CS 480: MOBILE NETWORKS

Lecture PowerPoints

Lecture 5

Wireless Transmission

Topics Covered

- The electromagnetic spectrum
- Frequencies for Radio Transmission
  - Regulations
- Antennas
- Signal Propagation
  - Path Loss of Radio Signals
  - Additional Signal Propagation Effects
  - Multi-Path Propagation
- Multiplexing
  - Space Division Multiplexing
  - Frequency Division Multiplexing
  - Time Division Multiplexing
  - Code Division Multiplexing

The electromagnetic spectrum (1)

- Electromagnetic waves were predicted by Scottish physicist James Maxwell in 1865
  - and observed by German physicist Heinrich Hertz in 1887
- These waves are created by the movement of electrons
  - and have the ability to propagate through space
- Using appropriate antennas, transmission and reception of electromagnetic waves through space is feasible
- This is the basis for all wireless communication
- Electromagnetic waves are generated through generation of an electromagnetic field
- Transmitters are based on this principle:
  - to generate electromagnetic waves transmitter vibrates electrons
  - Speed of electron vibration determines the wave's frequency
  - Frequency refers to the number of times the wave is repeated in one second. It is measured in Hertz.

The electromagnetic spectrum (2)

- Reception of a wave works in the same way,
  - by examining values of electric signals that are induced to the receiver's antenna by the incoming wave
- The wavelength
  - is distance between two successive maximum or minimum peaks of the electromagnetic wave and is measured in meters
- The amplitude of an electromagnetic wave
  - is the height from the axis to a wave peak and represents the strength of the wave's transmission.
  - It is measured in volts or watts.
- The wavelength λ and frequency f of an electromagnetic wave are related according to

  $c = f\lambda$, where c is a constant representing the speed of light.

The electromagnetic spectrum (3)

- The constant nature of *c* means that, given the wavelength, the frequency can be determined.
- The complete range of electromagnetic radiation is known as the **electromagnetic spectrum**
  - It comprises parts called bands which help explain different properties of various spectrum parts
- Figure 1 shows the electromagnetic spectrum
- Higher bands have bigger bandwidth, carry more data.
- Bands above visible light are rarely used in wireless communication systems
  - they are difficult to modulate and dangerous to human beings
- Higher frequency signals typically have a shorter range than lower frequency signals
  - since they are more easily blocked by obstacles. Light cannot penetrate walls while radio signals can.

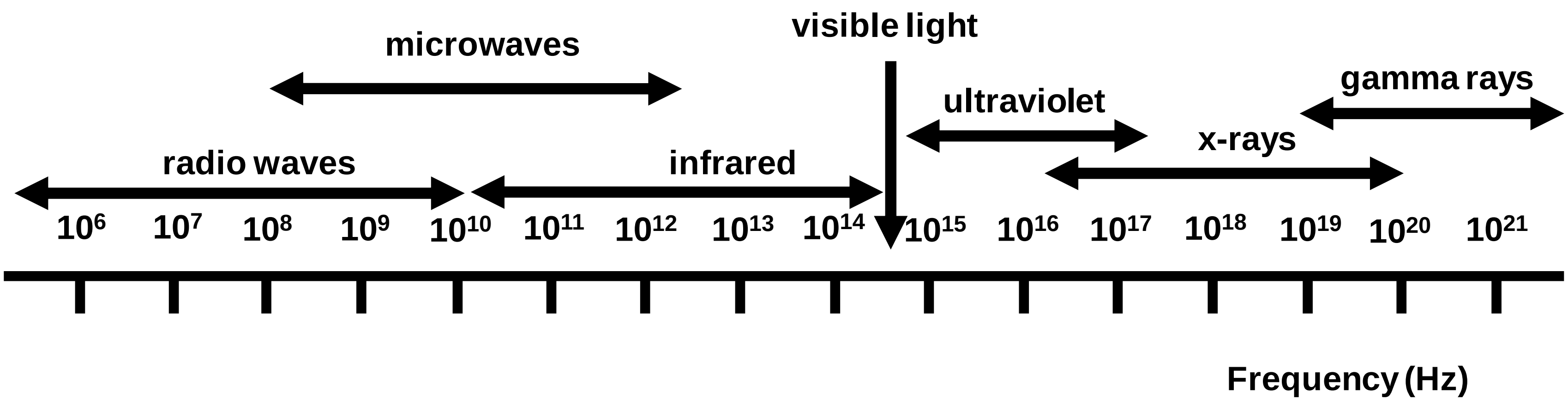


Figure 1: The electromagnetic spectrum

The electromagnetic spectrum (4)

- *Gamma rays:* have the highest frequency and occupy the highest part of the electromagnetic spectrum.
  - They carry very large amounts of energy and are usually emitted by radioactive material such as cobalt-60 and cesium-137.
  - Can easily penetrate the human body and its cells and are thus very dangerous to human life.
  - Their use is confined to certain medical applications
- *X-rays*: are also dangerous to human health as they can easily penetrate body cells
  - used in medical applications, the most well known being the examination of possible broken bones
- *Ultraviolet* (UV): such rays can be produced by the sun and ultraviolet lamps.
  - They are dangerous to humans.

The electromagnetic spectrum (5)

- *Visible light*: the tiny part of the spectrum between UV and infrared.
- *Infrared (IR)*: emitted by very hot objects and frequency depends on the temperature of the emitting body.
  - emitted by the human body and night vision is based on this fact.
  - IR also find use in some wireless communication system.
- *Microwaves:* the high frequency radio bands (UHF, SHF and EHF) are referred to as microwaves.
  - name comes from the fact that they have small wavelengths compared to radio waves
  - Have a large number of applications in wireless communication which stem from their high bandwidth

Frequencies for Radio Transmission (1)

- Radio transmission can take place using many different frequency bands.
- Figure 2 gives a rough overview of the frequency spectrum that can be used for data transmission.
- For traditional wired networks, frequencies up to several kHz are used for distances up to some km with twisted cooper wires,
  - frequencies of several hundred MHz are used with coaxial cable.
- Fiber optics are used for frequency ranges of several hundred THz
- Radio transmission start at several kHz, the *very low frequency* (VLF) range

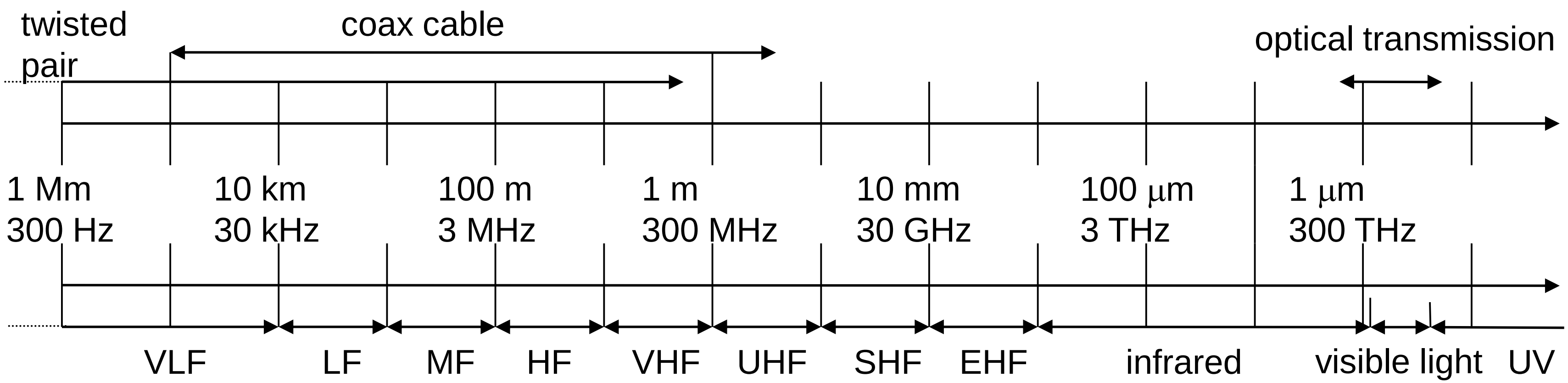


Figure 2: Frequency spectrum

Frequencies for Radio Transmission (2)

