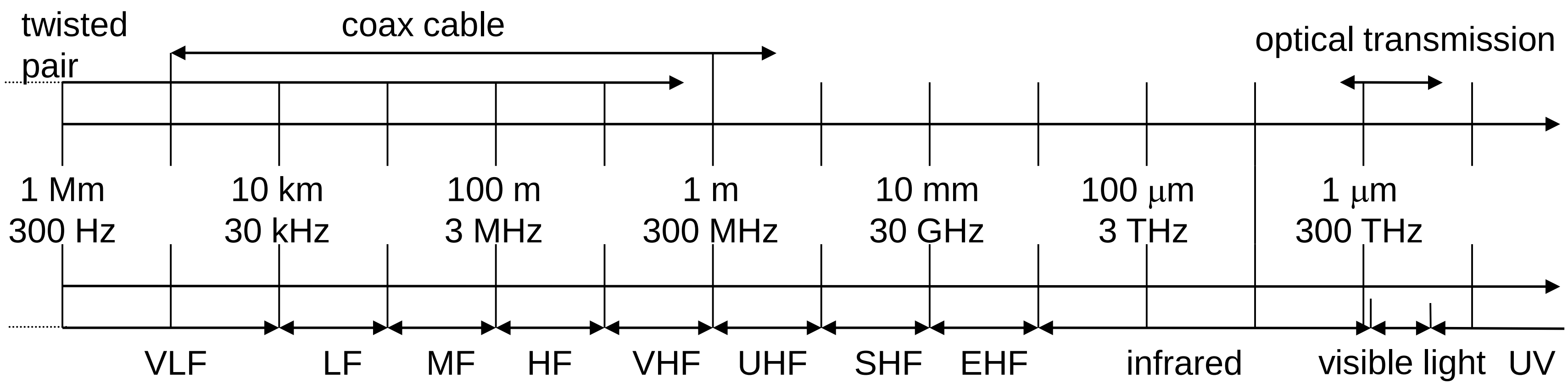
Mobile Communications
Chapter 2: Wireless Transmission

- Frequencies
- Signals
- Antennas
- Signal propagation
- Multiplexing
- Spread spectrum
- Modulation
- Cellular systems

Frequencies for communication



VLF = Very Low Frequency

LF = Low Frequency

MF = Medium Frequency

HF = High Frequency

VHF = Very High Frequency

UHF = Ultra High Frequency

SHF = Super High Frequency

EHF = Extra High Frequency

UV = Ultraviolet Light

Frequency and wave length:

$\lambda = c/f$

wave length λ, speed of light $c \cong 3\text{x}10^8$m/s, frequency f

Frequencies for mobile communication

- LF waves are used for communication with submarines because they can penetrate water and can follow the Earth's surface
- MF and HF used for transmission by radio stations:
  - AM – amplitude modulation, hundreds, thousand kHz
  - SW – short wave, several MHz, travel long distances, being reflected by the ionosphere (used also by amateur radio: transmit power 500 kW, compared to 1W for mobile phones)
  - FM – frequency modulation 80-100 MHz
- VHF and UHF used for analog TV stations (now replaced by digital TV)
- UHF used for mobile phones
- SHF: microwave links and satellite communications
- UHF, SHF and even EHF: WLANs; EHF - planned also for 5G.
- IR: IrDA (Infra red data association), for connecting laptops, PDAs, etc
- Visible light: has been used for wireless transmissions for thousands years

Frequencies for mobile communication

- VHF-/UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links (microwave), satellite communication
  - small antenna, beam forming
  - large bandwidth available
- Wireless LANs use frequencies in UHF to SHF range
  - some systems planned up to EHF
  - limitations due to absorption by water and oxygen molecules (resonance frequencies)
    - weather dependent fading, signal loss caused by heavy rainfall etc.

Frequencies and regulations

ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences)

	Europe	USA	Japan
Cellular Phones	**GSM** 450-457, 479-486/460-467,489-496, 890-915/935-960, 1710-1785/1805-1880 **UMTS** (FDD) 1920-1980, 2110-2190 **UMTS** (TDD) 1900-1920, 2020-2025	**AMPS**, **TDMA**, **CDMA** 824-849, 869-894 **TDMA**, **CDMA**, **GSM** 1850-1910, 1930-1990	**PDC** 810-826, 940-956, 1429-1465, 1477-1513
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** 254-380
Wireless LANs	**IEEE 802.11** 2400-2483 **HIPERLAN 2** 5150-5350, 5470-5725	902-928 **IEEE 802.11** 2400-2483 5150-5350, 5725-5825	**IEEE 802.11** 2471-2497 5150-5250
Others	**RF-Control** 27, 128, 418, 433, 868	**RF-Control** 315, 915	**RF-Control** 426, 868

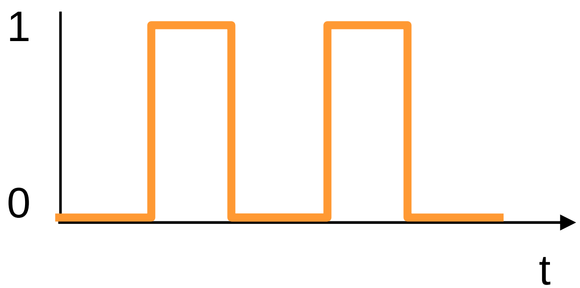
Signals I

- physical representation of data
- function of time and location
- signal parameters: parameters representing the value of data
- classification
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values
- signal parameters of periodic signals:
  period T, frequency f=1/T, amplitude A, phase shift φ
  - sine wave as special periodic signal for a carrier:

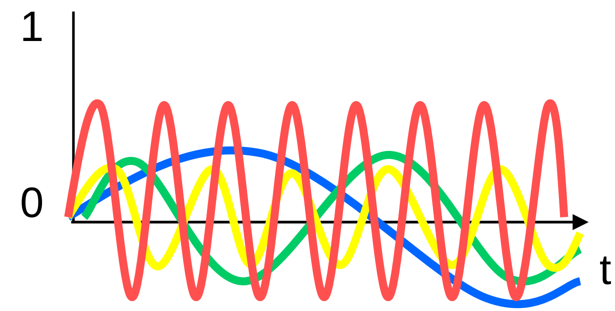
$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$

Fourier representation of periodic signals

$$g(t) = \frac{1}{2}c + \sum_{n=1}^{\infty} a_n \sin(2\pi nft) + \sum_{n=1}^{\infty} b_n \cos(2\pi nft)$$



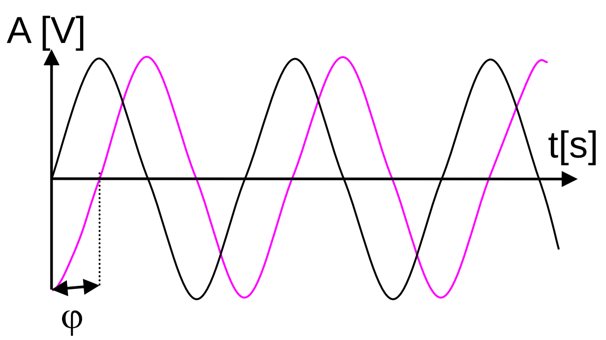
ideal periodic signal

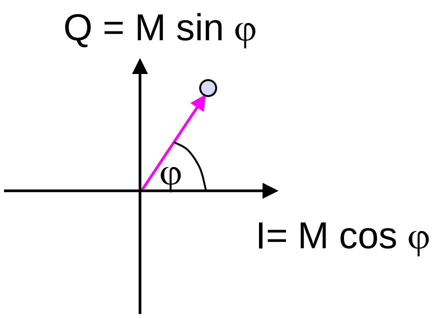


real composition
(based on harmonics)

Signals II

- Different representations of signals
  - amplitude (amplitude domain)
  - frequency spectrum (frequency domain)
  - phase state diagram (amplitude M and phase φ in polar coordinates)

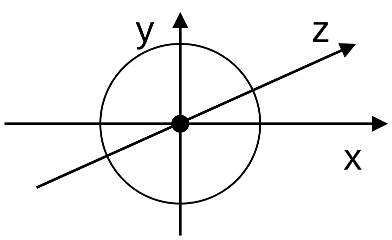


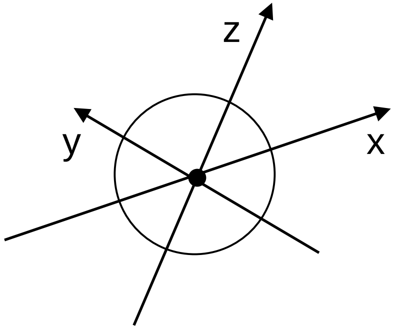


- Composed signals transferred into frequency domain using Fourier transformation
- Digital signals need
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)

Antennas: isotropic radiator

- Radiation and reception of electromagnetic waves, coupling of wires to space for radio transmission
- Isotropic radiator: equal radiation in all directions (three dimensional) - only a theoretical reference antenna
- Real antennas always have directive effects (vertically and/or horizontally)
- Radiation pattern: measurement of radiation around an antenna

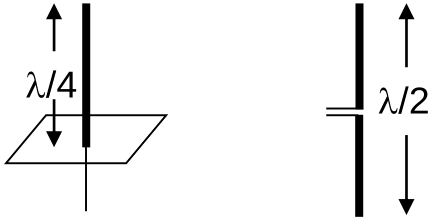




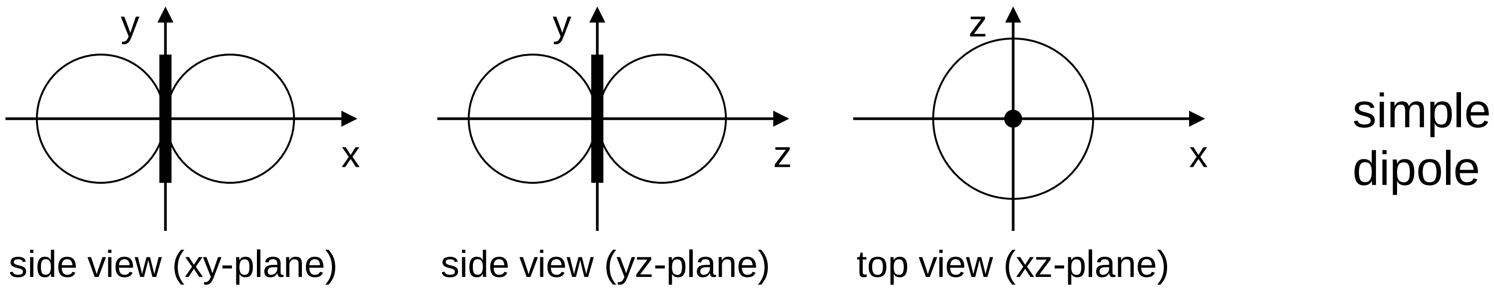
ideal
isotropic
radiator

Antennas: simple dipoles

- Real antennas are not isotropic radiators but, e.g., dipoles with lengths λ/4 on car roofs or λ/2 as Hertzian dipole
  ➔ shape of antenna proportional to wavelength



