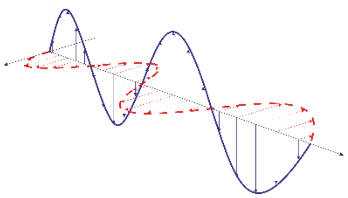
Właściwości fali elektrmagnetycznej Properities of electromagnetic waves

dr inż. Stefan Jankowski
s.jankowski@am.szczecin.pl

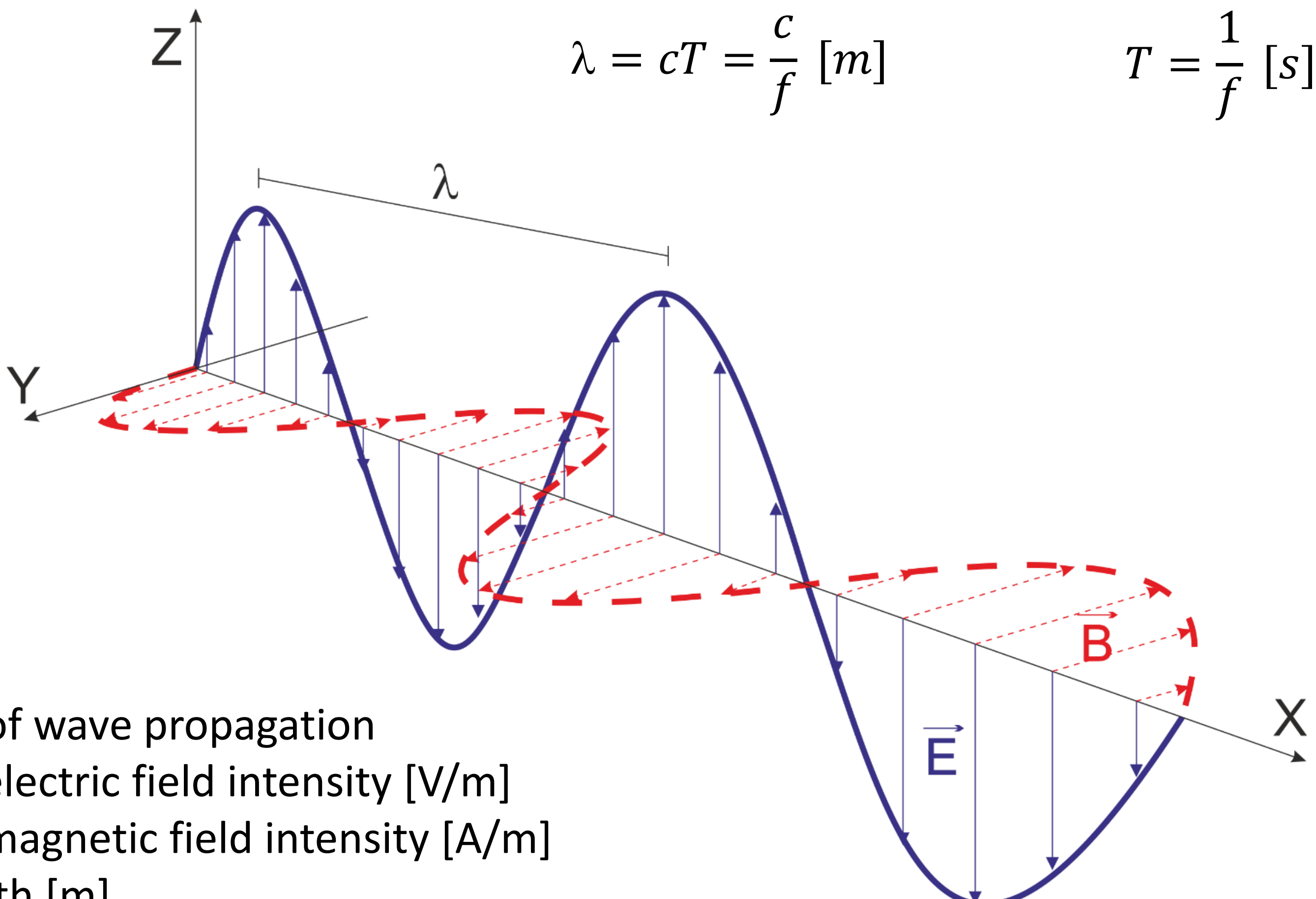
Elecromagnetic radiation

- the flow of energy at the universal speed of light through free space or through a material medium in the form of the electric and magnetic fields that make up electromagnetic waves such as radio waves, visible light and gamma rays
- In such a wave, time-varying electric and magnetic fields are mutually linked with each other at right angles and perpendicular to the direction of motion.
- The electromagnetic wave is characterized by the density of power and the frequency of changes in time of electric and magnetic fields
- The movement in which the periodic phenomenon moves in space is called the wave motion



The EM wave

$$\lambda = cT = \frac{c}{f}\ [m] \qquad T = \frac{1}{f}\ [s]$$



X – direction of wave propagation
Z – vector of electric field intensity [V/m]
Y – vector of magnetic field intensity [A/m]
λ – wave length [m]
T – period; time of full cycle [s]
f – frequency; number of full cycles of wave in unit of time [1/s = Hz]
c – light speed 299 762 458 [m/s] ≈ $3 \cdot 10^8$ [m/s]

The phase

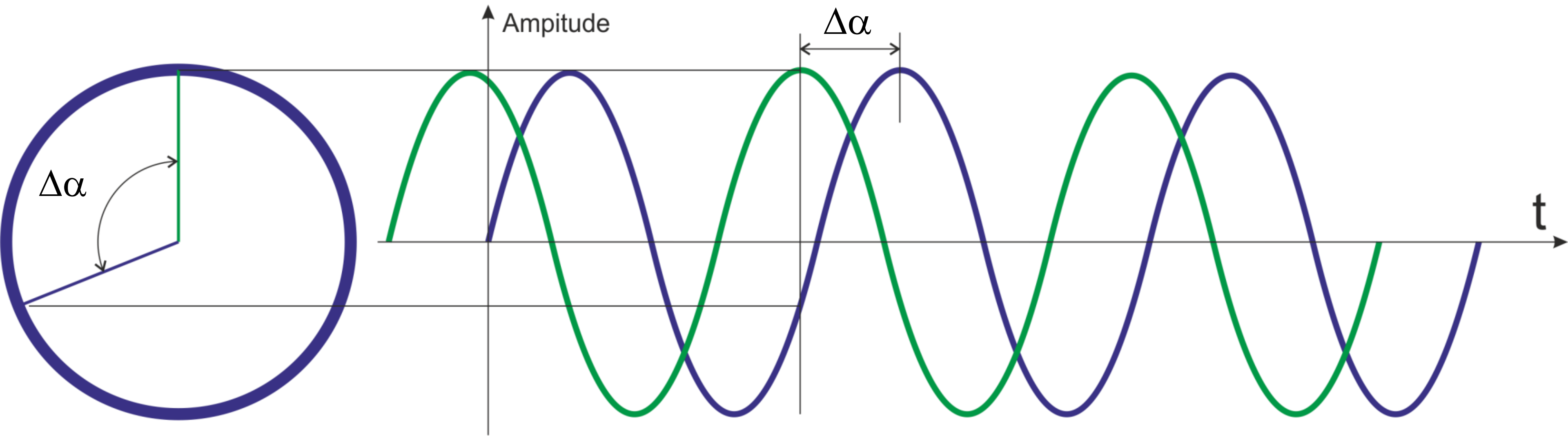
Periodic changings of the of electromagnetic wave (amplitude of a vector e) can be described by rotational speed ω, which depend on its frequency **f**:

$$\omega = 2\pi f$$

A momentary phase angle α is given by time as follow:

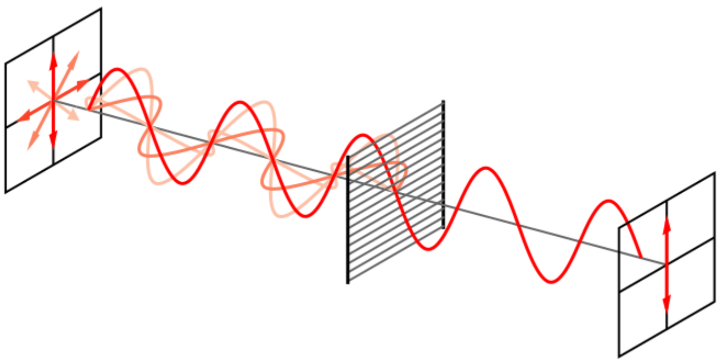
$$\alpha = \omega t = 2\pi f t$$

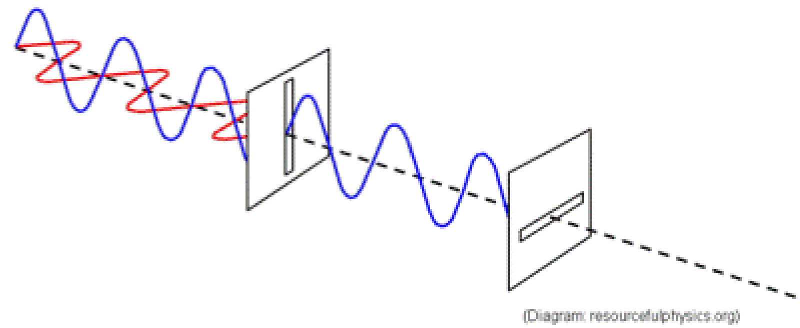
Phase difference



Difference of momentary values of the phase angle between two periodic oscillations (wave motions)

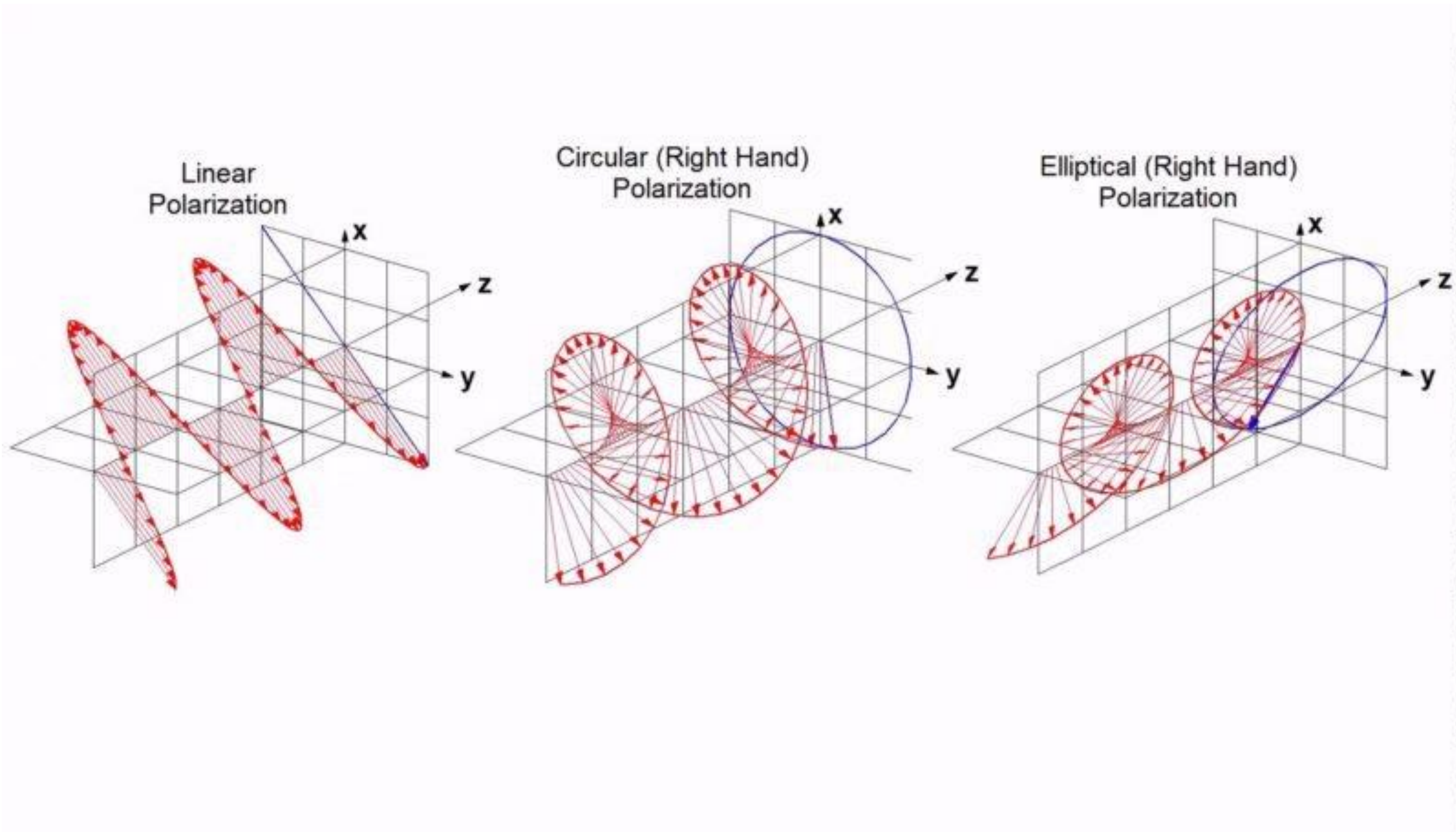
Polarization





- The electromagnetic waves may be described by transverse waves of E and B (at right angles to each other). However, there is nothing special about any particular direction for the E or B vectors to oscillate.
- In fact an unpolarized wave contains waves with E vectors in all possible directions (for each E wave there is a B wave at right angles).
- In a polarized wave the E vector oscillates in a specific direction - the direction of polarization.

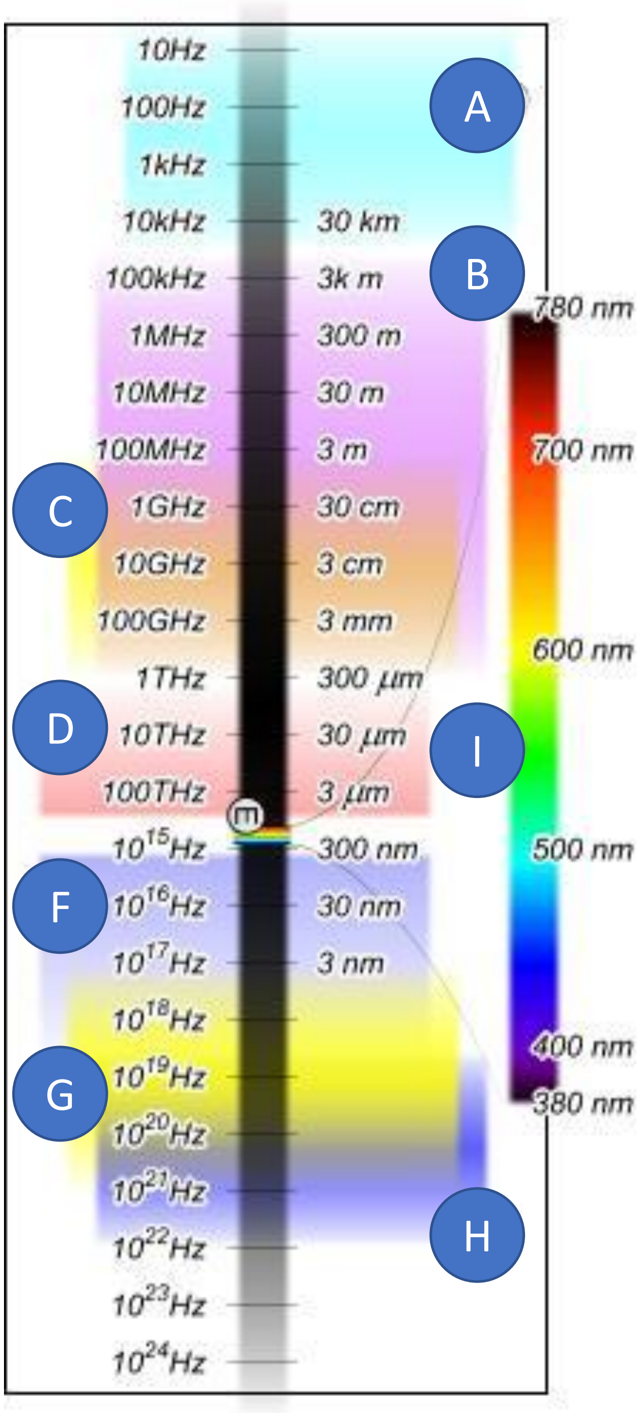
Different type of polarization



Frequency spectrum

A – ELF, SLF, ULF, VLF
B – radio waves
C – microwaves
D – infrared
E – visible light
F – ultraviolet
G – X rays
H – Gamma rays