- Waves in *low frequency* (LF) range are used by submarines because they can penetrate water and can follow the earth's surface
- The *medium frequency* (MF) and *high frequency* (HF) ranges are typical for transmission of hundreds of radio stations either as
  - amplitude modulation (AM) between 520 kHz and 160.5kHz, as short waves (SW) between 5.9 MHz and 26.1 MHz, or
  - frequency modulation (FM) between 87.5 MHz and 108 MHz
- Conventional analog TV is transmitted in ranges of 174 - 230 MHz using *very high frequency* (VHF) band and 470-790 MHz using *ultra high frequency* (UHF) bands

Frequencies for Radio Transmission (3)

  - In this range, digital audio broadcasting (DAB) takes place as well (223-230 MHz and 1452-1472 MHz).
  - Digital TV is planned or currently being installed in the range 470-862 MHz
- UHF is also used for mobile phones
  - with analog technology (450-465 MHz),
  - the digital GSM (890-960 MHz, 1710-1880 MHz),
  - digital cordless telephones following the DECT standard (1880-1900 MHz),
  - 3G cellular systems following the UMTS standard (1900-1980 MHz, 2020-2025 MHz, 2110-2190 MHz)
- VHF and especially UHF allow for small antennas and relatively reliable connections for mobile telephony

Frequencies for Radio Transmission (4)

- *Super high frequencies* (SHF) are typically used for
  - directed microwave links (approx. 2-40 GHz)
  - and fixed satellite services in the C-band (4 and 6 GHz), Ku-band (11 and 14 GHz), or Ka-band (19 and 29 GHz)
- Some systems are planned in the *extremely high frequency* (EHF) range which comes close to infrared.
- All radio frequencies are regulated to avoid interference
- The next step into higher frequencies involves optical transmission, which is not only used for fiber optical links but also for wireless communications
  - *Infra red* (IR) transmission is used for directed links, e.g to connect different buildings via laser links.
  - The most widespread IR technology, infra red data association (IrDA), uses wavelengths of approx 850-900 nm to connect laptops, PDAs etc.

Frequencies for Radio Transmission (5)

- Visible light has been used for wireless transmission for thousands of years.
  - While not very reliable due to interference, it is useful due to built-in human receivers.

Regulations

- Radio frequencies are scarce resources
- Many national (economic) interests make it hard to find common, worldwide regulations.
- ITU (a sub-organization of UN) in Geneva is responsible for worldwide coordination of telecommunication activities (wired and wireless)
- The ITU Radio communication sector (ITU-R) handles standardization in the wireless sector.
- Figure 3 gives some examples for frequencies used for mobile phones, cordless telephones, wireless LANs and other radio frequency (RF) systems for countries representing the major economies.

Examples	Europe	USA	Japan
Cellular phones	**GSM** 880-915, 925-960, 1710-1785, 1805-1880 **UMTS** 1920-1980, 2110-2170	**AMPS, TDMA, CDMA, GSM** 824-849, 869-894 **TDMA, CDMA, GSM, UMTS** 1850-1910, 1930-1990	**PDC, FOMA** 810-888, 893-958 **PDC** 1429-1453, 1477-1501 **FOMA** 1920-1980, 2110-2170
Cordless phones	**CT1+** 885-887, 930-932 **CT2** 864-868 **DECT** 1880-1900	**PACS** 1850-1910, 1930-1990 **PACS-UB** 1910-1930	**PHS** 1895-1918 **JCT** 245-380
Wireless LANs	**802.11b/g** 2412-2472	**802.11b/g** 2412-2462	**802.11b** 2412-2484 **802.11g** 2412-2472
Other RF systems	27, 128, 418, 433, 868	315, 915	426, 868

Figure 3: Example systems and their frequency allocations (all values in MHz). AMPS- Advanced Mobile Phone System, PDC-Personal Digital Cellular, FOMA-Freedom of Mobile Multimedia Access, JCT – Japanese Cordless Telephone, PACS-UB –Personal Access Communications System (PACS-UB)

Antennas (1)

- Antennas couple electromagnetic energy to and from space, to and from a wire or coaxial cable (or any other appropriate conductor)
- A theoretical reference antenna is the *isotropic radiator* which is a point in space radiating equal power in all directions
  - i.e. all points with equal power are located on a sphere with the antenna as its centre
  - the *radiation pattern* is symmetric in all directions (see Figure 4, a 2-D cross section of the real 3-D pattern).

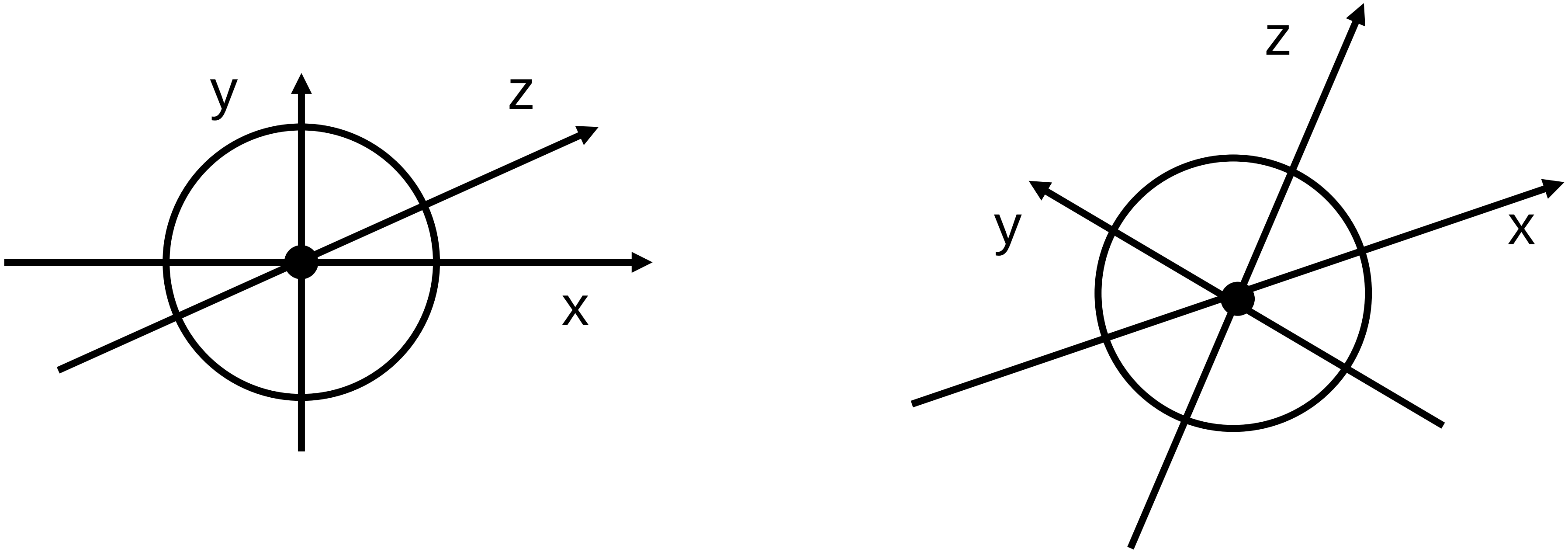


Figure 4: Radiation pattern of an isotropic radiator.