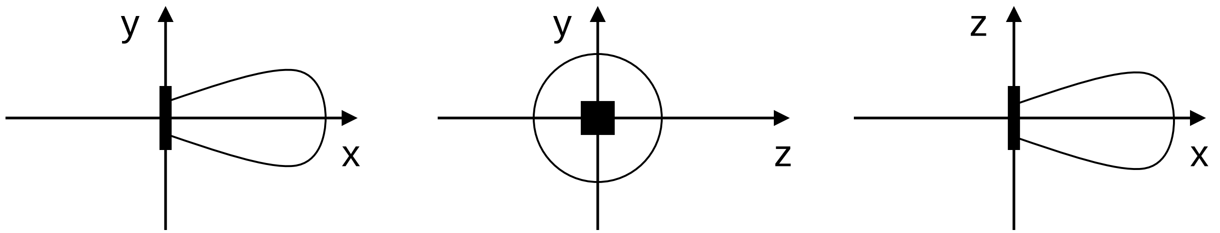
- Example: Radiation pattern of a simple Hertzian dipole



- Gain: maximum power in the direction of the main lobe compared to the power of an isotropic radiator (with the same average power)

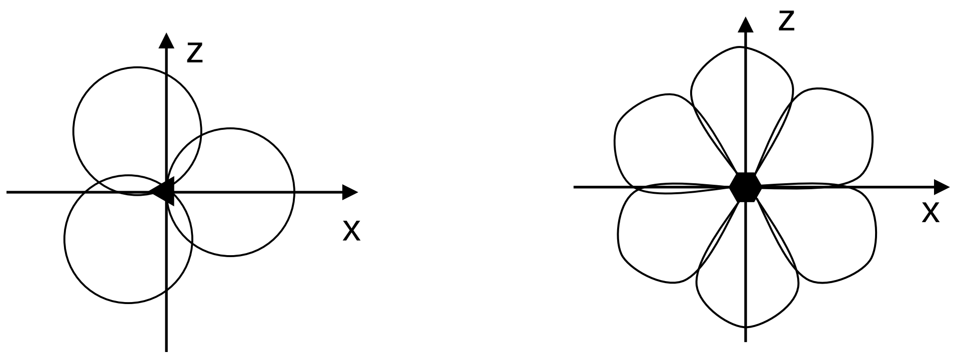
Antennas: directed and sectorized

Often used for microwave connections or base stations for mobile phones (e.g., radio coverage of a valley)



side view (xy-plane) side view (yz-plane) top view (xz-plane)

directed antenna

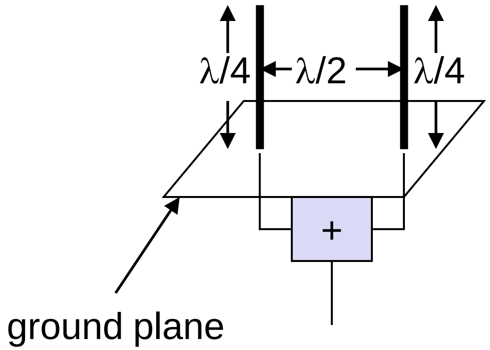


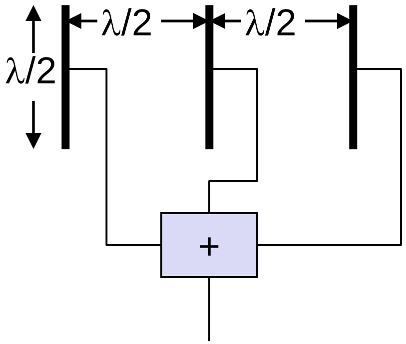
top view, 3 sector top view, 6 sector

sectorized antenna

Antennas: diversity

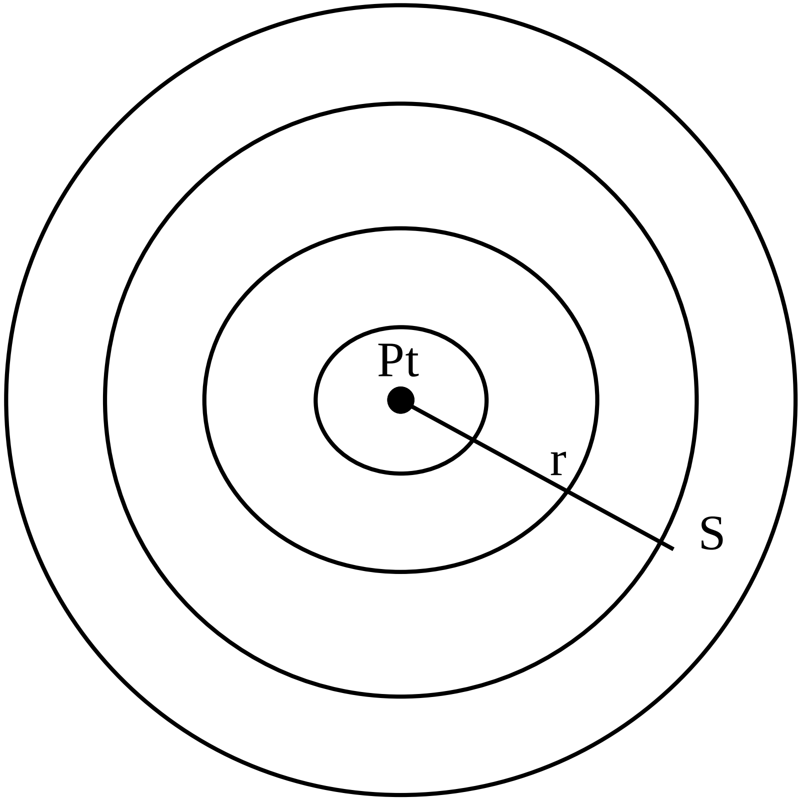
- Grouping of 2 or more antennas
  - multi-element antenna arrays
- Antenna diversity
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain
    - cophasing needed to avoid cancellation





Radio and propagation [PP]

- Wireless = Radio
- Consider an radio transmitter that radiates equally in all directions.
- Wavefronts will be spherical.
- Power is evenly spread over the surface of a sphere.
- Received power at point S is a function of transmit power, antenna gains, distance and the frequency of operation.
- Pr is proportional to $1/r^2$

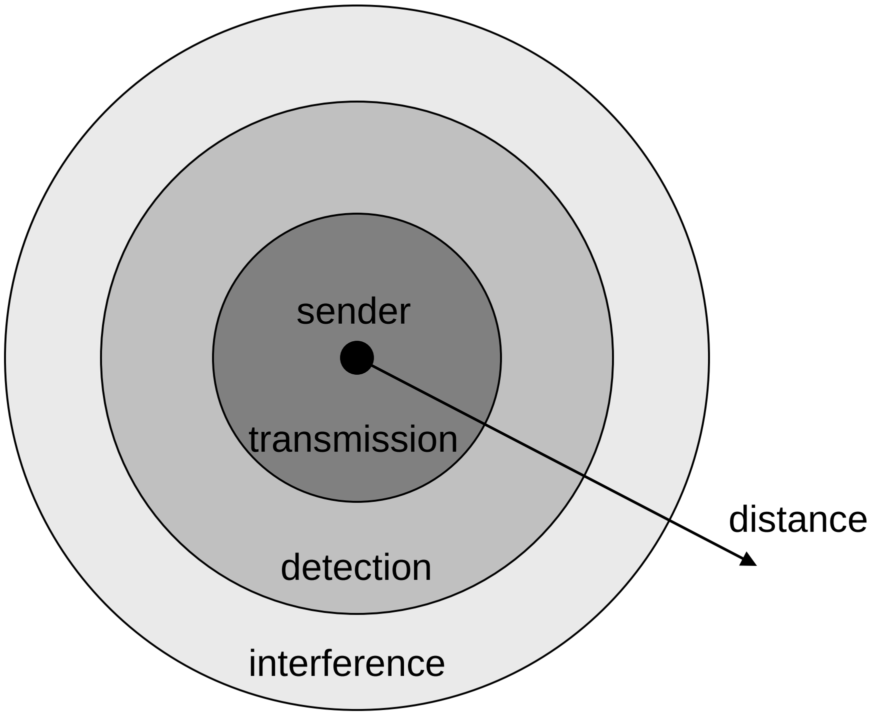


Signal propagation ranges

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



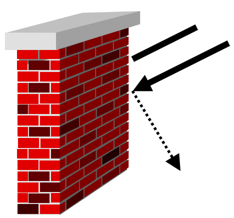
Signal propagation

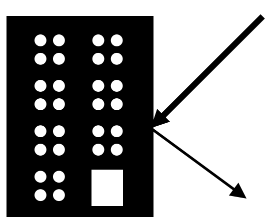
Propagation in free space always like light (straight line)

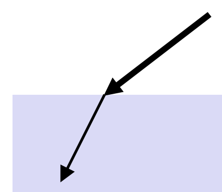
Receiving power proportional to $1/d^2$ in vacuum – much more in real environments
(d = distance between sender and receiver)

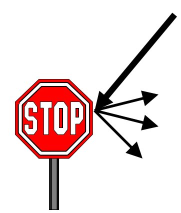
Receiving power additionally influenced by