I – spectrum of visible lights



Radio frequency

Frequency	Wavelength	Designation	Abbreviation[6]	IEEE bands[7]
3–30 Hz	10^5–10^4 km	Extremely low frequency	ELF	-
30–300 Hz	10^4–10^3 km	Super low frequency	SLF	-
300–3000 Hz	10^3–100 km	Ultra low frequency	ULF	-
3–30 kHz	100–10 km	Very low frequency	VLF	-
30–300 kHz	10–1 km	Low frequency	LF	-
300 kHz – 3 MHz	1 km – 100 m	Medium frequency	MF	-
3–30 MHz	100–10 m	High frequency	HF	HF
30–300 MHz	10–1 m	Very high frequency	VHF	VHF
300 MHz – 3 GHz	1 m – 10 cm	Ultra high frequency	UHF	UHF, L, S
3–30 GHz	10–1 cm	Super high frequency	SHF	S, C, X, Ku, K, Ka
30–300 GHz	1 cm – 1 mm	Extremely high frequency	EHF	Ka, V, W, mm
300 GHz – 3 THz	1 mm – 0.1 mm	Tremendously high frequency	THF	-

The spectrum of frequencies divided into bands with conventional names designated by the International Telecommunications Union (ITU)

Propagation of radio waves

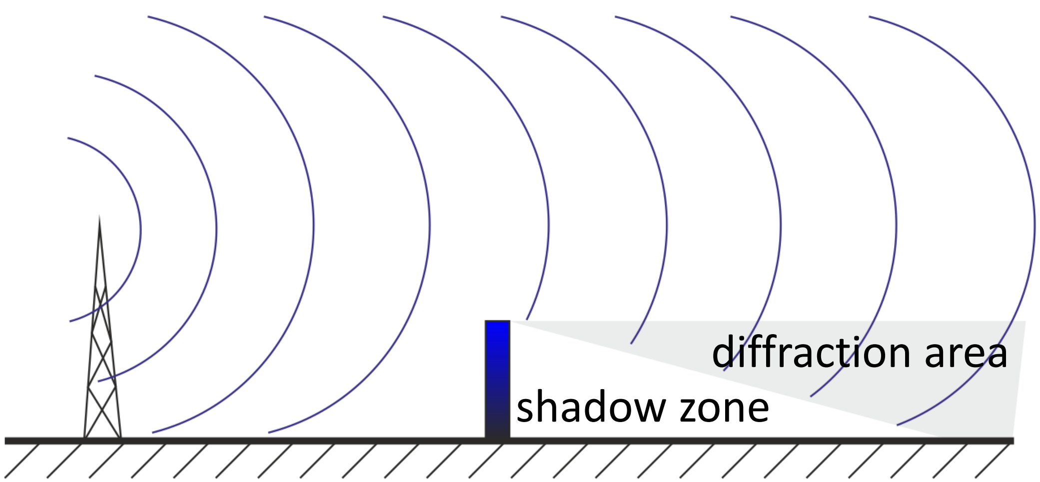
Only in the vacuum electromagnetic waves can propagate straight and indefinitely with the constant light speed **c**.

In any other medium they encounter following phenomena:

- Diffraction - bending of waves over the surface of the Earth or on an obstacles
- Refraction - on the bound of two mediums
- Continuous refraction - bending of waves in the troposphere
- Absorbing the waves in the atmosphere

Diffraction

- It arises when waves encounter an obstacle
- The larger bend if the dimensions of the obstacle are the smaller in relation to the wavelength
- The intensity of the electric field in the diffraction area, directly behind the obstacle, is weaker than before the obstacle and decreases with increasing frequency.
- Long waves – practically no obstacles on the Earth (mountains)
- Ultra-short waves – there are shadow zones behind obstacles



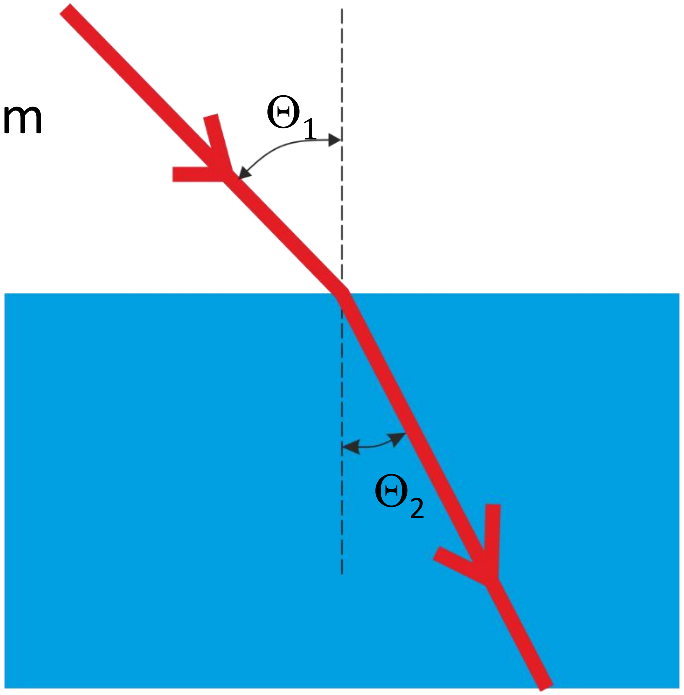
Refraction

- Occurs on the border of two mediums (various electrical permittivity parameters).
- The most frequent is: deflection, reflection, dissipation
- The refractive index is equal to:

$$n = \frac{c}{v}$$

Where:

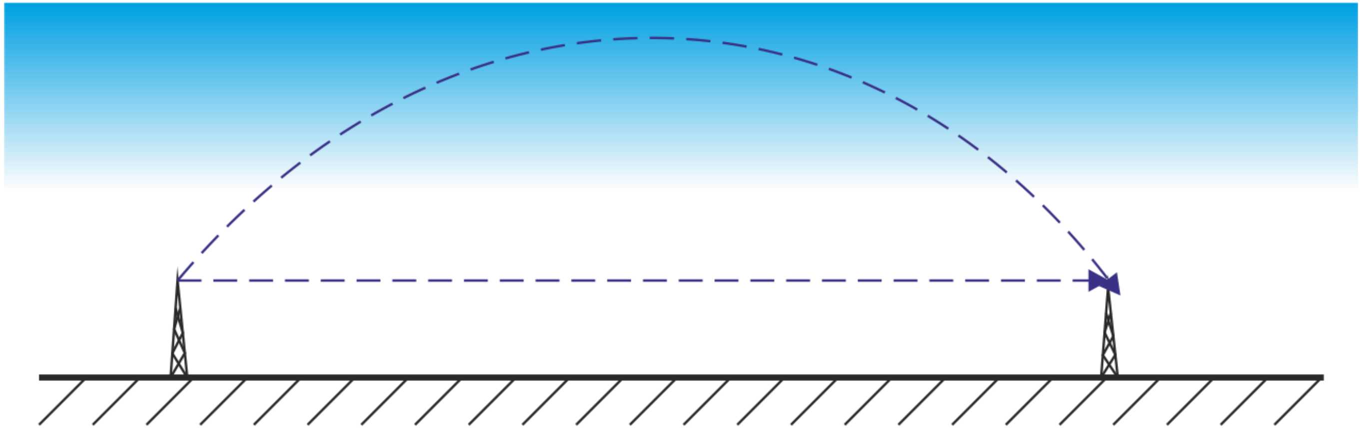
v – speed of electromagnetic waves in the medium



$$\frac{sin\Theta_1}{sin\Theta_2} = \frac{n_1}{n_2} = \frac{v_1}{v_2}$$

Continuous refraction

- The continuous changing of electrical permeability in a given medium causes the deflection and bending of the wave.
- The inhomogeneous structure of the medium favors the absorption of energy of the wave and its dissipation.
- Radio waves from different sources may cause interference



Absorption

- absorption of electromagnetic radiation is the way in which the energy of a photon is taken up by matter, typically the electrons of an atom
- Thus, the electromagnetic energy is transformed into internal energy of the absorber, for example thermal energy