Antennas (2)

- An isotropic radiator does not exist in reality.
- Real antennas all exhibit *directive effects*
  - i.e. the intensity of radiation is not the same in all directions from the antenna.
- The simplest real antenna is a thin, center-fed *dipole*, called a Hertzian dipole, see Figure 5 (right hand side)
- The dipole consists of two collinear conductors of equal length, separated by a small feeding gap.
- The length of the dipole is not arbitrary, but for example, half the wavelength λ of the signal to transmit results in a very efficient radiation of energy

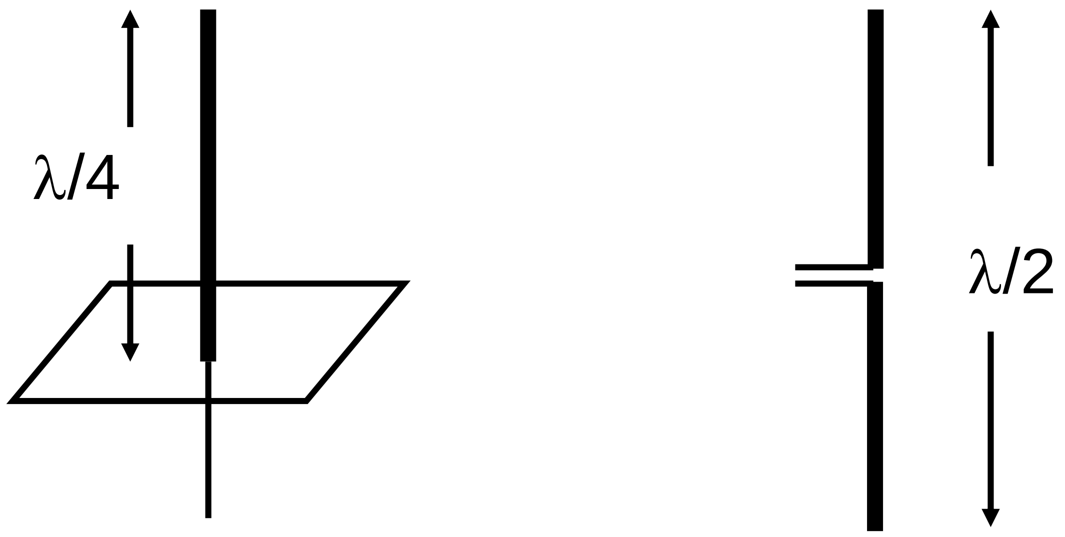


Figure 5: Simple antennas.

Antennas (3)

- If mounted on the roof of a car, the length of $\lambda/4$ is efficient (Figure 5 (left)).
  - This is also known as Marconi antenna.
- A $\lambda/2$ dipole has a uniform or *omni-directional* radiation pattern in one plane and a figure eight pattern in the other two planes as shown in Figure 6.
  - This type of antenna can only overcome environmental challenges by boosting the power level of a signal
  - Challenges could be mountains, valleys, buildings, etc.

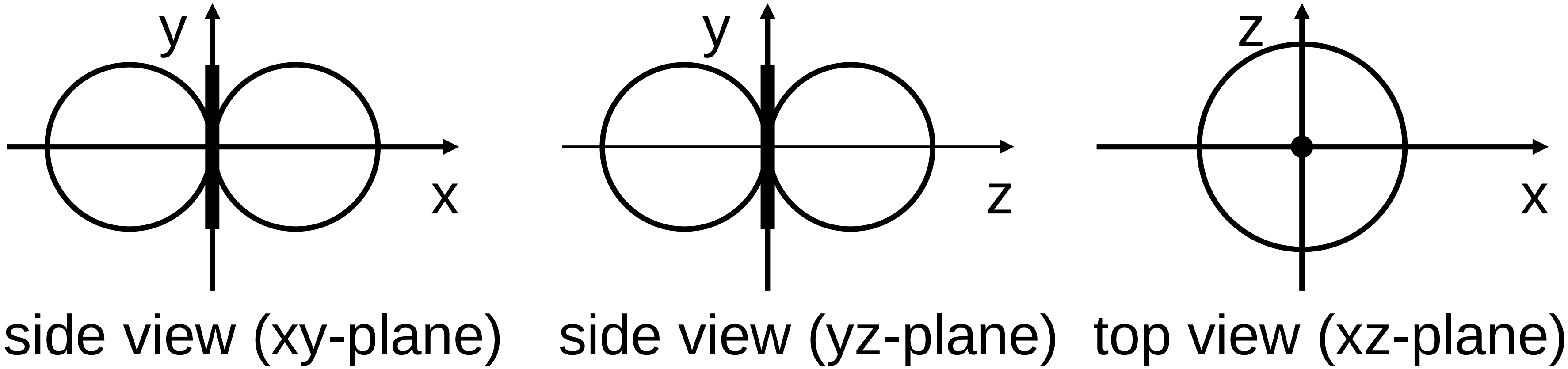


Figure 6: Radiation pattern of a simple dipole

Antennas (4)

- If an antenna is positioned, e.g. in a valley or between buildings, an omni-directional radiation pattern is not very useful.
- In this case, *directional antennas* with certain preferential transmission and reception directions can be used.
  - Figure 7 shows the radiation pattern of a directional antenna with the main lobe in the direction of the x-axis.
  - A special example of directional antennas is constituted by satellite dishes
- Directional antennas are applied in cellular systems
- Several directed antennas can be combined on a single pole to construct a *sectorized antenna*.
  - A cell can be sectorized into, for example, three or six sectors, thus enabling frequency reuse
  - Figure 8 shows radiation patterns of these sectorized antennas.