- shadowing
- reflection at large obstacles
- refraction depending on the density of a medium
- scattering at small obstacles
- Diffraction at edges
- Fading (frequency dependent)


shadowing


reflection

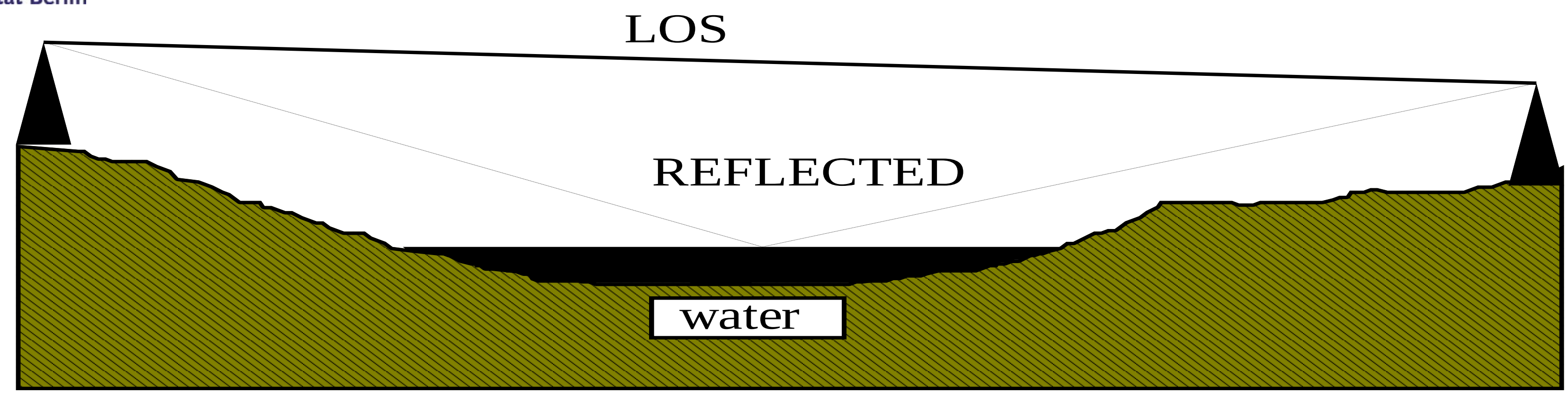

refraction



scattering


diffraction

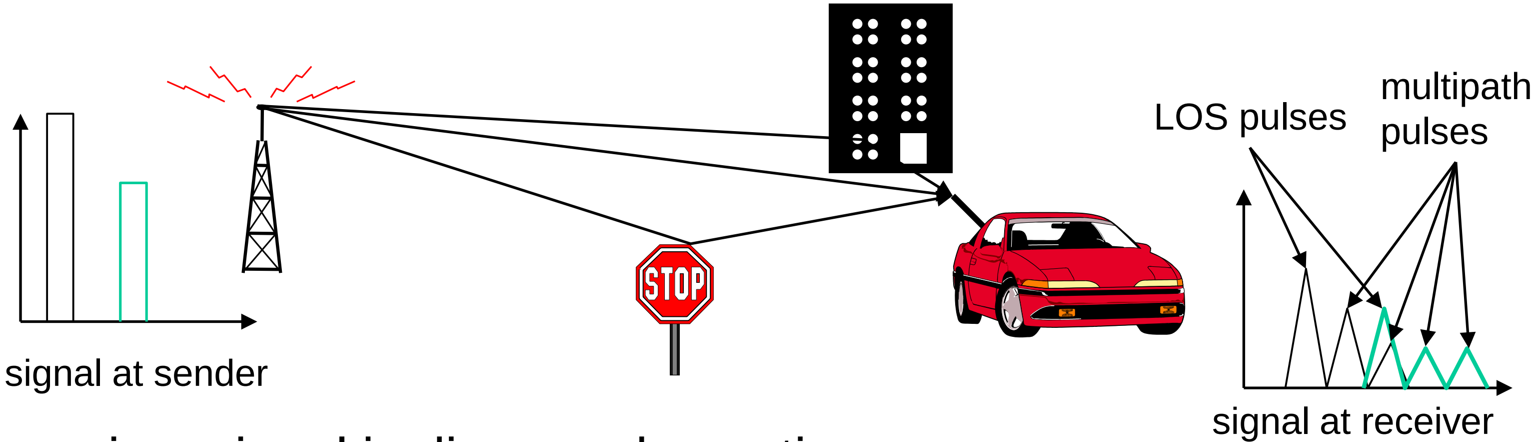
Multipath [PP]



- The existence of multiple routes for the radio signal from TX to RX leads to multiple signals arriving with different phases.
- These signals add vectorially so there can be constructive interference to give a larger signal.
- Destructive interference will give a smaller signal - multipath fading.
- LOS = Line of sight
- Small changes to the path will make the phase relationship between multipath signals vary so that fades will come and go.
- e.g. at 1GHz, a change of 15cm will move us from constructive interference to a deep fade.

Multipath propagation

Signal can take many different paths between sender and receiver due to reflection, scattering, diffraction



Time dispersion: signal is dispersed over time

➔ interference with “neighbor” symbols, Inter Symbol Interference (ISI)

The signal reaches a receiver directly and phase shifted

➔ distorted signal depending on the phases of the different parts

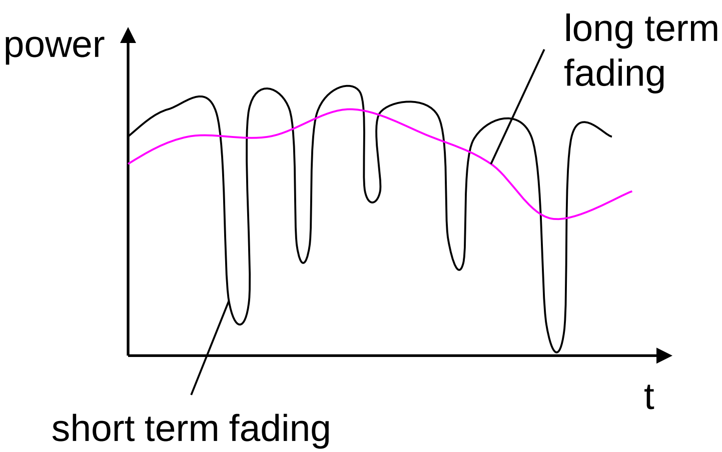
Effects of mobility

Channel characteristics change over time and location
- signal paths change
- different delay variations of different signal parts
- different phases of signal parts

➔ quick changes in the power received (short term fading)

Additional changes in
- distance to sender
- obstacles further away

➔ slow changes in the average power received (long term fading)



Fading [PP]

- Fixed point radio – quite stable, slowly varying fades
- Cellular – slow and fast fading phenomenon
- Analogue mobile – narrow band fades corrupt entire channel
- GSM – interleaving and error correction combat narrow band fading
- UMTS – wide band modulation, can tolerate up to 30% channel loss
- LTE – a user receives radio resources in the spectrum part that is not (or less) affected by interference
  - This requires a real-time knowledge of the radio channel !

Multiple Access Systems [PP]

Sharing of radio resources between many users.

central hub with more subscribers than can be fully serviced.

e.g. Fixed rural system:-

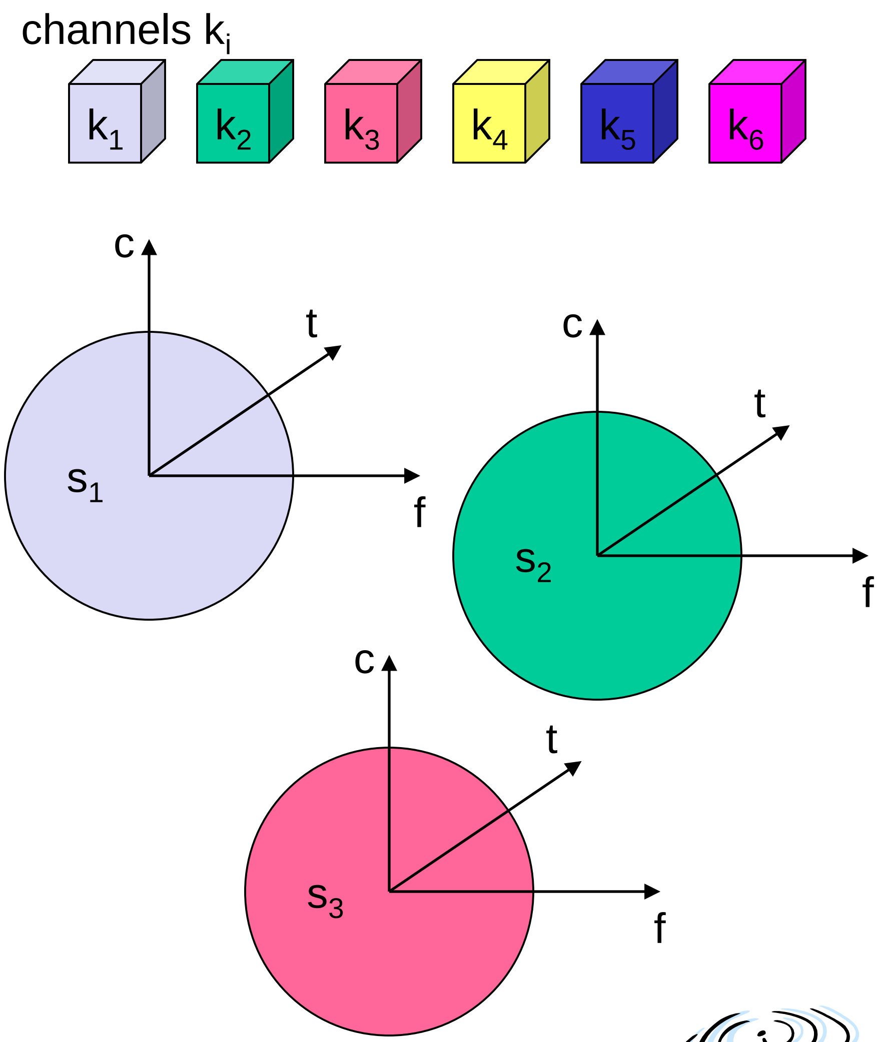
- 32 channels with 64kB/s = 2.048 MB/s data
- Can be implemented as a radio system with 32 radio channels, each 64kHz wide - each channel dedicated to a specific user for the duration of their call – this is Frequency Division Multiple Access (FDMA).
- Can be implemented as a radio system with two 2MHz wide radio channels, each with 32 time slots – this is Time Division Multiple Access (TDMA).
- Can be implemented as a radio system with two 2MHz wide radio channels, each with 32 scrambling codes – this is Code Division Multiple Access (CDMA).

GSM uses a combination of FDMA and TDMA

Multiplexing

Multiplexing in 4 dimensions

- space (s_i)
- time (t)
- frequency (f)
- code (c)



Goal: multiple use
of a shared medium

Important: guard spaces needed!

