Mobile Communications

Semester B, Mandatory modules, ECTS Units: 3

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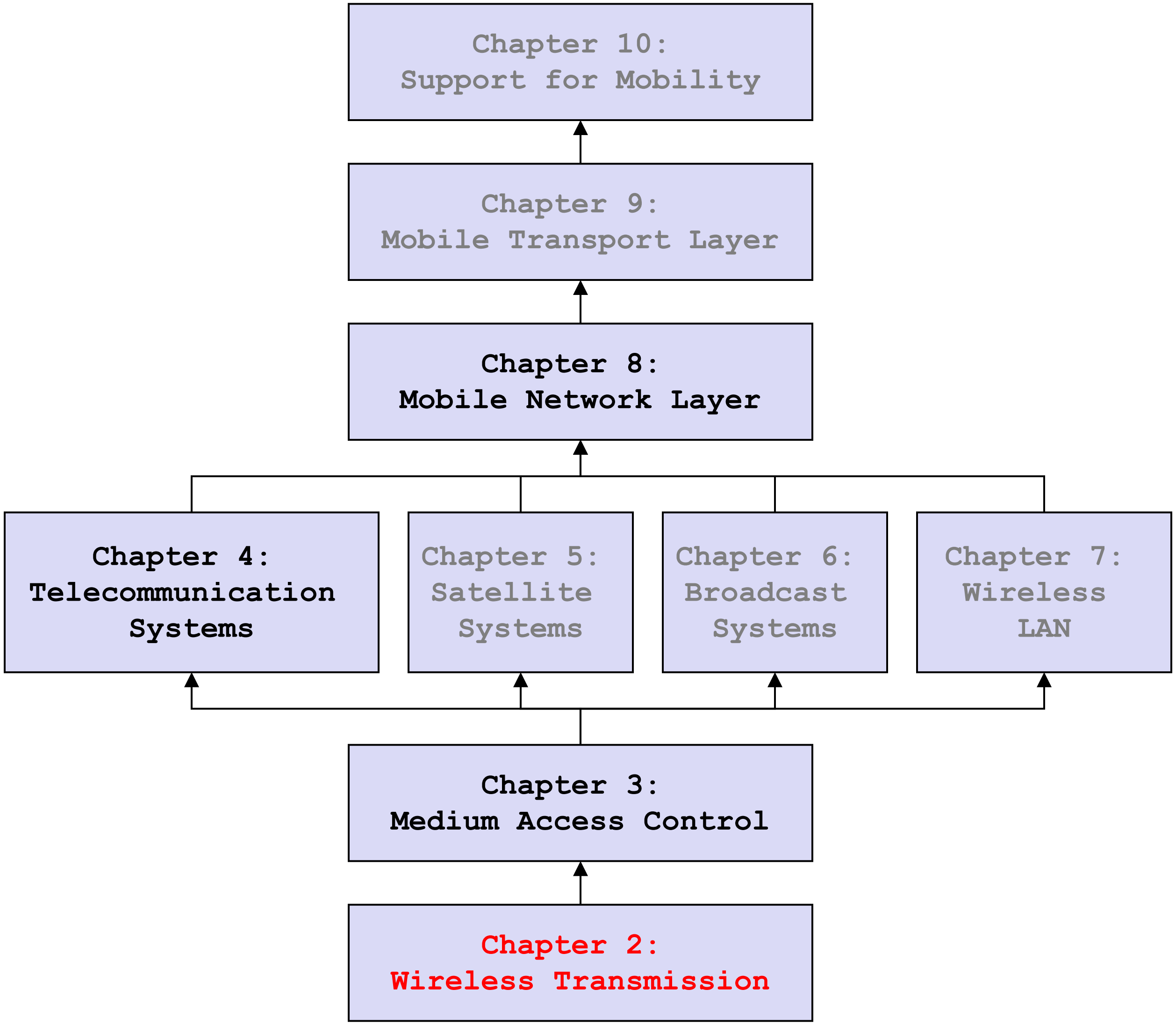
Book: Jochen H. Schiller, “Mobile Communications” Second Edition, Addison-Wesley, Pearson Education Limited, ISBN 0321123816

Presentation based on the course presentation by
Prof. Dr.-Ing. Jochen H. Schiller, Freie Universität Berlin - Computer Systems & Telematics

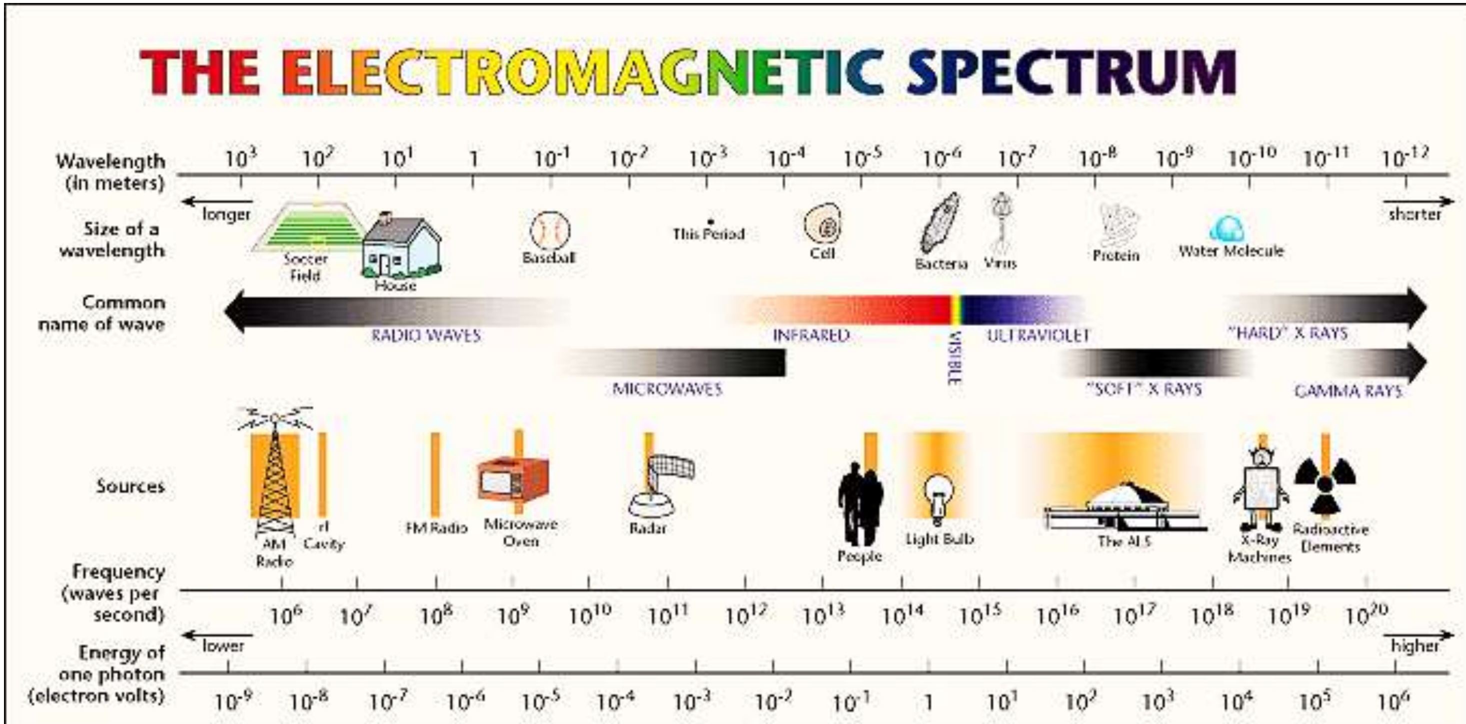
course outline

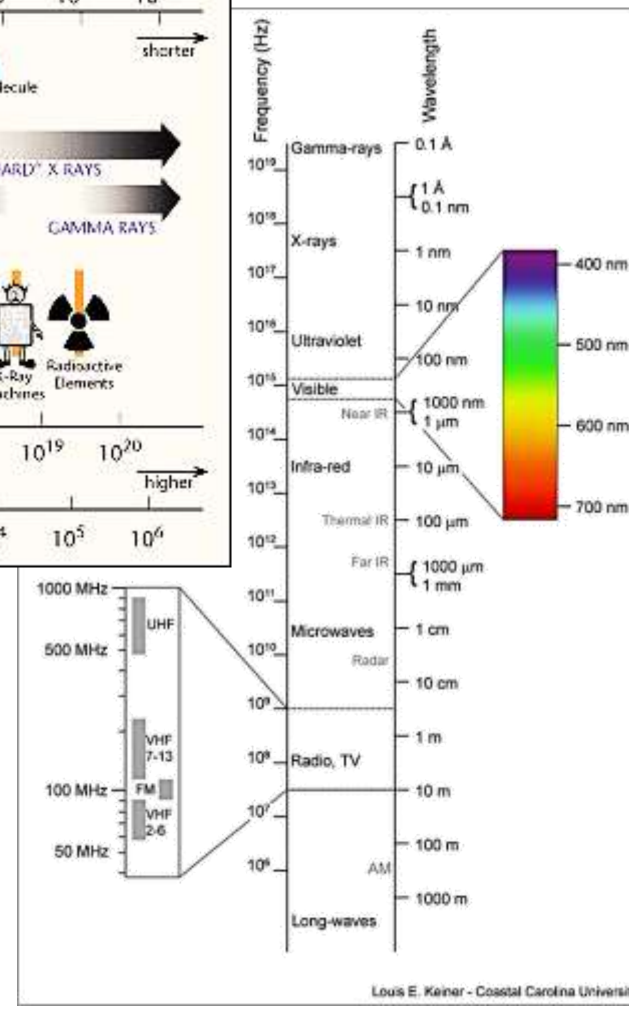


Wireless Transmission

Frequencies
Signals, antennas, signal propagation, MIMO
Multiplexing, Cognitive Radio
Spread spectrum, modulation
Cellular systems

electromagnetic spectrum





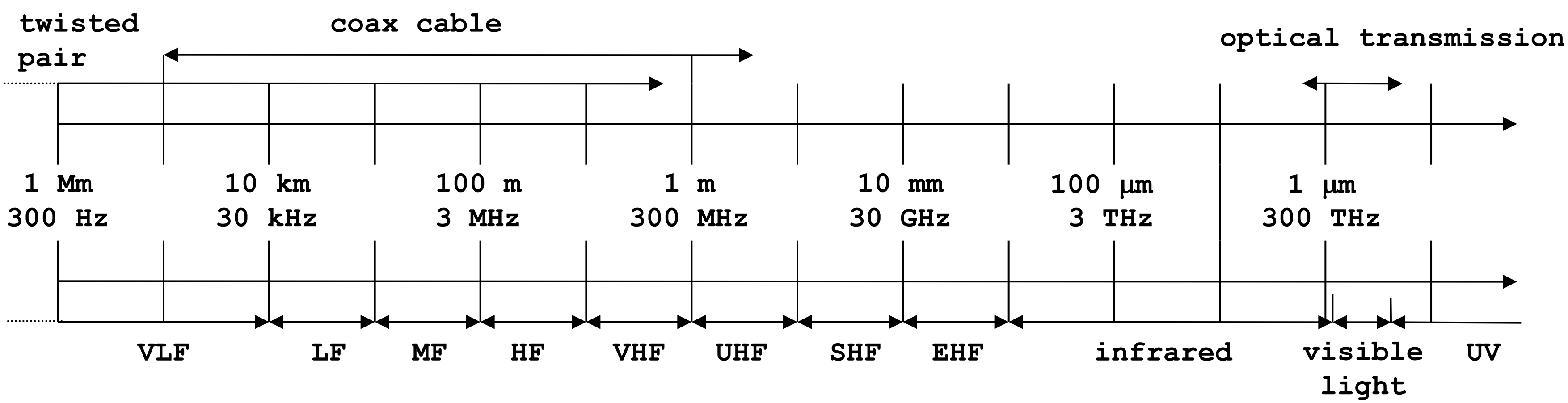
For a brief intro take a tour at NASA http://missionscience.nasa.gov/ems/

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



Frequency converter: http://goo.gl/lDMK4

example frequencies for mc

- **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 water and oxygen molecules (resonance frequencies)
    - weather dependent fading, signal loss caused by heavy rainfall etc.

frequencies and regulations

- 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)
    - User Equipment (UE) radio transmission and reception

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

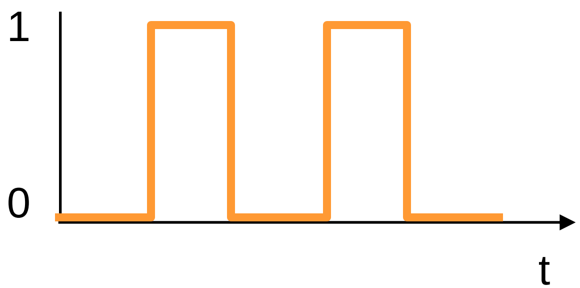
signals

- 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:

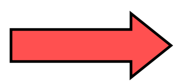
$$s(t) = A_t \sin(2 \pi f_t t + \varphi_t)$$

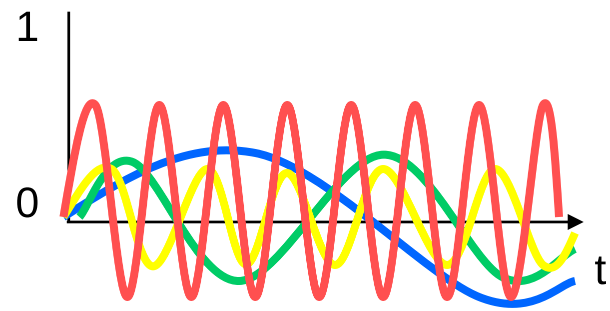
Fourier representation of periodic signals

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



ideal periodic signal





real composition
(based on harmonics)

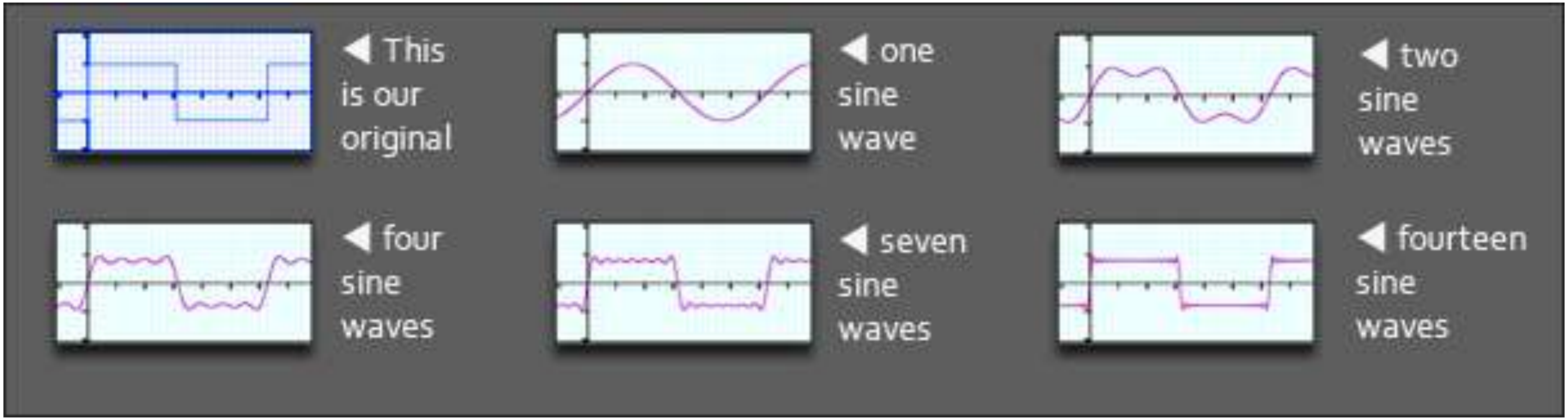
Fourier transform

- 1811, Jean-Baptiste Joseph Fourier (1768–1830) won a scientific competition organized by the French Academy of Sciences, introducing a novel technique (Fourier Series)
  - The essay was not published due to lack of ‘elegance’
  - Till late 1970s Fourier was not even mentioned in the Encyclopædia Universalis.
  - Today, the name can be found in every engineering textbook
- Fourier transform is a way to detect the frequencies within a signal and is used in many applications
  - Creation and filtering of signals for mobiles/WiFi
  - Compression of audio, image and video signals
  - In solving differential equations
  - …….

