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Kiel University
Christian-Albrechts-Universität zu Kiel

DS Research Group
Distributed Systems

Internet of Things & Wireless Networks

Wireless Transmission - Lectures 3 & 4

(Matches Chapter 2 in the Course Book)

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Lecture today via Video from Jochen Schiller, FU Berlin

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IoT & Wireless Networks

Mobile Communications
Chapter 2: Wireless Transmission

Frequencies

Signals, antennas, signal propagation, MIMO

Multiplexing, Cognitive Radio

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
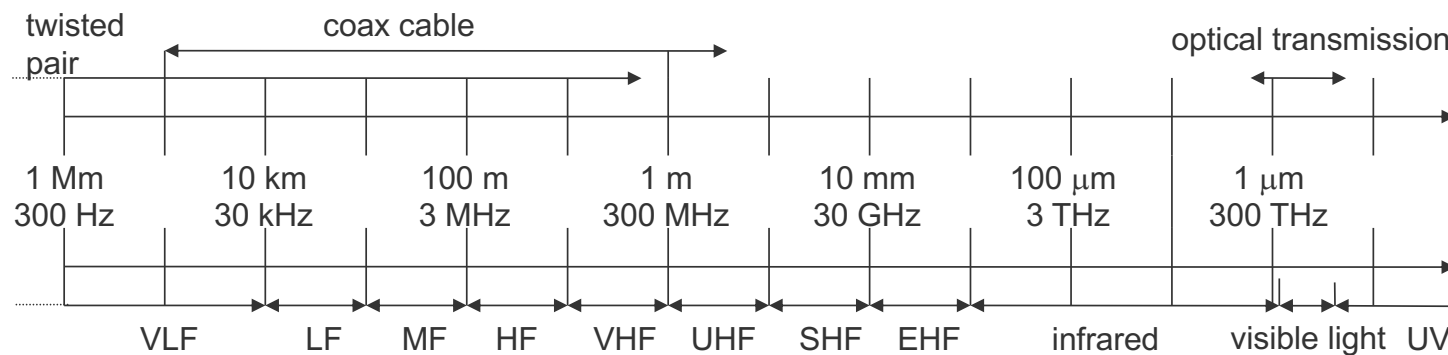
SHF = Super High Frequency

EHF = Extra High Frequency

UV = Ultraviolet Light

Frequency and wave length

- $\lambda = c/f$

- wave length λ, speed of light $c \cong 3\times10^8$ m/s, frequency f

twisted pair	coax cable									optical transmission	
1 Mm 300 Hz	10 km 30 kHz	100 m 3 MHz		1 m 300 MHz		10 mm 30 GHz	100 μm 3 THz		1 μm 300 THz		
	VLF	LF	MF	HF	VHF	UHF	SHF	EHF	infrared	visible light	UV

Example 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, 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, e.g., water (dielectric heating, see microwave oven)
  - weather dependent fading, signal loss caused by heavy rainfall etc.

Frequencies and regulations

Examples	Europe	USA	Japan
Cellular networks	**GSM** 880-915, 925-960, 1710-1785, 1805-1880 **UMTS** 1920-1980, 2110-2170 **LTE** 791-821, 832-862, 2500-2690	**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

In general: ITU-R holds auctions for new frequencies, manages frequency bands worldwide (WRC, World Radio Conferences); 3GPP specific: see e.g. 3GPP TS 36.101 V11.4.0 (2013-03)

Great flexibility with LTE

See, e.g., en.wikipedia.org/wiki/LTE_frequency_bands or 3GPP TS 36.101 E-UTRA: User Equipment (UE) radio transmission and reception

E-UTRA Band	Duplex-Mode	ƒ (MHz)	Common name	Included in (subset of) Band	Uplink (UL) BS receive UE transmit (MHz)	Downlink (DL) BS transmit UE receive (MHz)	Duplex spacing (MHz)	Channel bandwidths (MHz)
1	FDD	2100	IMT	65	1920 − 1980	2110 − 2170	190	5, 10, 15, 20
2	FDD	1900	PCS blocks A-F	25	1850 − 1910	1930 − 1990	80	1.4, 3, 5, 10, 15, 20
3	FDD	1800	DCS		1710 − 1785	1805 − 1880	95	1.4, 3, 5, 10, 15, 20
4	FDD	1700	AWS blocks A-F (AWS-1)	66	1710 − 1755	2110 − 2155	400	1.4, 3, 5, 10, 15, 20
5	FDD	850	CLR	26	824 − 849	869 − 894	45	1.4, 3, 5, 10
7	FDD	2600	IMT-E		2500 − 2570	2620 − 2690	120	5, 10, 15, 20
8	FDD	900	E-GSM		880 − 915	925 − 960	45	1.4, 3, 5, 10
10	FDD	1700	Extended AWS blocks A-I	66	1710 − 1770	2110 − 2170	400	5, 10, 15, 20
11	FDD	1500	Lower PDC		1427.9 − 1447.9	1475.9 − 1495.9	48	5, 10
70	FDD	1700	AWS-3 A1/B1 + EPCS H		1695 − 1710	1995 − 2020	295 − 300 [5]	5, 10, 15
71	FDD	600	USDD 600		663 − 698	617 − 652	46	5, 10, 15, 20

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)
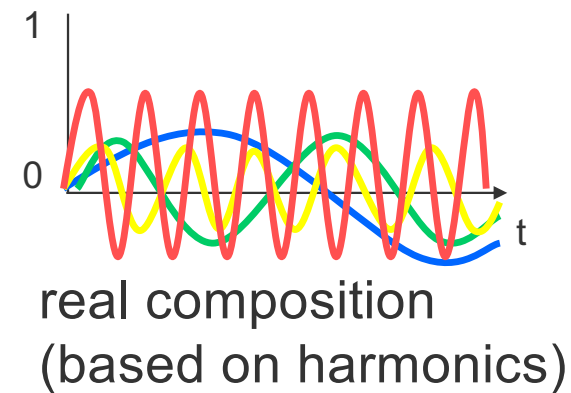
Signals II

Different representations of signals

- amplitude (amplitude domain)

- frequency spectrum (frequency domain)

- constellation diagram (amplitude M and phase φ in polar coordinates)
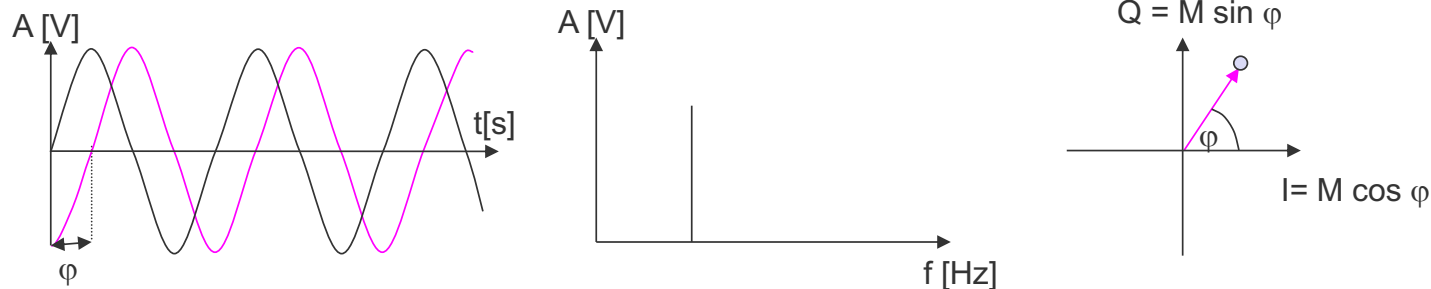
Composed signals transferred into frequency domain using Fourier transformation

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
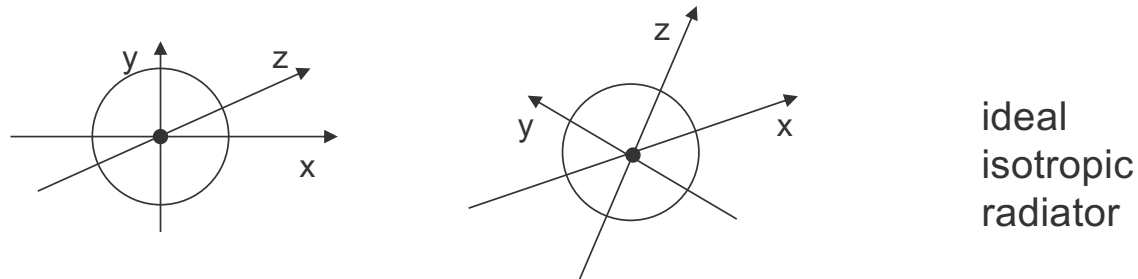
Antennas: simple dipoles