Mediums

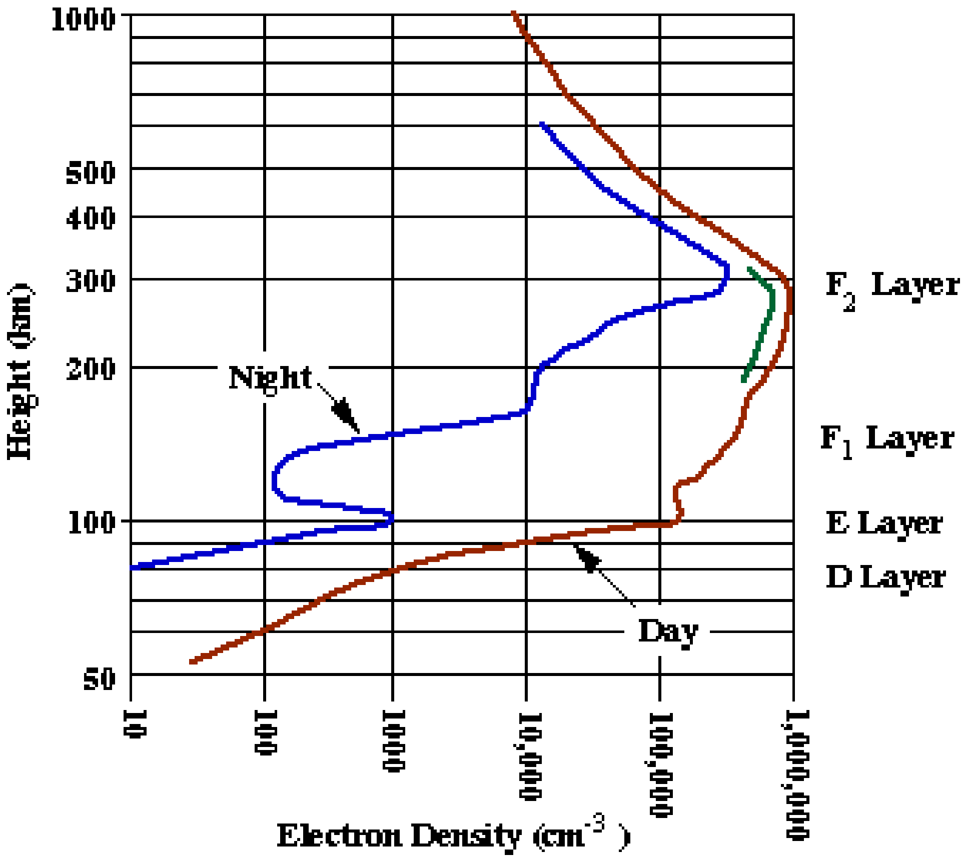
- Vacuum
  - in free space, all electromagnetic waves obey the inverse-square law which states that the power density of an electromagnetic wave is proportional to the inverse of the square of the distance from a point source
- Ground of the Earth and Sea surface
  - The medium is electrically heterogeneous
  - Changes with depth and place
  - Unevenness of the area causes loss of energy
  - The effect is a gradual attenuation of the electromagnetic wave

Mediums

- Troposphere
  - the lowest layer of atmosphere, from 0 to 10 km close to pole areas and 0 to 20 km at equator area
  - the temperature decreases with increasing height
  - variable meteorological conditions cause: refraction, dispersion and absorption
  - big influence on ultra-short waves
- Stratosphere
  - between troposphere and ionosphere
  - neutral for radio waves

Mediums

- Ionosphere
  - Upper atmosphere 60 to 1000 km,
  - divided into layers according to a number of free electrons (TEC – total electron content)



Example of ionosphere configuration at middle latitudes

Mediums

- Ionosphere
  - Ionization - the phenomenon of separation of valence electrons from atoms or molecules leading to the formation of positive ions and free electrons
  - Ionization takes place under the influence of ultraviolet , corpuscular solar and cosmic radiation
  - According to the concentration of electrons, in the ionosphere can be distinguished several layers:
    - D - the nearest to the surface of the Earth approx. 90 km, in the daytime it shows fluctuations in terms of height and concentration of electrons, disappears at nighttime
    - E - 90 to 140 km - depends on altitude, latitude and seasonal changes.
    - F – 140 to 450 km
      - F1 – 140 to 250 km, above 250 km only F2,
      - F2 remains at nighttime

Modes of propagation

- Ground waves
  - Propagation in close to the area Earth.
  - ground waves spread along the spherical surface of the Earth due to diffraction
  - used in systems working on long waves
  - a transmitting antenna with vertical polarization is located directly above the surface of the Earth.

  - short waves - range mostly limited to the horizon
    - greater range caused by diffraction on earth surface and refraction in troposphere
    - In case of ultra-shortwaves and microwaves occur refraction, super refraction and interference

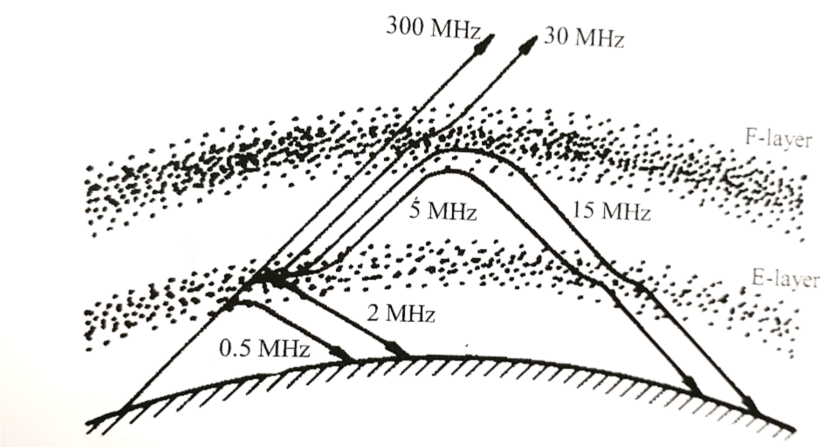
Modes of propagation

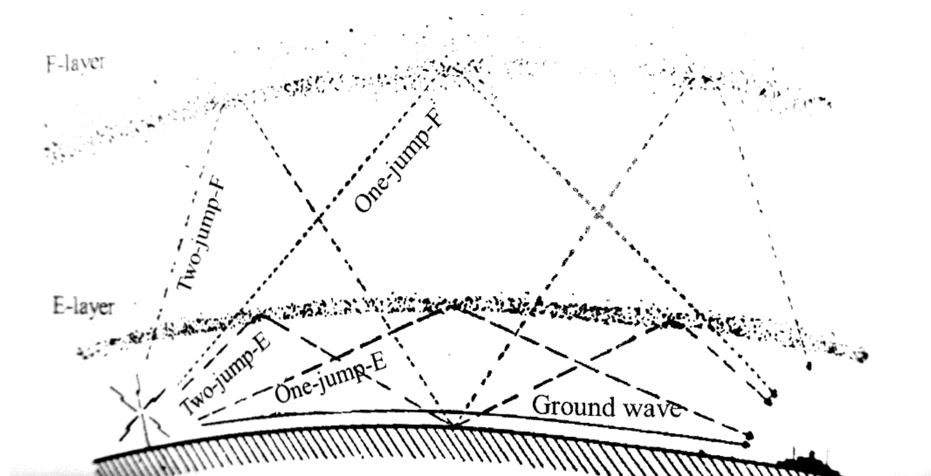
- Skywaves - troposphere
  - propagation through ducts or dispersion on the troposphere inhomogeneities
  - Range often exceeds the distance of the radio horizon.
  - Ultrashort waves and microwaves are spreading over long distances with small damping

Duct - a waveguide channel in the troposphere, created in a favorable system of atmospheric layers and atmospheric pressure

Modes of propagation

- Skywaves – ionosphere
  - Propagation is due to ionospheric refraction
  - Propagation depends on the route, time of day, year, and solar activity
  - Multiple reflections from the ionosphere and the surface of the Earth allow propagation to very long distances, global range.
  - Propagation depends on the frequency: critical – the highest, at which the EM waves are able to reflect off the ionosphere and the lowest at which absorption still allows to establish communication
  - The boundary frequencies are in the short wave range
    - MUF – Maximal Usable Frequency
    - LUF – Lowest Usable Frequency