Frequency multiplex

Separation of the whole spectrum into smaller frequency bands

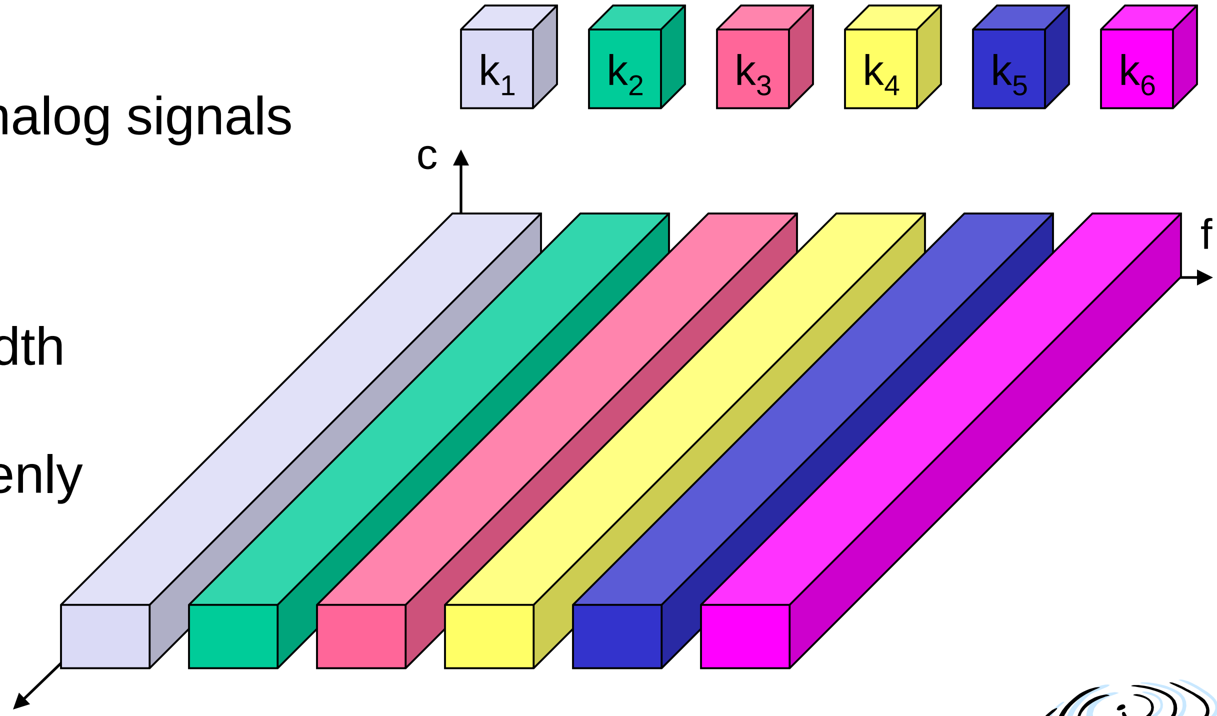
A channel gets a certain band of the spectrum for the whole time

Advantages:

- no dynamic coordination necessary
- works also for analog signals

Disadvantages:

- waste of bandwidth if the traffic is distributed unevenly
- inflexible
- guard spaces



Time multiplex

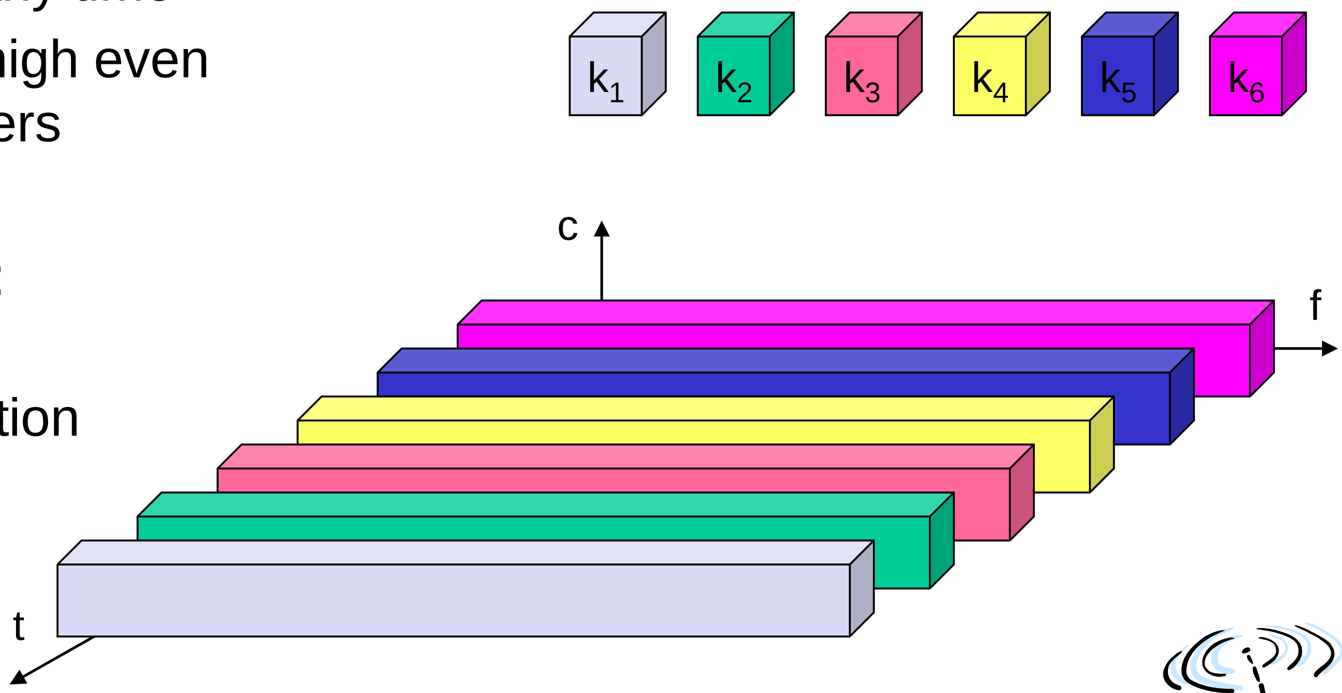
A channel gets the whole spectrum for a certain amount of time

Advantages:

- only one carrier in the medium at any time
- throughput high even for many users

Disadvantages:

- precise synchronization necessary



Time and frequency multiplex

Combination of both methods

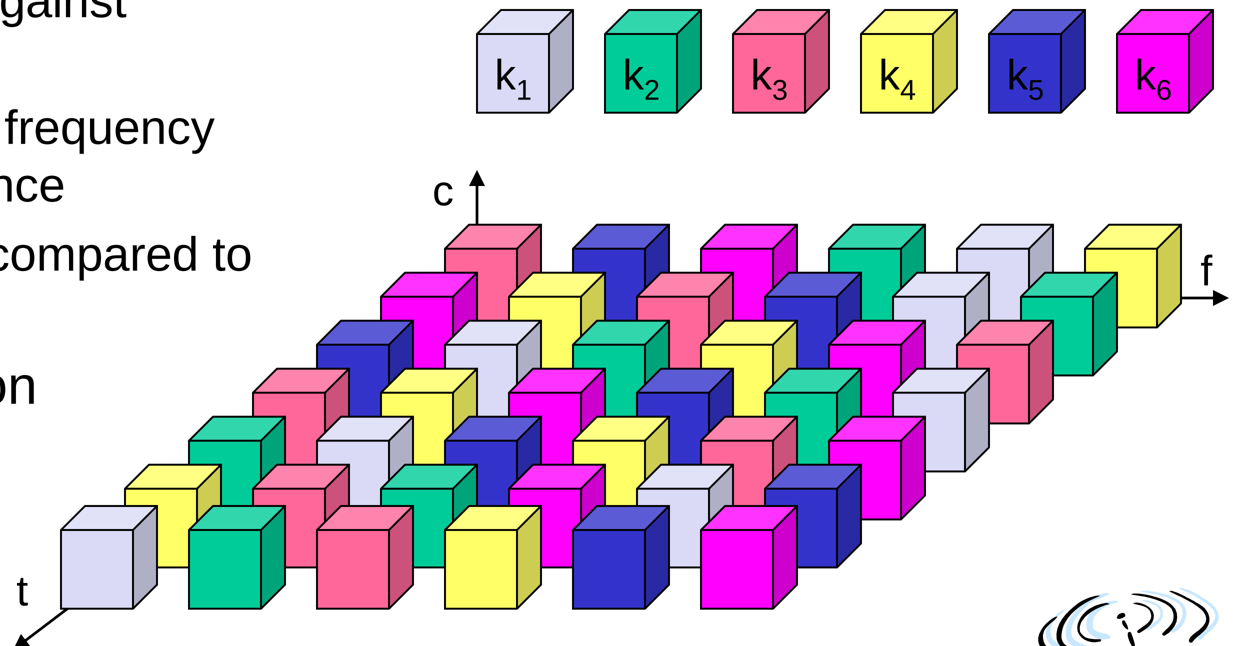
A channel gets a certain frequency band for a certain amount of time

Example: GSM

Advantages:

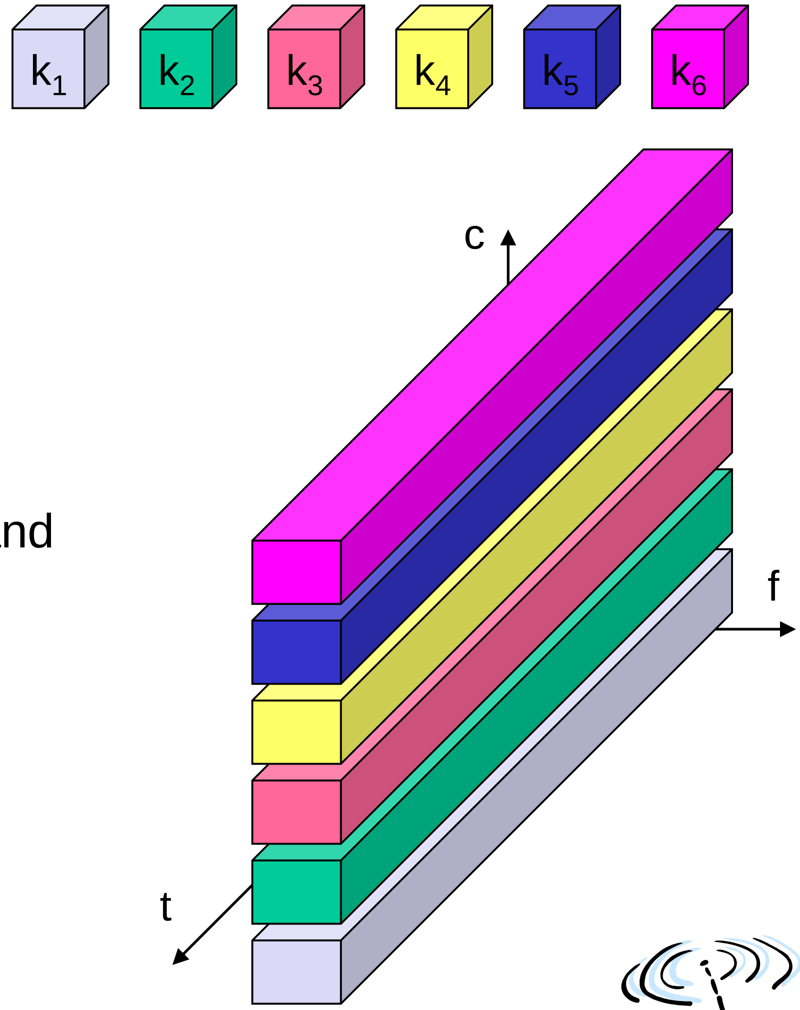
- better protection against tapping
- protection against frequency selective interference
- higher data rates compared to code multiplex

but: precise coordination required



Code multiplex

Each channel has a unique code



All channels use the same spectrum at the same time

Advantages:

- bandwidth efficient
- no coordination and synchronization necessary
- good protection against interference and tapping

Disadvantages:

- lower user data rates
- more complex signal regeneration

Implemented using spread spectrum technology

Modulation

Digital modulation

- digital data is translated into an analog signal (baseband)
- ASK, FSK, PSK - main focus in this chapter
- differences in spectral efficiency, power efficiency, robustness

Analog modulation

- shifts center frequency of baseband signal up to the radio carrier

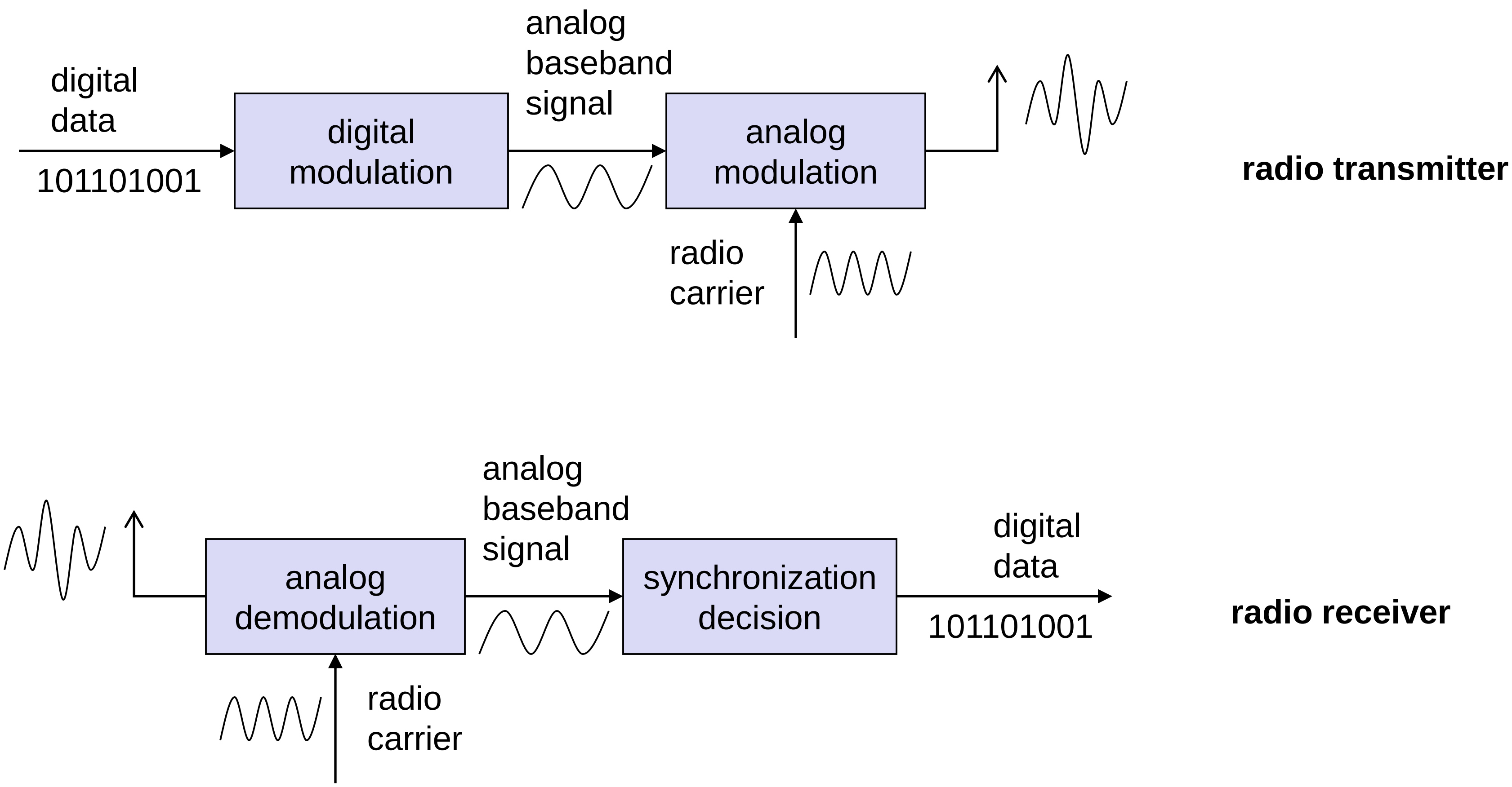
Motivation

- smaller antennas (e.g., $\lambda/4$)
- Frequency Division Multiplexing
- medium characteristics

Basic schemes

- Amplitude Modulation (AM)
- Frequency Modulation (FM)
- Phase Modulation (PM)

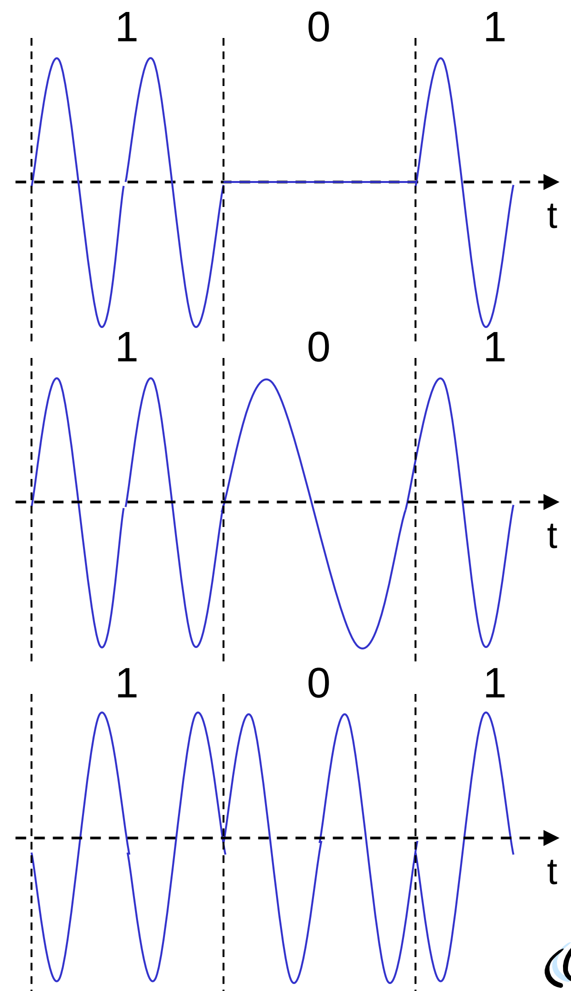
Modulation and demodulation



Digital modulation

Modulation of digital signals known as Shift Keying

- Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - more complex
  - robust against interference

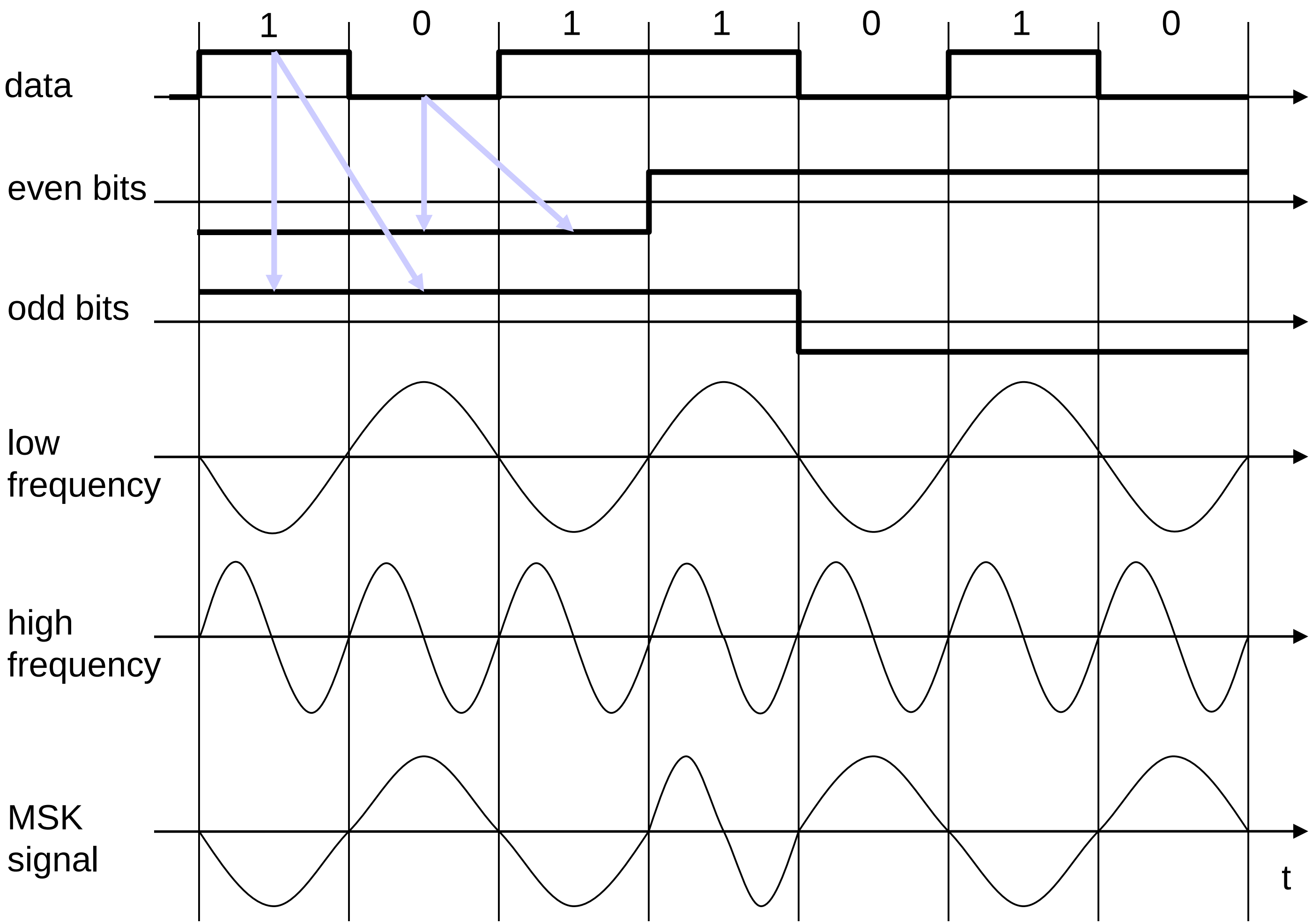


Advanced Frequency Shift Keying

- bandwidth needed for FSK depends on the distance between the carrier frequencies
- special pre-computation avoids sudden phase shifts
  ➔ MSK (Minimum Shift Keying)
- bit separated into even and odd bits, the duration of each bit is doubled
- depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
- the frequency of one carrier is twice the frequency of the other
- Equivalent to offset QPSK

