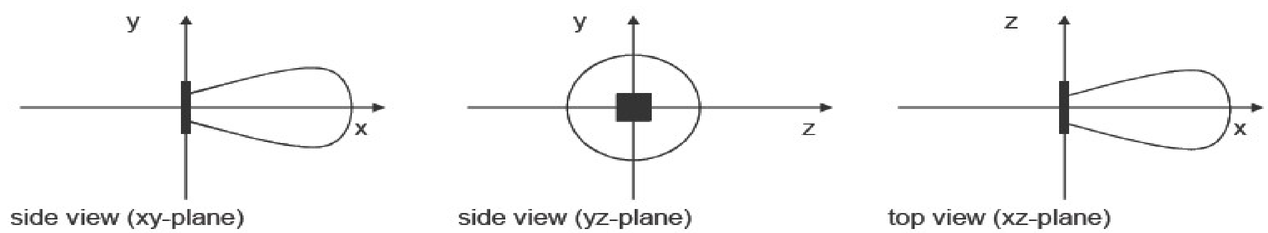
Antennas Example- Dipoles

- Real antennas are not isotropic radiators
- e.g. dipoles with lengths $\lambda/4$ (on car roofs) or $\lambda/2$ as Hertzian dipole

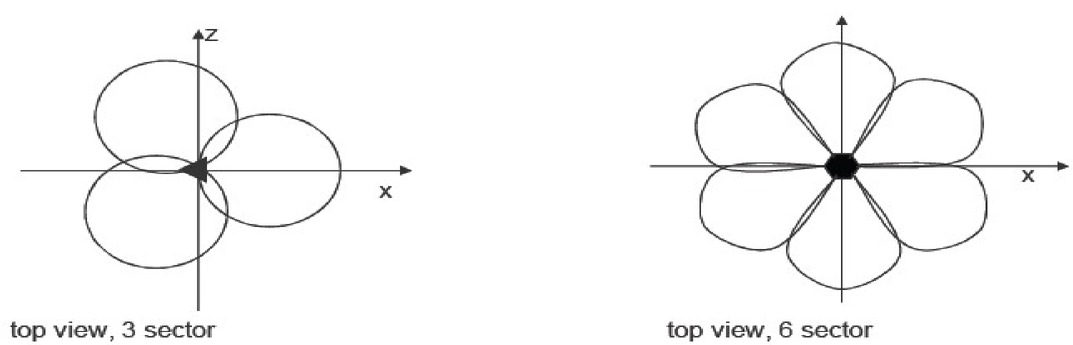
- shape of antenna proportional to wavelength

Antennas – Directed and Sectorized

- Often used in microwave connections and base stations (mobile phones)



directed antenna



sectorized antenna

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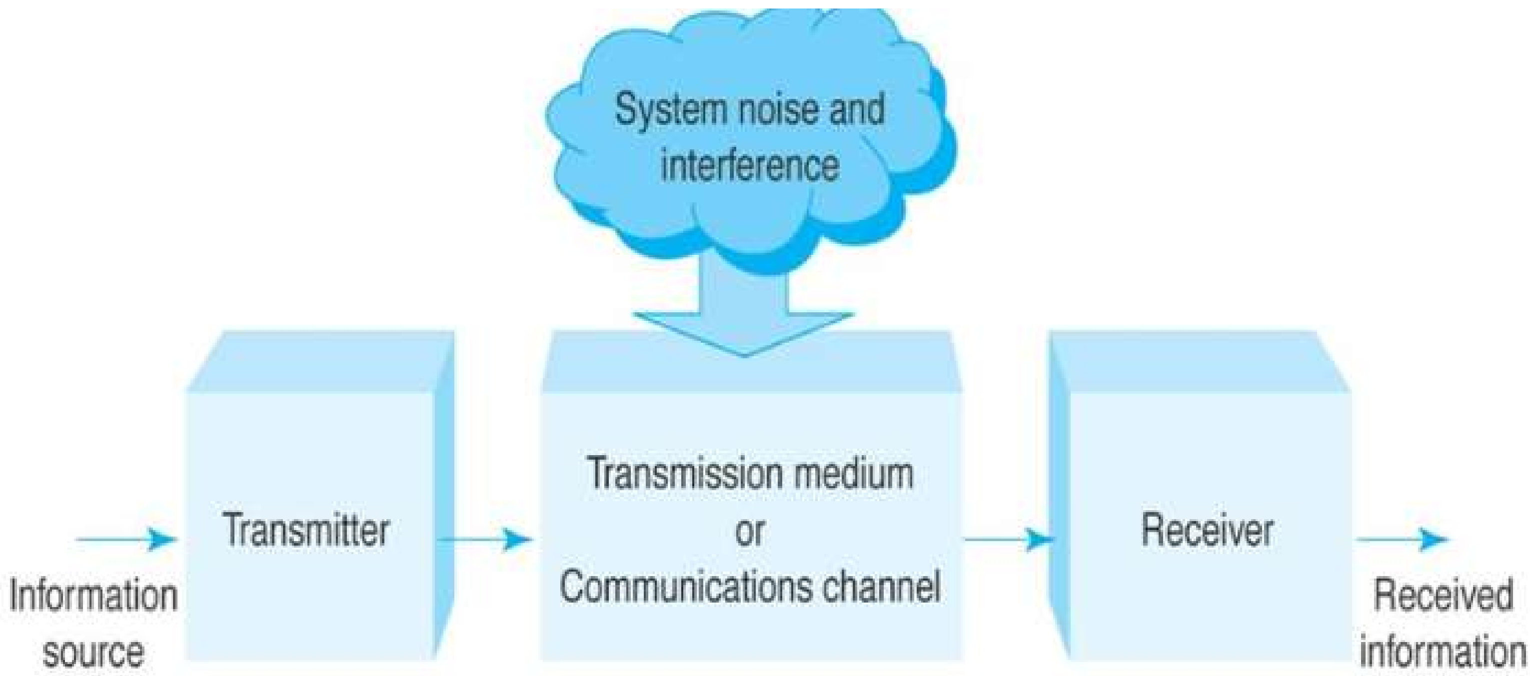
Channel Capacity



- Channel Capacity – the **maximum** rate at which data can be transmitted over a given communication path, or channel, under given conditions

- The data rate that can be achieved is limited by impairments such as noise!

Concepts Related to Channel Capacity

- Data rate - rate at which data can be communicated *(bps)*
- Bandwidth *(Hertz)* $B = f_{high} - f_{low}$
  - It is the narrow band of frequencies that the most of the signal's energy is contained in
  - constrained by the transmitter and the nature of the transmission medium
  - The greater the bandwidth, the higher the information-carrying capacity
- Noise - average level of noise over the communications path
- Error rate - rate at which errors occur
  - Error = transmit 1 and receive 0; transmit 0 and receive 1
  - Implying the probability of one bit error
    - Example : Bit error rate of 10^{-3} means probability of a single bit flipped, or in other words, in every 1000 bit, one bit error is found

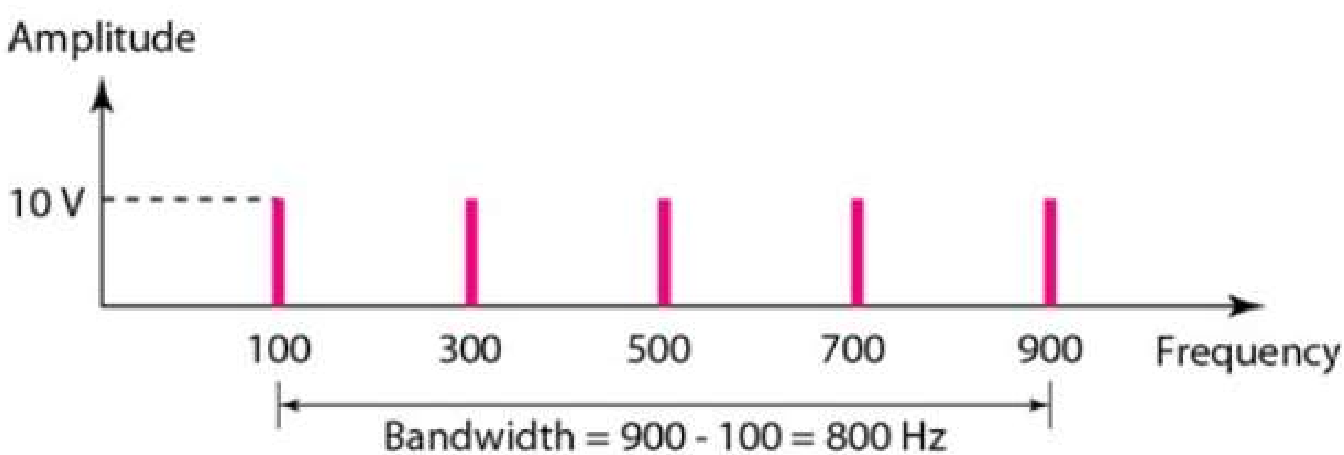
Signal Bandwidth Example

- If a signal is decomposed into 5 sine waves with frequencies of 100, 300, 500, 700, and 900 Hz. What is the bandwidth of this signal?

- Answer: let f_{high} be the highest frequency and f_{low} be the lowest frequency.