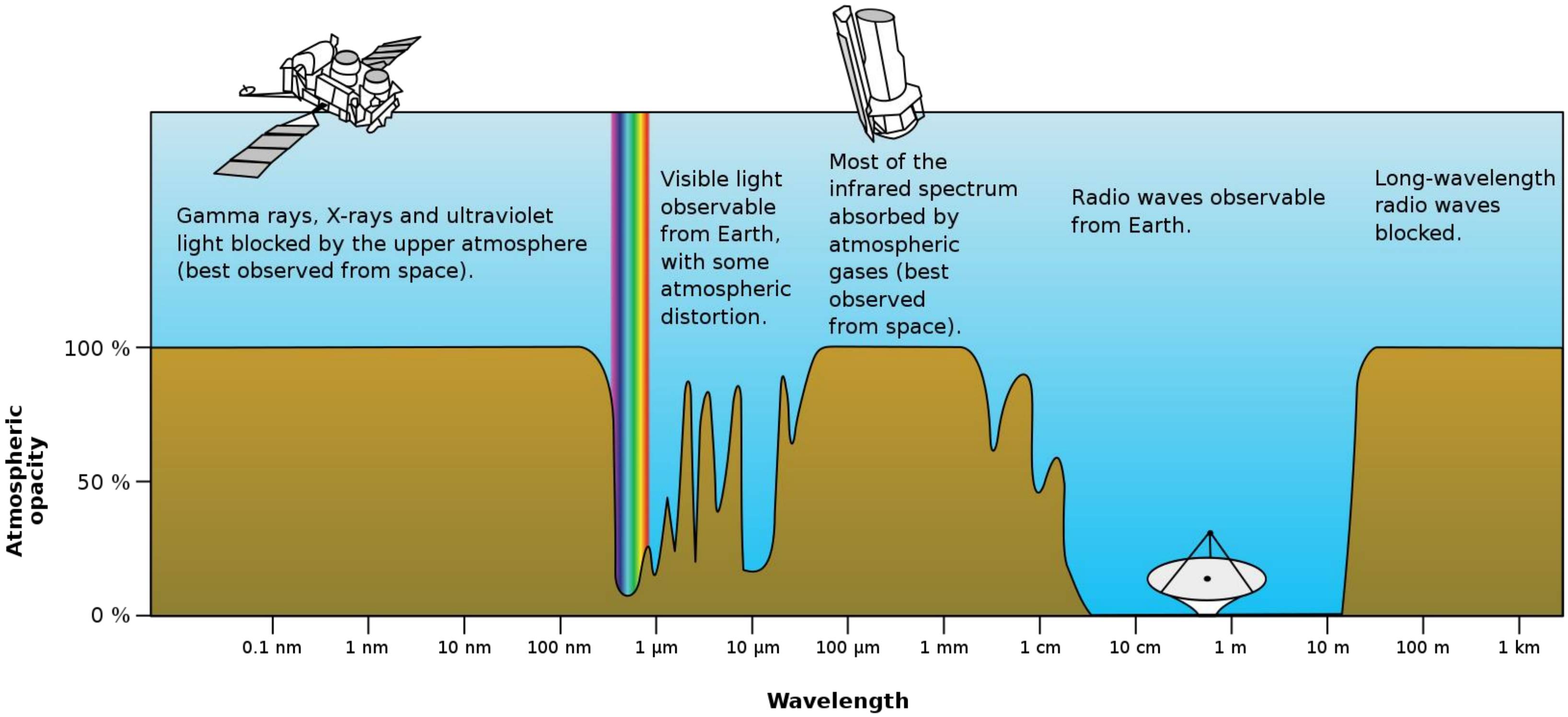




Modes of propagation

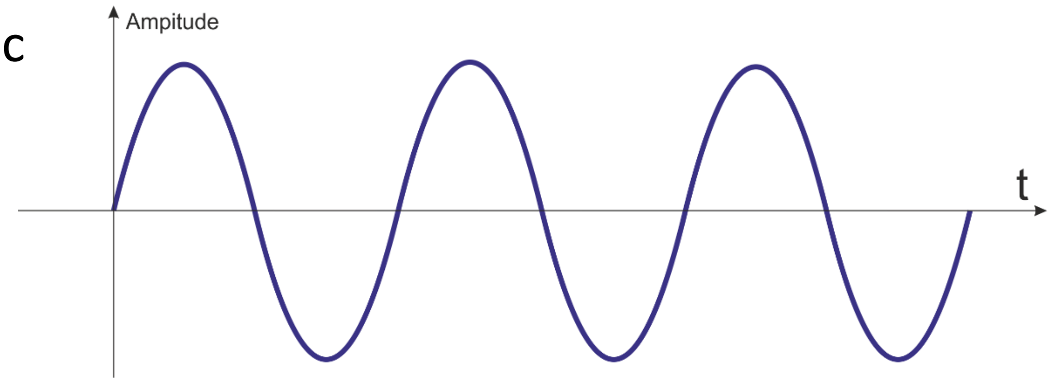
Band		Frequency	Wavelength	Propagation via
ELF	Extremely Low Frequency	3–30 Hz	100,000–10,000 km	Guided between the Earth and the D layer of the ionosphere.
SLF	Super Low Frequency	30–300 Hz	10,000–1,000 km	Guided between the Earth and the ionosphere.
ULF	Ultra Low Frequency	0.3–3 kHz (300–3,000 Hz)	1,000–100 km	Guided between the Earth and the ionosphere.
VLF	Very Low Frequency	3–30 kHz (3,000–30,000 Hz)	100–10 km	Guided between the Earth and the ionosphere.
LF	Low Frequency	30–300 kHz (30,000–300,000 Hz)	10–1 km	Guided between the Earth and the ionosphere. Ground waves.
MF	Medium Frequency	300–3000 kHz (300,000–3,000,000 Hz)	1000–100 m	Ground waves. E, F layer ionospheric refraction at night, when D layer absorption weakens.
HF	High Frequency (Short Wave)	3–30 MHz (3,000,000–30,000,000 Hz)	100–10 m	E layer ionospheric refraction. F1, F2 layer ionospheric refraction.
VHF	Very High Frequency	30–300 MHz (30,000,000–300,000,000 Hz)	10–1 m	Line-of-sight propagation. Infrequent E ionospheric (E_s) refraction. Uncommonly F2 layer ionospheric refraction during high sunspot activity up to 50 MHz and rarely to 80 MHz. Sometimes tropospheric ducting or meteor scatter
UHF	Ultra High Frequency	300–3000 MHz (300,000,000–3,000,000,000 Hz)	100–10 cm	Line-of-sight propagation. Sometimes tropospheric ducting.
SHF	Super High Frequency	3–30 GHz (3,000,000,000–30,000,000,000 Hz)	10–1 cm	Line-of-sight propagation. Sometimes rain scatter.
EHF	Extremely High Frequency	30–300 GHz (30,000,000,000–300,000,000,000 Hz)	10–1 mm	Line-of-sight propagation, limited by atmospheric absorption to a few kilometers
THF	Tremendously High frequency	0.3–3 THz (300,000,000,000–3,000,000,000,000 Hz)	1–0.1 mm	Line-of-sight propagation.

Modes of propagation

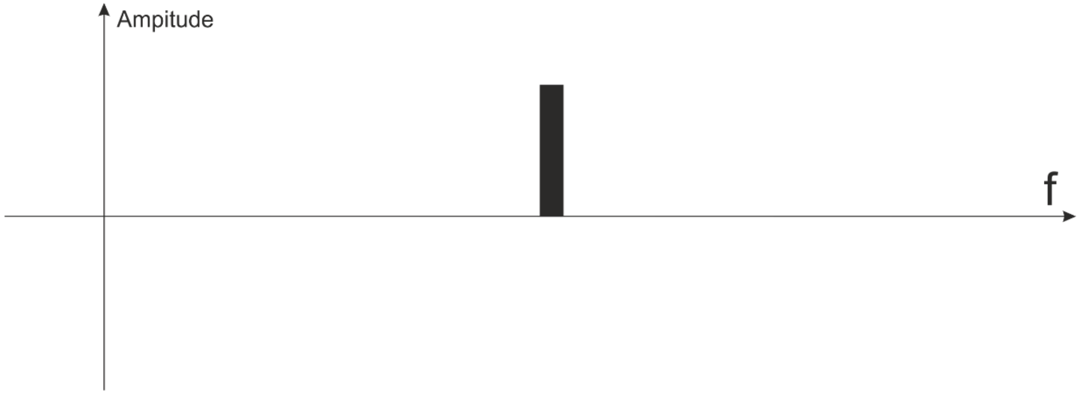


Radio signal domains

- Time domain – periodic oscillation in a time domain



- Frequency domain – obtained with the aid of FFT (Fast Fourier Transform) analysis