- *Laurent Demanet (MIT-Math): “You don’t really study the Fourier transform for what it is. You take a class in signal processing, and there it is. You don’t have any choice.”*

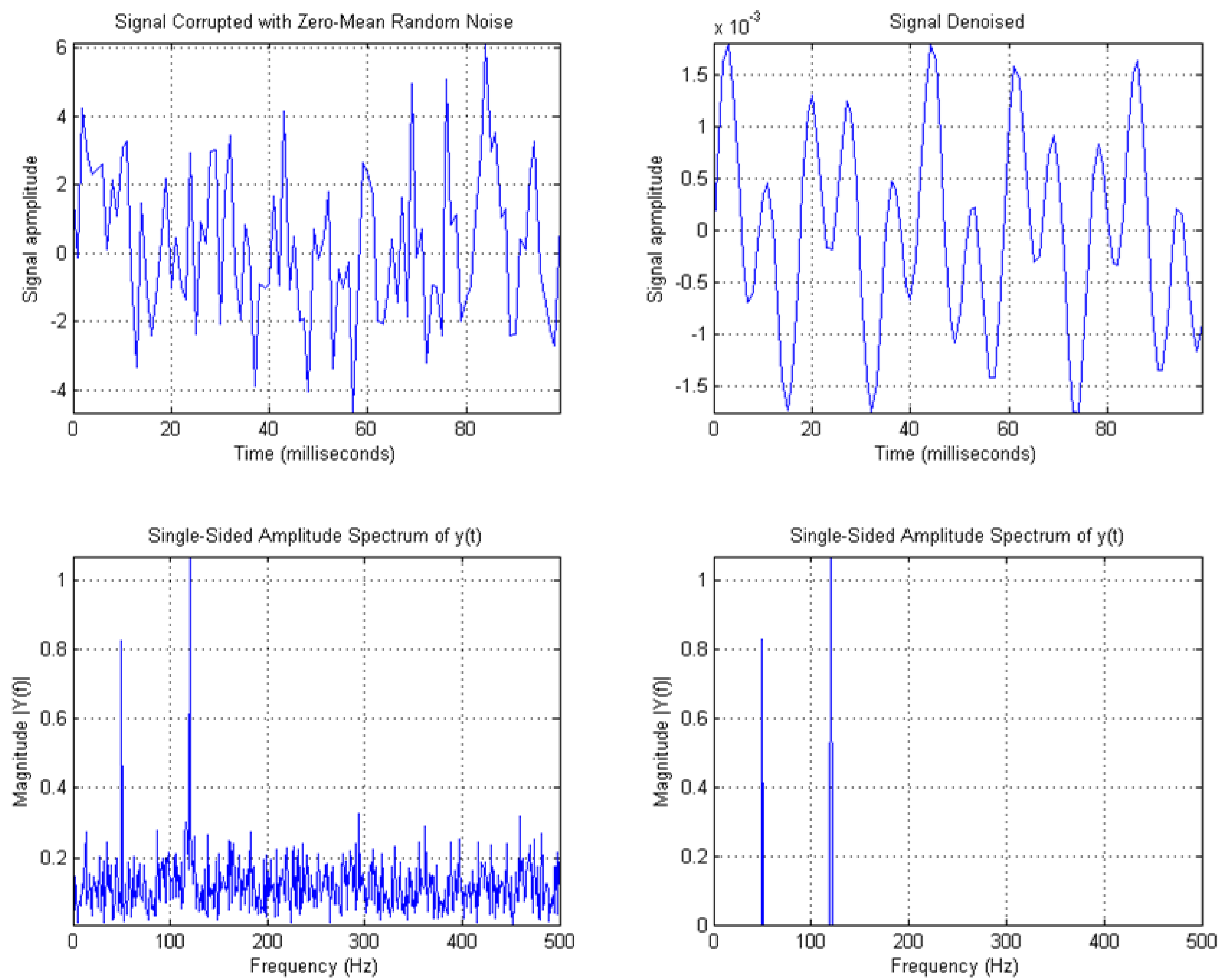
Fourier transform

- Fourier discovered that **any signal,** no matter how complex, **can be represented by a summation of various sinusoids** of different frequency and amplitude

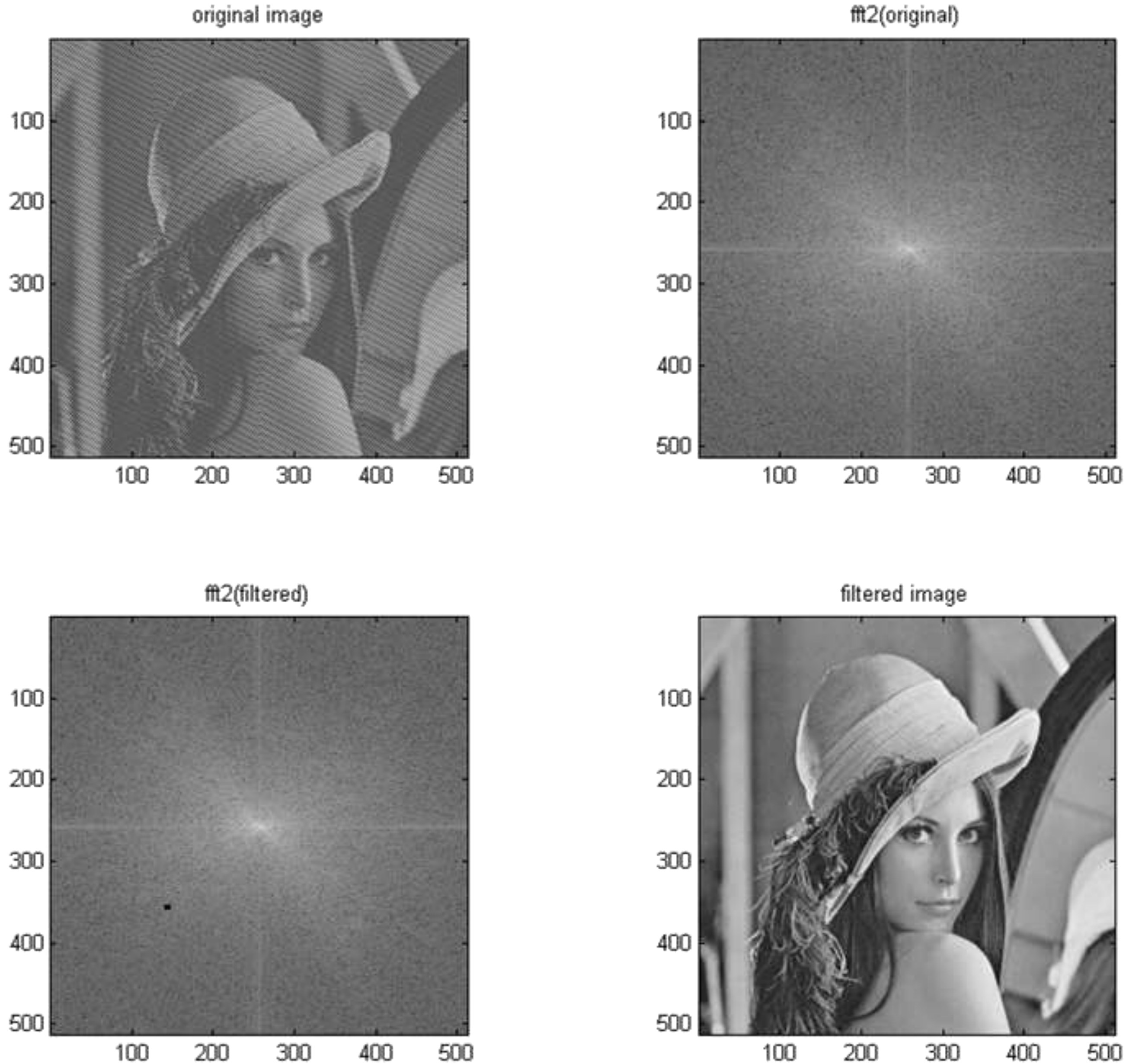


Source: http://www.dspdimension.com/admin/dft-a-pied/

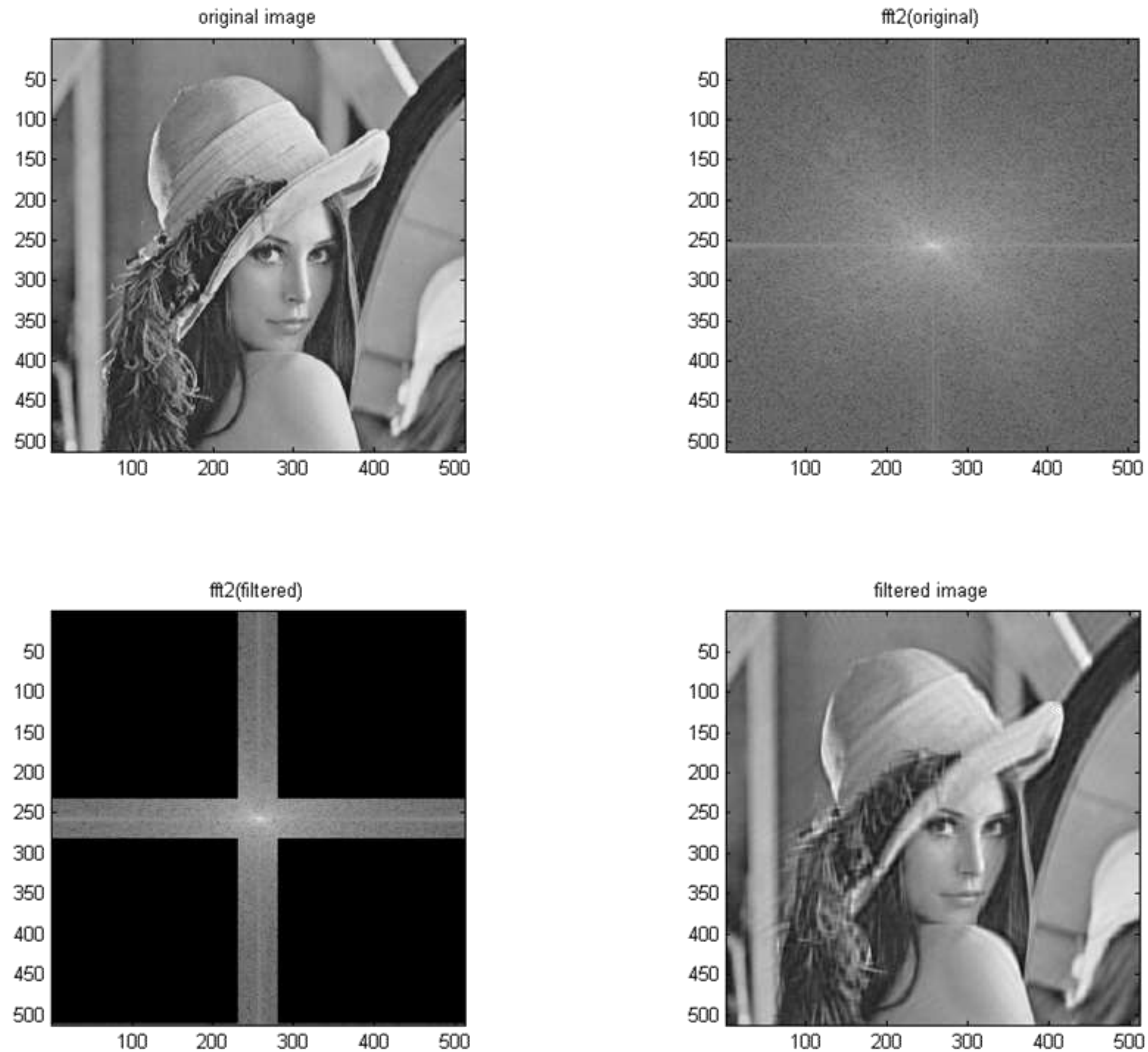
Fourier transform of a 1D signal



Fourier transform of a 2D signal

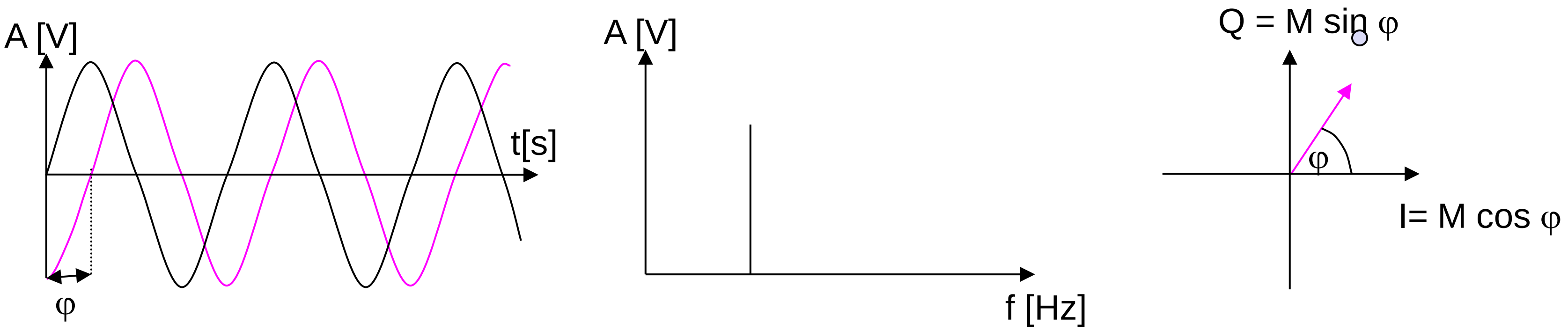


Fourier transform of a 2D signal



signals

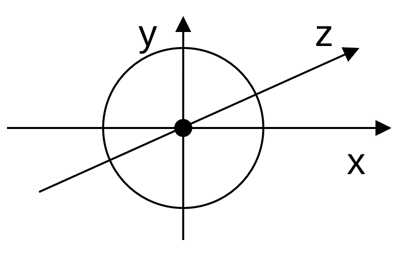
- Different representations of signals
  - amplitude (amplitude domain)
  - frequency spectrum (frequency domain)
  - phase state diagram (amplitude M and phase φ in polar coordinates)