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

Example: Radiation pattern of a simple Hertzian dipole

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

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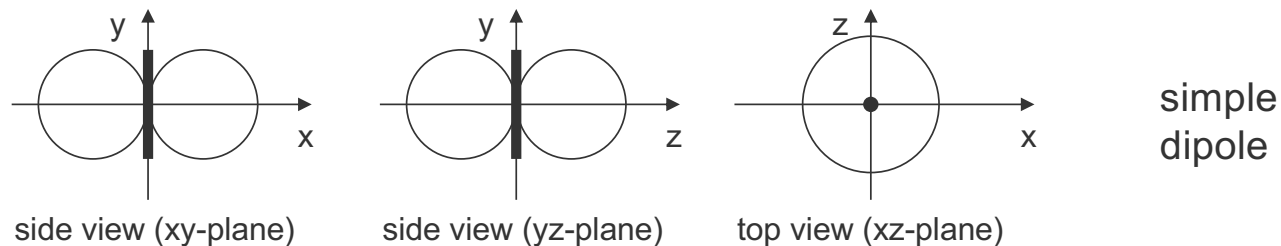
Gain: maximum power in the direction of the main lobe compared to the power of an isotropic radiator (with the same average power)

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
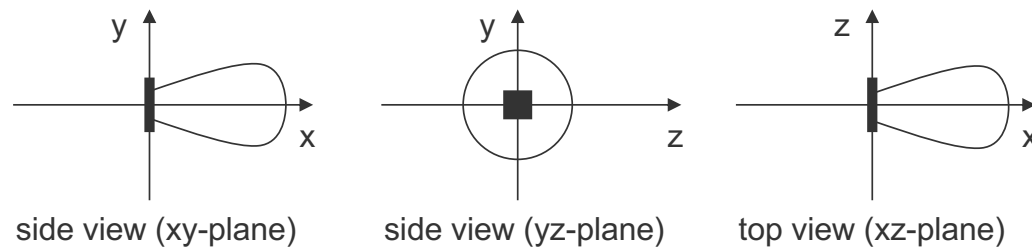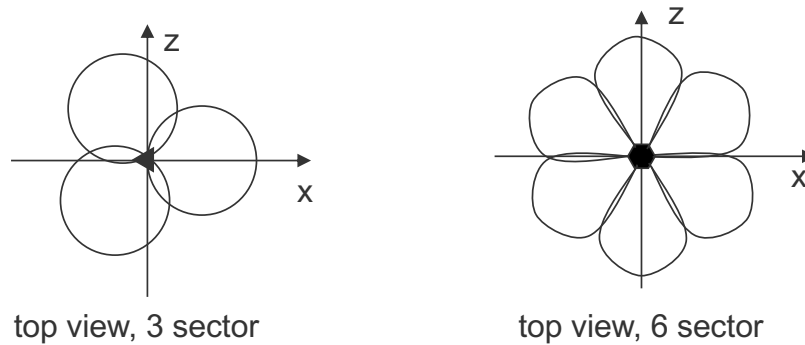
top view, 3 sector   top view, 6 sector   sectorized antenna

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
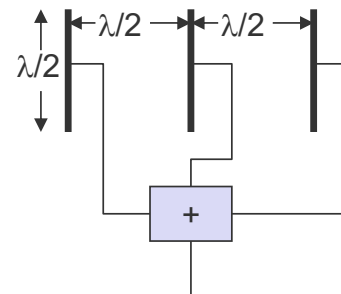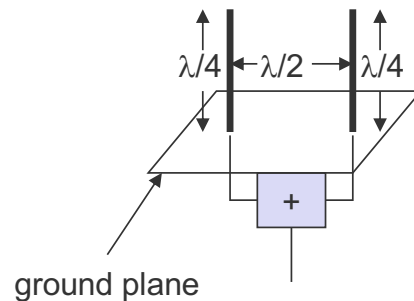
MIMO

Multiple-Input Multiple-Output
- Use of several antennas at receiver and transmitter
- Increased data rates and transmission range without additional transmit power or bandwidth via higher spectral efficiency, higher link robustness, reduced fading

Examples
- IEEE 802.11n, LTE, HSPA+, …

Functions
- "Beamforming": emit the same signal from all antennas to maximize signal power at receiver antenna
- Spatial multiplexing: split high-rate signal into multiple lower rate streams and transmit over different antennas
- Diversity coding: transmit single stream over different antennas with (near) orthogonal codes

t_1

t_3

3

t_2

sender

2

Time of flight
$t_2 = t_1 + d_2$
$t_3 = t_1 + d_3$

Sending time
1: t_0
2: $t_0 - d_2$
3: $t_0 - d_3$

receiver
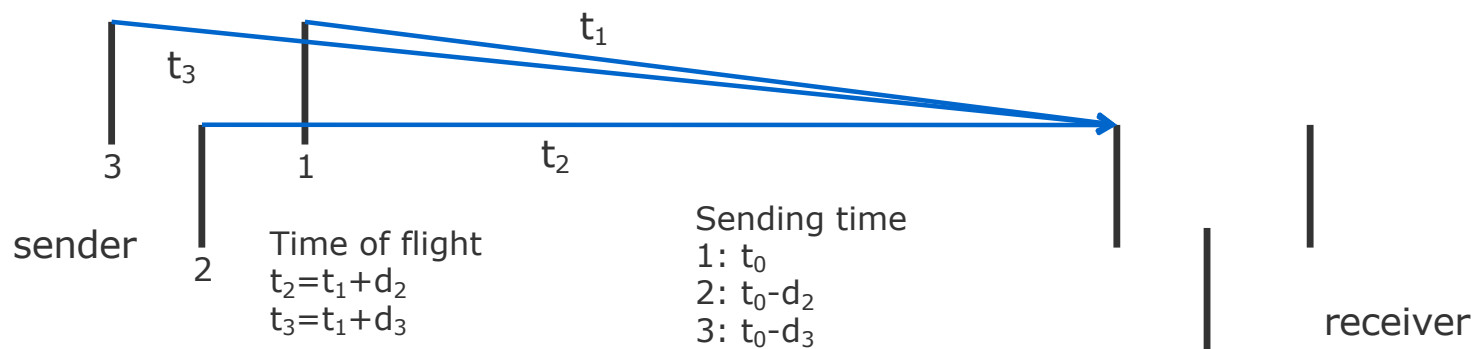
Signal propagation ranges

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
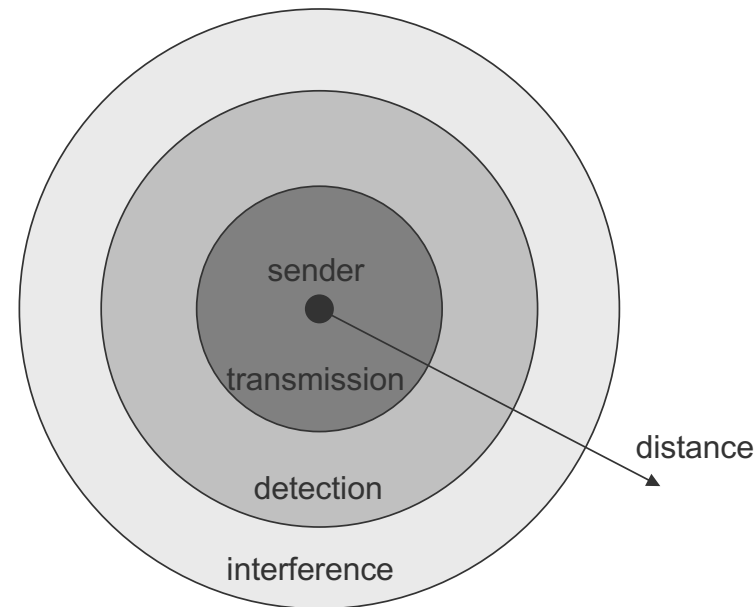
Warning: figure misleading – bizarre shaped, time-varying ranges in reality!