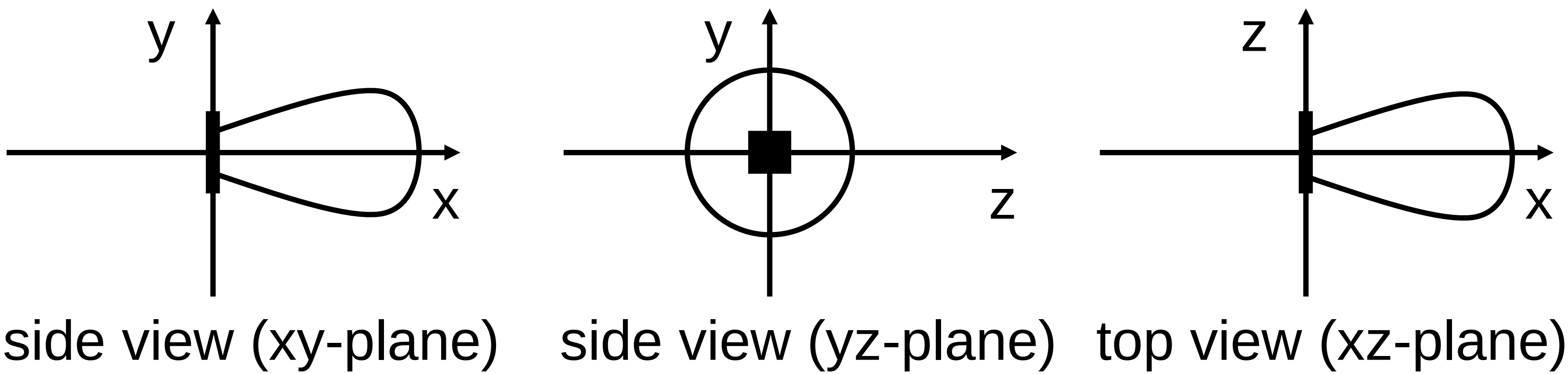
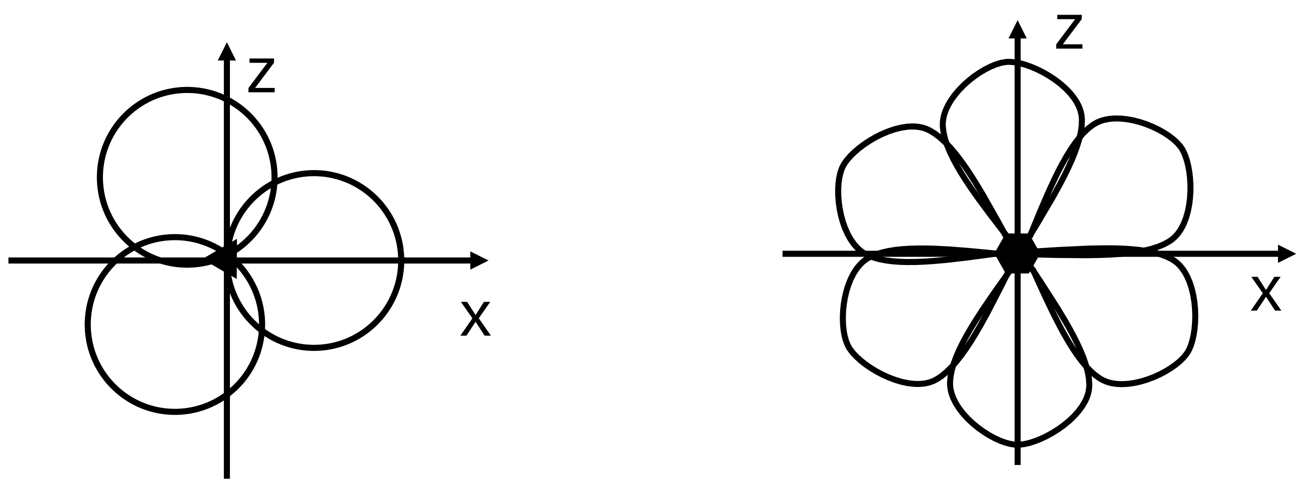


Figure 7: Radiation pattern of a directional antenna.



top view, 3 sector

top view, 6 sector

Figure 8: Radiation patterns of sectorized antennas.

Antennas (5)

- Two or more antennas can also be combined to improve reception by counteracting the negative effects of multipath propagation.
- These antennas, also called *multi-element antenna arrays*, allow different diversity schemes
  - One such scheme is *switched diversity* or *selection diversity*,
    - receiver always uses the antenna element with the largest output
  - *Diversity combining* constitutes a combination of the power of all signals to produce gain.
    - The phase is first corrected (cophasing) to avoid cancellation
    - As shown in Figure 9, different schemes are possible.
    - On the left, two λ/4 antennas are combined with a distance of λ/2 between them on top of a ground plane.
    - On the right, three standard λ/2 dipoles are combined with a distance of λ/2 between them.

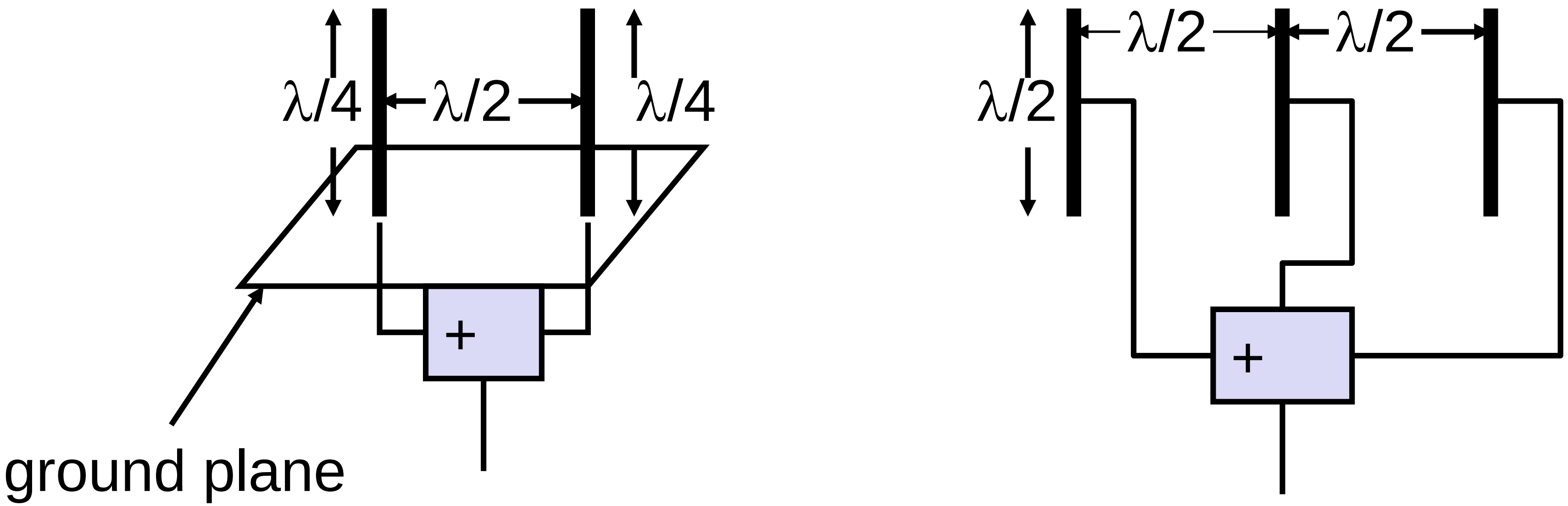


Figure 9: Diversity antenna systems.

Antennas (6)

- A more advanced solution is provided by *smart antennas*
  - These combine multiple antenna elements (also called antenna array) with signal processing to optimize the radiation/reception in response to the signal environment.
- These can adapt to changes in reception power, transmission conditions.

Signal propagation (1)

- Like wired networks, wireless communication networks also have senders and receivers of signals
- In connection to signal propagation, these two networks exhibit considerable differences
- In wireless networks, signals have no wire to determine the direction of propagation
- In wired networks, signals only travel along the wire.
  - As long as the wire is not interrupted or damaged, it exhibits the same characteristics at each point
- For wireless communication, the predictable behavior is only valid in a vacuum.