- even higher bandwidth efficiency using a Gaussian low-pass filter ➔ GMSK (Gaussian MSK), used in GSM

Example of MSK



bit	
even	0 1 0 1
odd	0 0 1 1
signal value	h n n h - - + +

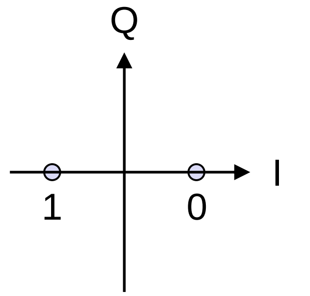
h: high frequency
n: low frequency
+: original signal
-: inverted signal

No phase shifts!

Advanced Phase Shift Keying

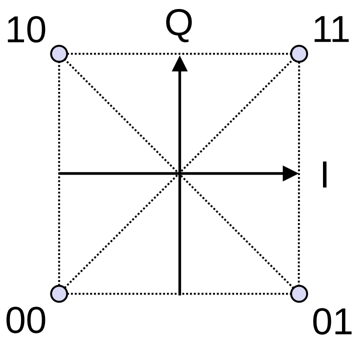
BPSK (Binary Phase Shift Keying):

- bit value 0: sine wave
- bit value 1: inverted sine wave
- very simple PSK
- low spectral efficiency
- robust, used e.g. in satellite systems

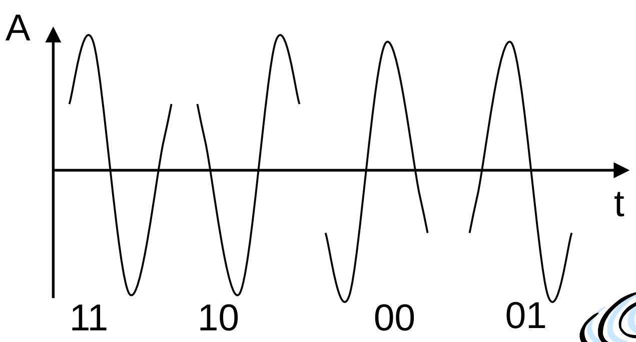


QPSK (Quadrature Phase Shift Keying):

- 2 bits coded as one symbol
- symbol determines shift of sine wave
- needs less bandwidth compared to BPSK
- more complex



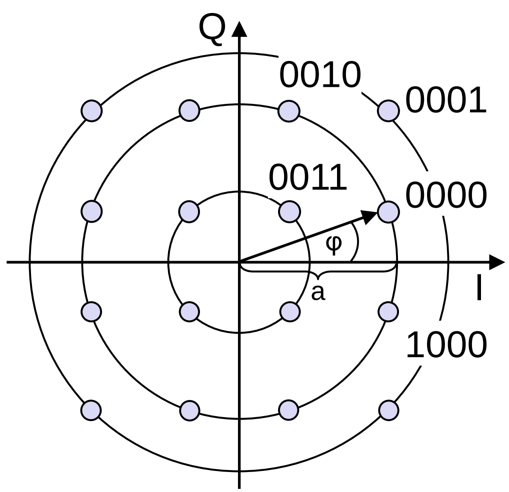
Often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK (IS-136, PHS)



Quadrature Amplitude Modulation

Quadrature Amplitude Modulation (QAM): combines amplitude and phase modulation

- it is possible to code n bits using one symbol
- 2^n discrete levels, n=2 identical to QPSK
- bit error rate increases with n, but less errors compared to comparable PSK schemes



Example: 16-QAM (4 bits = 1 symbol)

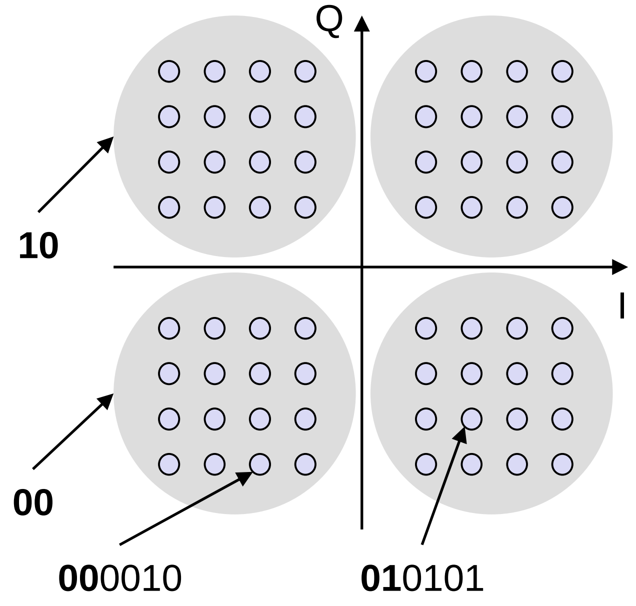
Symbols 0011 and 0001 have the same phase φ, but different amplitude a. 0000 and 1000 have different phase, but same amplitude.

➔ used in standard 9600 bit/s modems

Hierarchical Modulation

DVB-T modulates two separate data streams onto a single DVB-T stream

- High Priority (HP) embedded within a Low Priority (LP) stream
- Multi carrier system, about 2000 or 8000 carriers
- QPSK, 16 QAM, 64QAM
- Example: 64QAM
  - good reception: resolve the entire 64QAM constellation
  - poor reception, mobile reception: resolve only QPSK portion
  - 6 bit per QAM symbol, 2 most significant determine QPSK
  - HP service coded in QPSK (2 bit), LP uses remaining 4 bit

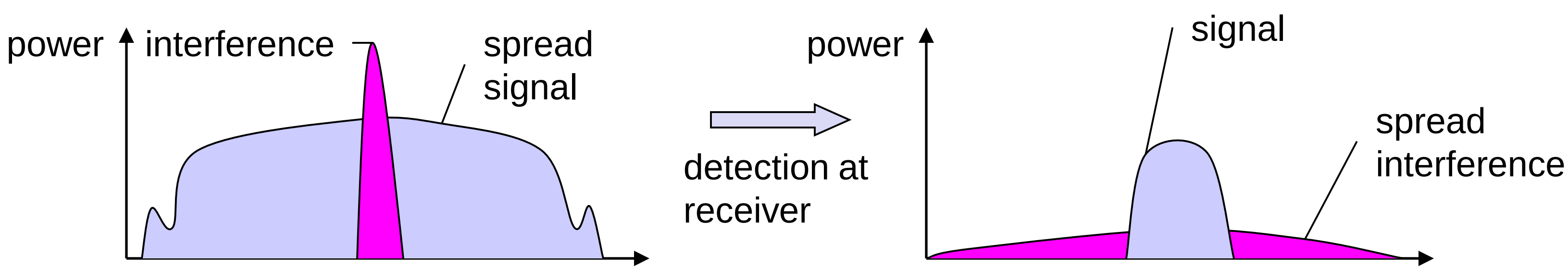


Spread spectrum technology

Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference

Solution: spread the narrow band signal into a broad band signal using a special code

protection against narrow band interference



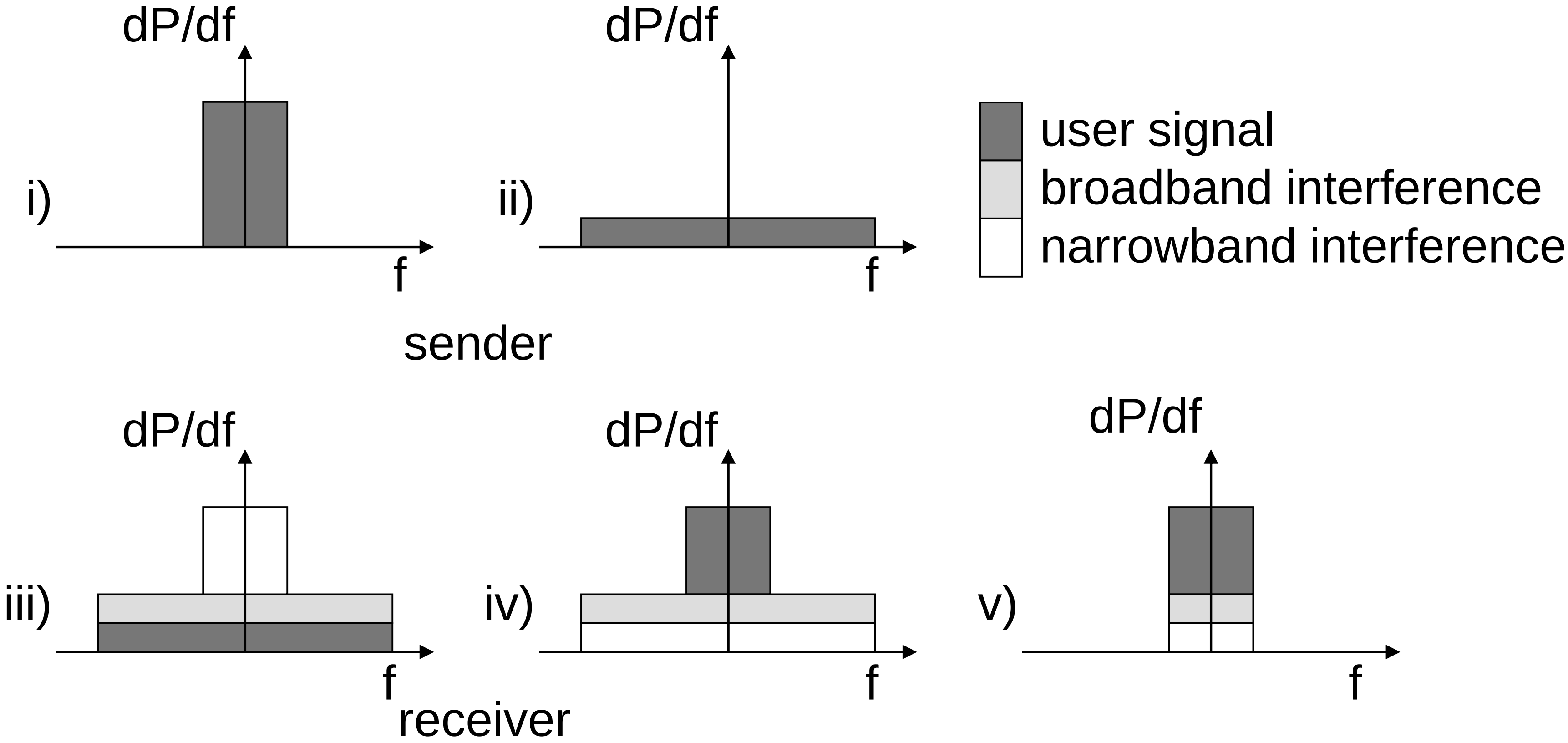
protection against narrowband interference