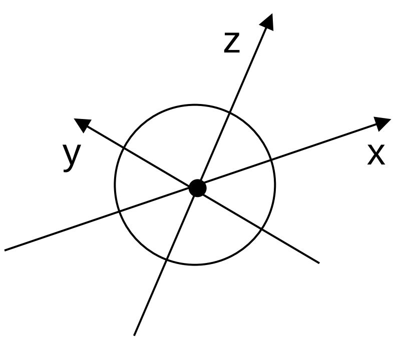


- Composed signals transferred into frequency domain using Fourier transformation
- Digital signals need
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)

antennas - isotropic radiator

- Radiation and reception of electromagnetic waves, coupling of wires to space for radio transmission
- Isotropic radiator (ideal point source)
  - equal radiation in all directions (3 dimensional) - only a theoretical reference antenna
- Real antennas always have directive effects (vertically and/or horizontally)
- Radiation pattern: measurement of radiation around an antenna

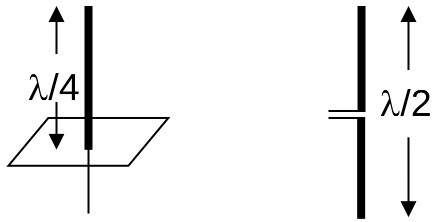




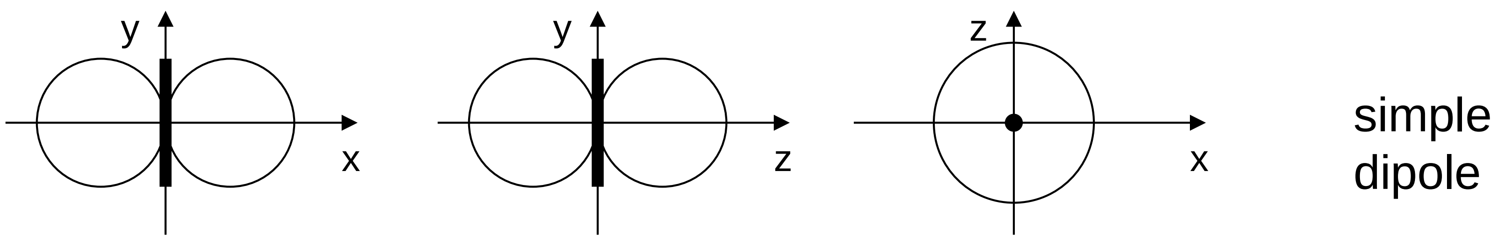
ideal isotropic radiator

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

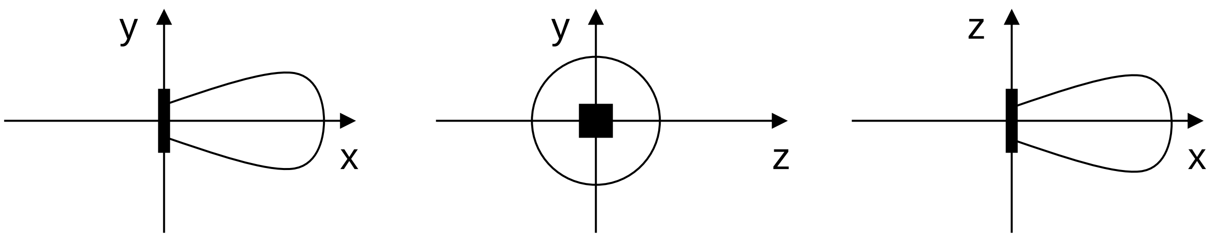


side view (xy-plane) side view (yz-plane) top view (xz-plane)

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

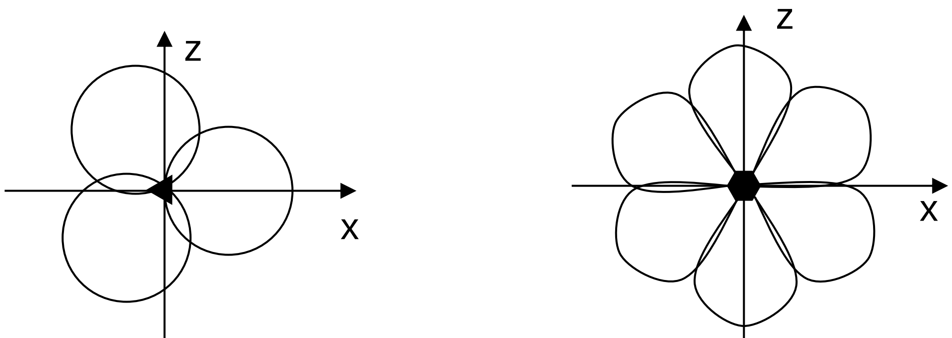
antennas - directed and sectorized

- 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

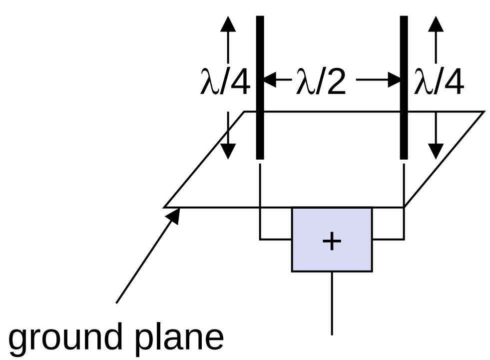


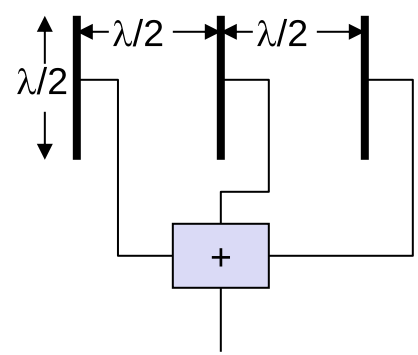
top view, 3 sector top view, 6 sector

sectorized antenna

antennas - diversity

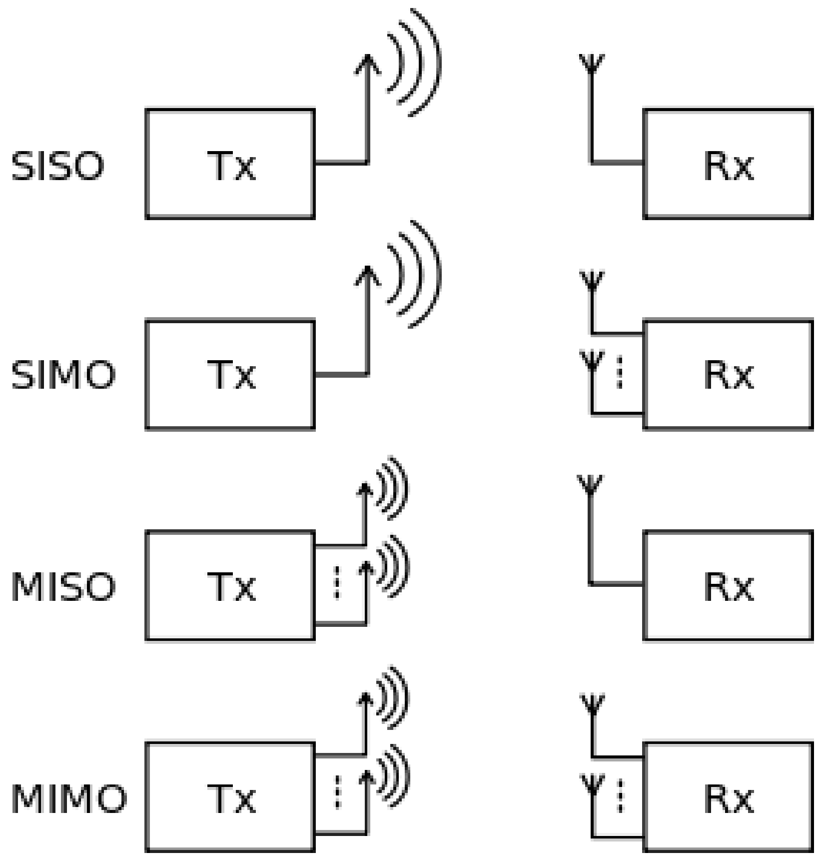
- Grouping of 2 or more antennas
  - multi-element antenna arrays
- Antenna diversity
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain
    - cophasing needed to avoid cancellation





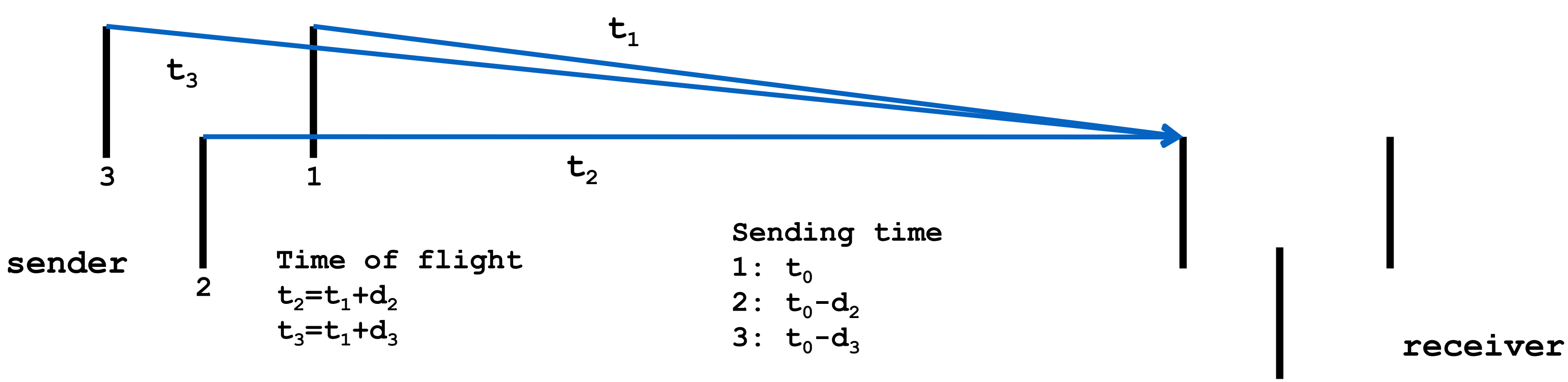
forms of smart antenna technology

- Multi-antenna types
  - SISO/SIMO/MISO/MIMO
    - Single/Multiple input, Single/Multiple output



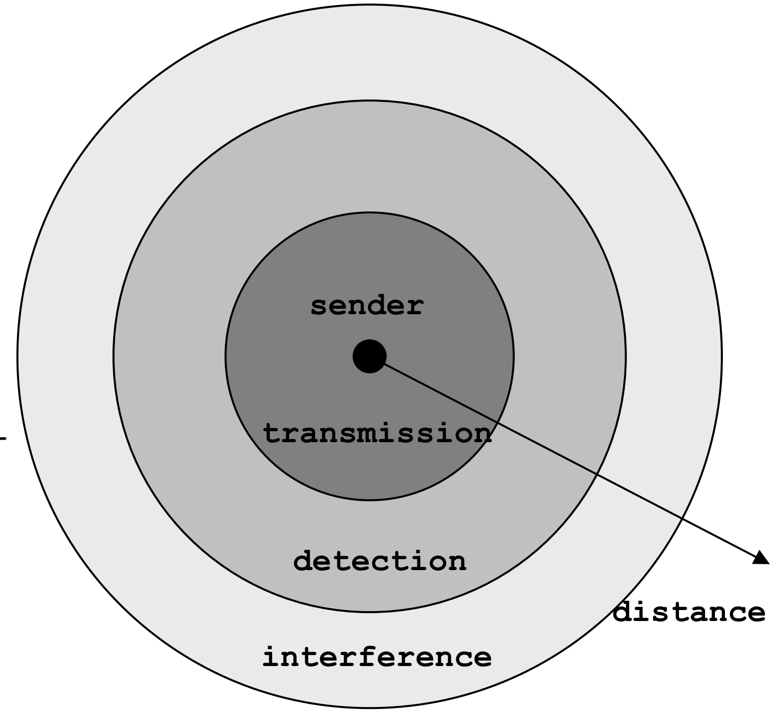
MIMO

- 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



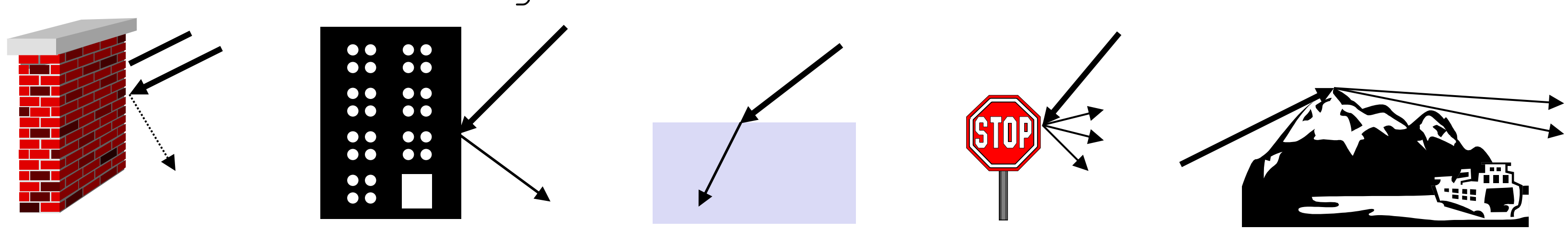
signal propagation ranges

- **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**



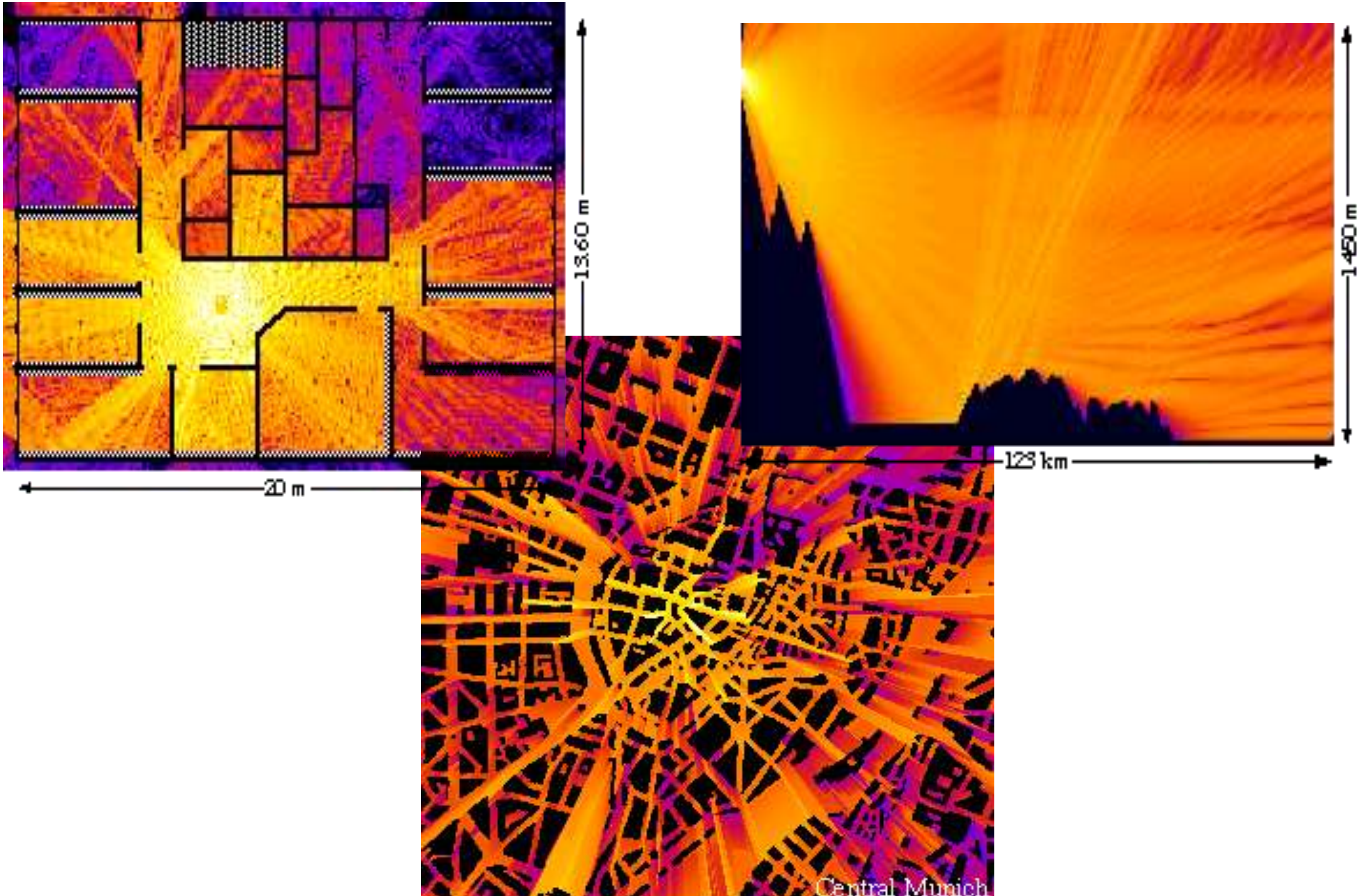
signal propagation

- **Propagation** in free space
  - always like light (straight line)
- **Receiving power** proportional to $1/d^2$ in vacuum
  - much more 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**