Signal propagation

Propagation in free space always like light (straight line)

Receiving power proportional to $1/d^2$ in vacuum – much more attenuation in real environments, e.g., $d^{3.5}...d^4$
(d = distance between sender and receiver)

Receiving power additionally influenced by

- fading (frequency dependent)

- shadowing

- reflection at large obstacles

- refraction depending on the density of a medium

- scattering at small obstacles

- diffraction at edges
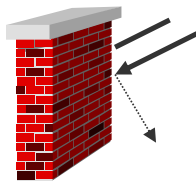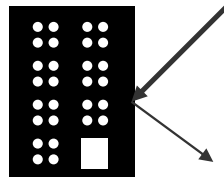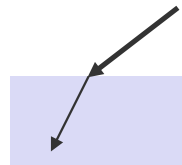
| shadowing | reflection | refraction | scattering | diffraction |

Real world examples
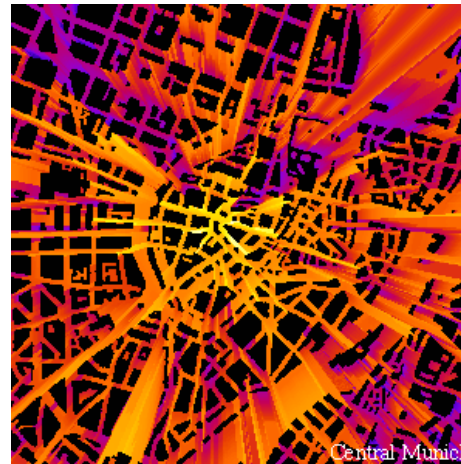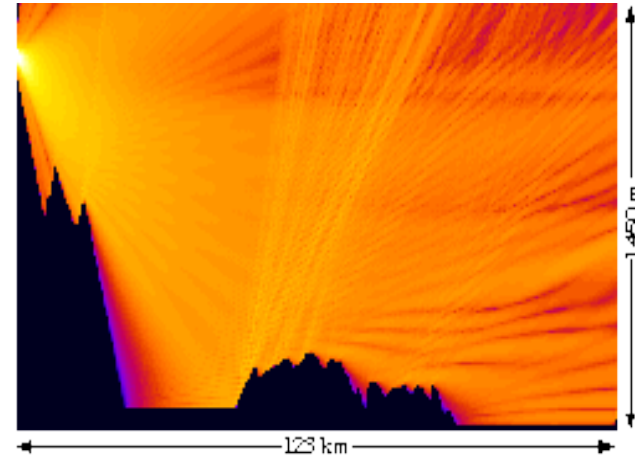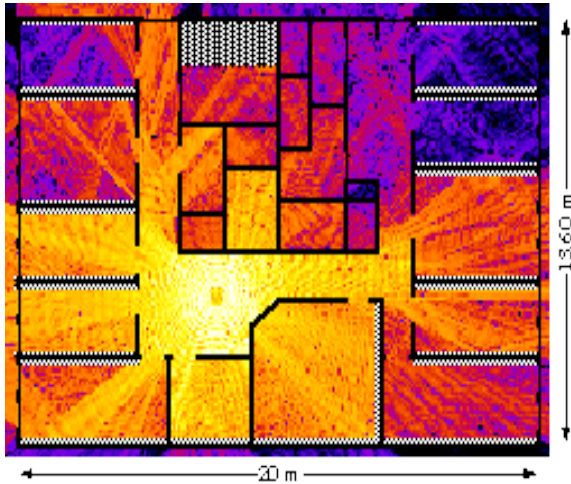
www.ihe.kit.edu/index.php

Multipath propagation

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

signal at sender

LOS
(line-of-sight)

LOS pulses

multipath pulses
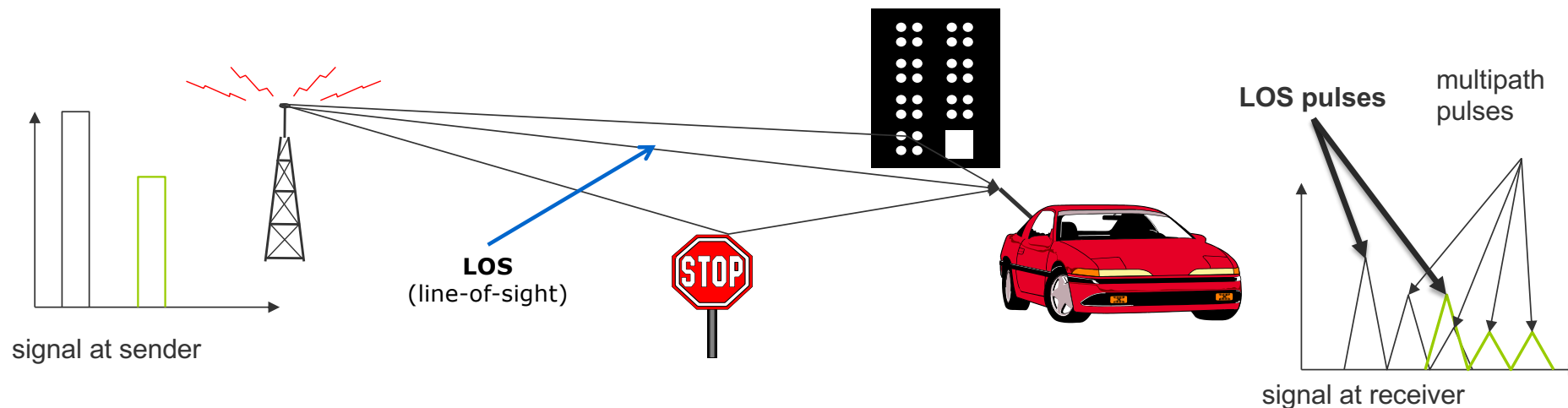
signal at receiver

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)
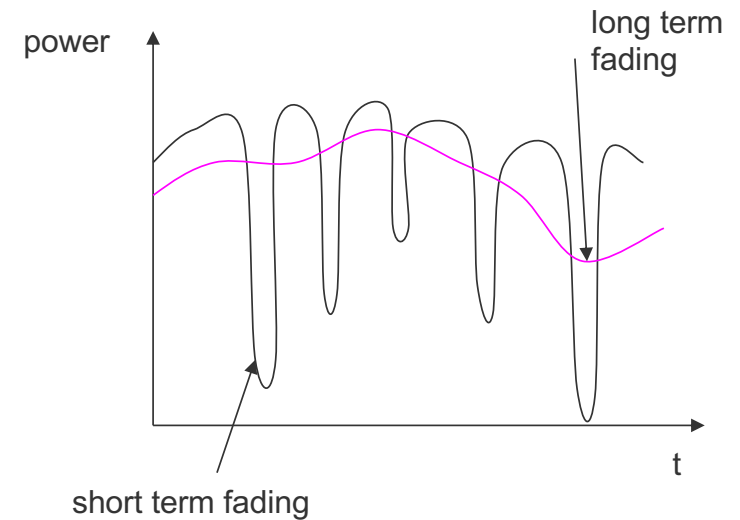
Multiplexing

Multiplexing in 4 dimensions

- space (s_i)

- time (t)

- frequency (f)

- code (c)

Goal: multiple use of a shared medium

Important: guard spaces needed!

channels k_i
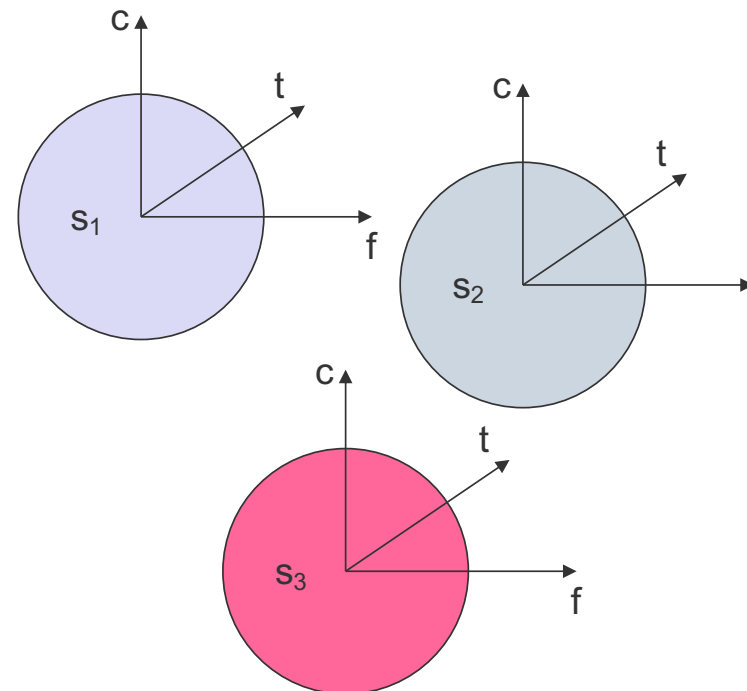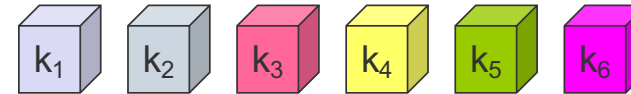
Frequency multiplex