The bandwith *B* is then: $B = f_{high} - f_{low}$

$$B = 900 - 100 = 800 \text{ Hz}$$



Signal-to-Noise Ratio (SNR)

- Ratio of the power in a signal to the power contained in the noise that's present at a particular point in the transmission
  - Typically measured at a receiver

- Signal-to-noise ratio

$$(SNR)_{\text{dB}} = 10\log_{10}\frac{\text{signal power}}{\text{noise power}}$$

- SNR is an essential parameter that shows signal quality
  - A high SNR means a high-quality signal
  - A low SNR means low quality signal, may require further signal processing to recover original signal

Nyquist Bandwidth

- Noisless channel

$$C = 2B \log_2 M$$

  - C = bit rates [bps]
  - B = Bandwidth [Hz]
  - M = number of discrete signal or voltage levels to represent the data. Ex. in BPSK, 2 signal levels are used
- Example: Consider noisless channel of 3 kHz, transmitting signal of 2 levels. Find the bit rate

  $C = 2B \log_2 M = 2 \times 3000 \times 1 = 6000$ *bps*

- *What is the bit rate for transmitting signal of 4 levels?*

  The bit rate is doubled!

Wireless Channel Capacity - Shannon Formula

- Noisy channel
- Equation:

$$C = B\log_2\left(1+\mathrm{SNR}\right)$$

    - C = bit rates [bps]
    - B = Bandwidth [Hz]
    - SNR = signal to noise ratio (in linear scale)

- Represents the theoretical maximum that can be achieved
    - In practice, only much lower rates achieved
    - Formula assumes white noise (thermal noise), other types of noise are not accounted for
    - Attenuation distortion not accounted for!

- Example: Extremely noisy channel, SNR = 0

C = B log_2(1+0) = 0 → we cannot receive data

Example – Shannon formulation

- Spectrum of a channel between 3 MHz and 4 MHz ; SNR_{dB} = 24 dB

$$B = 4\ \mathrm{MHz} - 3\ \mathrm{MHz} = 1\ \mathrm{MHz}$$

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

$$\mathrm{SNR} = 251$$

- Using Shannon's formula $C = B\log_2(1+\mathrm{SNR})$

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

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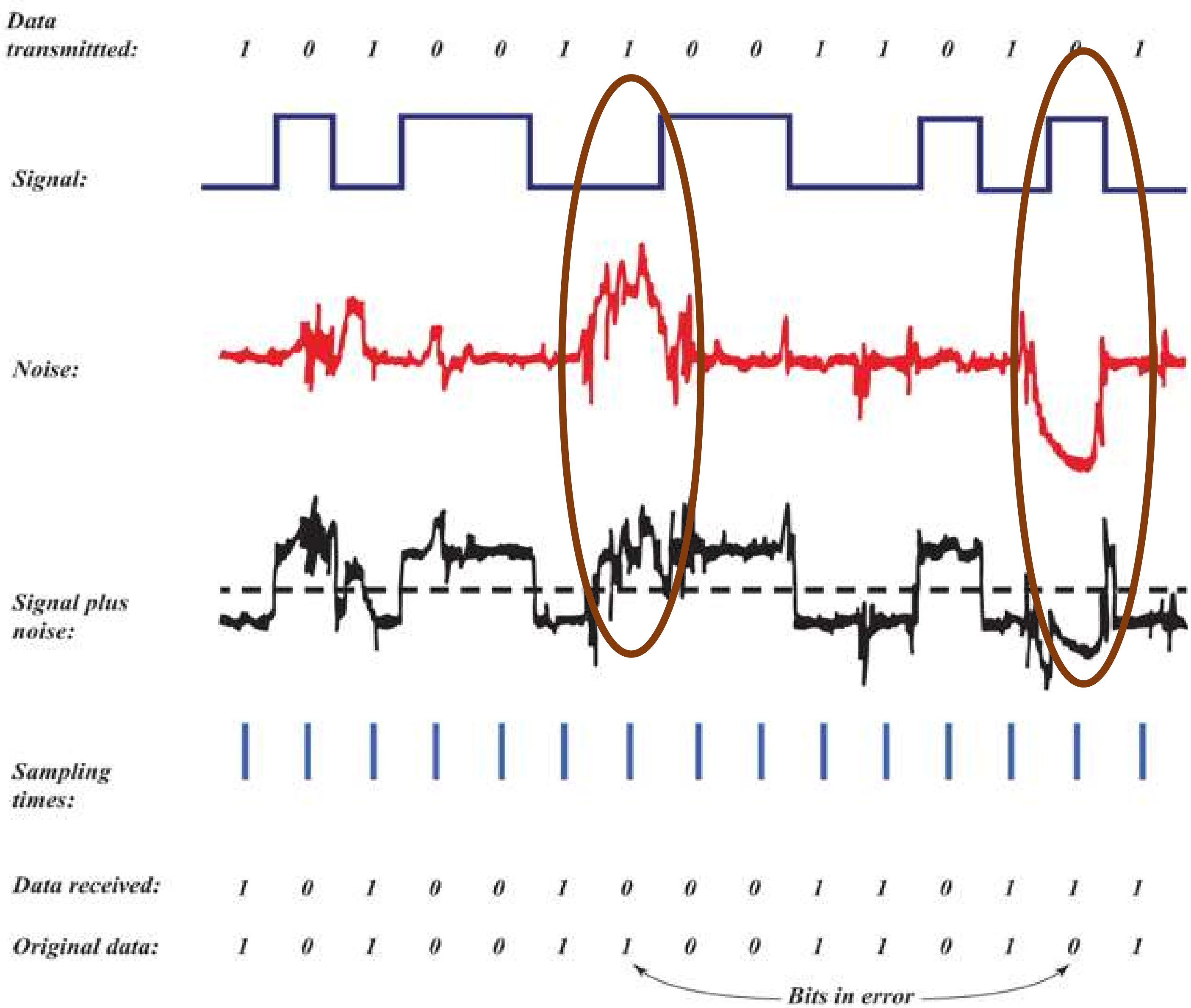
Wireless Transmission: Impairments

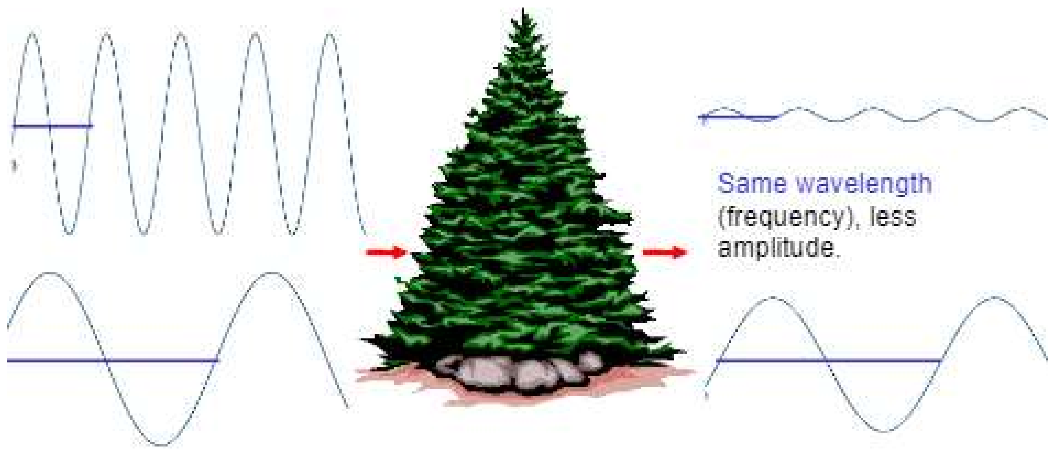
- Noise: unwanted external signal that can impair original signal
- Transmission loss (mainly by signal attenuation)
- Multipath: caused by reflection, refraction, and scattering
- Doppler spread: signal distortion that is caused by the movement of mobile unit

Effect of Noise on a Digital Signal



Attenuation

- Strength of signal falls off with distance
  - Receiving power proportional to $1/d^2$ in vacuum – much more attenuation in real environments, e.g., $d^{3.5}...d^4$
- Attenuation is greater at higher frequencies



- Received signal:
  - must have sufficient strength so that the receiver can interpret the signal
  - must maintain a level sufficiently higher than noise to be received without error