Signal propagation (2)

The situation would be as follows (see Figure 10)

- *Transmission range*:
  - within a certain radius of the sender transmission is possible
  - receiver receives signals with low error rate to be able to communicate and can also act as sender
- *Detection range*:
  - within a second radius, detection of the transmission is possible
  - the transmitted power is large enough to differ from background noise but error rate is too high to establish connection
- *Interference range*:
  - within a third even larger radius, the sender may interfere with other transmission by adding to the background noise.
  - A receiver will not be able to detect signals
- This scheme led to a notion of cells around a transmitter

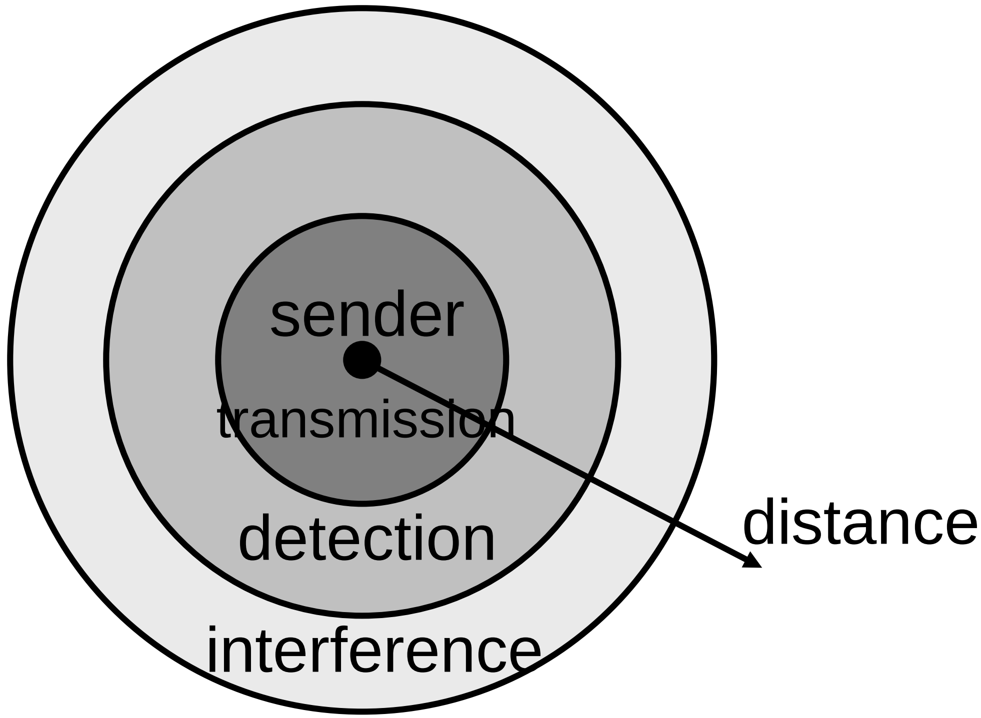


Figure 10: Ranges for transmission, detection, and interference of signals.

Path loss of radio signals (1)

- In free space, radio signals follow a straight line.
  - Such a line between sender and receiver is called *line of sight* (LOS)
- A signal always experiences the *free space* loss.
  - The received power is proportional to $1/d^2$ where d is the distance between sender and receiver (inverse square law)
- Receiving power additionally influenced by
  - *Fading* (frequency dependent):
    - radio waves can also penetrate objects
    - The lower the frequency, the better the penetration.
  - *Blocking* or *shadowing* of radio signals:
    - is an extreme form of attenuation due to large obstacles (Figure 11).
    - The higher the frequency of a signal, the more it behaves like light.
    - Small obstacles like simple wall, truck on street may block a signal.

Path loss of radio signals (2)

- *Reflection* of signals at large obstacles:
  - Occurs if an object is large compared to wavelength of the signal
  - The reflected signal is not as strong as the original.
  - Reflection helps transmitting signals as soon as no LOS exists.
- *Refraction* depending on the density of a medium:
  - Occurs because the velocity of electromagnetic waves depends on the density of the medium.
  - Waves that travel into a denser medium are bent towards medium
- *Scattering* at small obstacles:
  - if the size of an obstacle is of the order of the wavelength or less, then waves can be scattered (see Figure 11).
  - An incoming signal is scattered into several weaker outgoing signals
- *Diffraction* at edges:
  - similar to scattering, radio waves will be deflected at an edge and propagate in different directions.

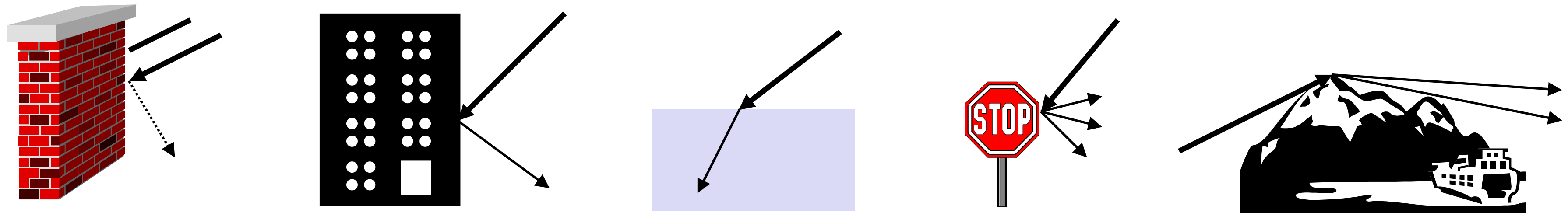


Figure 11: Blocking (shadowing), reflection, refraction, scattering and diffraction of waves.

Multi-path propagation (1)

- A signal can take several paths between sender and receiver
  - due to reflection, scattering, diffraction.
- Multi-path propagation leads to one of the most severe radio channel impairments.
- Figure 12 shows a sender on the left and one possible receiver on the right.
- Radio waves emitted by sender can either travel along a straight line, or may be reflected at a large building, or scattered at smaller obstacles.
- Signals travelling along different paths arrive at receiver at different times due to finite speed of light
- This effect is called *delay spread*
  - It is caused by multi-path propagation
  - original signal is spread due to different delays of parts of signal

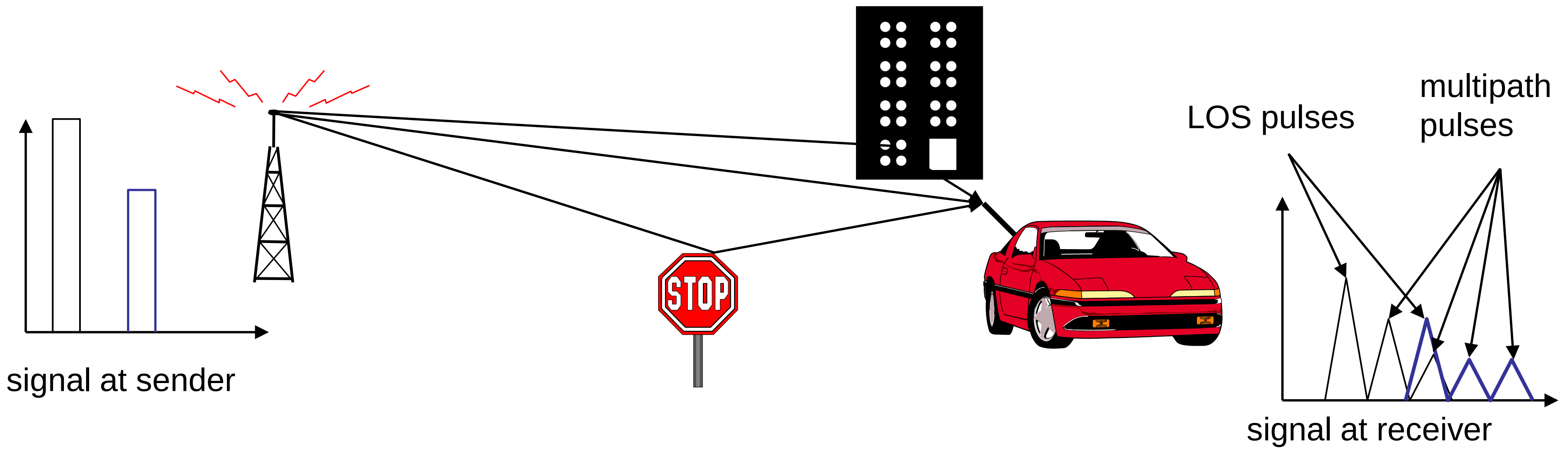


Figure 12: Multipath propagation and intersymbol interference.