Bandwidth

- The concept which is used during transmitting and receiving of radio signals. On transmitter side determines the scope of frequency (spectrum), the signal occupies. On the receiver side determines the scope of frequency on which the receiver is sensitive when set at a given frequency
- The value of a bandwidth depends on a methods used for transmission and quantity of data which need to be sent in particular interval of time - a bits rate

Modulation

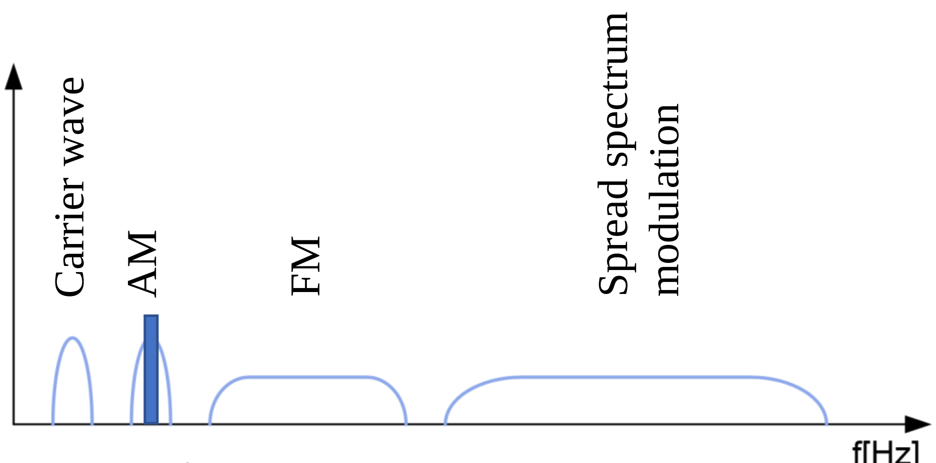
- modulation is the process of varying one or more properties of a periodic waveform, called the carrier signal, with a modulating signal that typically contains information to be transmitted. The most common modulation are frequency modulation FM, amplitude modulation AM and spread spectrum modulation
- the value of a bandwidth is directly related to the method of access to the radio channel and type of modulation.
- In order to transmit a data signal with bandwidth **B** [Hz, b/s], use the radio band with the width **P** [Hz]:

$$P = 2kB$$

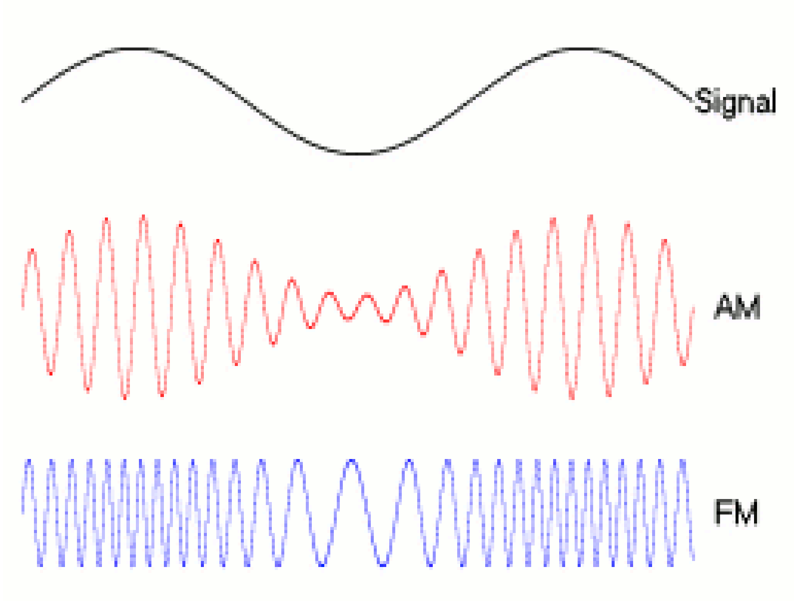
k - widening factor of bandwidth (dependent of a modulation type)

Amplitude modulation AM

- is a modulation technique used in electronic communication, most commonly for transmitting information via a radio carrier wave
- In amplitude modulation, the amplitude (signal strength) of the carrier wave is varied in proportion to that of the message signal being transmitted

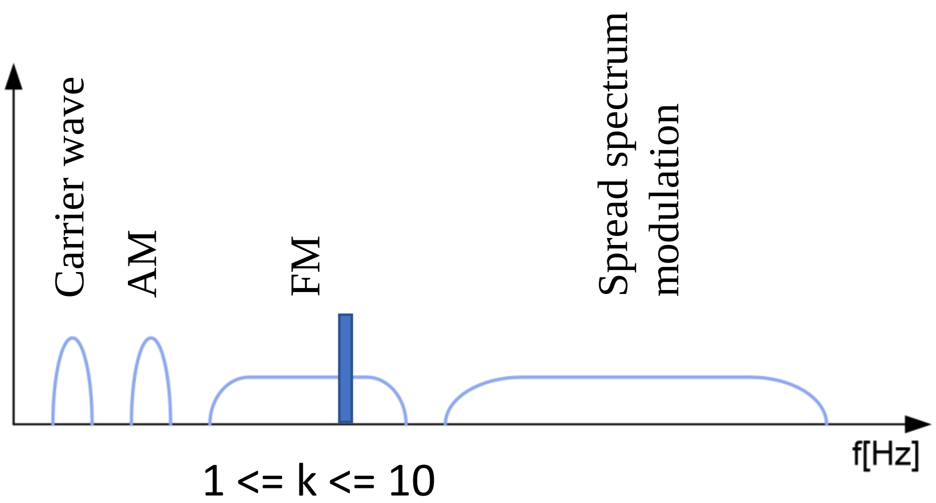


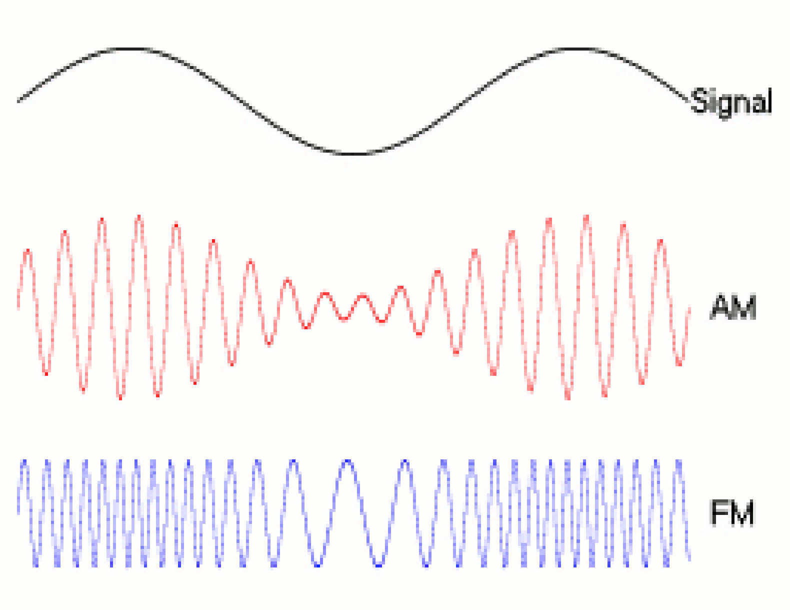
0.5 <= k <= 1



Frequency modulation FM

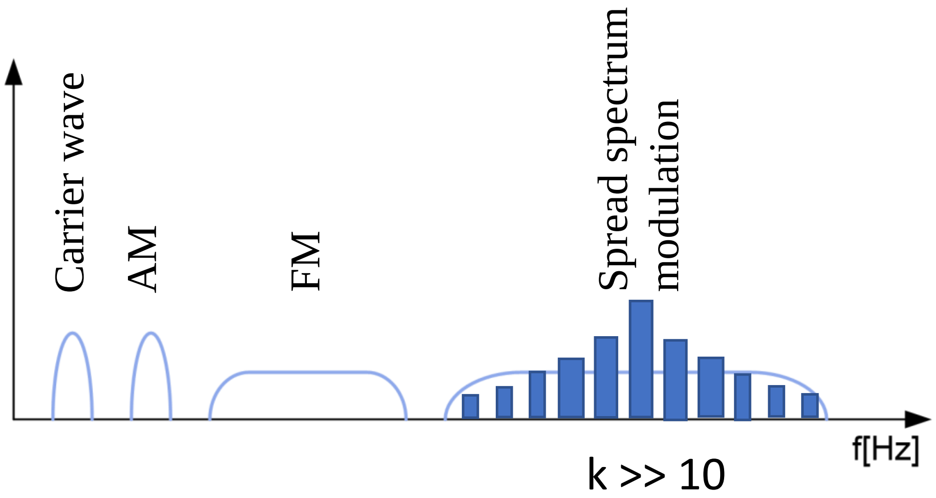
- is the encoding of information in a carrier wave by varying the instantaneous frequency of the wave