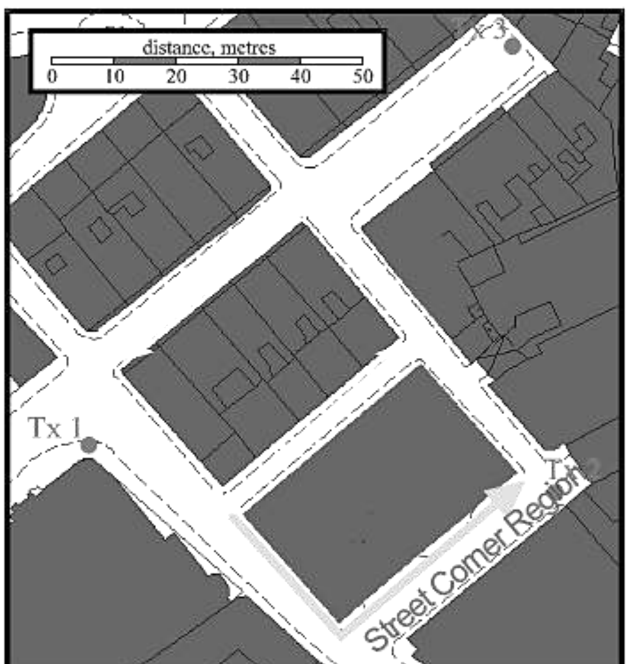
real world examples

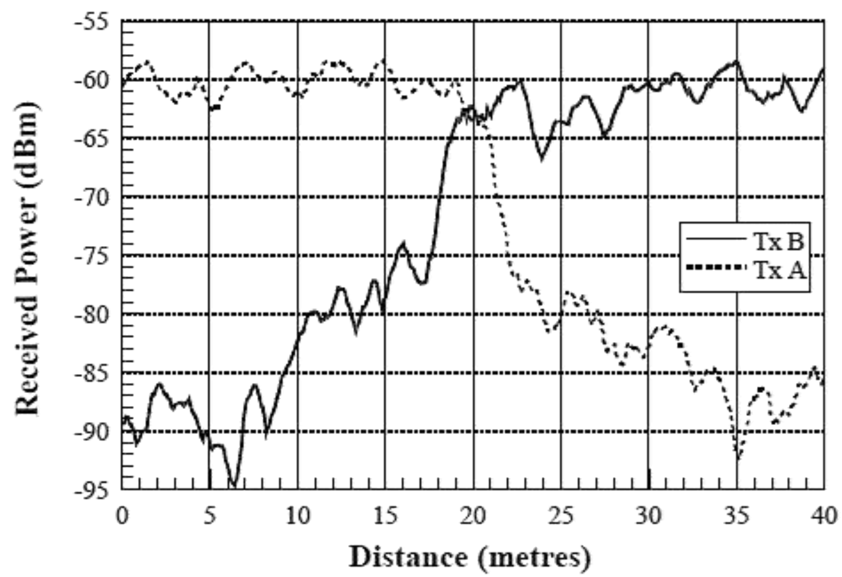


Institut für Hochfrequenztechnik und Elektronik (IHE)

real world examples

- Shadowing
  - Amplitude variation occurs as the receiver moves behind buildings and the propagation paths are obscured
  - Variations of up to 20dB will cause handovers and change quality-of-service

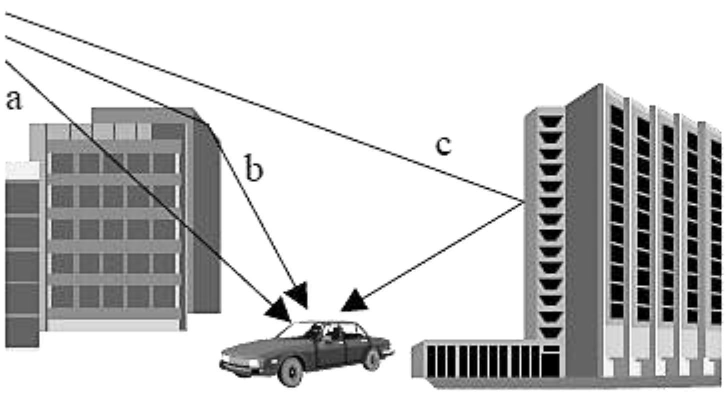


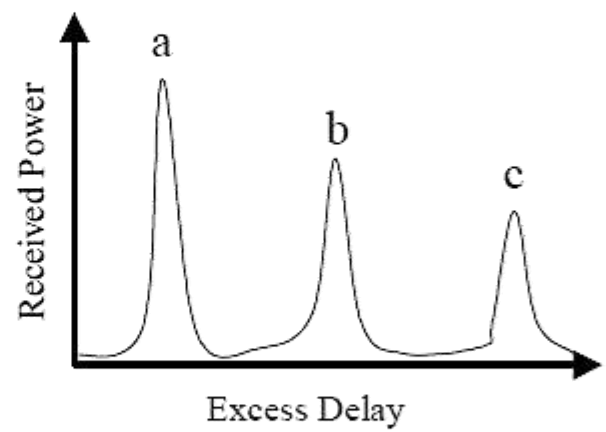


Reciprocal uplink/downlink

real world examples

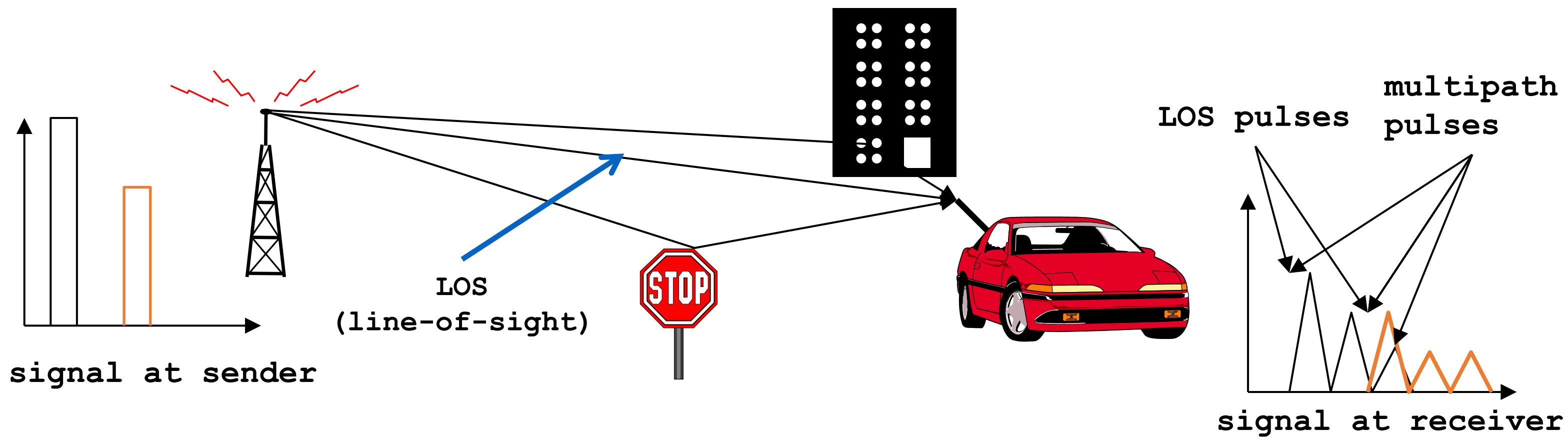
- Multipath environment
  - The received signal is made up of a sum of attenuated, phase-shifted and time delayed versions of the transmitted signal
  - Propagation modes include diffraction, transmission and reflection





multipath propagation

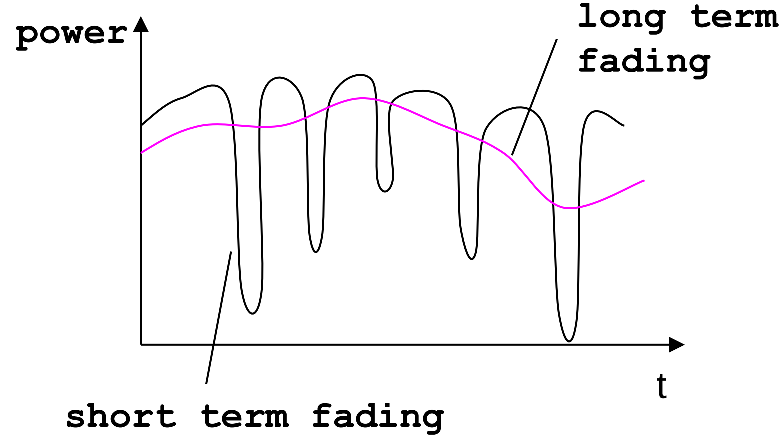
- Signal can take **many different paths** between sender and receiver due to reflection, scattering, diffraction



- **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

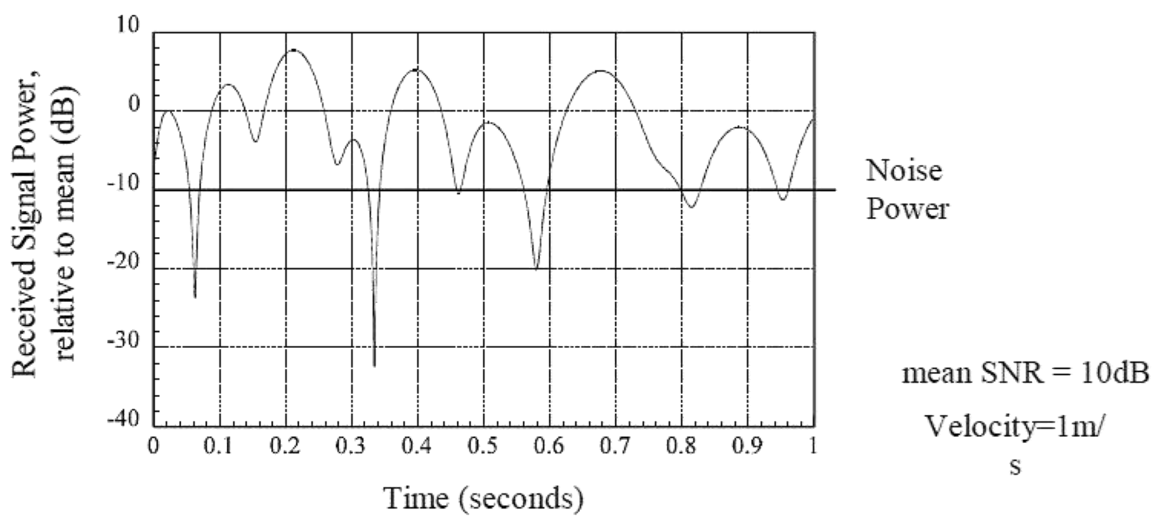
- **Channel characteristics change over time and location**
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
    - quick changes in the power received (short term fading)



- **Additional changes** in
  - distance to sender
  - obstacles further away
    - slow changes in the average power received (long term fading)

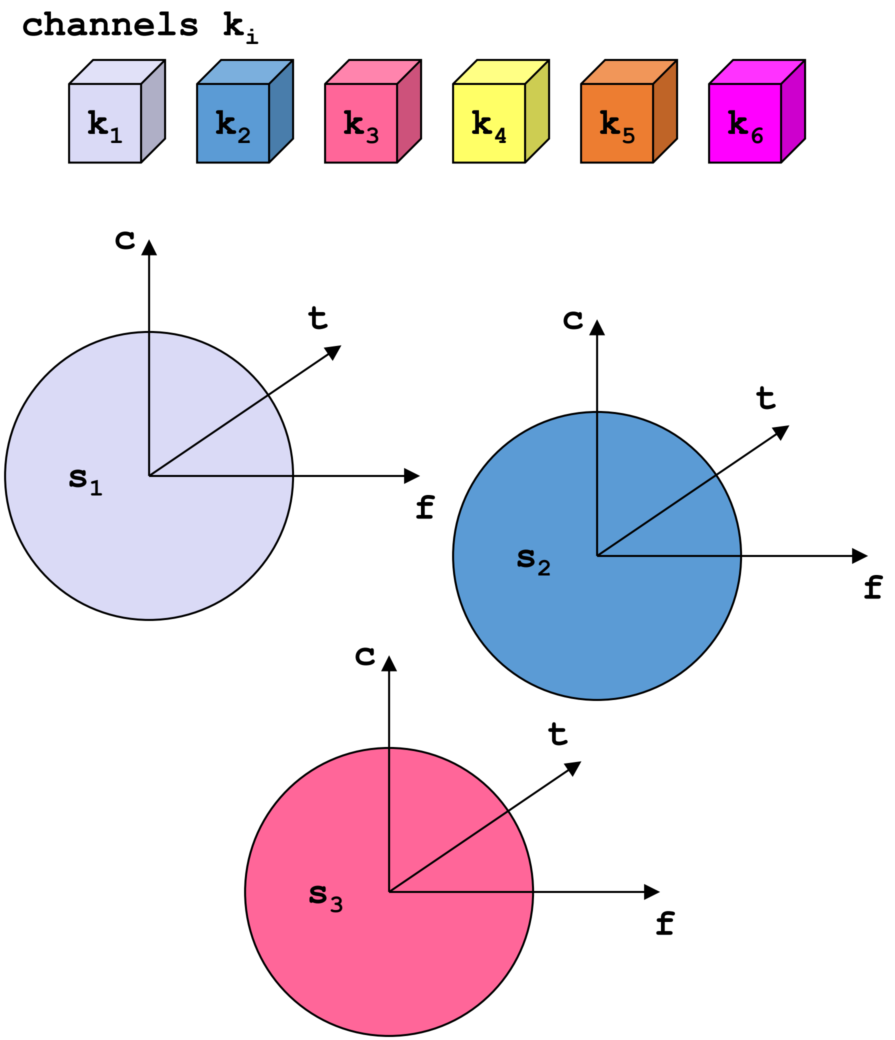
noise and interference

- In multipath environments
- The received signal exhibits large variations in magnitude
  - Although the mean SNR (or C/I) might be acceptable, the variations experienced mean that occasionally the noise will be far more significant
    - At these times the system will experience a large number of errors