Free space loss

- Free space loss, ideal isotropic antenna

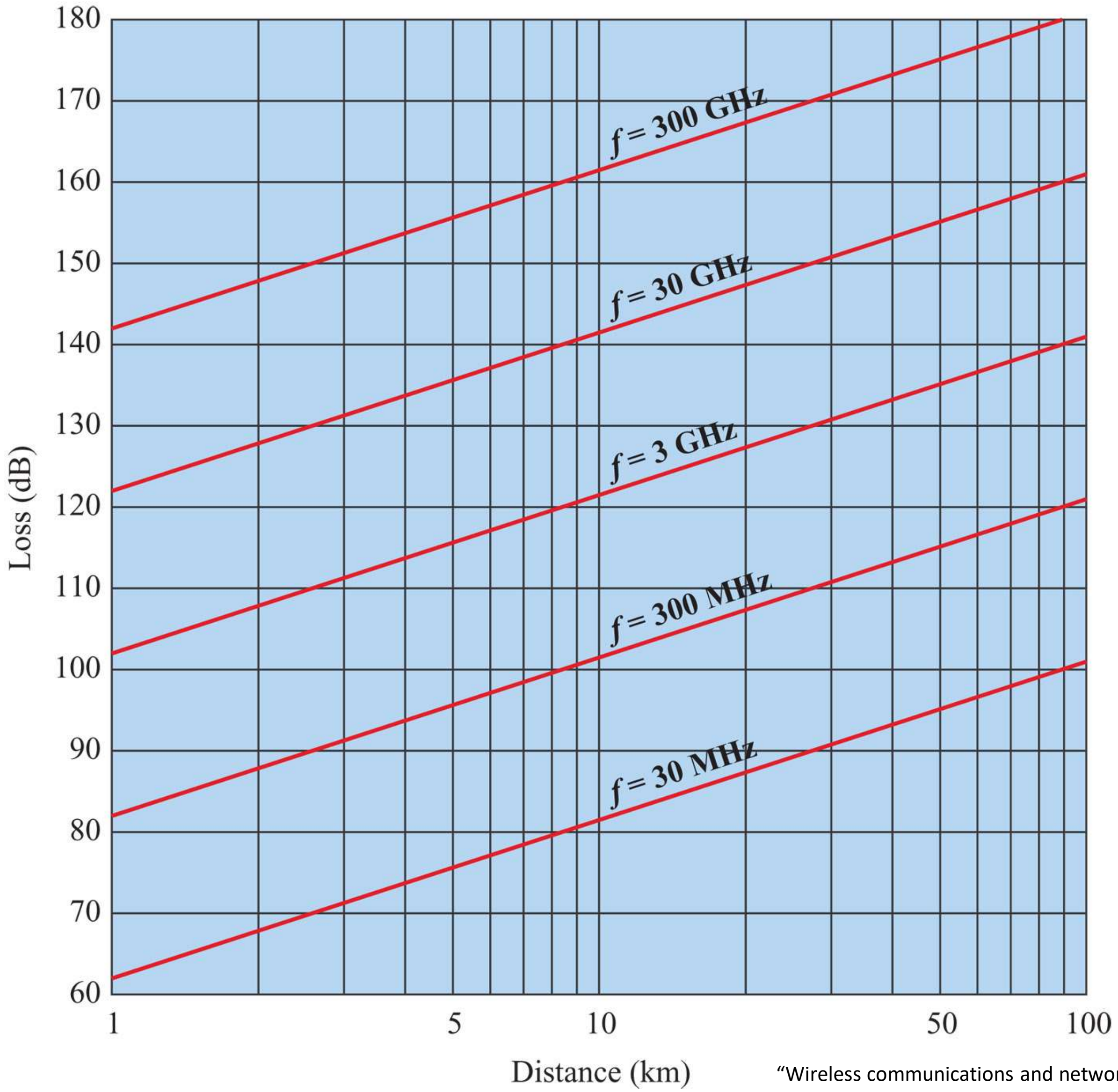
$$\frac{P_t}{P_r} = \frac{(4\pi d)^2}{\lambda^2} = \frac{(4\pi f d)^2}{c^2}$$

  - P_t = signal power at transmitting antenna
  - P_r = signal power at receiving antenna
  - λ = carrier wavelength
  - d = propagation distance between antennas
  - c = speed of light (3×10^8 m/s)

- In dB:

$$L_{dB} = 10 \log \frac{P_t}{P_r}$$

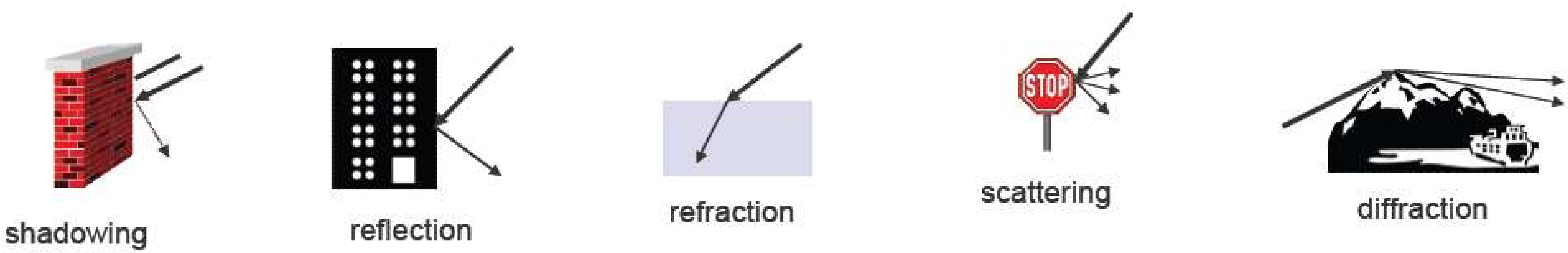
Path Loss vs Frequency



“Wireless communications and networks” by William Stallings, Figure 5-3

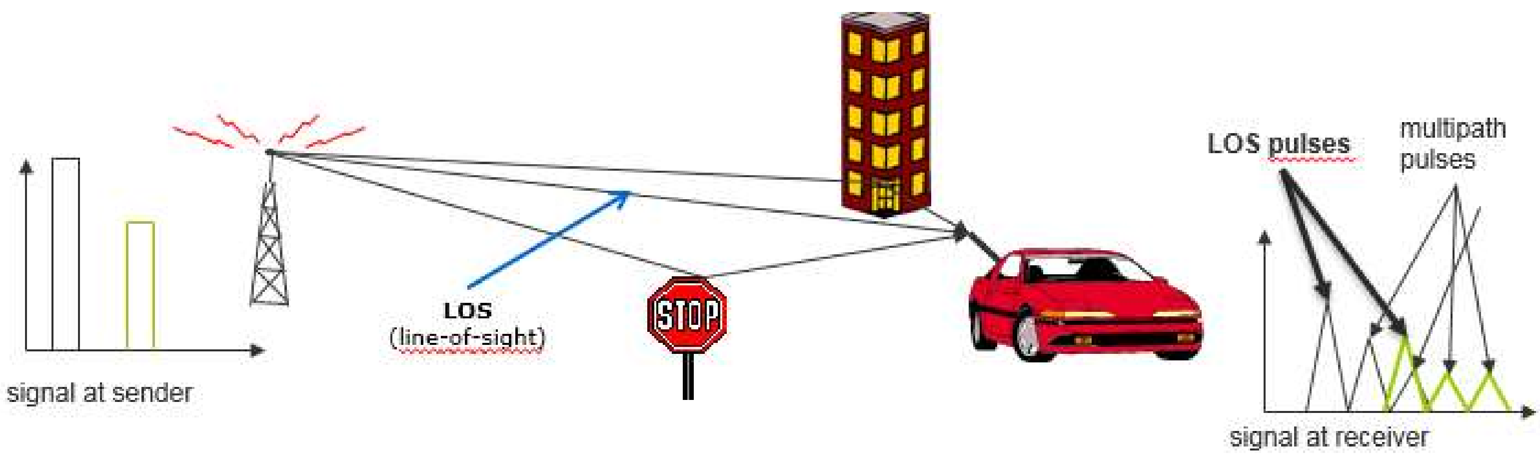
Signal propagation

- In addition to the attenuation, the power of the received signal is influenced by:
  - Shadowing
  - Reflection: smooth surface > λ (ex. Buildings, walls, earth surface)
  - Refraction: depends on the density of the medium
  - Scattering: object < λ , the reflected energy scatters in many direction
  - Diffraction: object with large dimensions relative to λ and sharp irregularities (edges), causing secondary waves