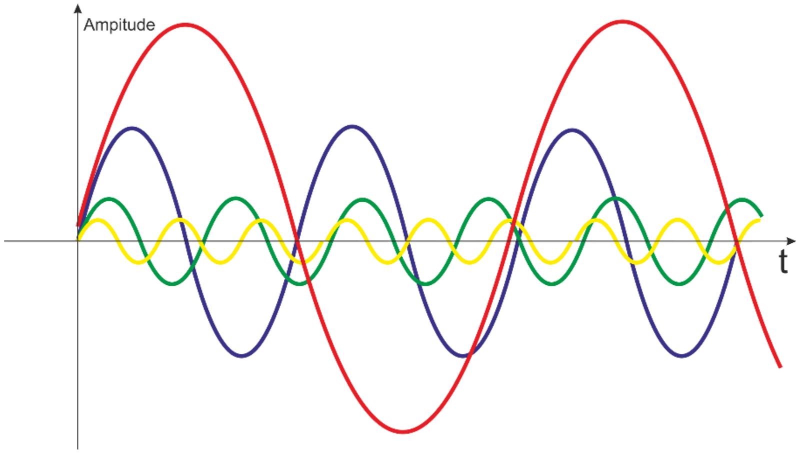




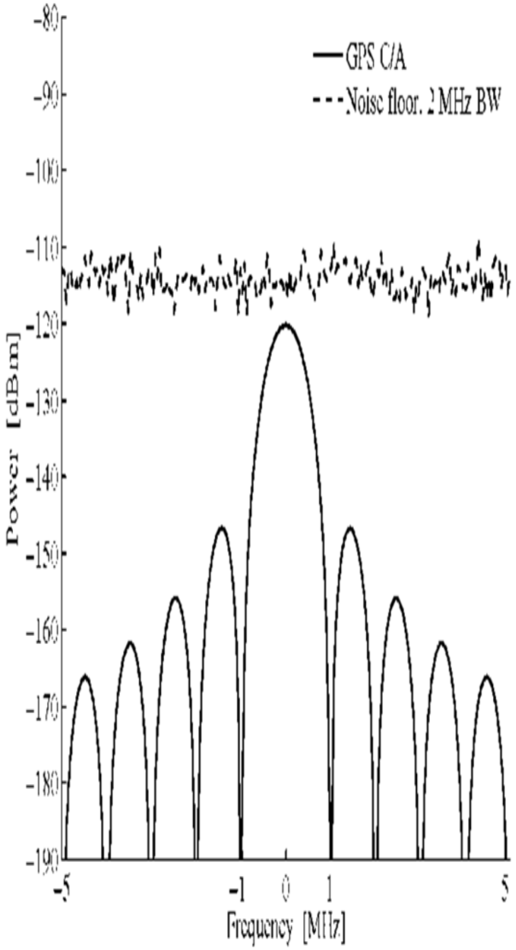
Spread spectrum modulation

- Is a method by which a signal generated with a particular bandwidth is deliberately spread in the frequency domain, resulting in a signal with a wider bandwidth.
- These techniques are used for a variety of reasons, including the establishment of secure communications, increasing resistance to natural interference, noise and jamming, to prevent detection, and to limit power flux density (e.g., in satellite down links)