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
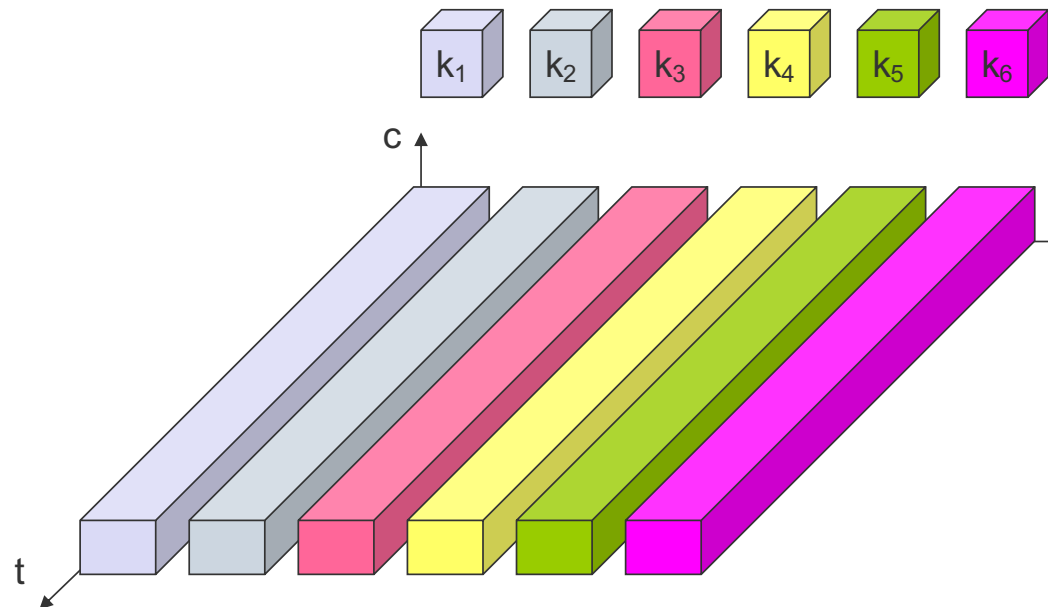
Time multiplex

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
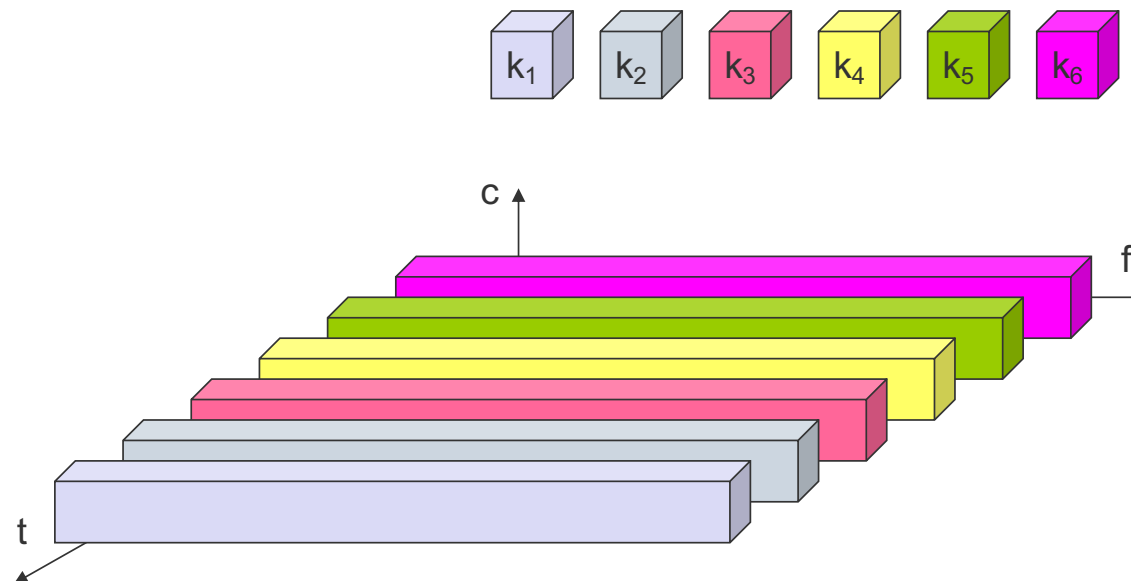
Time and frequency multiplex

Combination of both methods

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

Example: GSM, Bluetooth

Advantages
  - better protection against tapping
  - protection against frequency
    selective interference

but: precise coordination required
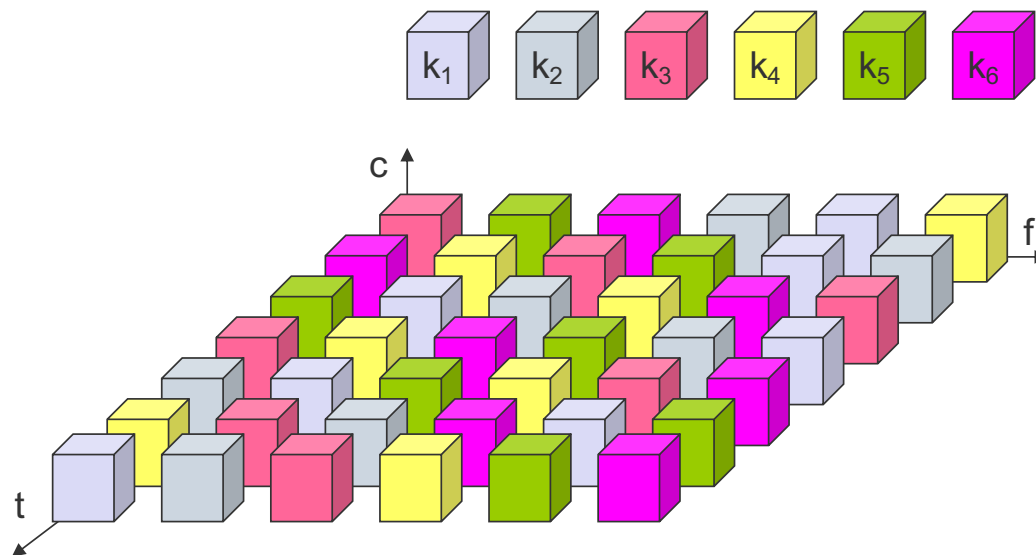
Cognitive Radio

Typically in the form of a spectrum sensing CR

- Detect unused spectrum and share with others avoiding interference
- Choose automatically best available spectrum (intelligent form of time/frequency/space multiplexing)

Distinguish

- Primary Users (PU): users assigned to a specific spectrum by e.g. regulation
- Secondary Users (SU): users with a CR to use unused spectrum

Examples

- Reuse of (regionally) unused analog TV spectrum (aka white space)
- Temporary reuse of unused spectrum e.g. of pagers, amateur radio etc.

space mux

frequency/time mux
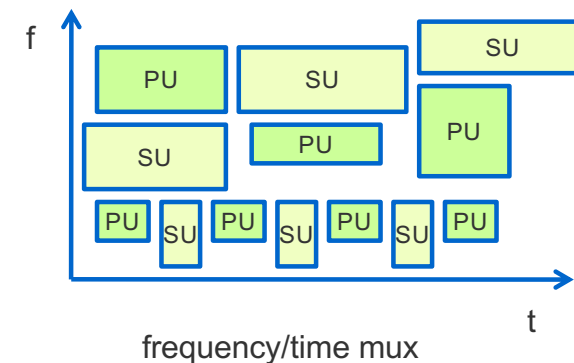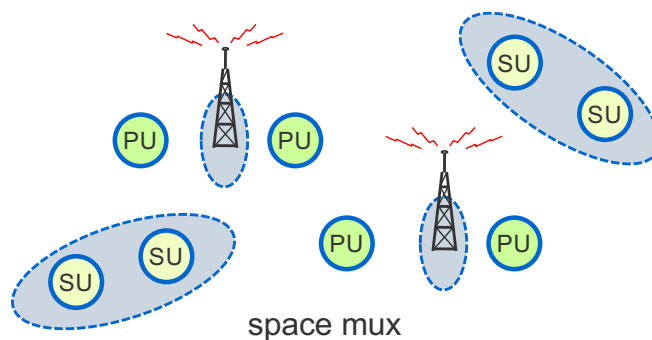
Code multiplex