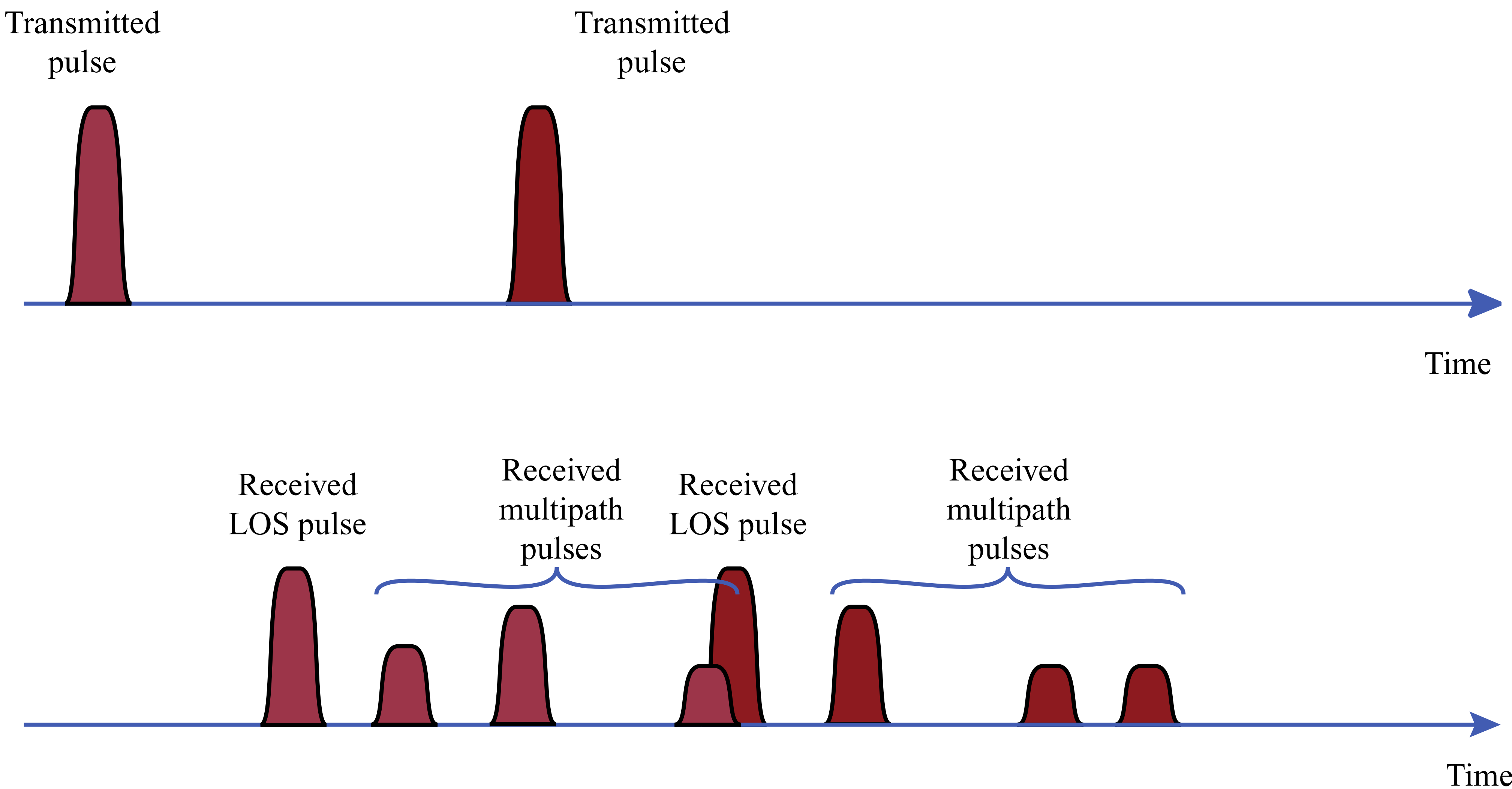


Multipath propagation

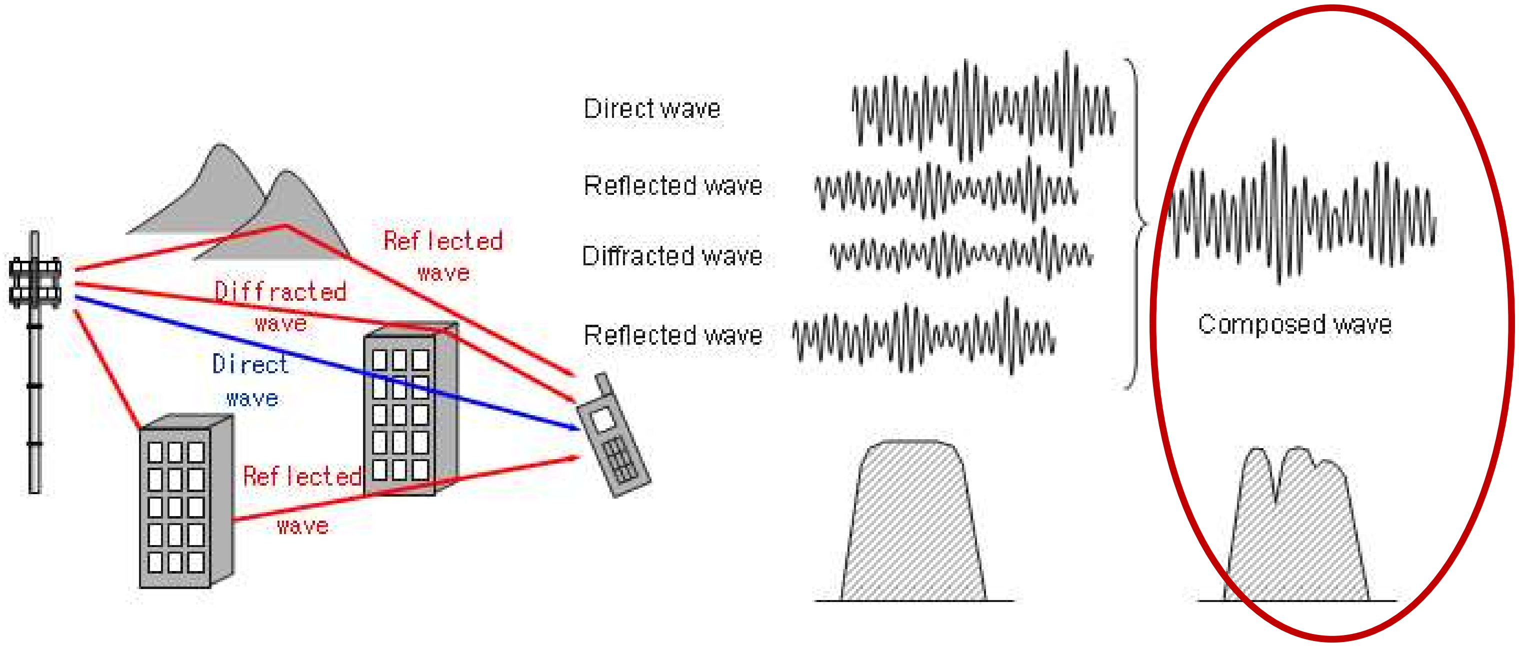
- Caused by reflection, diffraction, and scattering
- Multiple copies of a signal may arrive at different phases
  - If phases add destructively, the signal level relative to noise declines, making detection more difficult
- Intersymbol interference (ISI)
  - One or more delayed copies of a pulse may arrive at the same time as the primary pulse for a subsequent bit



Multipath propagation



Fading

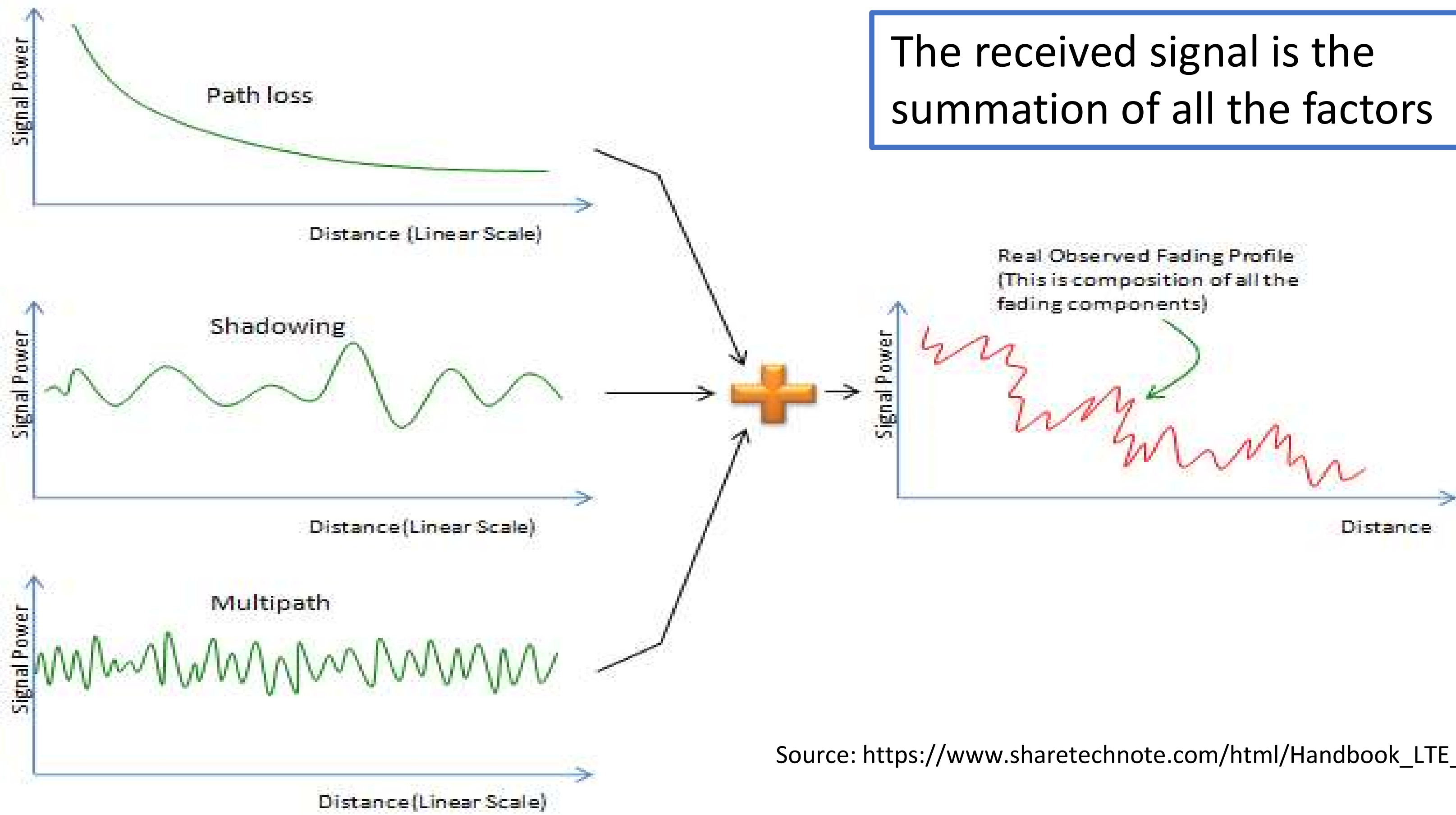


- A signal out of a transmitter radiates into wide direction
- These radiated signals take different paths and arrive at the receiver at different timing and with different signal strength(amplitude)
- The signal coming into the receiver is the composite of all the components that may add destructively or constructively
  - This is determined by the phase of the arriving copies of the signal
- In most case, the quality of the combined signal at the receiver gets deteriorated.