Side effects:

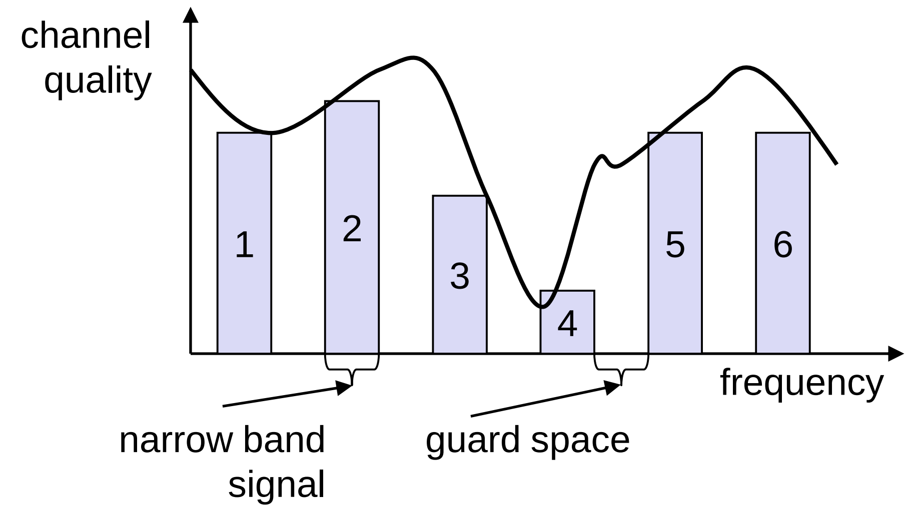
- coexistence of several signals without dynamic coordination
- tap-proof

Alternatives: Direct Sequence, Frequency Hopping

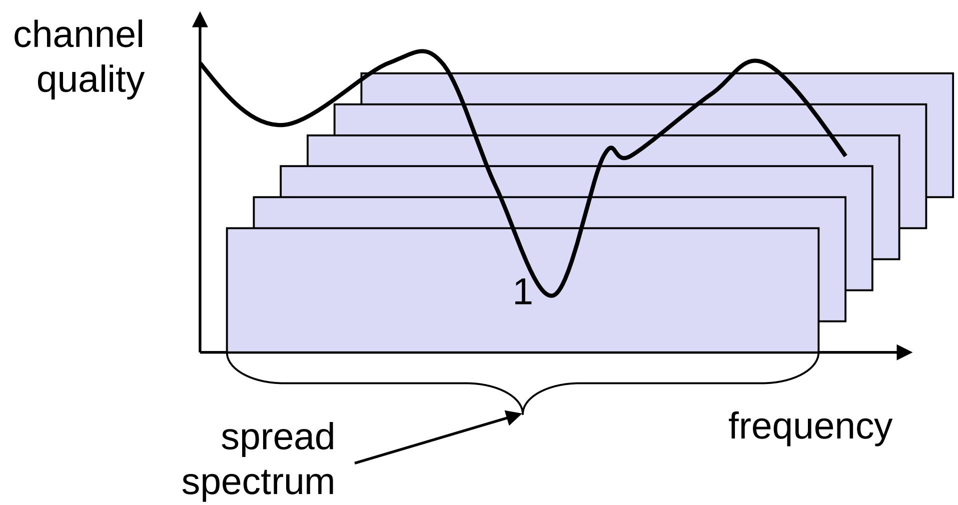
Effects of spreading and interference



Spreading and frequency selective fading



narrowband channels



spread spectrum channels

DSSS (Direct Sequence Spread Spectrum) I

XOR of the signal with pseudo-random number (chipping sequence)

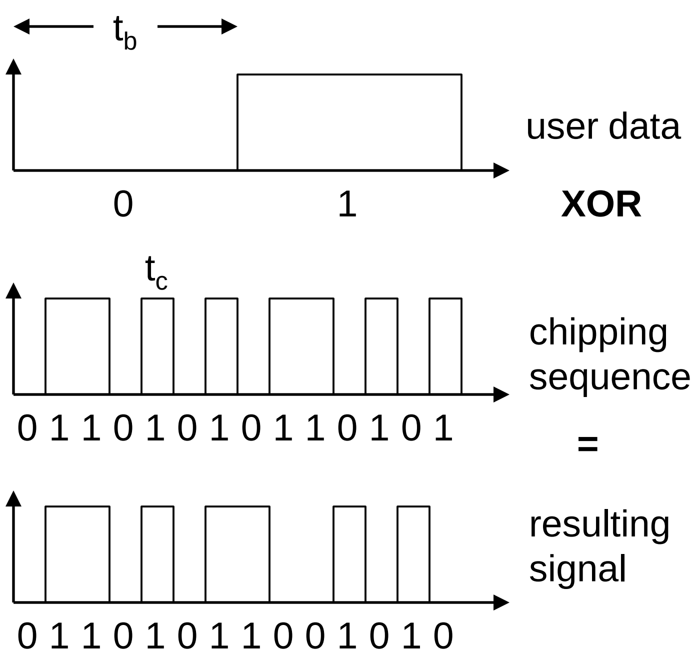
- many chips per bit (e.g., 128) result in higher bandwidth of the signal

Advantages

- reduces frequency selective fading
- in cellular networks
  - base stations can use the same frequency range
  - several base stations can detect and recover the signal
  - soft handover

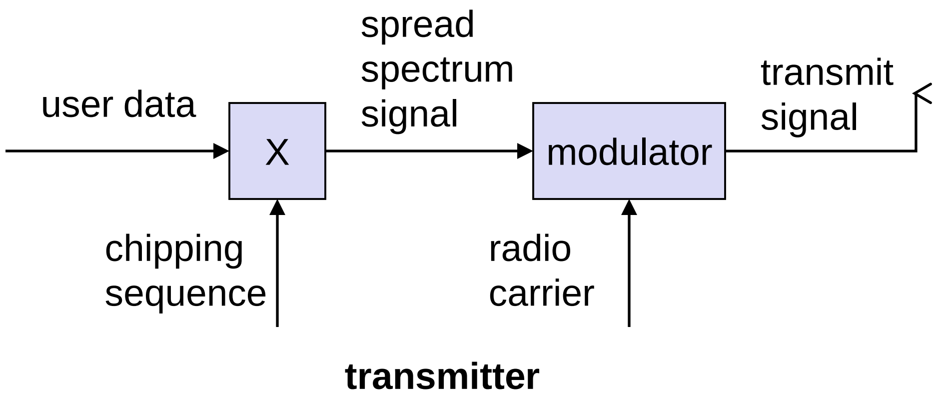
Disadvantages

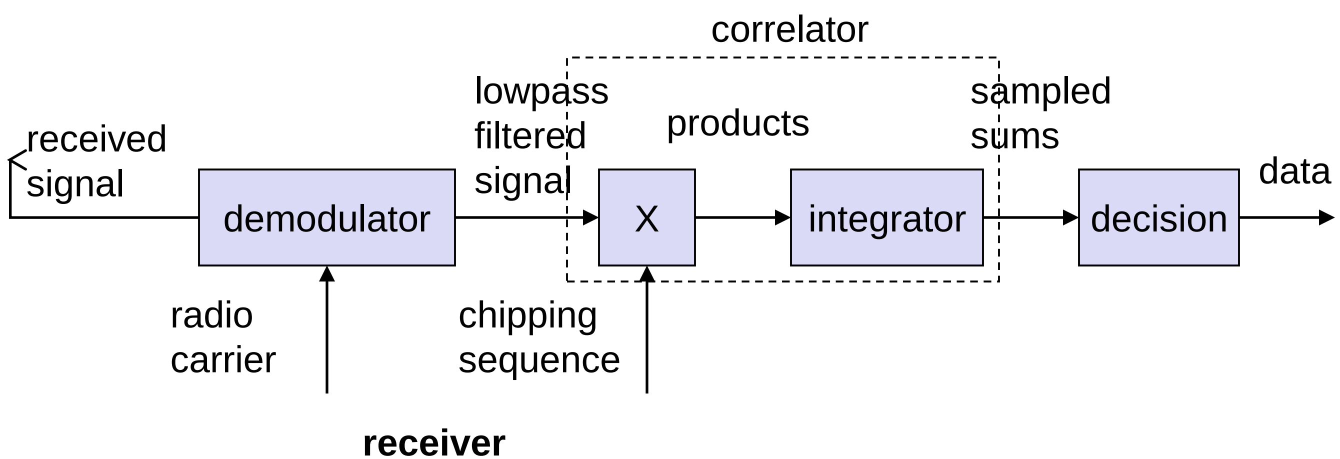
- precise power control necessary



t_b: bit period
t_c: chip period

DSSS (Direct Sequence Spread Spectrum) II





FHSS (Frequency Hopping Spread Spectrum) I

Discrete changes of carrier frequency

- sequence of frequency changes determined via pseudo random number sequence

Two versions

- Fast Hopping:
  several frequencies per user bit
- Slow Hopping:
  several user bits per frequency