Each channel has a unique code

All channels use the same spectrum
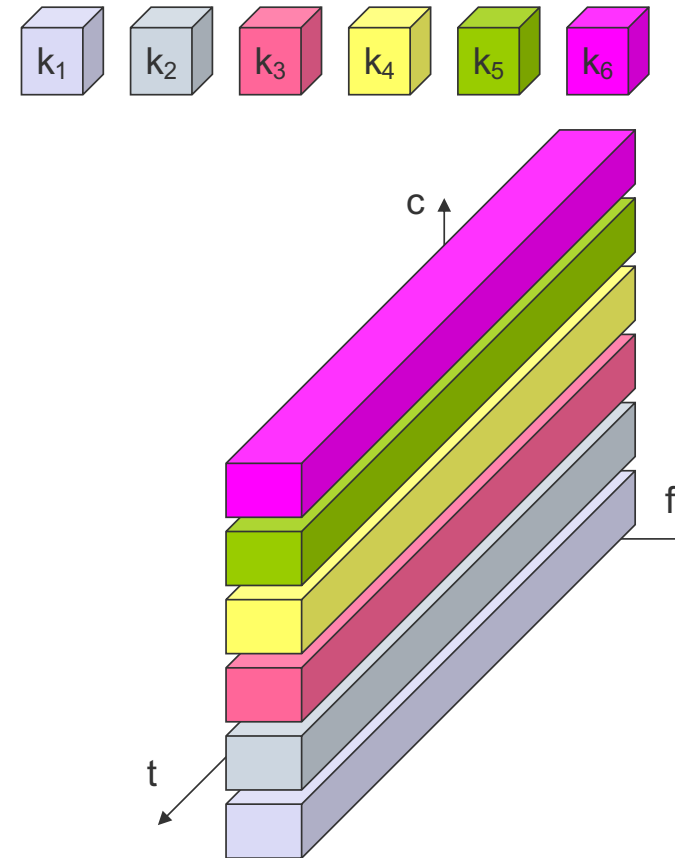at the same time

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

Disadvantages
 - varying 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
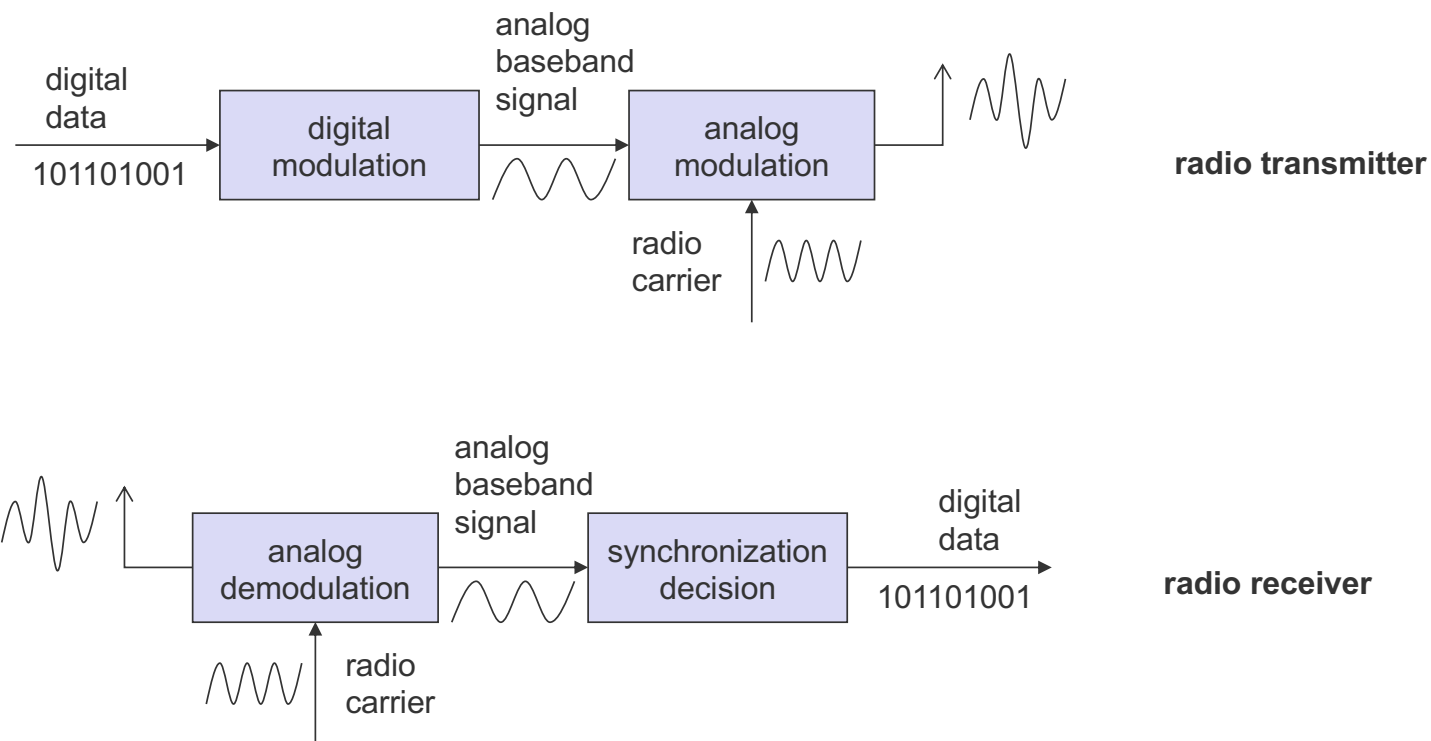
Digital modulation

Modulation of digital signals known as Shift Keying
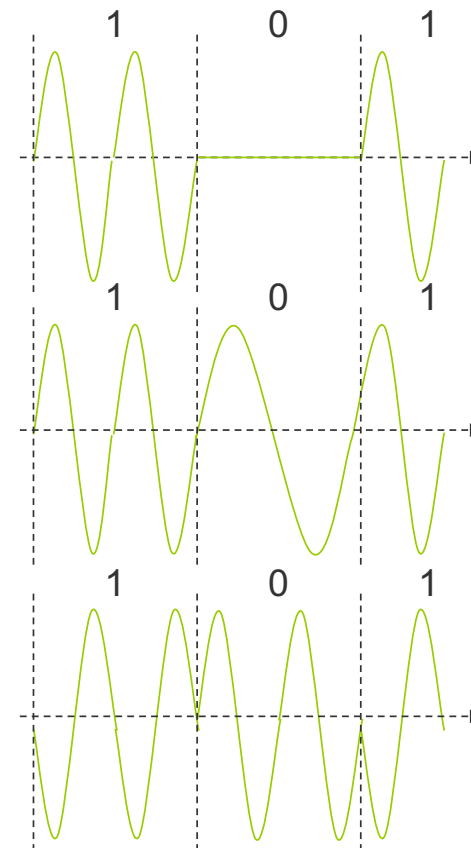
Amplitude Shift Keying (ASK):
  - very simple
  - low bandwidth requirements
  - very susceptible to interference

Frequency Shift Keying (FSK):
  - needs larger bandwidth

Phase Shift Keying (PSK):
  - more complex
  - robust against interference
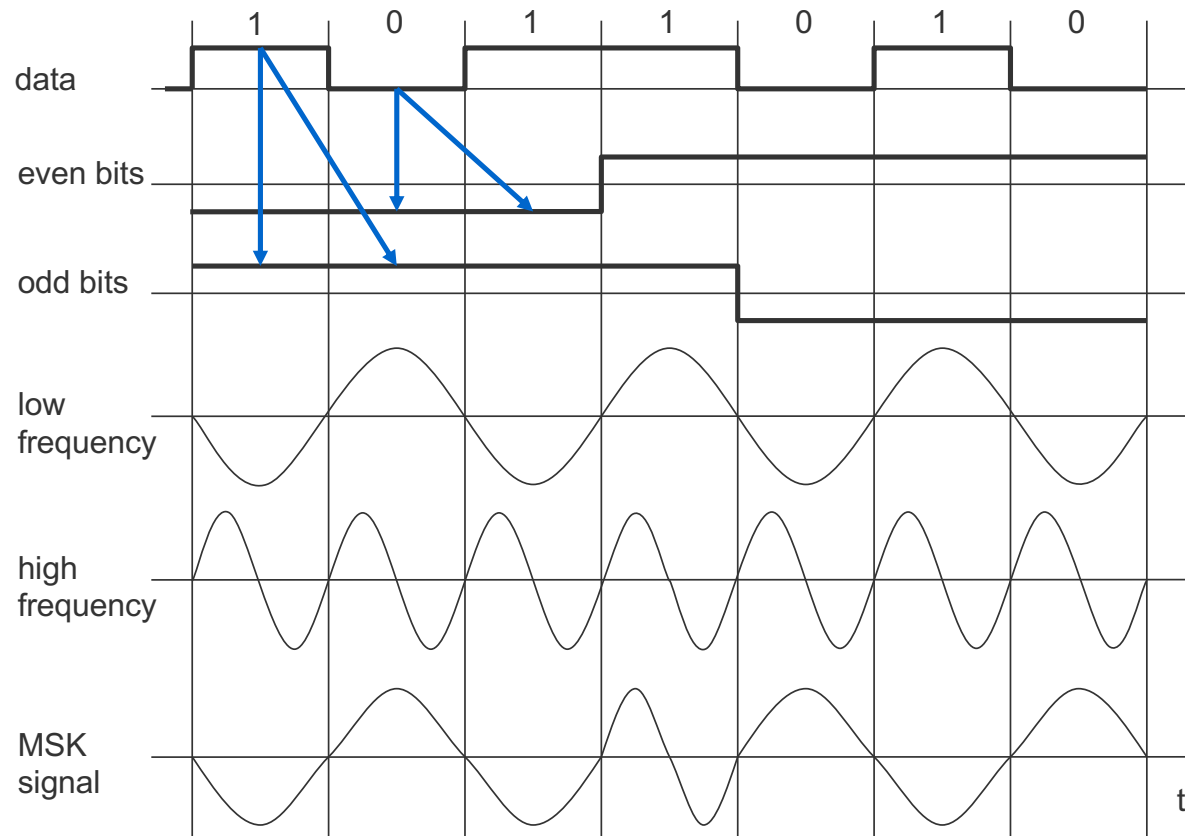
Advanced Frequency Shift Keying