Fading = Deterioration of the signal quality

Fading components

The received signal is the summation of all the factors

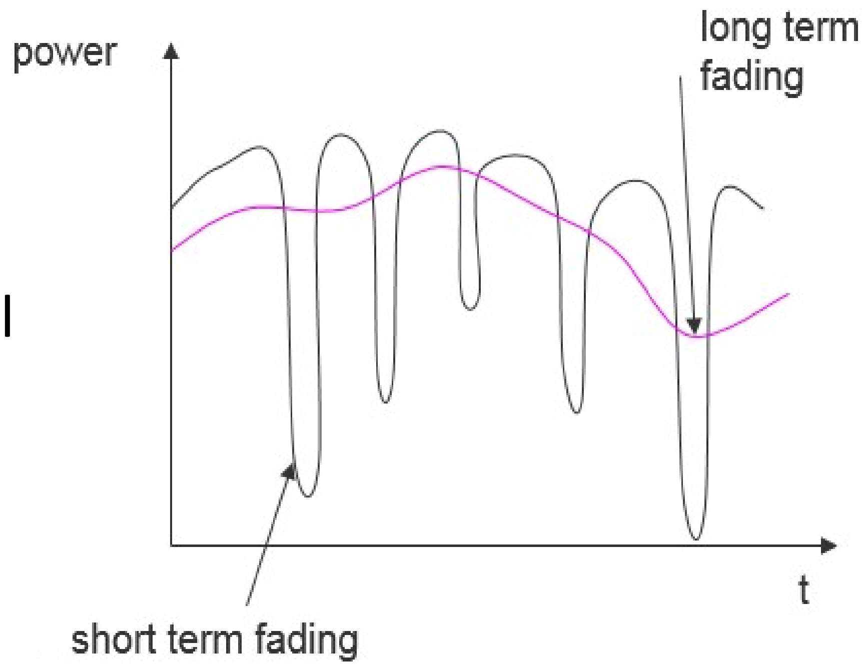


Source: https://www.sharetechnote.com/html/Handbook_LTE_Fading.html

- Path Loss
- Fluctuation of the received signal power
- Reflection and diffractions from various object
- Received power variation created by multipath
- …

Fast Fading vs. Slow Fading

- Rapid fluctuations of signal caused by movement (Doppler Spread)
- Time-domain



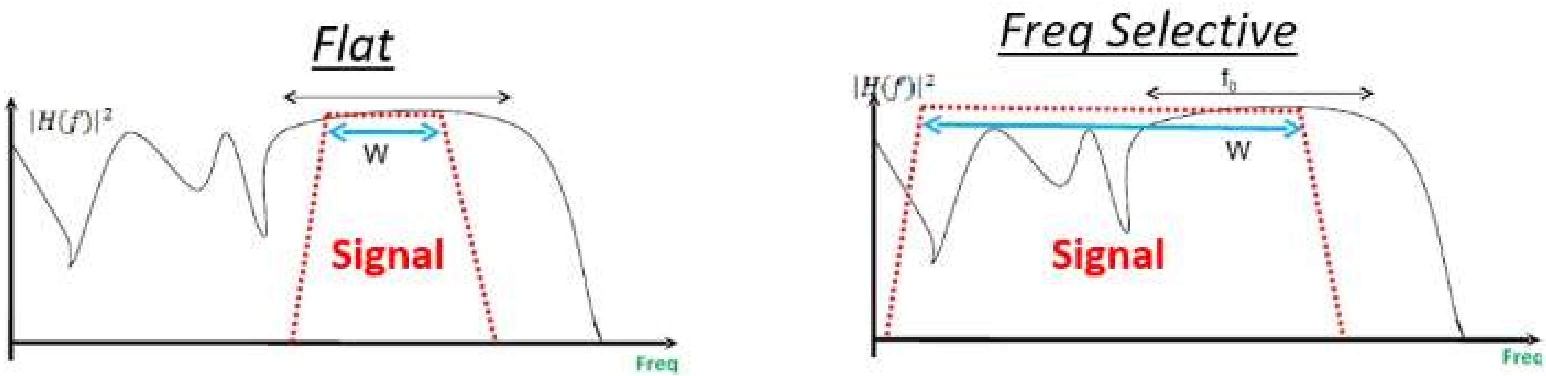
- Coherence time T_c = How long a channel remains relatively constant
- If Coherence time T_c >> bit time T_b, the channel does not change during the bit time →slow fading / long term fading
- Otherwise fast fading / short term fading

> - Slow fading: Rate of change of the channel characteristics is **much smaller** than the rate of change of the transmitted signal
> - Fast fading: Rate of change of the channel characteristics is **larger** than the rate of change of the transmitted signal

Example

- Suppose that a pedestrian is moving through an urban environment that has a wireless channel with a coherence time of 70 ms. The bit rate of the signal is 100 kbps. Do we have a fast fading or slow fading?

Flat Fading vs. Frequency-Selective Fading



- **Frequency** domain
- Caused by multipath (Multiple signals arrive at the receiver)
- Coherence bandwidth B_c: Bandwidth over which the channel response remains relatively constant
  - Related to delay spread, the spread in time of the arrivals of multipath signals
- Signal bandwidth B_s - If $B_c >> B_s$ → flat fading
  - The signal bandwidth fits well within the channel bandwidth
- Otherwise, frequency-selective fading

Flat Fading: Occurs when the signal's bandwidth is narrow enough that all frequencies experience roughly the same channel, i.e., the fading affect all frequencies
Frequency-selective fading: The fading occurs at certain frequencies only

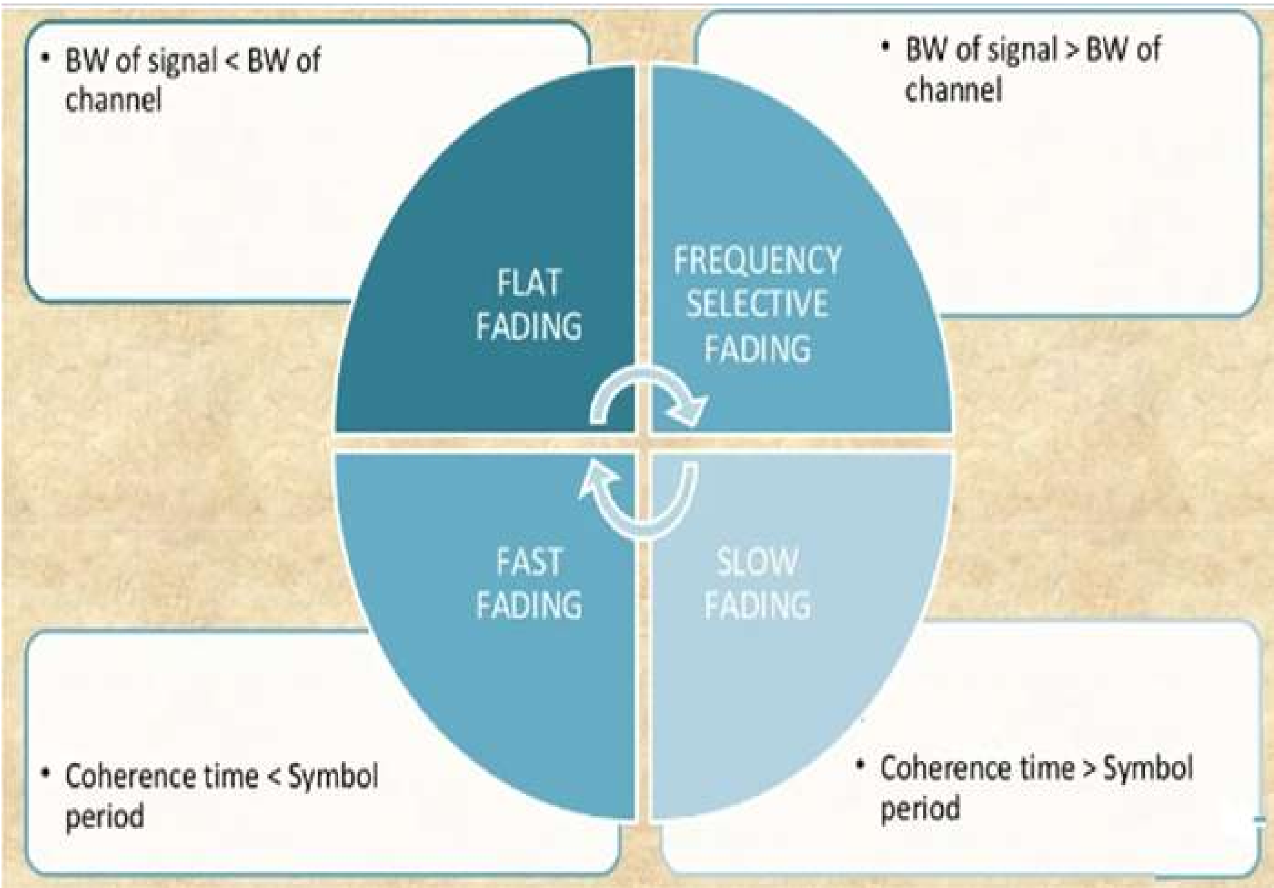
Example

- B_c = 150 kHz, bit rate r_b = 100 kbs
- Assume signal bandwidth B_s= 100 kHz

Do we have a flat fading scenario? (Use a factor of 10 for “>>”)

Fading - Summary

Fast Fading: occurs mainly due to reflections on surfaces and movement of transmitter or receiver
Slow Fading: occurs mainly due to shadowing where large buildings or geographical structures obstruct the LOS.