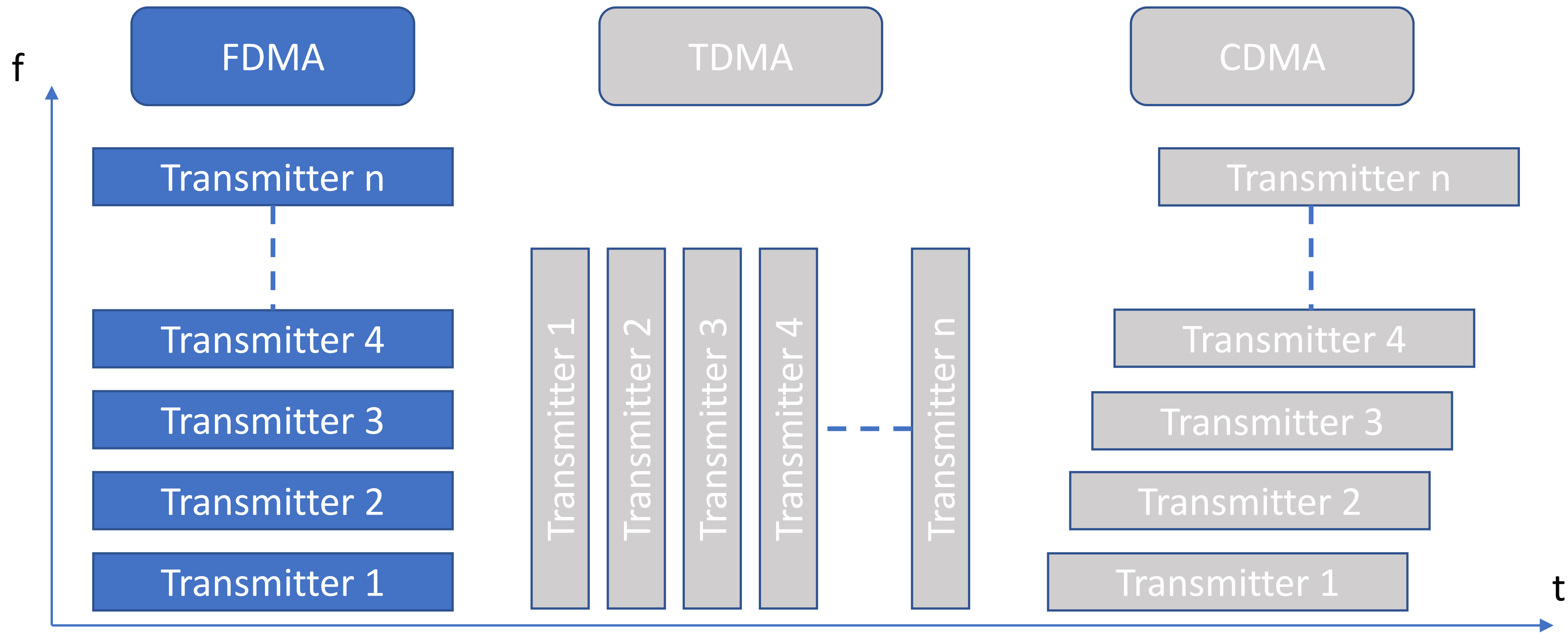




Spread spectrum modulation

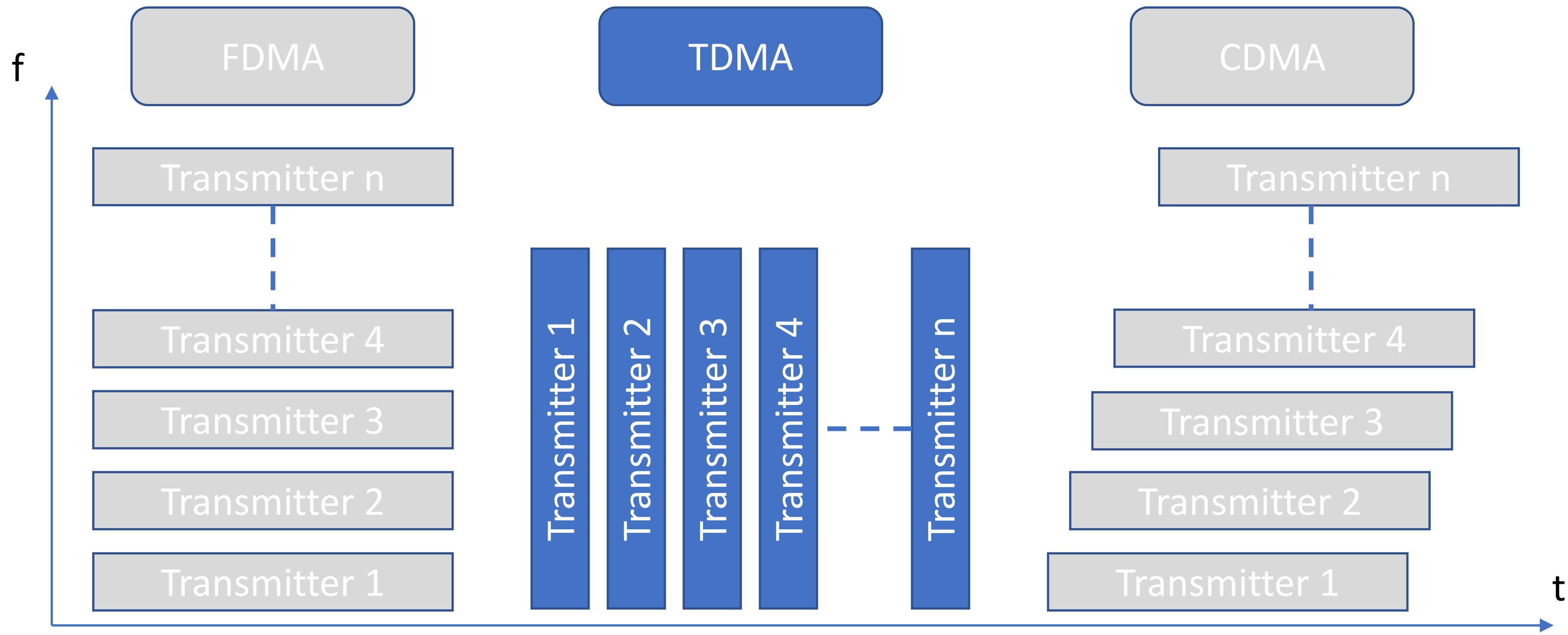


Methods of multiple access to a specific bandwidth



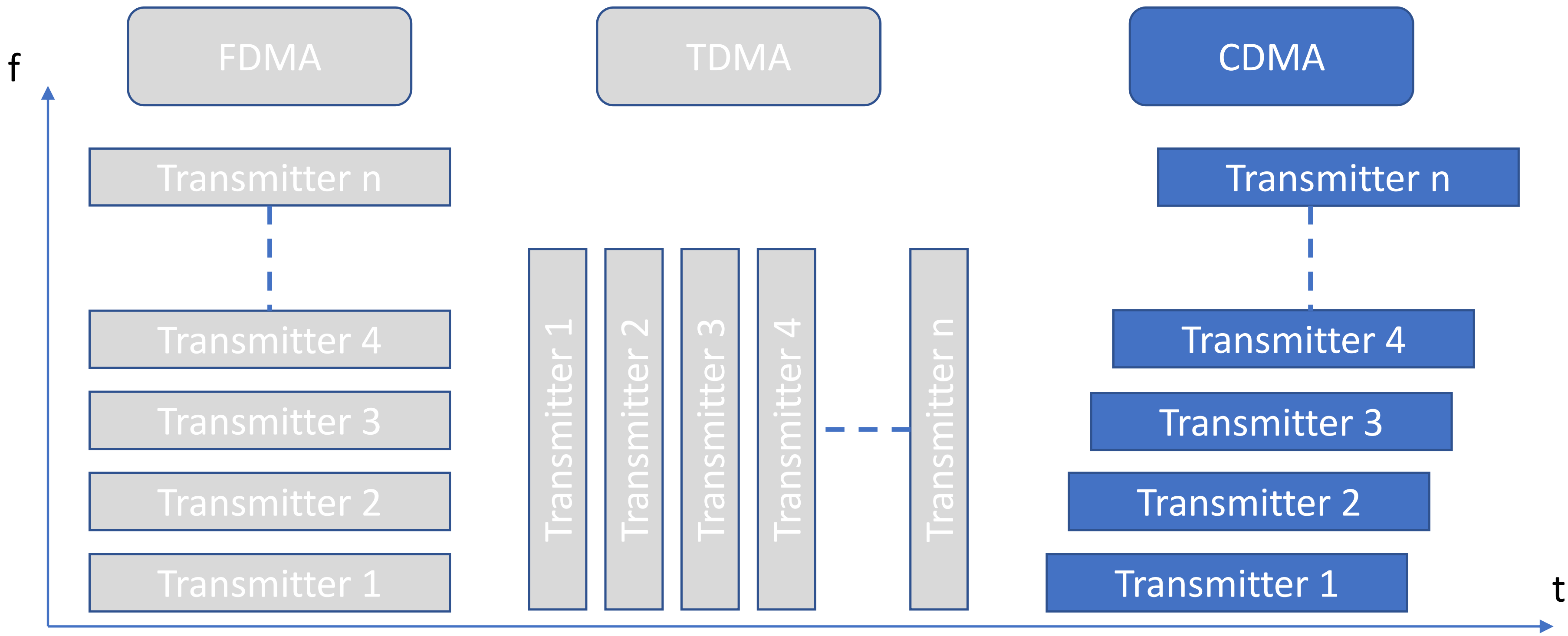
FDMA – frequency division multiple access
is a channel access method used in multiple-access protocols as a channelization protocol. FDMA gives users an individual allocation of one or several frequency bands, or channels. It is particularly commonplace in satellite communication. FDMA, like other multiple access systems, coordinates access between multiple users

Methods of multiple access to a specific bandwidth



TDMA – time division multiple access
is a channel access method for shared-medium networks. It allows several users to share the same frequency channel by dividing the signal into different time slots. The users transmit in rapid succession, one after the other, each using its own time slot.

Methods of multiple access to a specific bandwidth



CDMA – code division multiple access
is an example of multiple access, where several transmitters can send information simultaneously over a single communication channel. This allows several users to share a band of frequencies. To permit this without undue interference between the users, CDMA employs spread spectrum technology and a special coding scheme (where each transmitter is assigned a code)

Signal strength, SNR

According to Ohm's law the relation between current, voltage and resistance is as follow:

$$U = R \cdot I$$

or more complex dimensions in alternating current circuits with inductive and capacitive reactance, where the resultant of which is called impedance:

$$U = Z \cdot I$$

In such a circuit the energy (power) will be consumed proportional to resistance and the square of the current:

$$P = R \cdot I^2 = \frac{U^2}{R} = U \cdot I$$

where:

U – voltage, R – resistance, I – current, Z – impedance, P – power

Signal strength, SNR

Let's consider the power ratio between input and output in amplifier or between output of a transmitter and input of a receiver:

$$\frac{P_2}{P_1} = \frac{U_2 \cdot I_2}{U_1 \cdot I_1}$$

there is an amplification, if the value of the ratio is greater than 1 and a loss, if the ratio is less than 1:

$$A = \frac{P_2}{P_1}$$

because the energy at receiver can be millions of times less than the energy transmitted by transmitter, the loss Amp is expressed in decibels [dB], which is 10 times the logarithm to power ratio:

$$Amp = 10 \cdot log \frac{P_2}{P_1}$$

Signal strength, SNR

SNR – signal to noise ratio

- When described as a logarithmic ratio number [dB], equals to a difference between signal level S[dB/w] and noise level N[dB/w]:

$$SNR = S - N[\mathrm{dB}]$$

- when described as $\frac{C}{N_0}$, then SNR will be related to the ratio in a given part of the spectrum, specified in [dB-Hz]
  - where C describes the effect of the carrier wave

- In receivers the SNR can be presented as “SNR number” which can be stated in decibels or as a relative number on a scale from 1 – 10 or similar
- The significance of this number should be described in the receiver's manual

Signal strength, SNR

- SNR decreases when increasing distance from transmitter (the signal strength is weaker), due to "propagation loss" as a result of propagation itself:

$$power\ density = \frac{P_t}{2\pi r^2}$$

Signal strength, SNR

Additionally the SNR decreases because of a "noise" (an electromagnetic background), which is caused by:

- Irregularities in the medium – varying propagation speed
- Undesired radio signals at similar frequency
- Electromagnetic discharge in the atmosphere or from space
- Own noise in the receiver due to thermic movement of electrons in the electronic circuits
- Weakness / bad precision in the transmitter’s modulator and receiver’s demodulator
- Operator’s mistakes
- Increased number of transmitters using the same part of spectrum (satellites)

The end