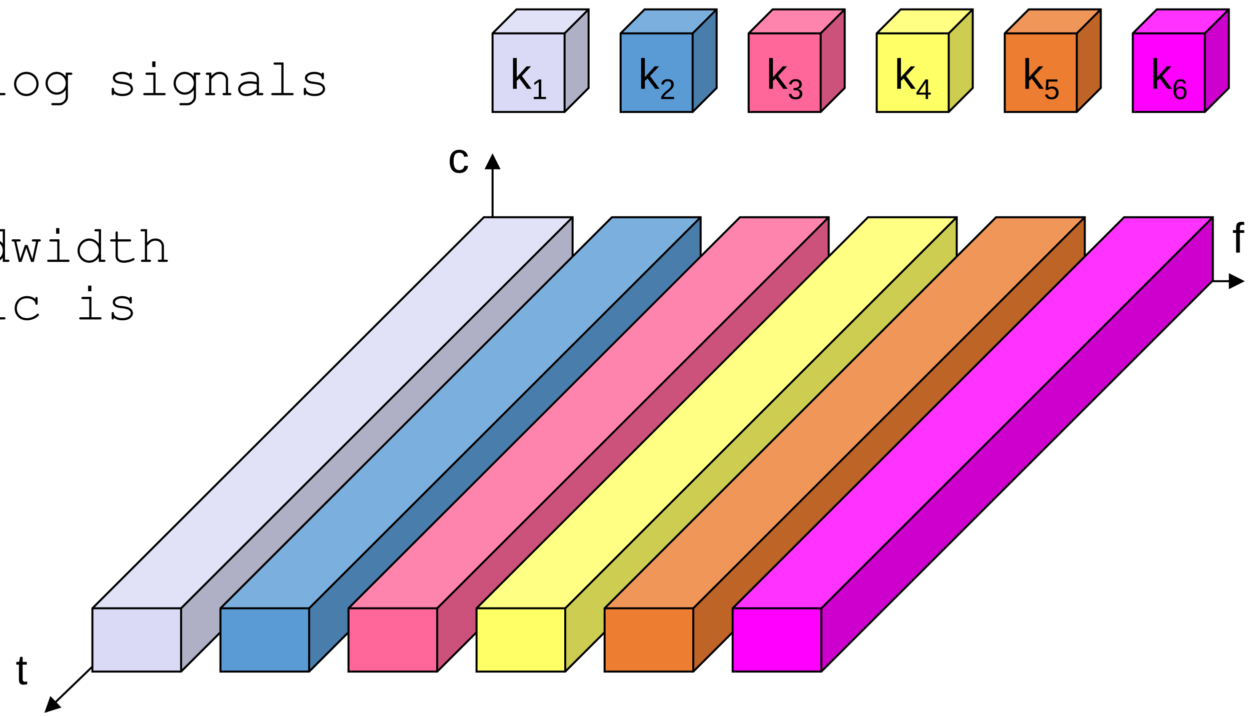
multiplexing

- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)
- Goal
  - multiple use of a shared medium
- Important:
  - guard spaces needed!



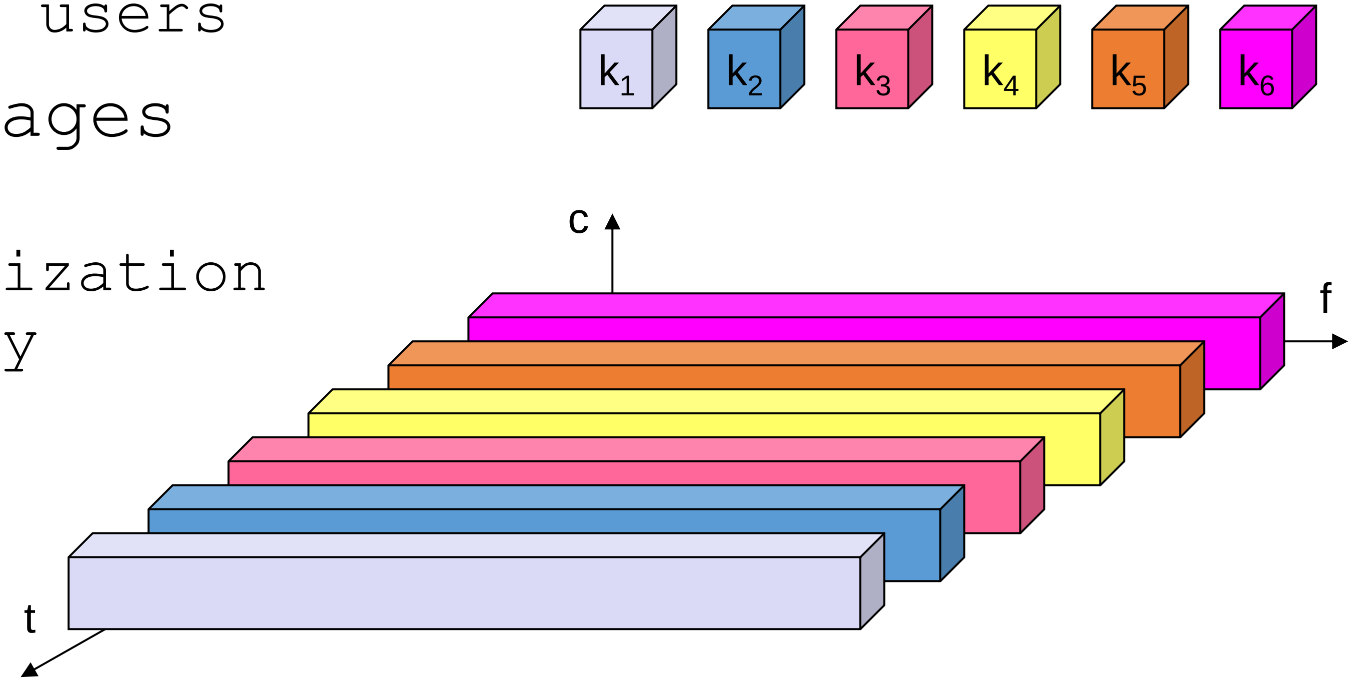
frequency-division multiplexing (FDM)

- **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
  - also for analog signals
- Disadvantages
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible



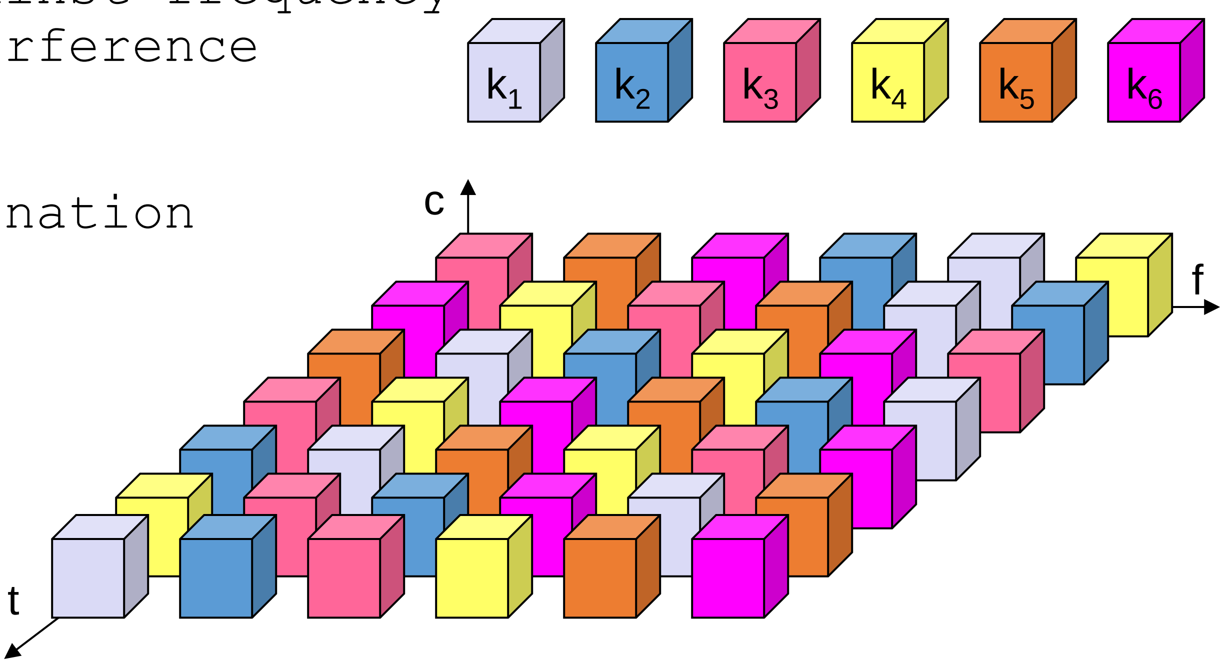
time-division multiplexing (TDM)

- **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



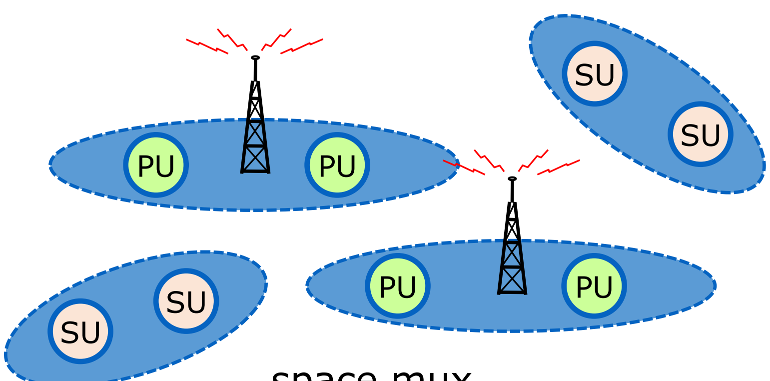
time and frequency multiplex

- 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
- Disadvantage
  - precise coordination required

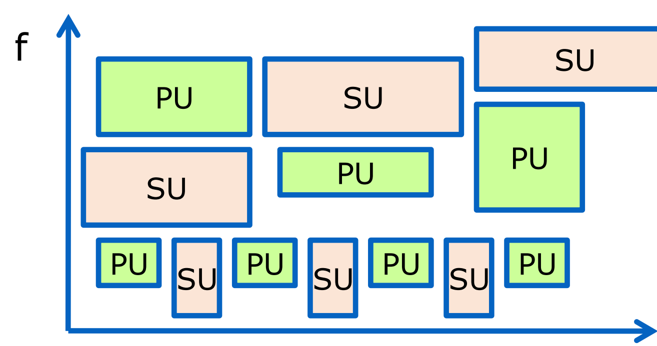


cognitive radio

- 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.



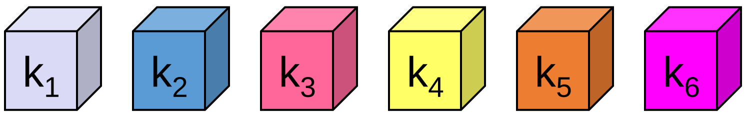
space mux

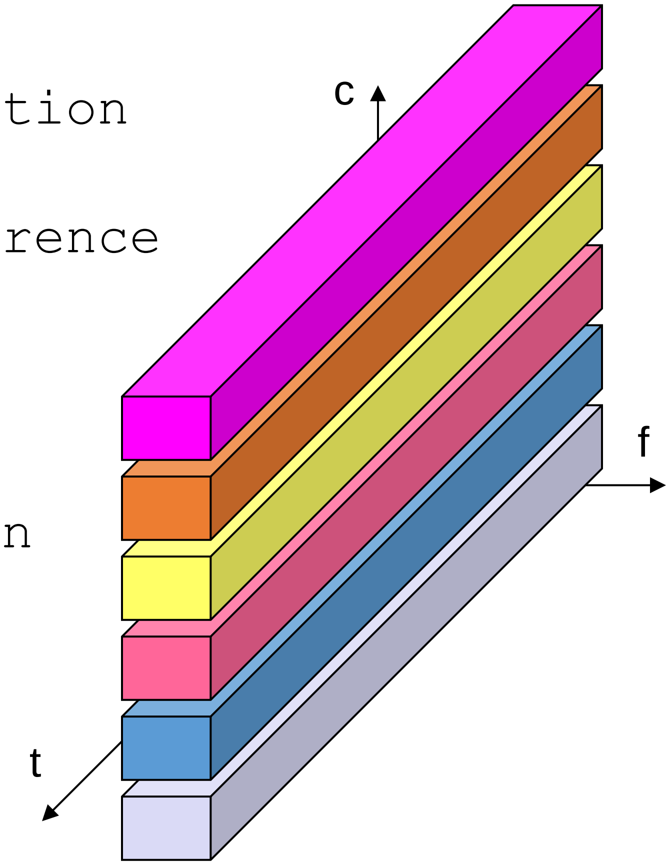


frequency/time mux

code-division multiplexing (CDM)

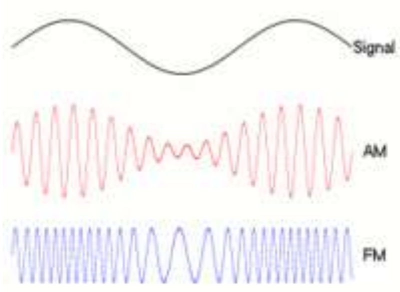
- Each channel has a **unique code**
- All channels use the same spectrum at the same time
- Advantages
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages
  - varying user data rates
  - more complex signal regeneration
- Implemented using spread spectrum technology