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

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)
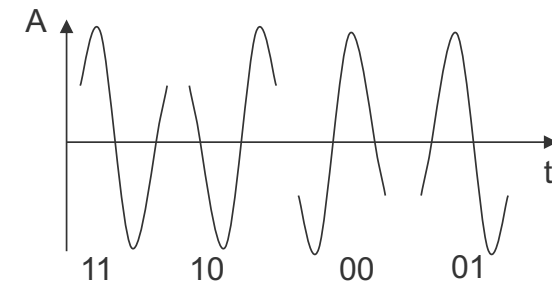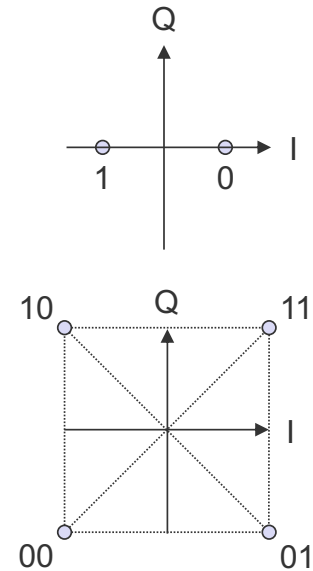
Quadrature Amplitude Modulation

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.
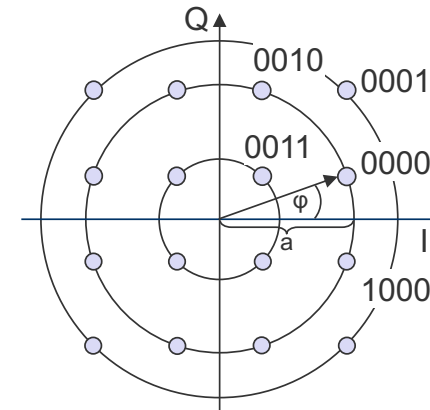
Hierarchical Modulation

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 (the newer DVB-T2 can additionally use 256QAM)

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

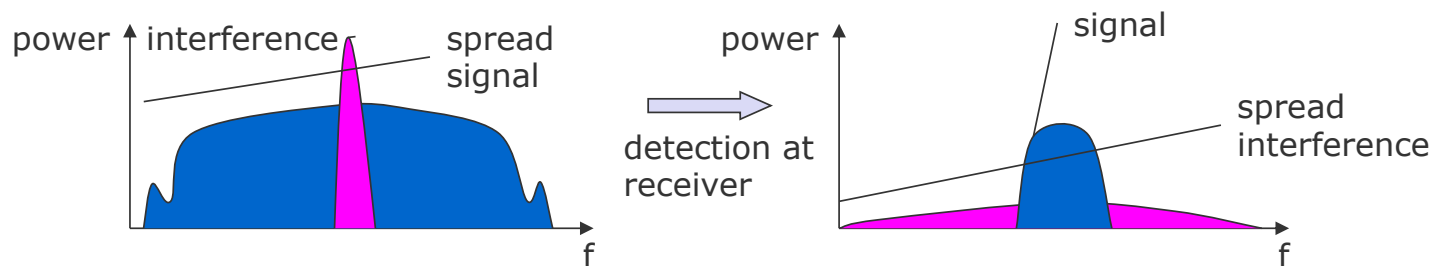- HP service coded in QPSK (2 bit), LP uses remaining 4 bit
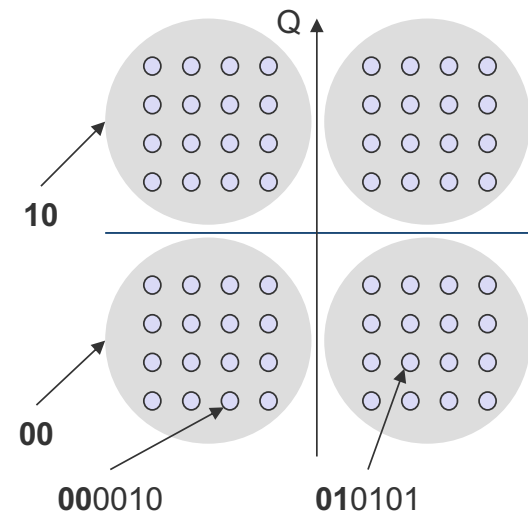
Spread spectrum technology

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
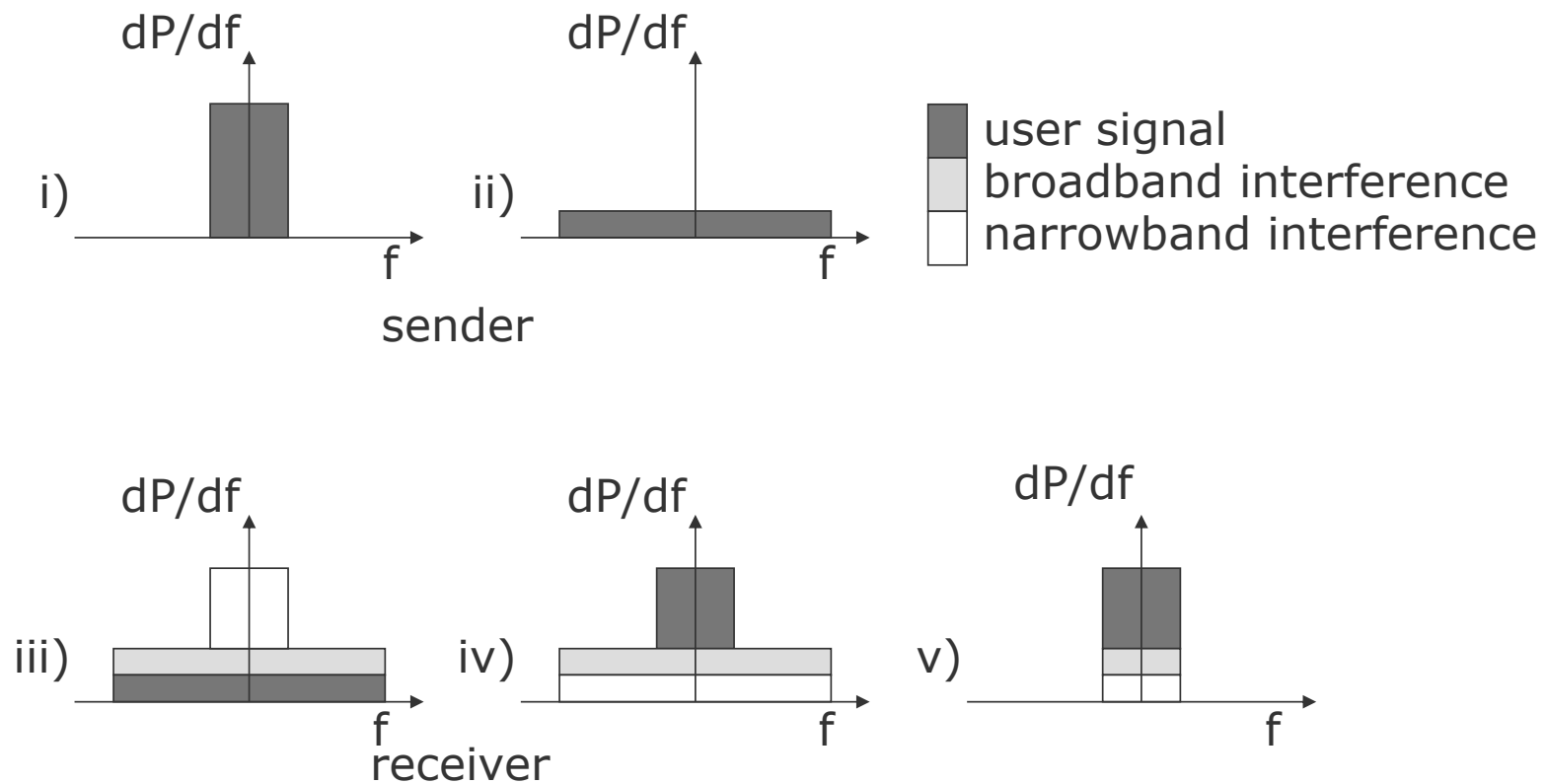
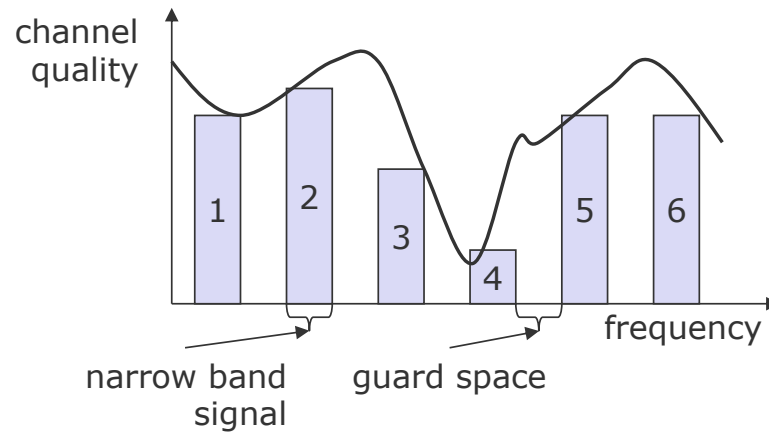 - protection against narrow band interference