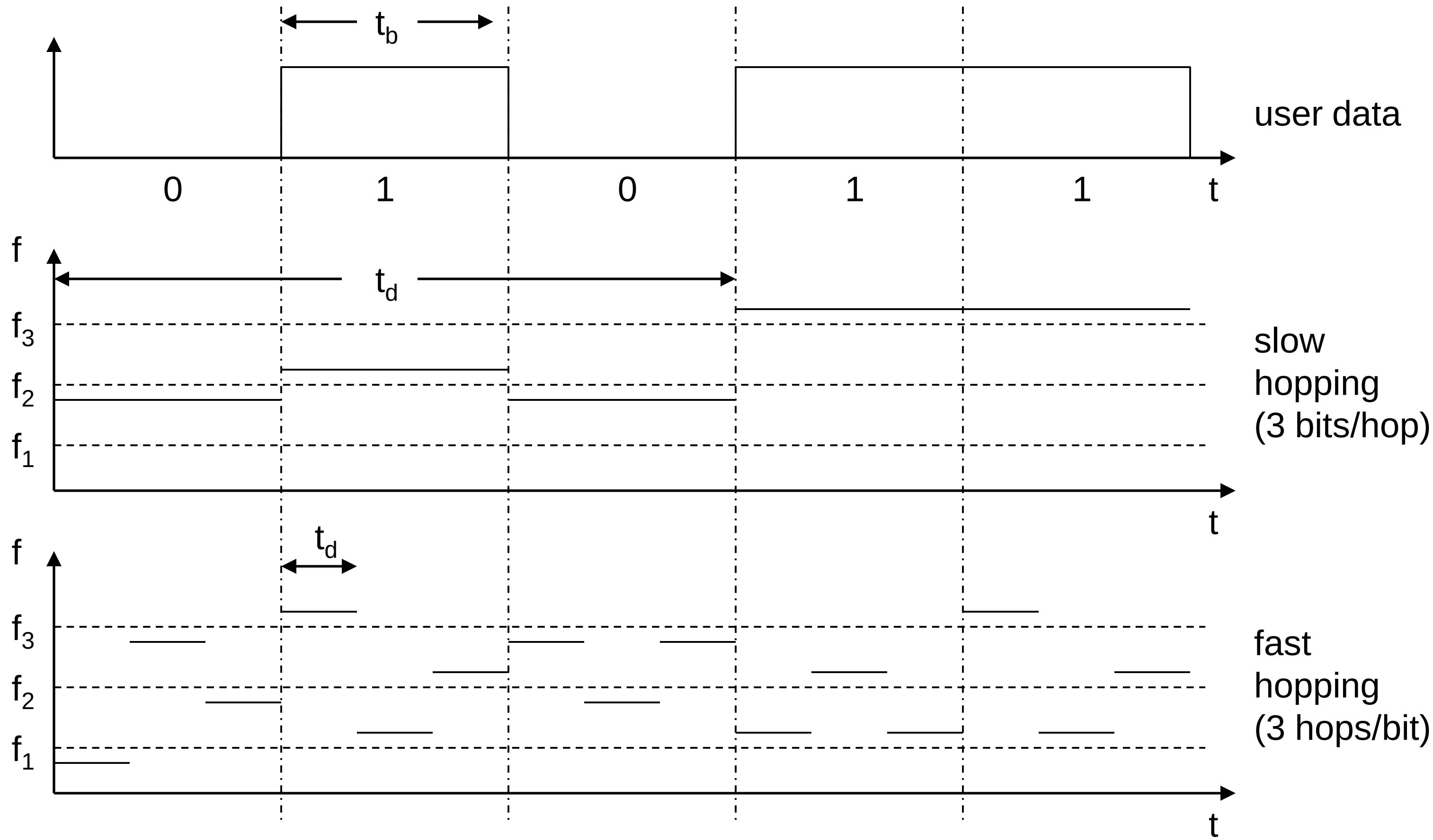
Advantages

- frequency selective fading and interference limited to short period
- simple implementation
- uses only small portion of spectrum at any time

Disadvantages

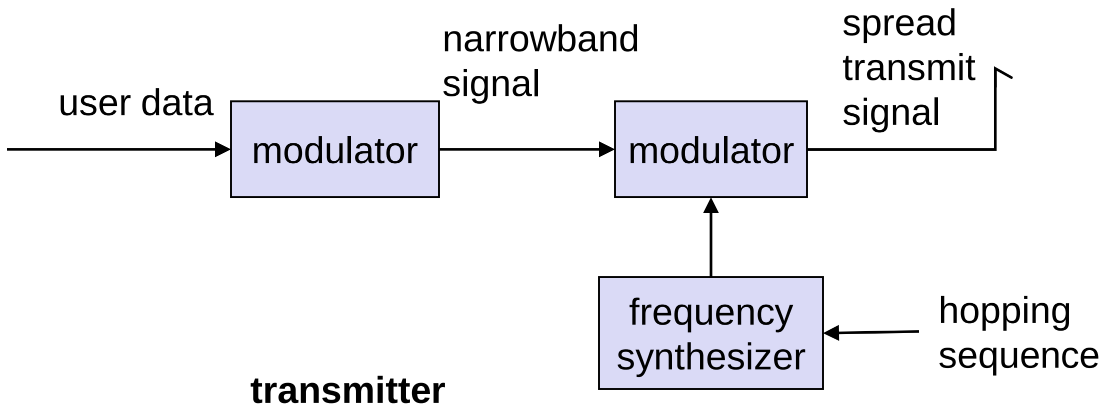
- not as robust as DSSS
- simpler to detect

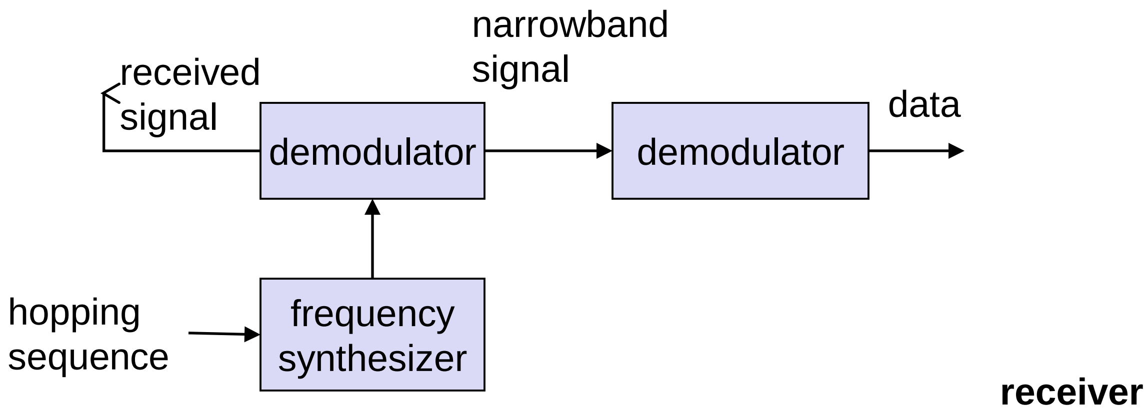
FHSS (Frequency Hopping Spread Spectrum) II



t_b: bit period t_d: dwell time

FHSS (Frequency Hopping Spread Spectrum) III





Cell structure

Implements space division multiplex: base station covers a certain transmission area (cell)

Mobile stations communicate only via the base station

Advantages of cell structures:

- higher capacity, higher number of users
- less transmission power needed
- more robust, decentralized
- base station deals with interference, transmission area etc. locally

Problems:

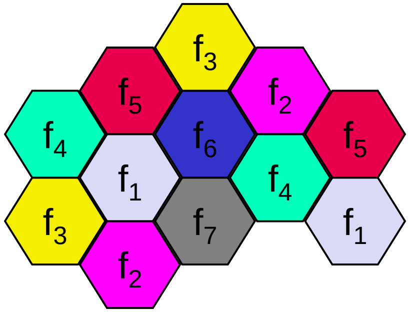
- fixed network needed for the base stations
- handover (changing from one cell to another) necessary
- interference with other cells

Cell sizes from some 100 m in cities to, e.g., 35 km on the country side (GSM) - even less for higher frequencies

Frequency planning I

Frequency reuse only with a certain distance between the base stations

Standard model using 7 frequencies:



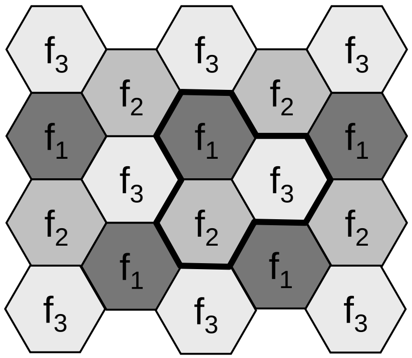
Fixed frequency assignment:

- certain frequencies are assigned to a certain cell
- problem: different traffic load in different cells

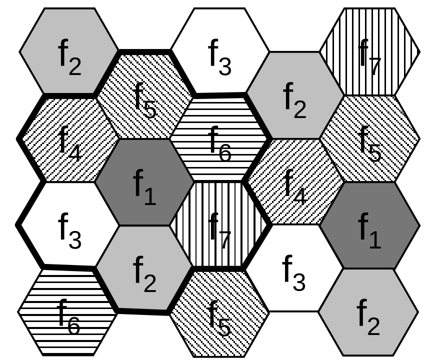
Dynamic frequency assignment:

- base station chooses frequencies depending on the frequencies already used in neighbor cells
- more capacity in cells with more traffic
- assignment can also be based on interference measurements

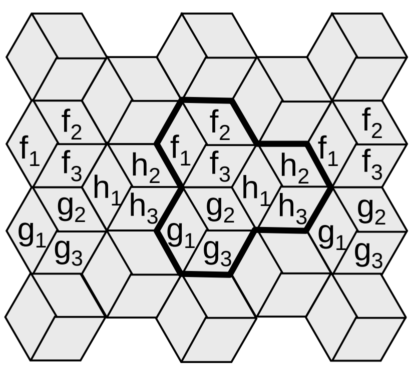
Frequency planning II



3 cell cluster



7 cell cluster



3 cell cluster
with 3 sector antennas

Cell breathing

- CDM systems: cell size depends on current load
- Additional traffic appears as noise to other users
- If the noise level is too high users drop out of cells