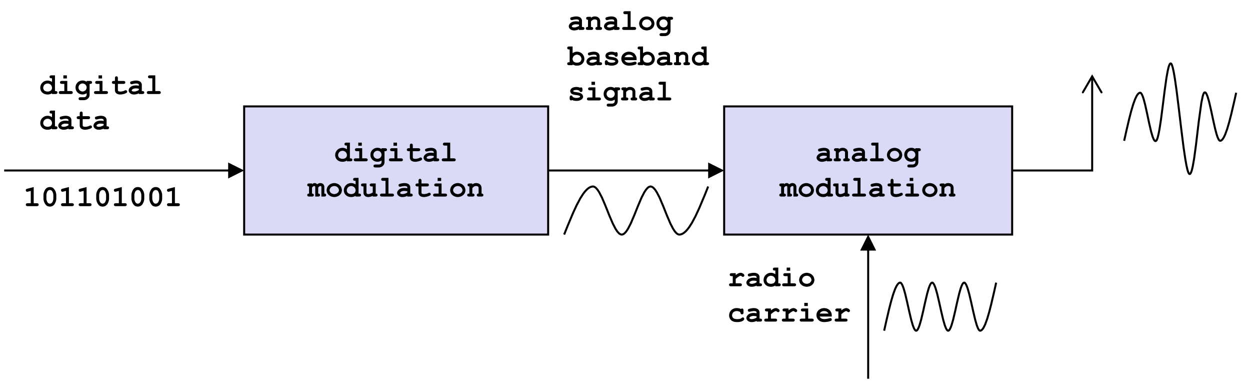


modulation

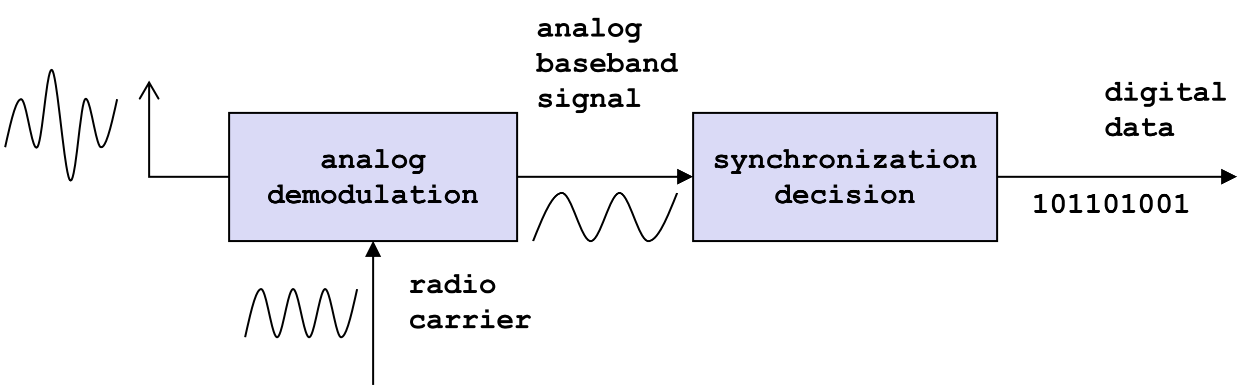
- **Digital modulation**
  - digital data is translated into an analog signal (baseband)
  - ASK (amplitude-shift keying), FSK (phase-shift keying), PSK (phase-shift keying) - main focus in this chapter
  - differences in spectral efficiency, power efficiency, robustness
- **Analog modulation**
  - shifts 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



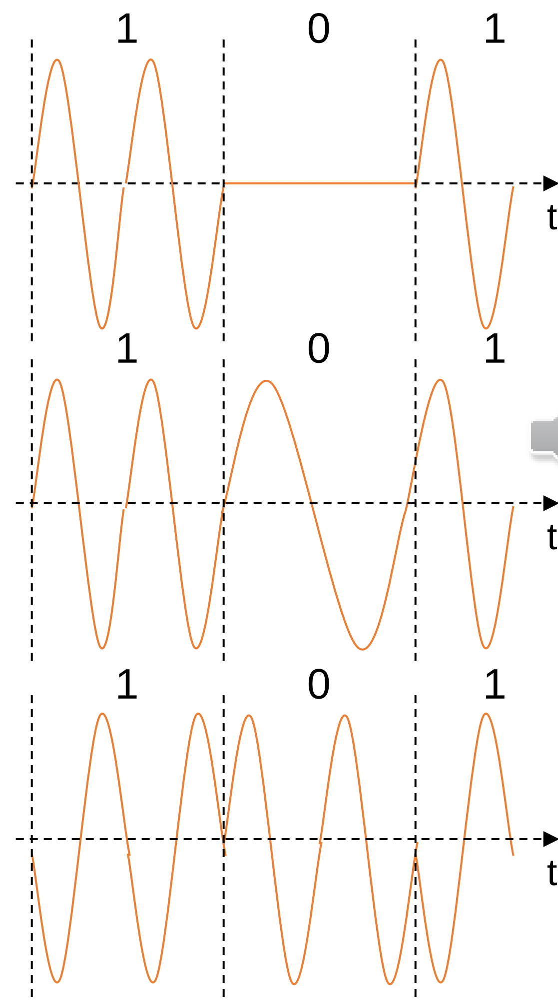
radio transmitter



radio receiver

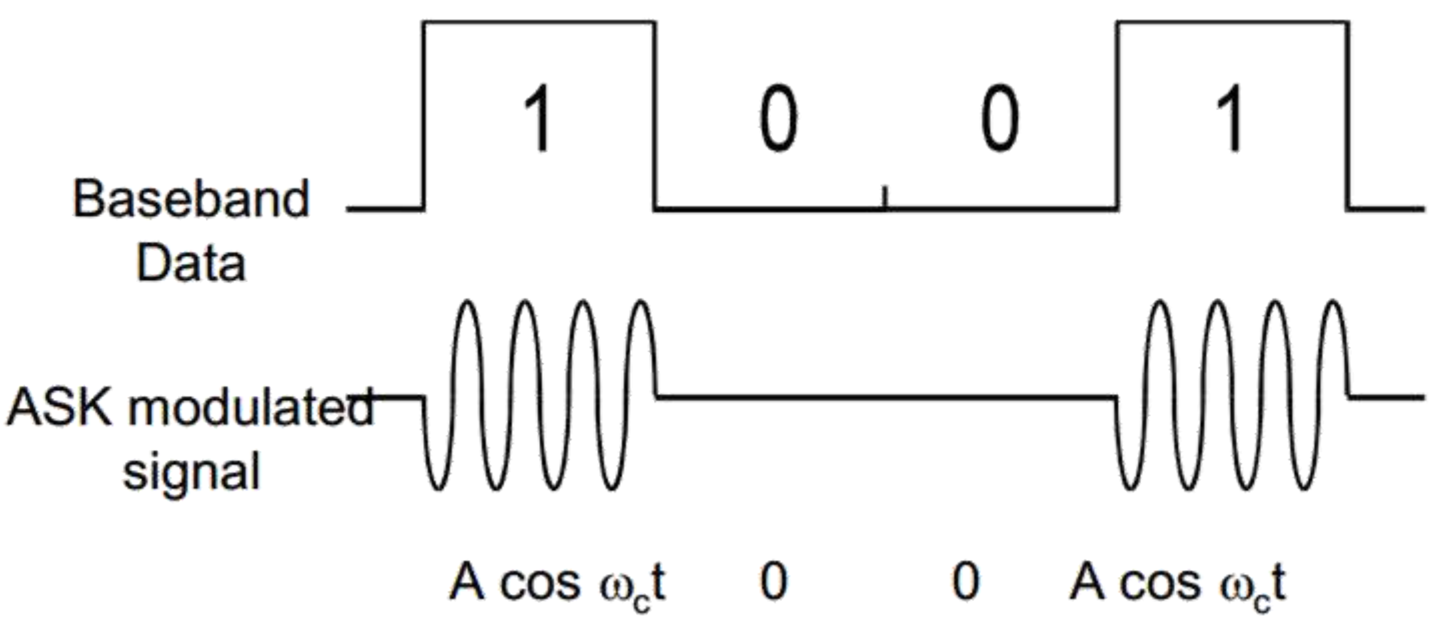
digital modulation

- Modulation of digital signals known as **Shift Keying**
- **Amplitude Shift Keying (ASK)**
  - digital data are represented as **changes in the amplitude**
  - very simple
  - low bandwidth requirements
  - very susceptible to interference
- **Frequency Shift Keying (FSK)**
  - digital data are represented as **changes in the frequency**
  - needs larger bandwidth
- **Phase Shift Keying (PSK)**
  - digital data are represented by **changes in the phase**
  - more complex
  - robust against interference



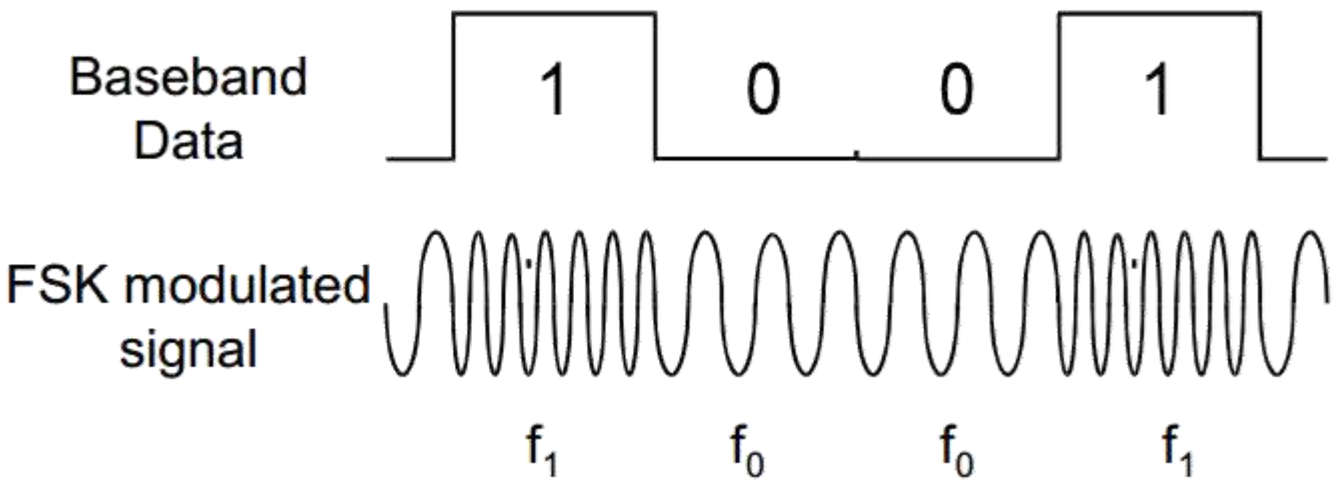
amplitude shift keying (ASK)

- Pulse shaping can be employed to remove spectral spreading
- Poor performance
  - Heavily affected by noise and interference



frequency shift keying (FSK)

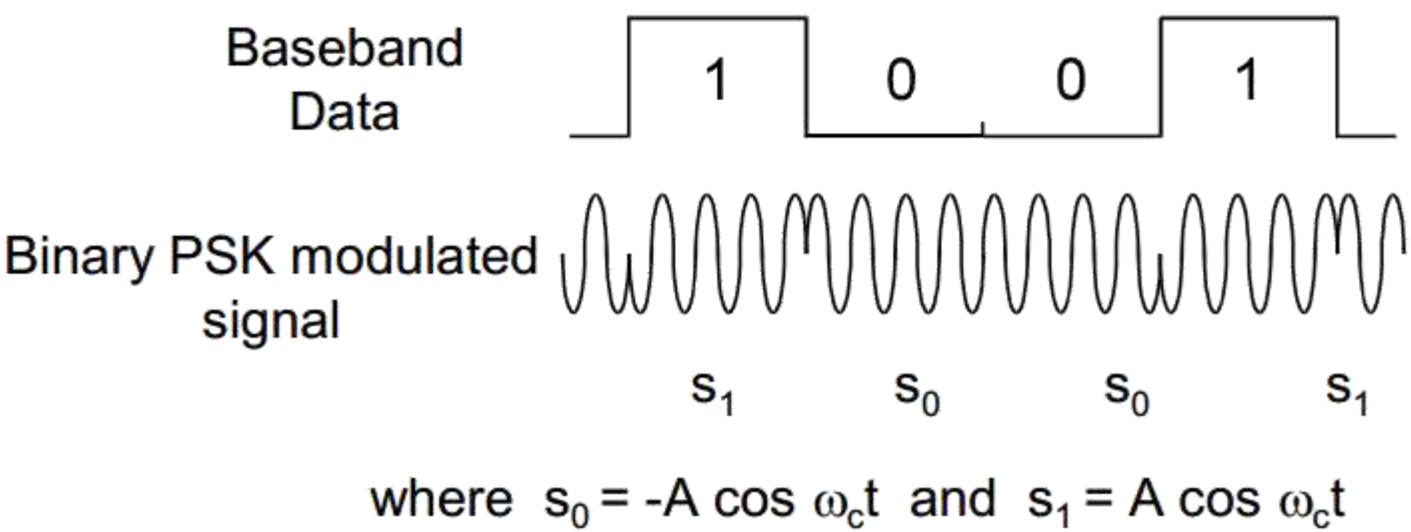
- Frequency spacing of 0.5 times the symbol period is typically used
- Can be expanded to multiple frequencies for different states



where $f_0 = A\cos(\omega_c - \Delta\omega)t$ and $f_1 = A\cos(\omega_c + \Delta\omega)t$

phase shift keying (PSK)

- Typically better performance, especially the binary (BPSK)
- Can be expanded to multiple phases and amplitudes for different states
- Typically filtering is applied to avoid spectral spreading

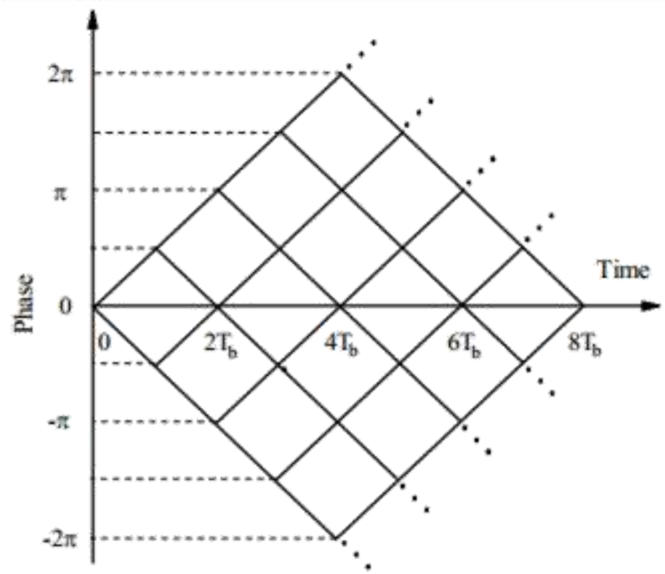


advanced frequency shift keying

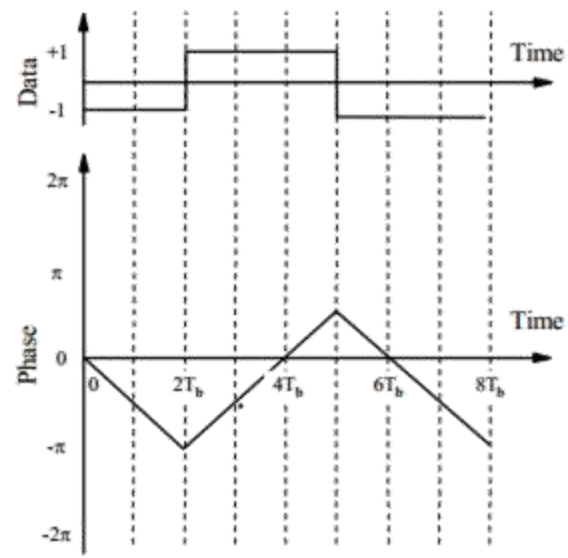
- bandwidth needed for FSK depends on the distance between the carrier frequencies
- special pre-computation avoids sudden phase shifts
  ➔ **MSK (Minimum Shift Keying)**
  - bit separated into even and odd bits, the duration of each bit is doubled
  - depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
  - the frequency of one carrier is twice the frequency of the other
  - Equivalent to offset QPSK (a variant of phase-shift keying)
- even higher bandwidth efficiency using a Gaussian low-pass filter
  ➔ GMSK (Gaussian MSK), used in GSM

minimum shift keying (MSK)