Side effects:

  - coexistence of several signals without dynamic coordination

  - tap-proof
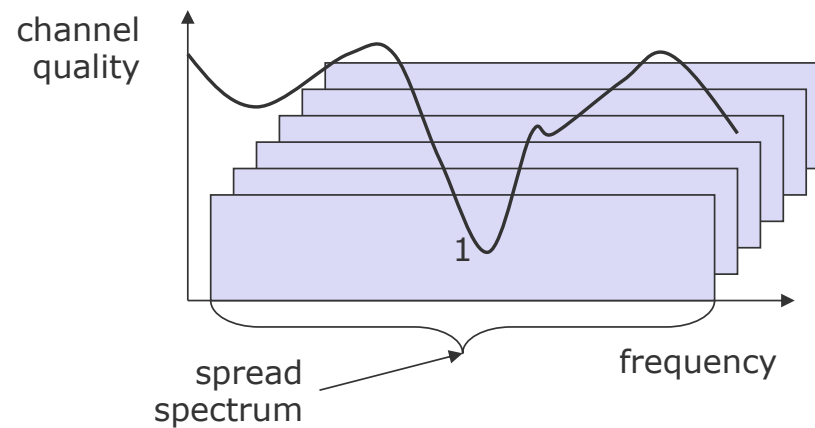
Alternatives: Direct Sequence, Frequency Hopping

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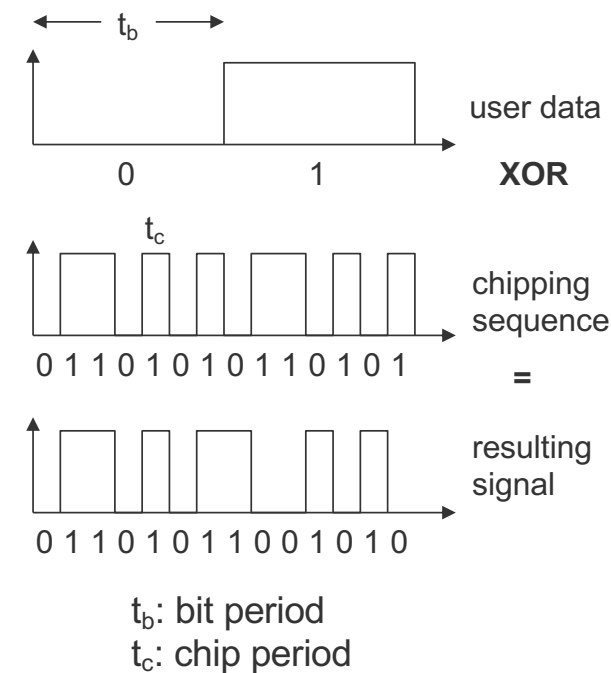
- many chips per bit (e.g., 128) result in higher bandwidth of the signal
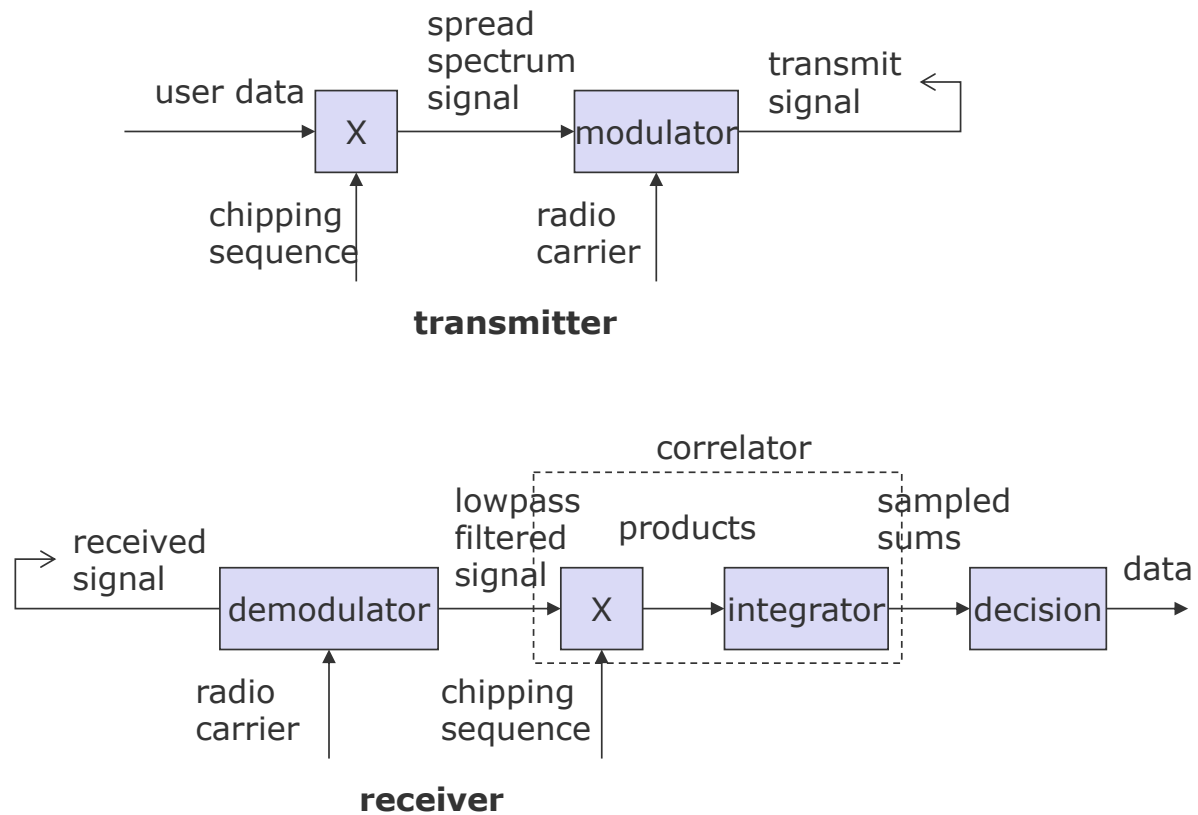
Advantages