Multi-path propagation (2)

Effects of delay spread on signals representing data

- Short impulse will be smeared out into a broader impulse or rather into several weaker impulses.
  - In Figure 12, only three possible paths are shown;
  - Impulse at sender results in three smaller impulses at receiver
  - For second impulse in Figure 12, on the sender side, both impulses are separated. At the receiver both impulses interfere.
- Energy intended for one symbol spills over to adjacent symbol. This is called intersymbol interference (ISI).
  - ISI limits the bandwidth of a radio channel with multipath propagation.
  - Signals of different symbols can cancel each other leading to misinterpretation at the receiver, causing transmission errors.

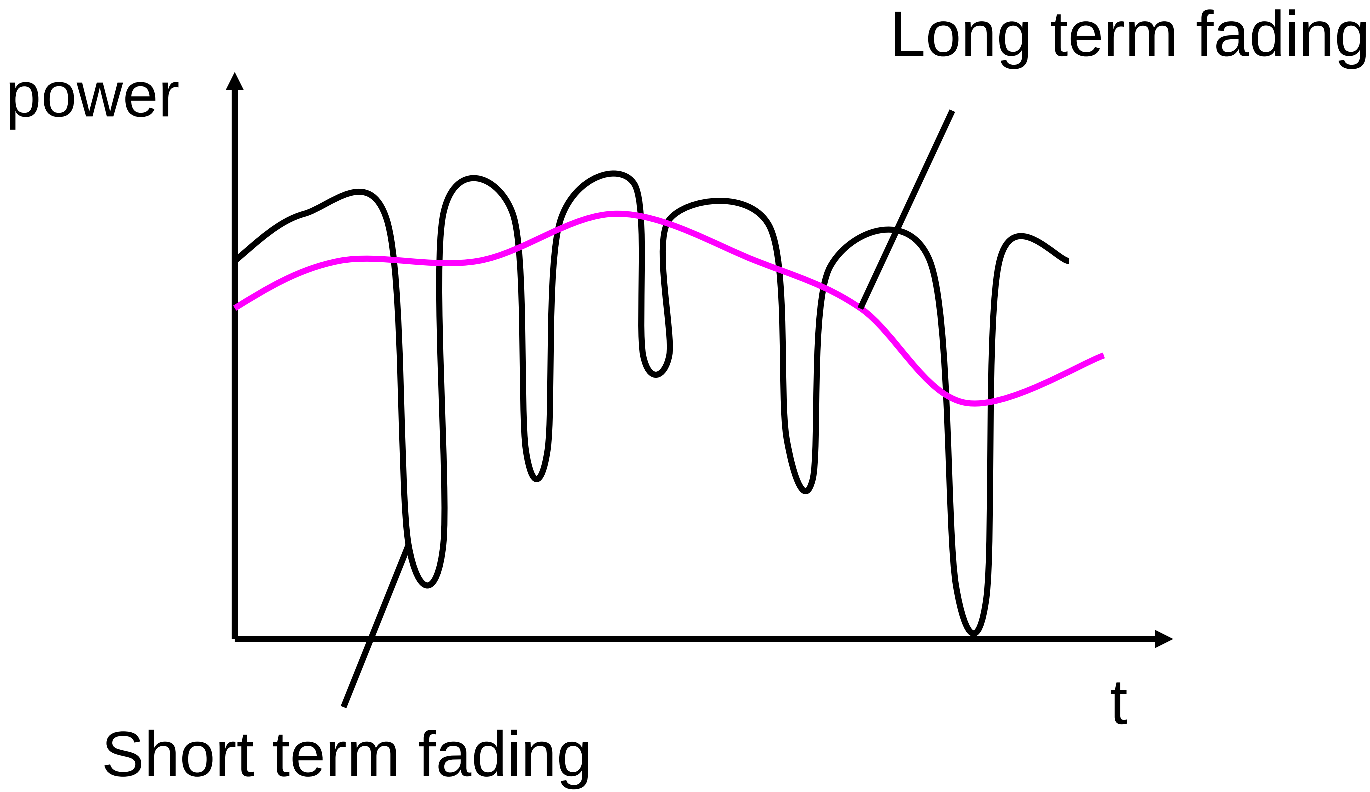


Figure 13: Short-term and long-term fading.

Multi-path propagation (3)

- The channel characteristics (delays of different paths) change over time if receivers or senders or both move.
  - Power of the received signal changes considerably over time.
  - These quick changes in the received power are called *short-term fading*.
  - Depending on the different paths taken, signals may have a different phase and cancel each other as shown in Figure 13.
  - An additional effect is *long-term fading* of the received signal, shown as here average power over time.
  - This can be caused by varying distance to the sender or more remote obstacles.

Multiplexing

- Multiplexing describes how several users can share a medium with minimum or no interference.
  - It is a fundamental mechanism in communication systems.
- For wireless communication, multiplexing can be carried out in four dimensions: *space*, *time*, *frequency* and *code*.
- The task of multiplexing is to assign space, time, frequency and code to each communication channel with minimum of interference and maximum media utilization
- Communication channel refers to an association of senders(s) and receiver(s) who want to exchange data.

Space division multiplexing (SDM) (1)

- Figure 14 shows six channels k_i and introduces a three dimensional coordinate system.
- This system shows the dimensions of code c, time t, and frequency f.
- In SDM, the three dimensional space s_i is also shown.
  - Space is represented via circles indicating the interference range
- The channels k_1 to k_3 can be mapped onto three "spaces" s_1 to s_3 which clearly separate the channels and prevent the interference ranges from overlapping.
- The space between the interference ranges is sometimes called *guard space*.
- For the remaining channels (k_4 to k_6), three additional spaces would be needed.

Space division multiplexing (SDM) (2)

- In wireless transmission, SDM implies a separate sender for each communication channel with a wide enough distance between senders.
- This multiplexing scheme is used for example at FM radio stations where the transmission range is limited to a certain region.