- Phase ramps up through 90° for a binary one and down 90° for a binary zero

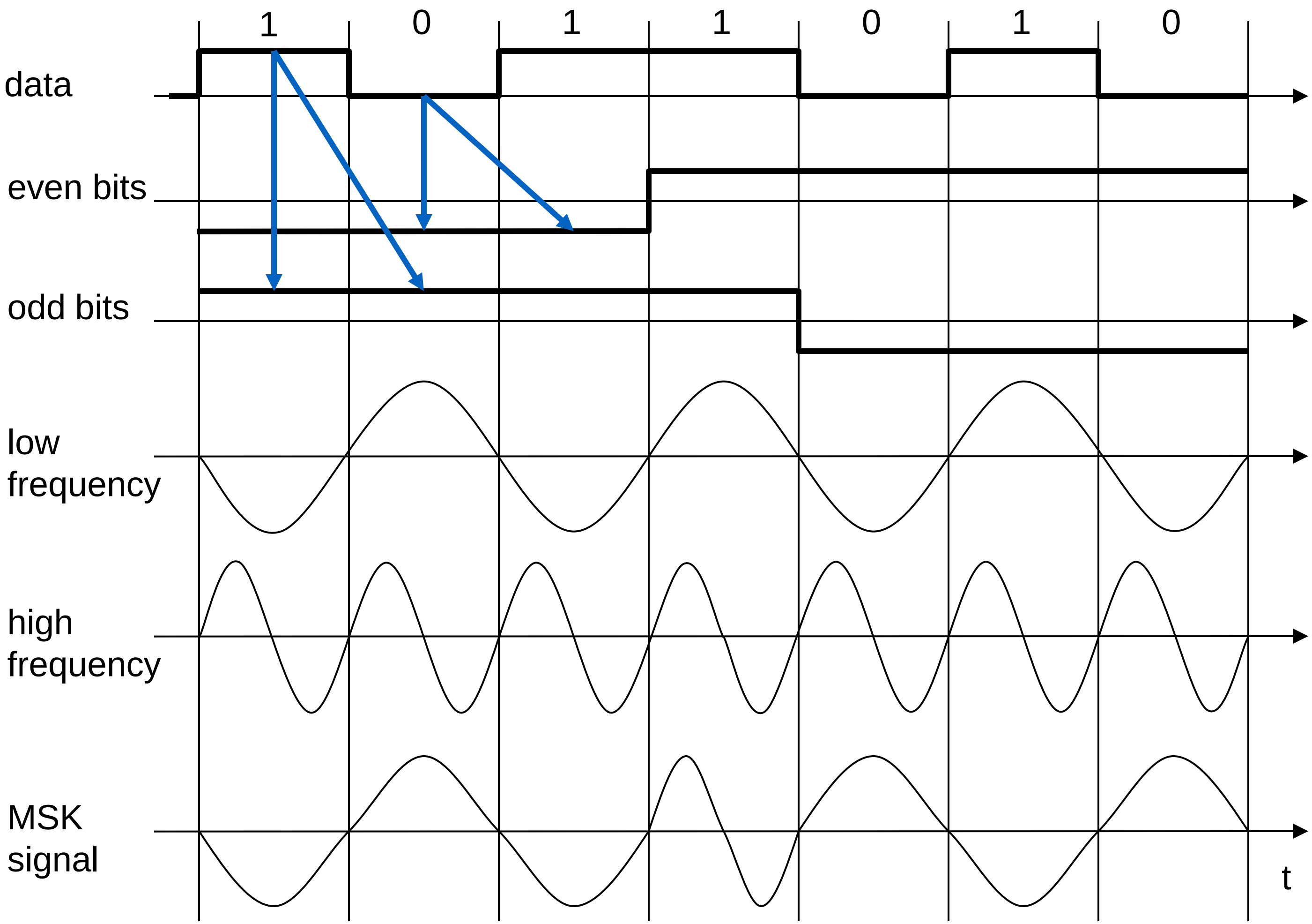


MSK possible phase transitions



MSK phase transitions for data: (00111000...)

example of MSK



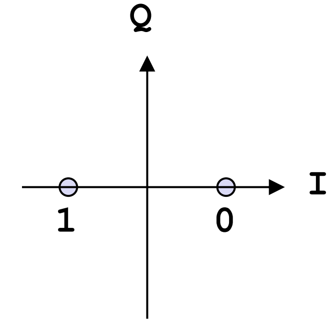
bit	
even	0 1 0 1
odd	0 0 1 1
signal	h n n h
value	- - + +

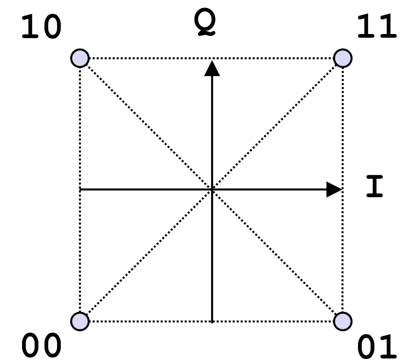
h: high frequency
n: low frequency
+: original signal
-: inverted signal

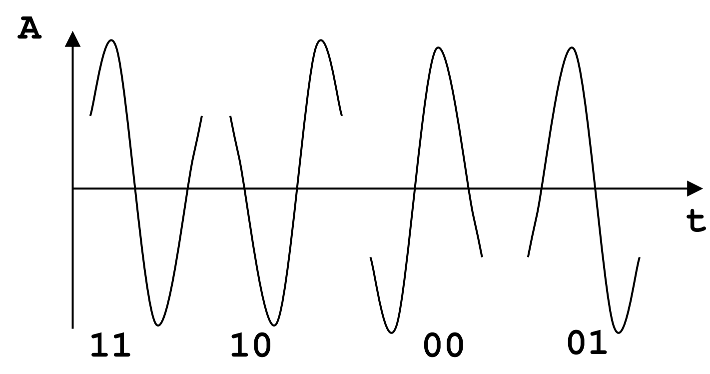
No phase shifts!

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)

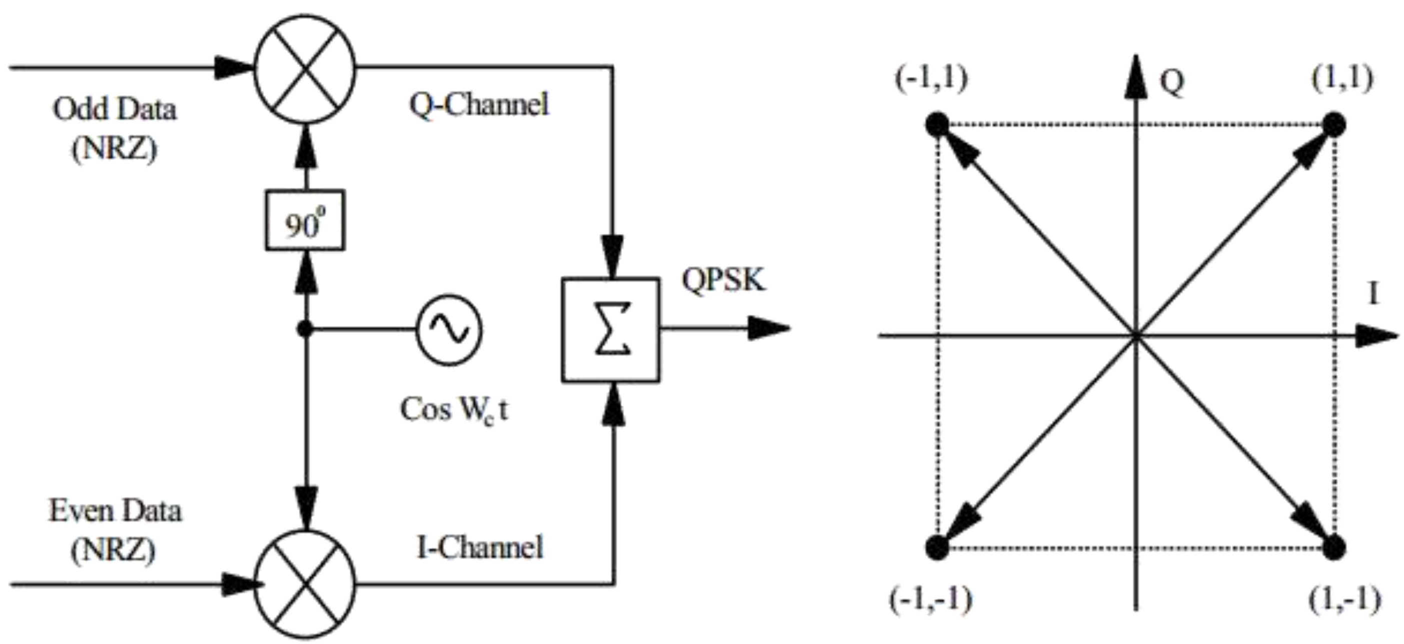






quadrature phase shift keying (QPSK)

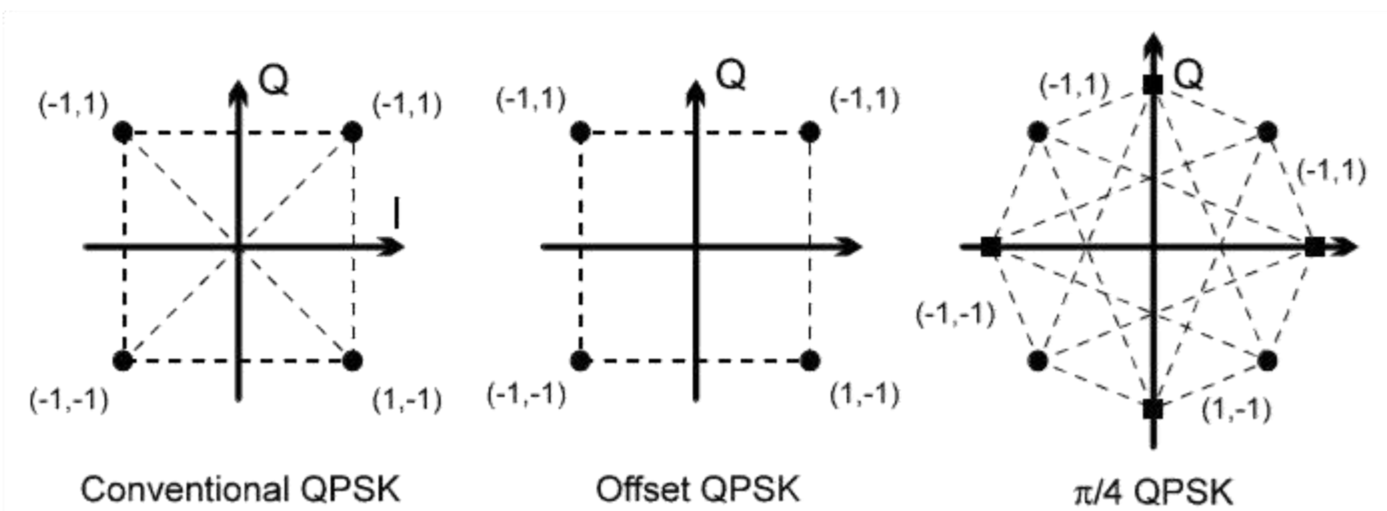
- Effectively two independent BPSK
  - Same performance, twice bandwidth efficiency



Wc = Carrier Frequency, I = In phase channel, Q = Quadrature channel

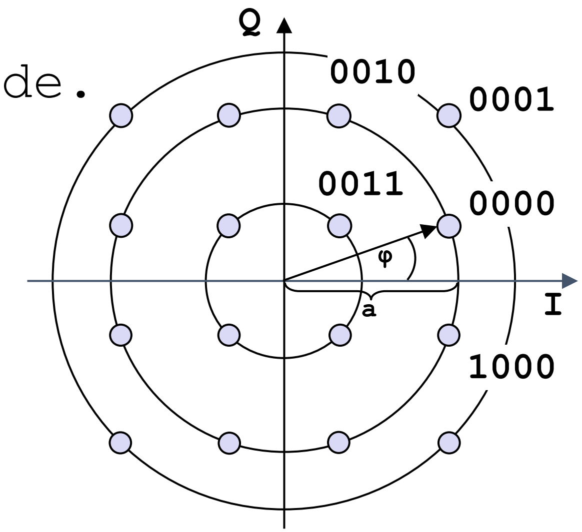
types of QPSK

- Conventional QPSK
  - has transition through zero
  - i.e. 180° phase transition
  - Highly linear amplifier required
- Offset QPSK
  - Phase transitions are limited to 90°
- π/4 QPSK
  - Transitions through zero cannot occur



quadrature amplitude modulation (QAM)

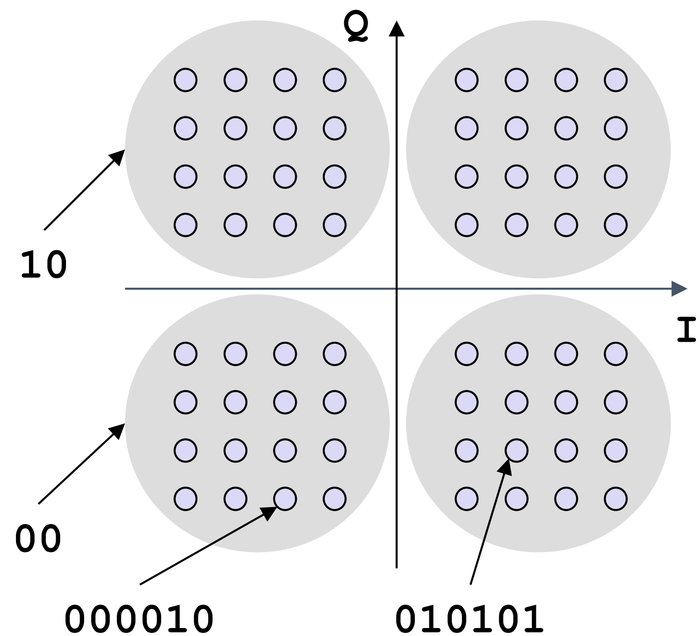
- Quadrature Amplitude Modulation (QAM)
  - **combines amplitude and phase modulation**
  - it is possible to code n bits using one symbol
  - **2^n discrete levels, n=2 identical to QPSK**
- Bit error rate increases with n
  - but less errors compared to comparable PSK schemes
  - Example: 16-QAM (4 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