- Fast fading is very difficult to adpat to, maybe some form of **FEC** or adopt different **modulation schemes** to recover our data
- Slow fading: we can adapt our **transmit power** based on feedback from the BS
- Frequency-selective fading can be overcome by techniques such as OFDM which **spreads the data across the frequency components** of the signal to reduce data loss

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Modulation

- Digital signals cannot be directly transmitted in the radio medium

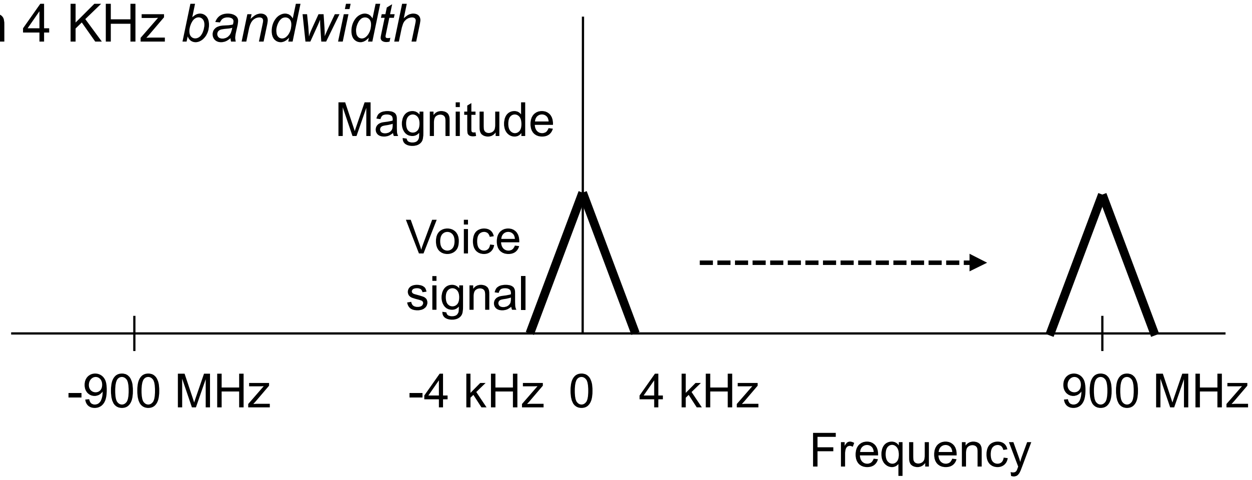
- Digital modulation: translate digital signals into (baseband) analog signals – Also known as shift keying
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)
  - Quadrature Amplitude Modulation (QAM)

- Analog modulation: shift the analog signals into passband signals

Why do we need modulation?

1. To generate a modulated signal suited and compatible to the characteristics of the transmission channel

Given an *information signal*
Example: Voice signal with 4 KHz *bandwidth*



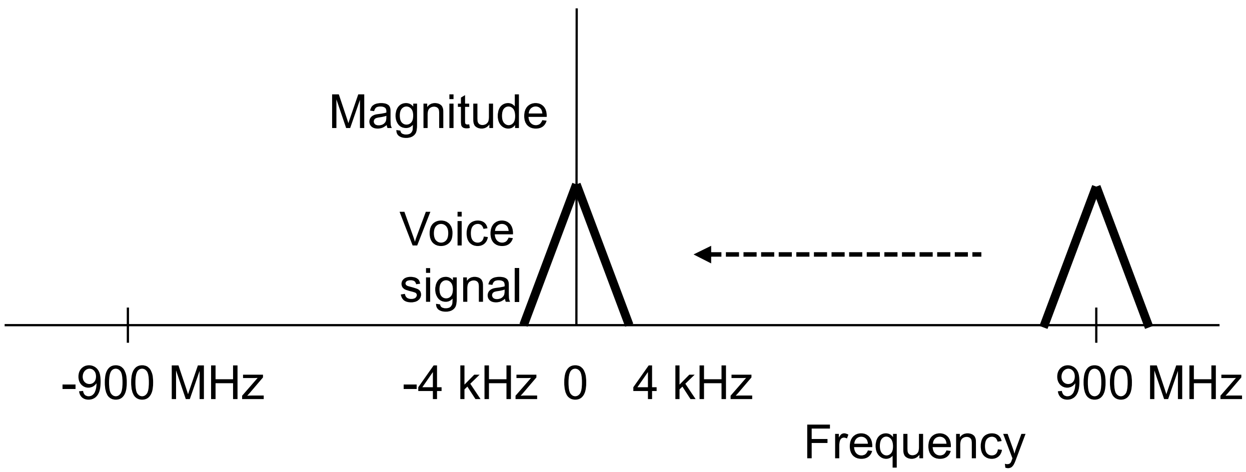
Shift information signal to the *carrier frequency*
Example: 900 MHz carrier frequency

→ Information signal *modulates* (changes) the carrier signal

2. Reduction of antenna size
   - Since the size of the antenna is proportional to wavelength, we want to move the information signal to a higher frequency for smaller devices

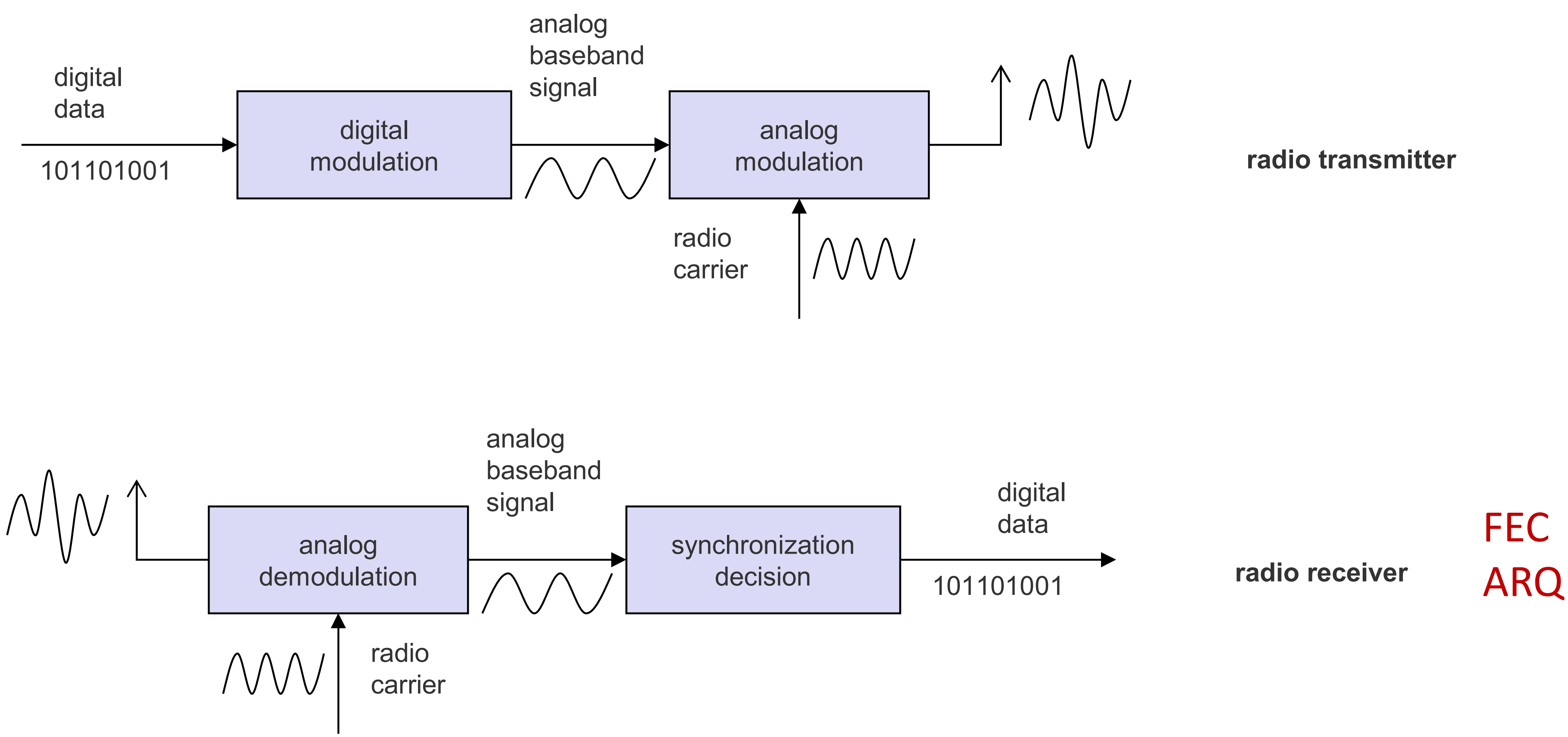
Demodulation

Given a transmitted signal,
Example: Voice signal centered at 900 MHz



Recover the original signal from the transmission.
Example: 4 KHz bandwidth voice signal centered at 0 Hz