- 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

user data

0   1   **XOR**

t_c

chipping sequence

0 1 1 0 1 0 1 0 1 1 0 1 0 1   **=**

resulting signal

0 1 1 0 1 0 1 1 0 0 1 0 1 0

t_b: bit period
t_c: chip period

DSSS (Direct Sequence Spread Spectrum) II

transmitter

receiver

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:
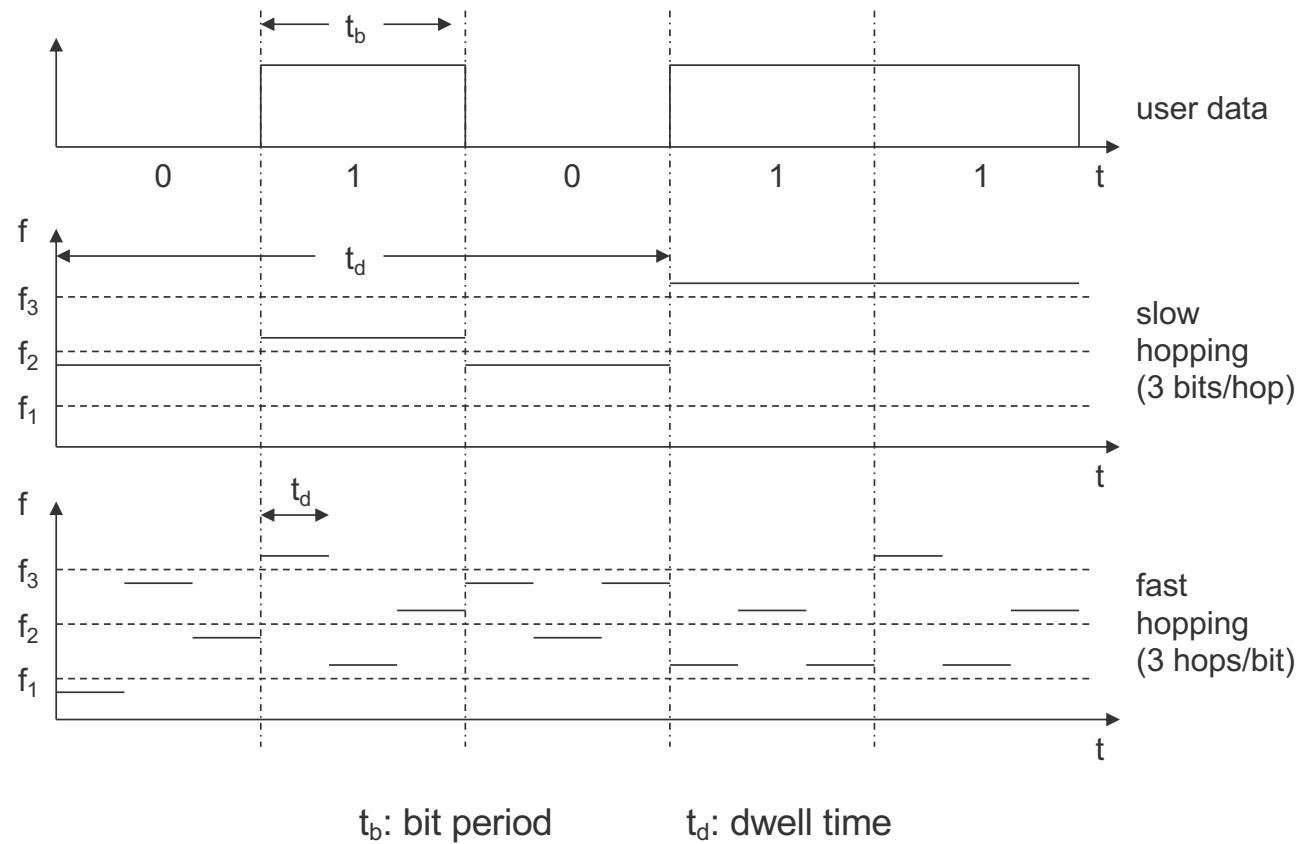   several user bits per frequency

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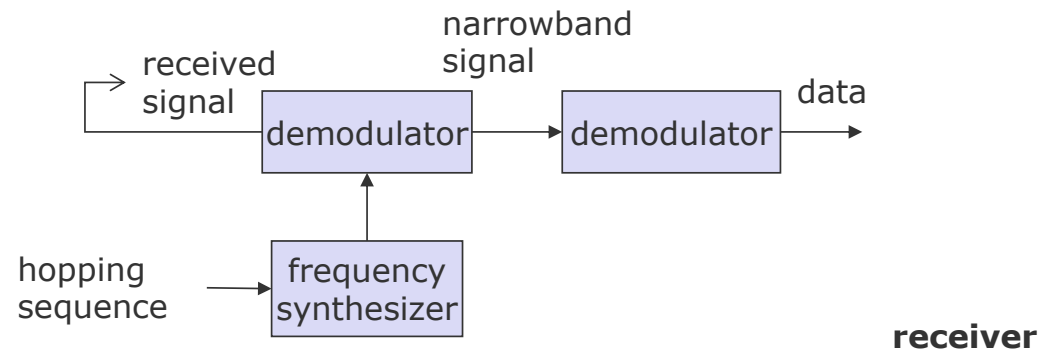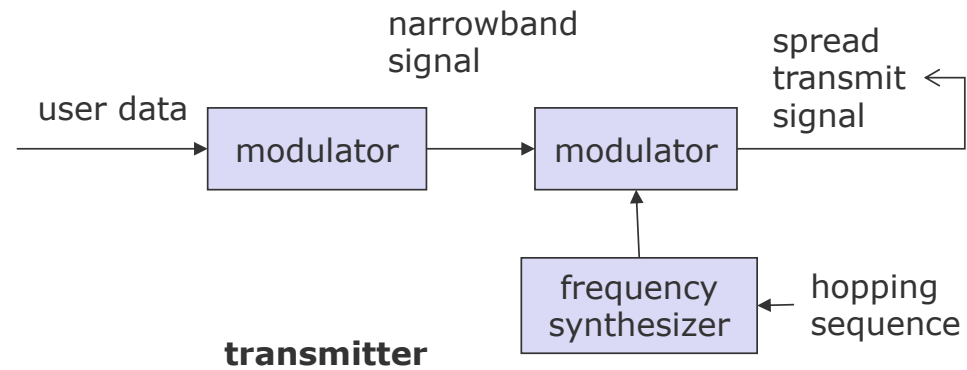 - uses only small portion of spectrum at any time

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

Software Defined Radio

Basic idea (ideal world)

- Full flexibility wrt modulation, carrier frequency, coding…

- Simply download a new radio!

- Transmitter: digital signal processor plus very fast D/A-converter

- Receiver: very fast A/D-converter plus digital signal processor

Real world

- Problems due to interference, high accuracy/high data rate, low-noise amplifiers needed, filters etc.

Examples

- Joint Tactical Radio System, GNU Radio, Universal Software Radio Peripheral, …

- see e.g. SDR – 20 Years Later, IEEE Communications Magazine, Sept. 2015 and Jan. 2016

Application	→	Signal Processor	→	D/A Converter	→

→	A/D Converter	→	Signal Processor	→	Application
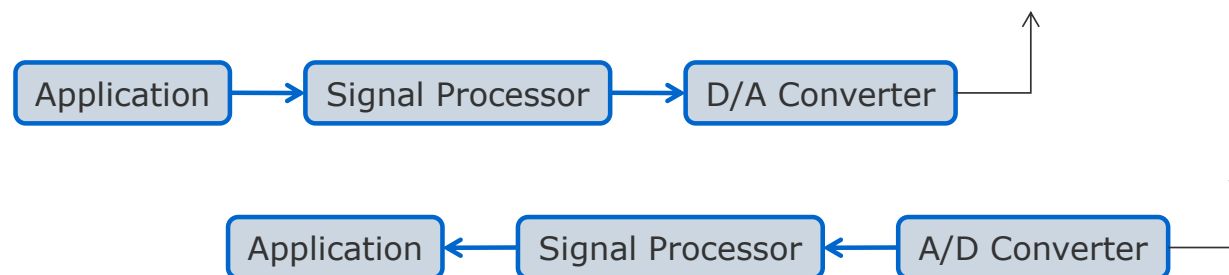
Cell structure

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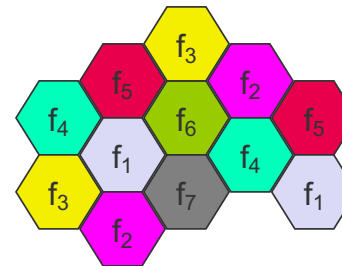
Problems
  - fixed network needed for the base stations
  - handover (changing from one cell to another) necessary
  - interference with other cells

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
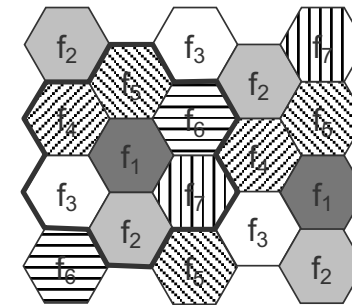 - problem: different traffic load in different cells

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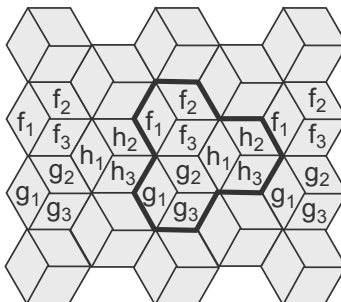 - assignment can also be based on interference measurements

Frequency planning II
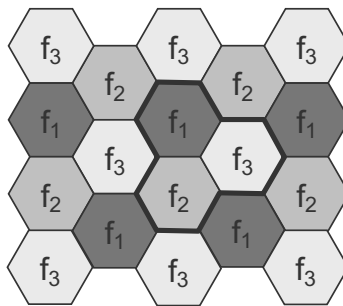
3 cell cluster

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