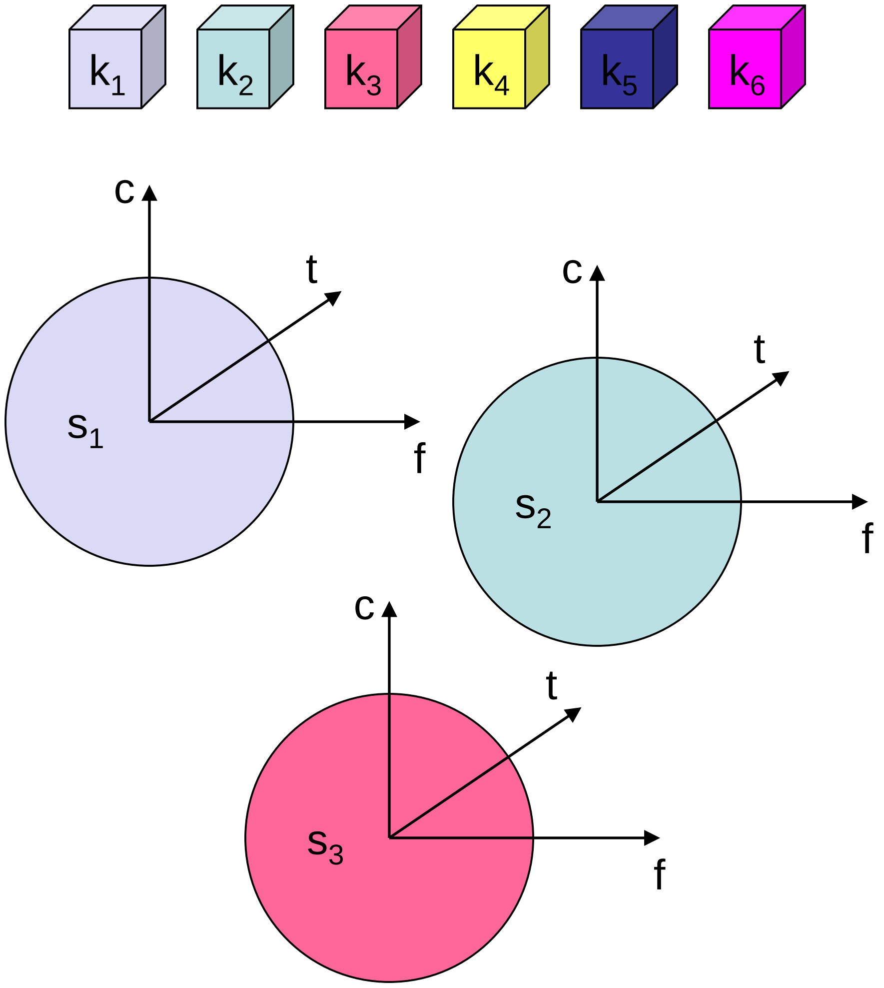


Figure 14: Space division multiplexing (SDM).

Frequency division multiplexing (FDM) (1)

- FDM describes schemes to subdivide the frequency dimension into several non-overlapping frequency bands as shown in Figure 15.
- Each channel k_i is allotted its own frequency band
  - Senders using a certain frequency band can use it continuously.
- Guard spaces are needed to avoid frequency band overlapping.
- This scheme is used for radio stations within the same region, where each radio station has its own frequency.

Frequency division multiplexing (FDM) (2)

- Advantages:
  - FDM does not need complex coordination between sender and receiver; the receiver only has to tune in to the specific sender.
  - FDM works also for analog signals.
- Disadvantages:
  - Assigning a separate frequency for each possible communication scenario would be a tremendous waste of (scarce) frequency resources.
  - The fixed assignment of a frequency to a sender makes this scheme very inflexible and limits the number of senders.

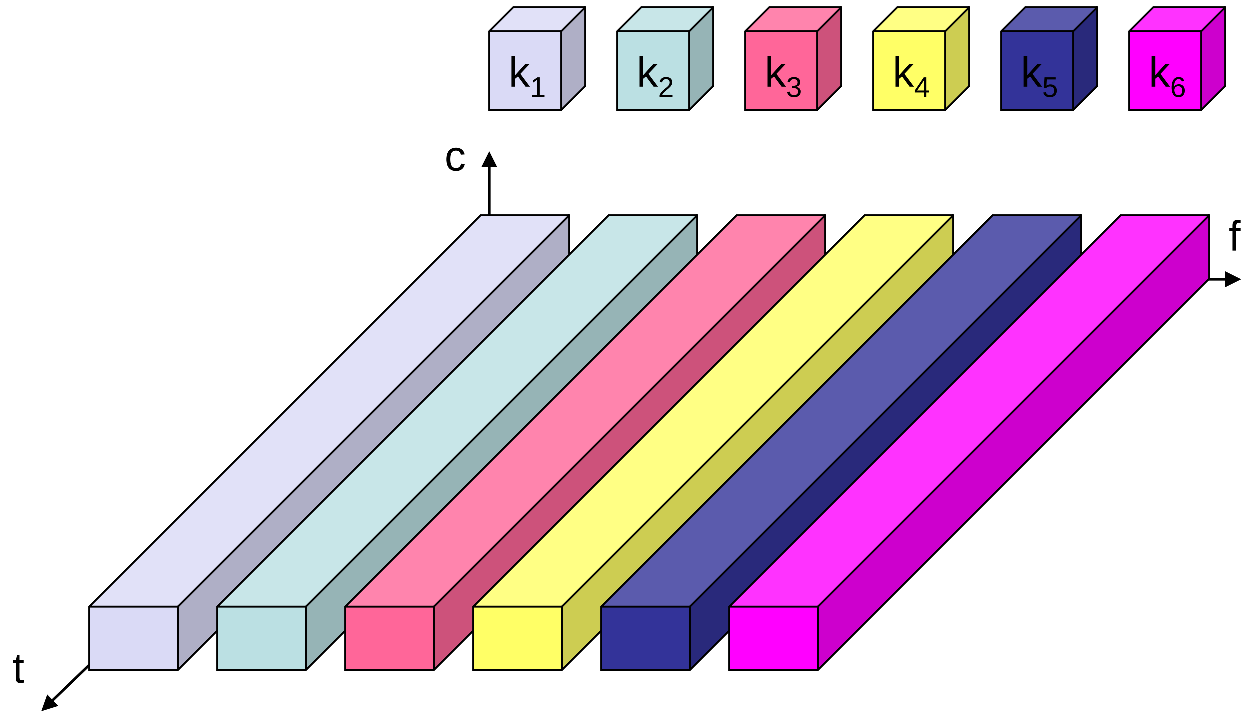


Figure 15: Frequency division multiplexing (FDM).

Time division multiplexing (TDM) (1)

- TDM is a more flexible scheme for typical mobile communication.
- Each channel k_i is given the whole bandwidth for a certain amount of time,
  - i.e. all senders use the same frequency but at different points in time (see Figure 16).
- Guard spaces, representing time gaps, have to separate the different periods when the senders use the medium.
- Advantages
  - only one carrier in the medium at any time
  - quite flexible as one can assign more sending time to senders with heavy load and less to those with light load.
- Disadvantage:
  - Precise synchronization necessary between different senders to avoid two transmissions overlapping in time.

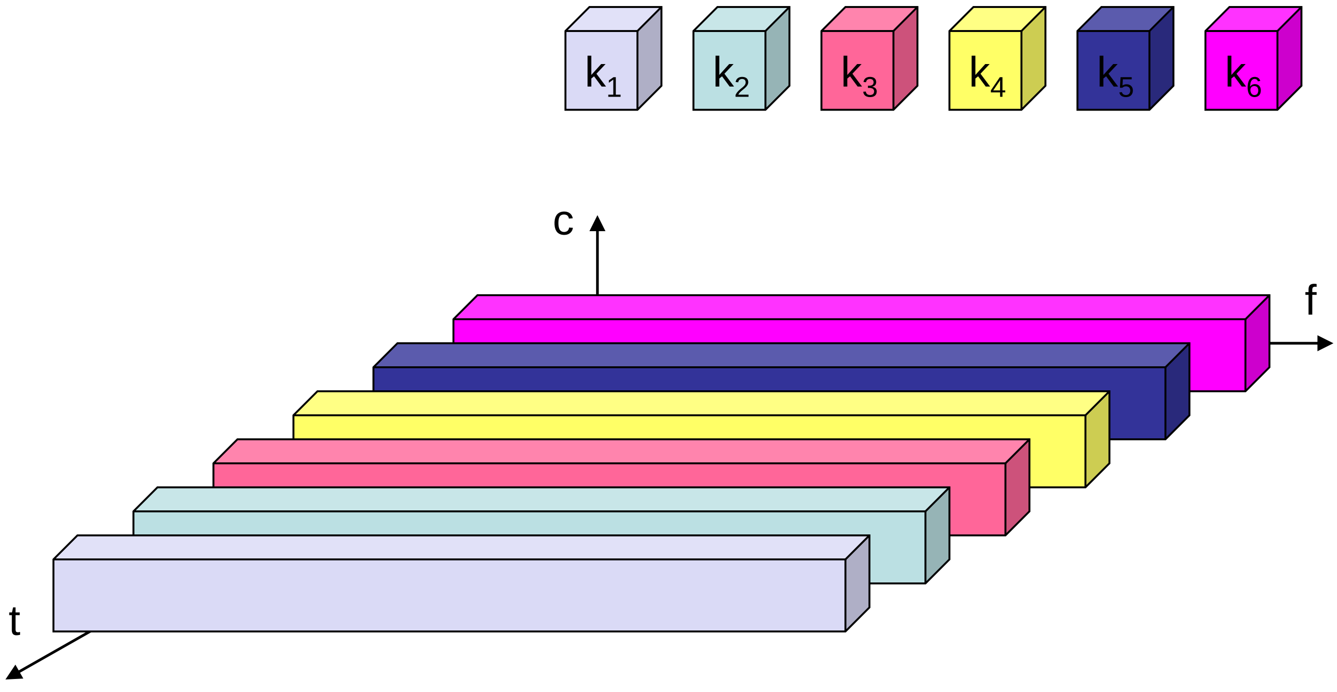


Figure 16: Time division multiplexing (TDM).