Modulation and Demodulation

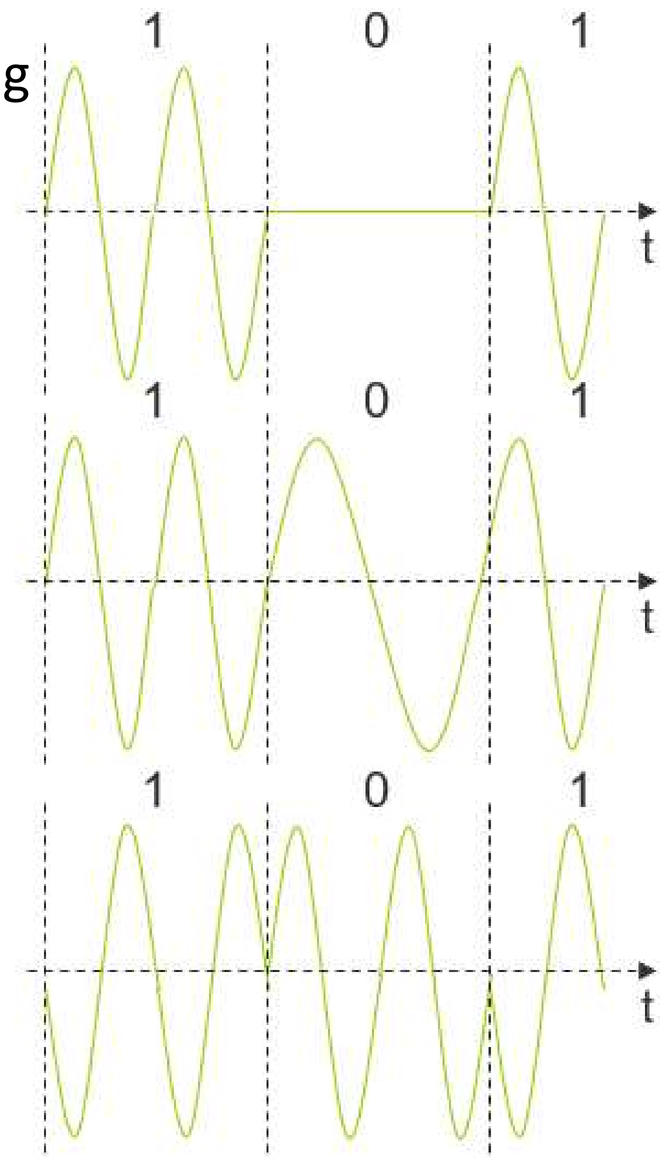


Modulation is the superposition of a low-frequency signal on a high-frequency carrier wave i.e. the baseband signal is translated (shifted) from low frequency to high frequency.

Digital Modulation

Modulation of digital signals is known as Shift Keying

- Amplitude Shift Keying (ASK):
  - One binary digit represented by presence of carrier, at constant amplitude, other binary digit represented by absence of carrier
  - Easy to implement, low bandwidth requirement
- Frequency Shift Keying (FSK):
  - Information data controls the frequency of the carrier
  - Needs larger bandwidth
- Phase Shift Keying (PSK):
  - Information data controls the phase of the carrier
  - More complex

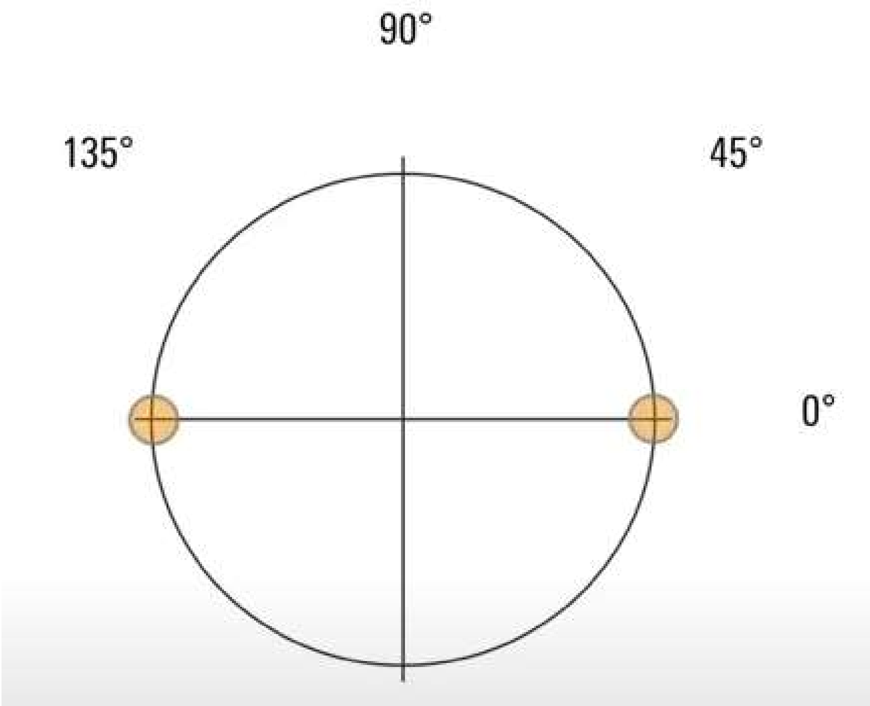


Binary Phase Shift Keying (BPSK)

- Most basic form of PSK
- Each symbol represents 1 bit

- Modulation that uses phase changes is represented by constellation diagram – Phase is shown as angle and amplitude as distance from the origin

- Since in PSK the amplitude is constant, all points lie on one circle



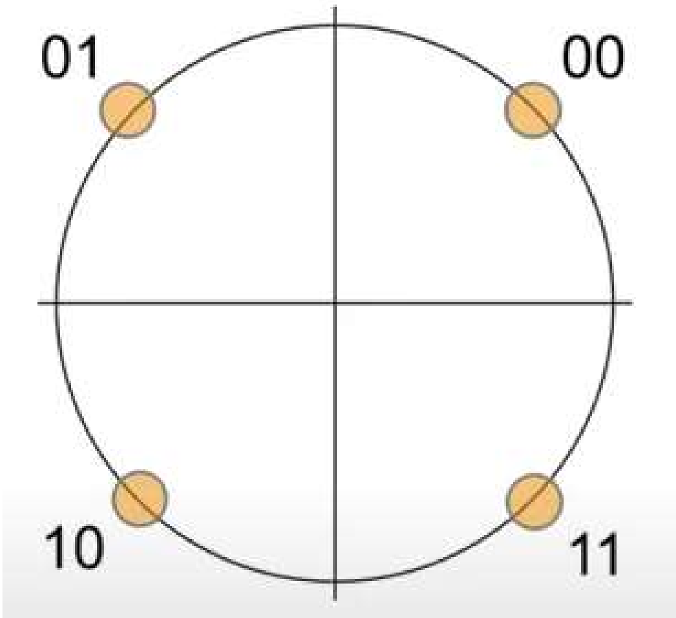
BPSK

The relationship between the number of available symbols, *M*, and the number of bits that can be represented by a symbol, *n*, is: $M = 2^n$

Quadrature Phase Shift Keying (QPSK)

- Each symbol represents two bits
- 4 phase shifts are used

$$\begin{cases} \phi_{0,0} = 0 \\ \phi_{0,1} = \pi/2 \\ \phi_{1,0} = \pi \\ \phi_{1,1} = 3\pi/2 \end{cases} \quad \text{or} \quad \begin{cases} \phi_{0,0} = \pi/4 \\ \phi_{0,1} = 3\pi/4 \\ \phi_{1,0} = -3\pi/4 \\ \phi_{1,1} = -\pi/4 \end{cases}$$



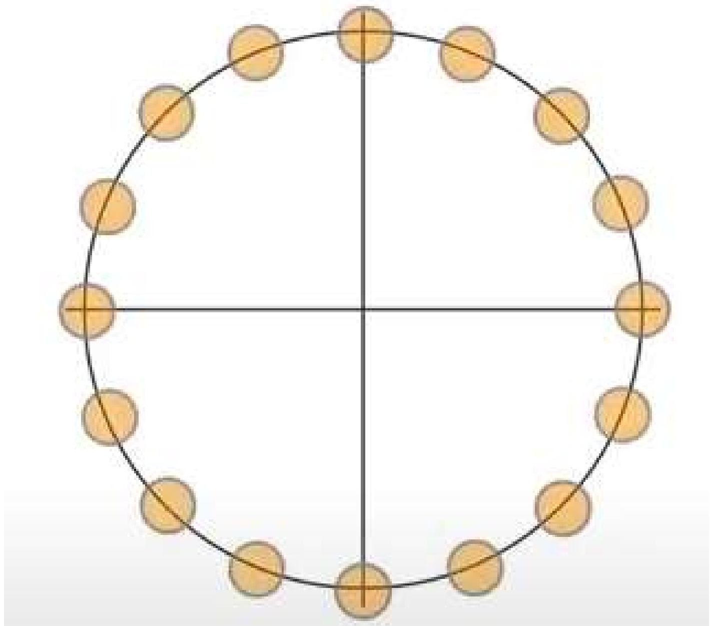
QPSK

Increasing the number of bits a symbol can represent, means that higher data rates can be achieved

Higher Order PSK

- We can keep increasing the number of states
- Ex. 8PSK has 8 possible states
  - 8 states means each symbol contains consists of 3 bits (2^3)
- Higher order PSK (16PSK, ..) is possible but less common

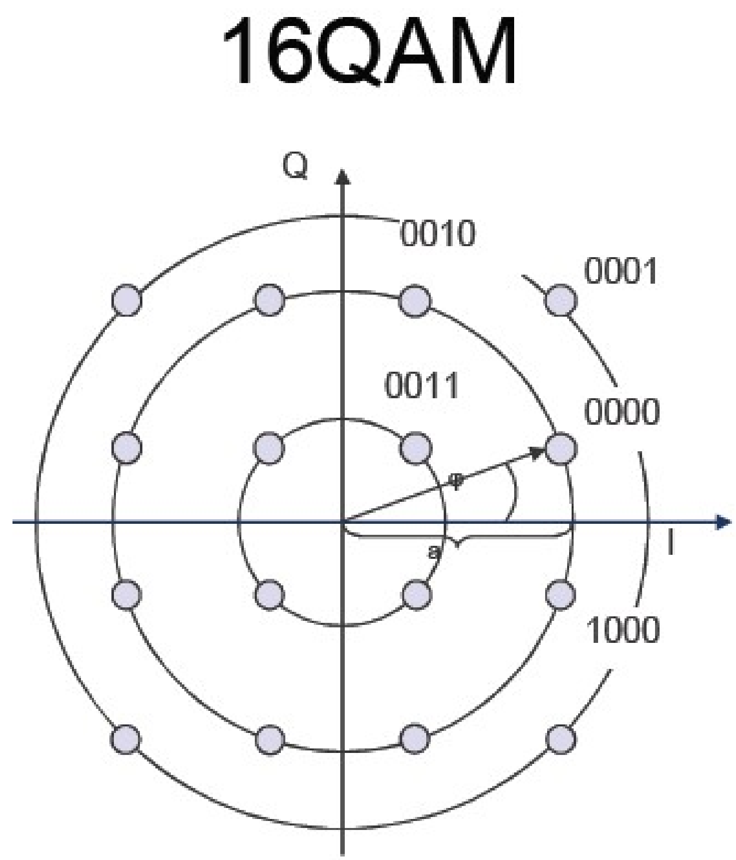
- If higher data rates are needed, more complex modulation (ex. QAM) is used



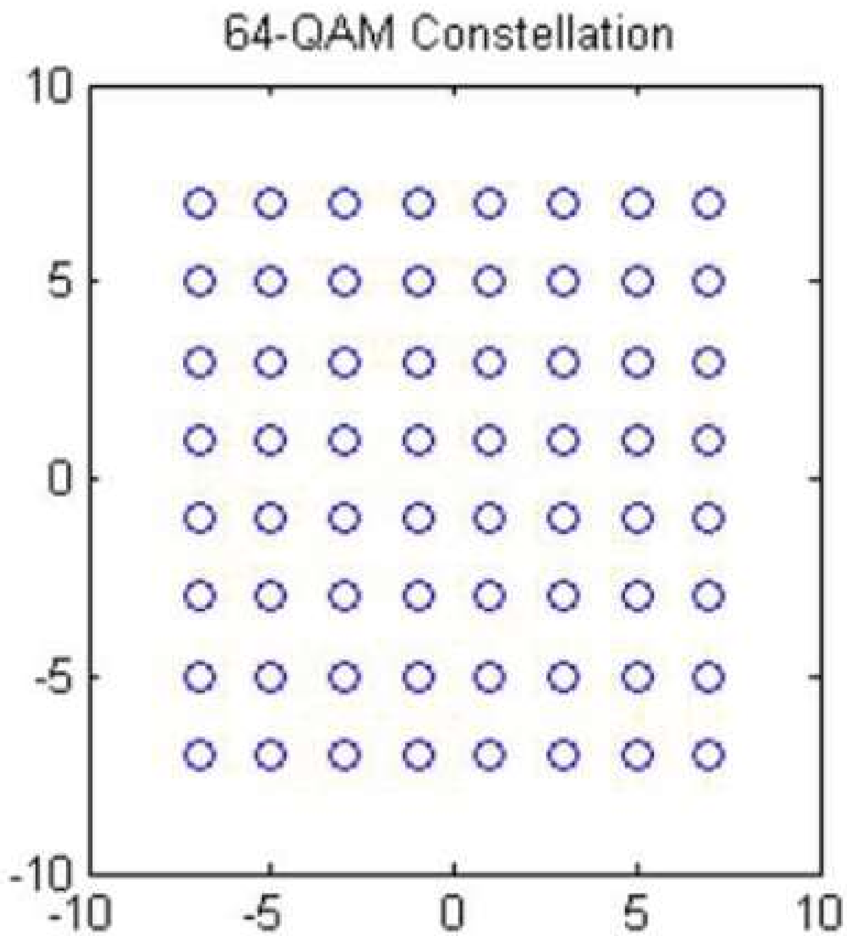
16PSK

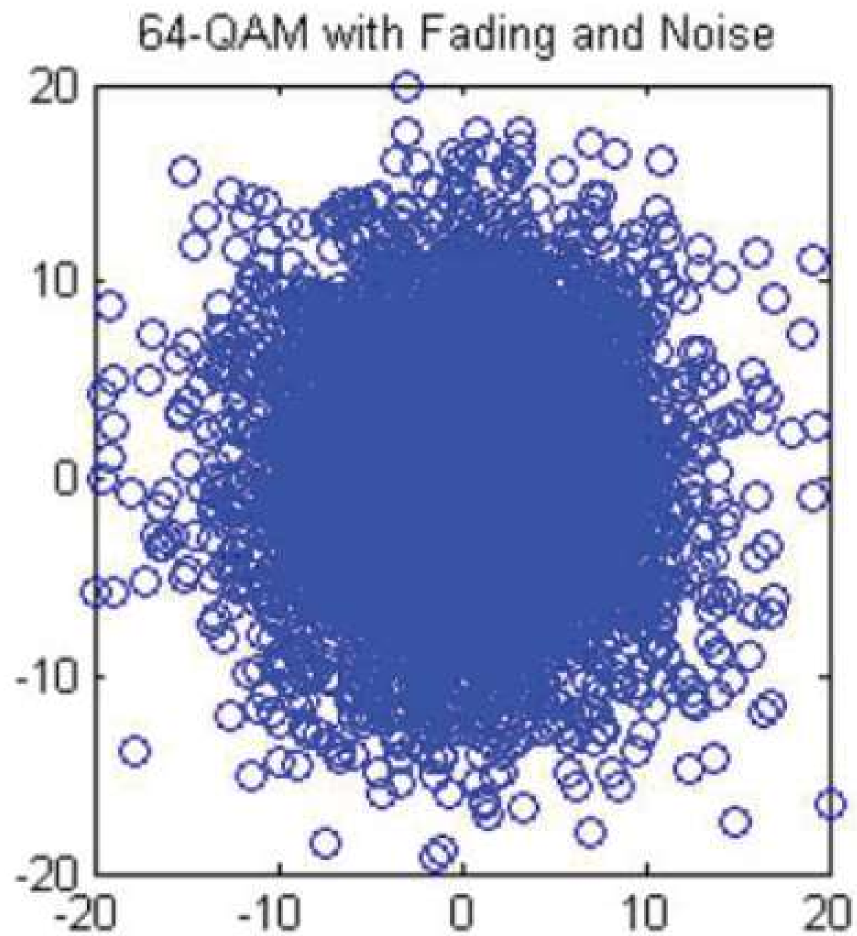
Quadrature Amplitude Modulation (QAM)

- Combines amplitude and phase modulation
- Example: 16-QAM (4 bits = 1 symbol)
  - $16 = 2^4$, $n = 4$
  - Symbols 0011 and 0001 have the same phase ϕ, but different amplitude a.
  - Symbols 0000 and 1000 have different phase, but same amplitude
- Bit error rate increases with *n*



QAM - Demodulation challenge





Which Modulation to Choose?

- Moving from BPSK → 64QAM, we increase the data rate
  - Works for users that are close to the sender
- However, if we are in a noisy environment, the demodulation becomes very difficult
  - Need to go back to lower QAM and then QPSK and BPSK
  - If BPSK problem, then there is no coverage