Time and Frequency division multiplexing (1)

- FDM and TDM can be combined, i.e. a channel k_i can use a certain frequency band for a certain amount of time as shown in Figure 17.

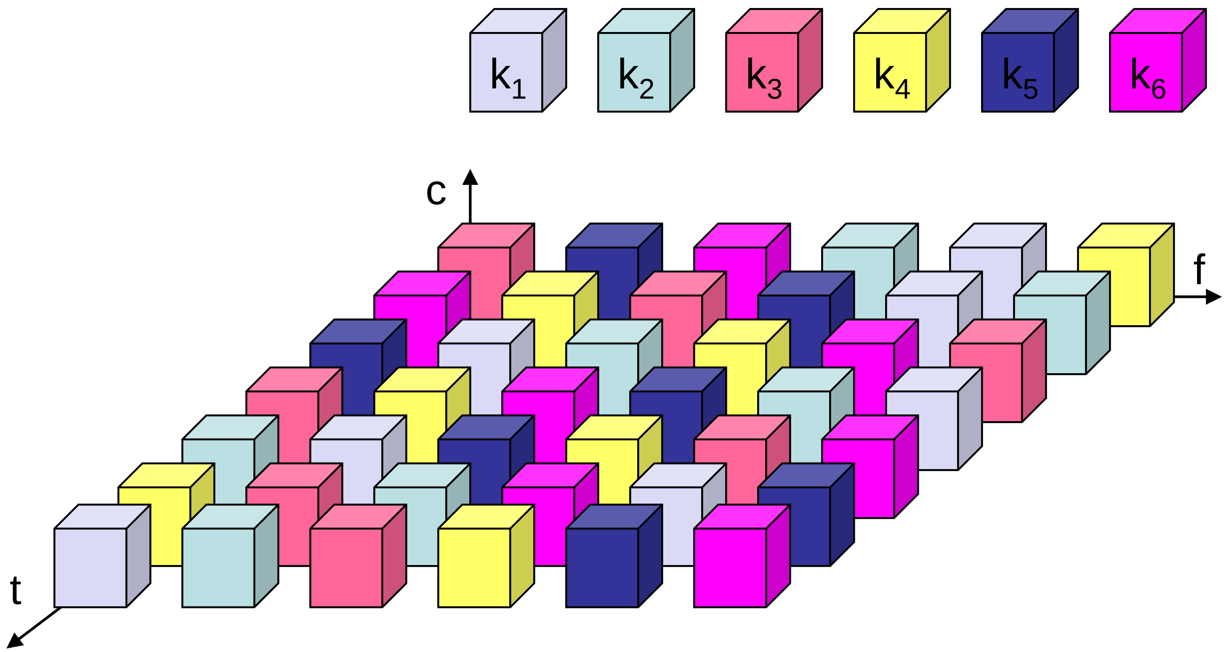


Figure 17: Frequency and time division multiplexing combined.

Time and Frequency division multiplexing (2)

- Advantages
  - More robust against frequency selective interference
  - Provides some (weak) protection against tapping
- Disadvantages
  - precise coordination required between senders.
- The mobile phone standard GSM uses this combination of FDM and TDM for transmission between a mobile phone and base station.

Code division multiplexing (CDM) (1)

- Each channel has a unique code.
- All channels use the same frequency at the same time for transmission (see Figure 18)
- Guard spaces are realized by using codes with the necessary “distance” in code space, e.g. orthogonal codes
- CDM is implemented using spread spectrum technology
- Advantages
  - Gives good protection against interference and tapping
  - Different codes have to be assigned but good thing is that code space is huge compared to frequency space

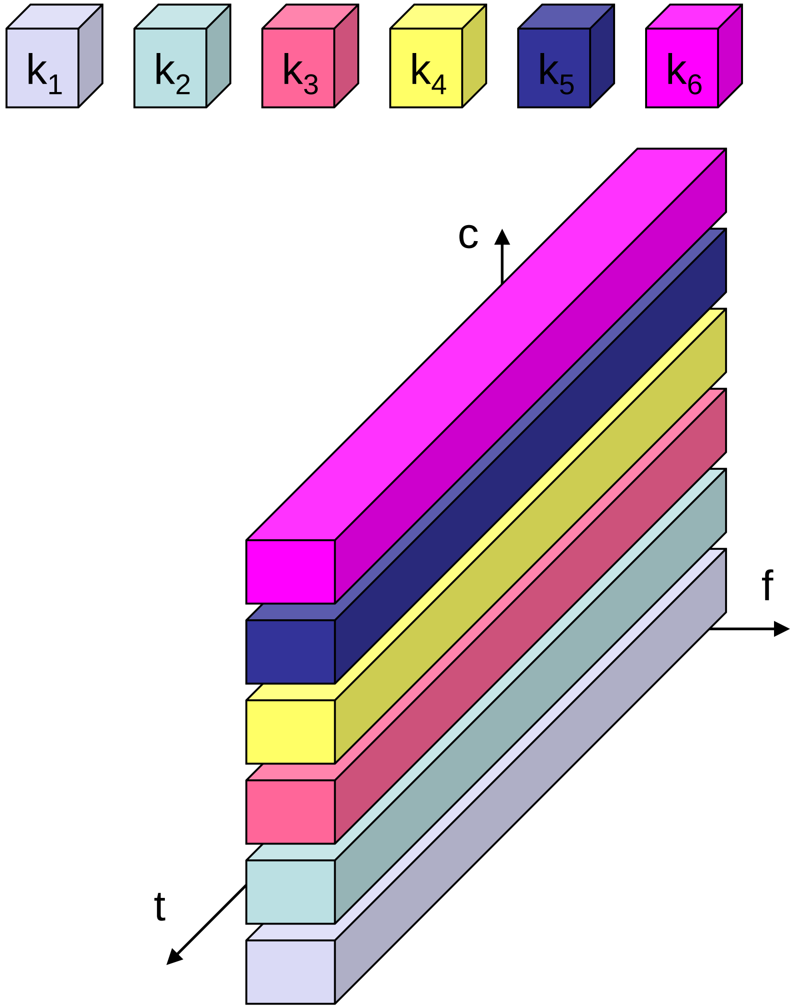


Figure 18: Code division multiplexing (CDM).

Code division multiplexing (CDM) (2)

- Disadvantage
  - Relatively high complexity of the receiver
  - A receiver has to know the code and must separate the channel user data from the background noise composed of other signals and environmental noise.
  - A receiver must be precisely synchronized with the transmitter to apply decoding correctly
  - All signals should reach a receiver with almost equal strength, otherwise some signals could drain others.