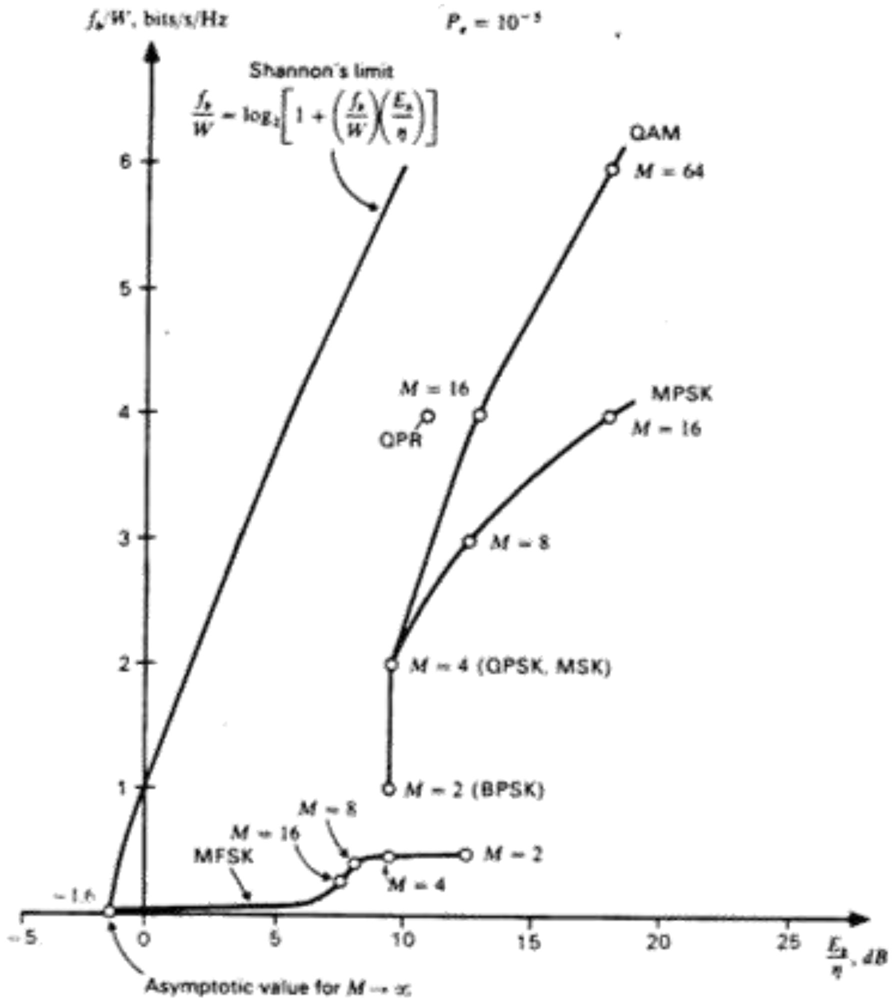
- **DVB-T** modulates separate data streams onto a single DVB-T stream
- High Priority (HP) embedded within a Low Priority (LP) stream
- Multi carrier system, about 2000 or 8000 carriers
  - Actually 1705 or 6817 subcarriers, 4KHz or 1KHz apart
- Supports three modulation schemes
  - QPSK, 16QAM, 64QAM

- 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



comparison of modulation schemes

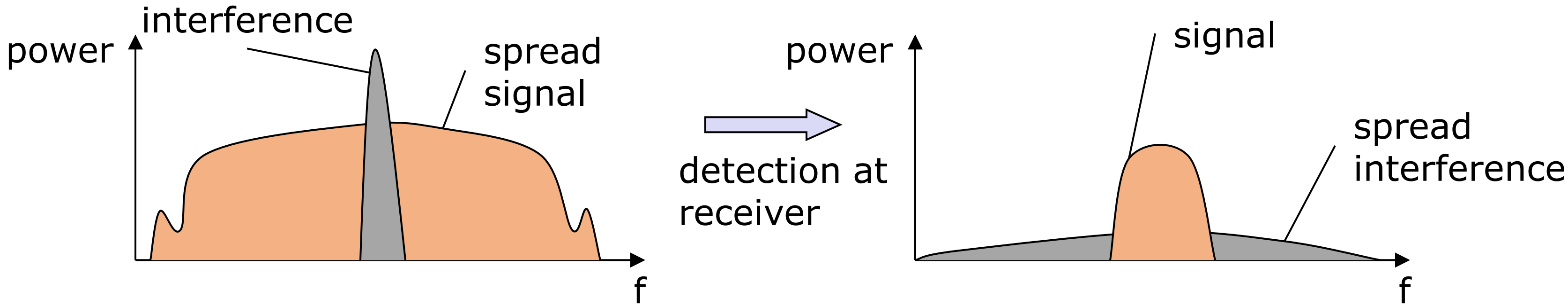
- **Bandwidth efficiency is traded off against power efficiency!!!**
  - MFSK is power efficient, but not bandwidth efficient
  - MPSK and QAM are bandwidth efficient but not power efficient
  - Mobile radio systems are bandwidth limited, therefore PSK is more suited



bits/s/Hz vs. E_b/η for Probability of Error = 10^{-5}
taken from "Principle of Communication Systems"
Taub & Schilling, page 482

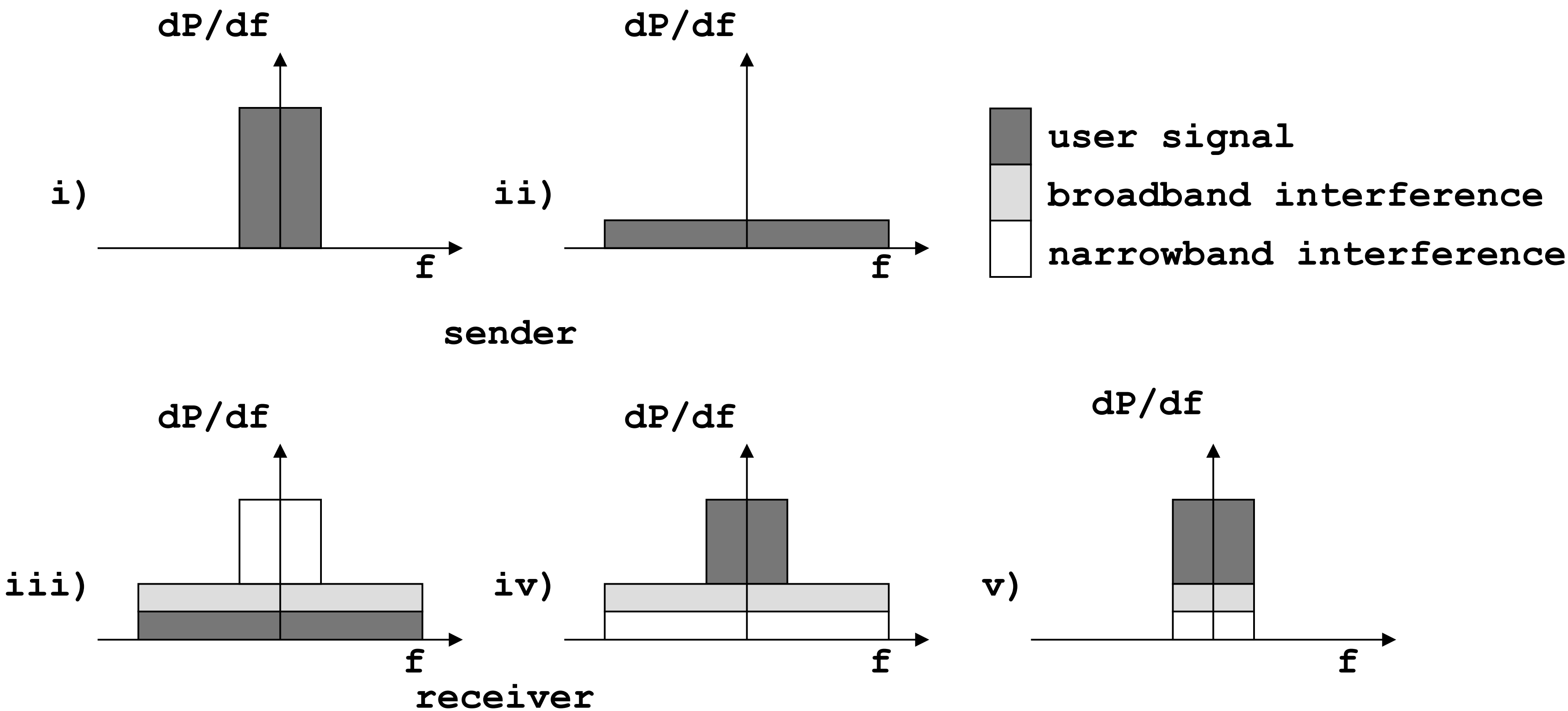
spread spectrum technology

- 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

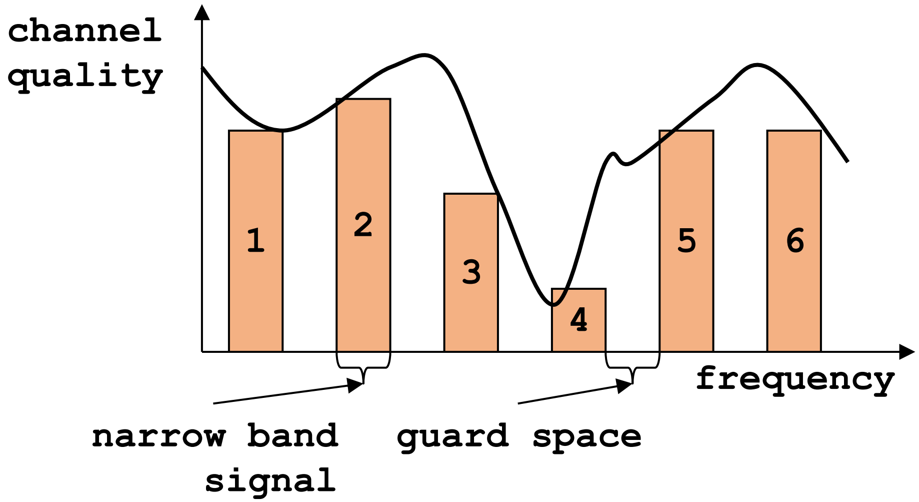


- Side effects
  - coexistence of several signals without dynamic coordination
  - tap-proof
- Alternatives
  - Direct Sequence, Frequency Hopping

effects of spreading and interference

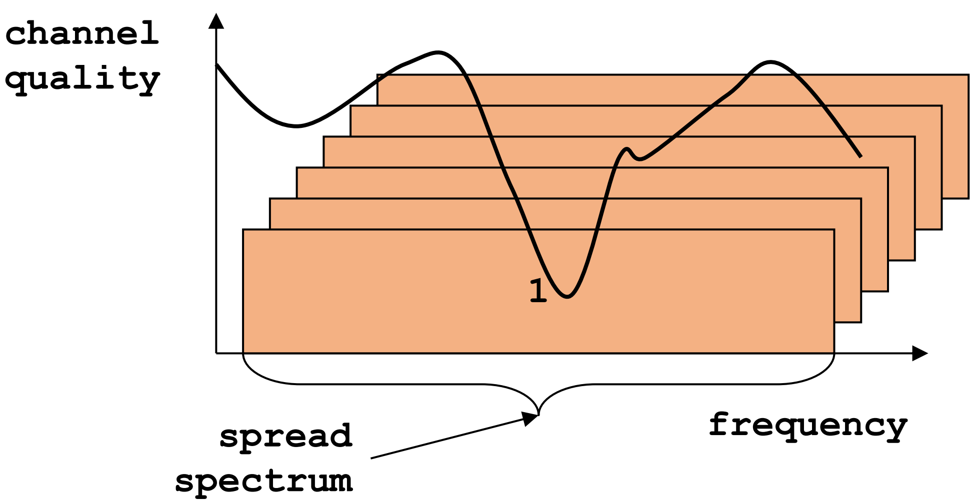


spreading and frequency selective fading



narrowband channels

- Only a snapshot
- Next moment can be different
- Ch#3,4 are destroyed

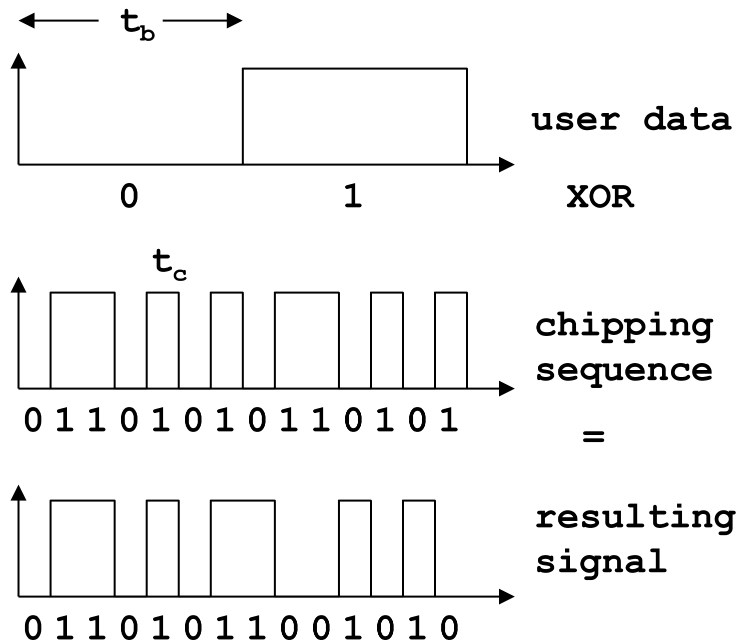


spread spectrum channels

- All spectrum occupied
- CDM is used to recover each channel

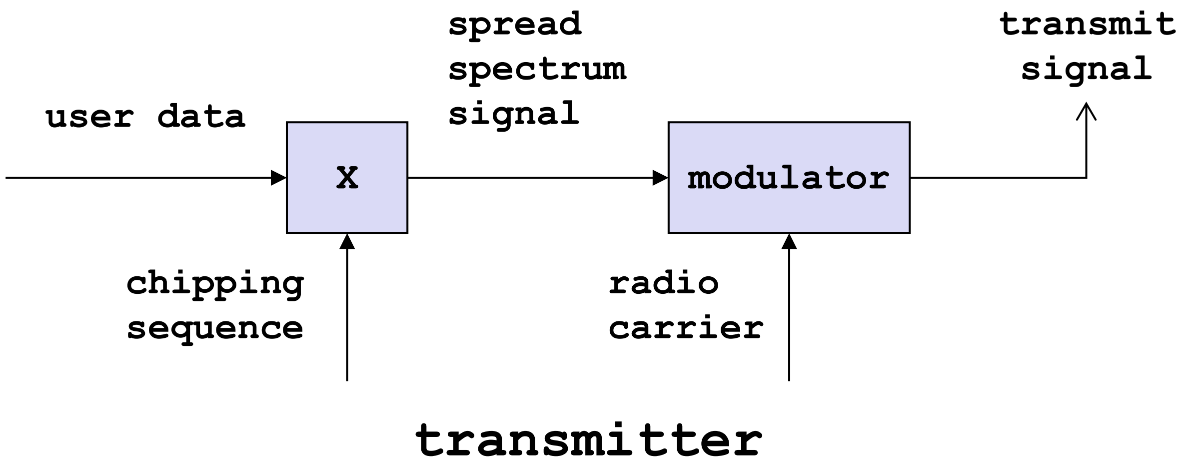
direct sequence spread spectrum (DSSS)

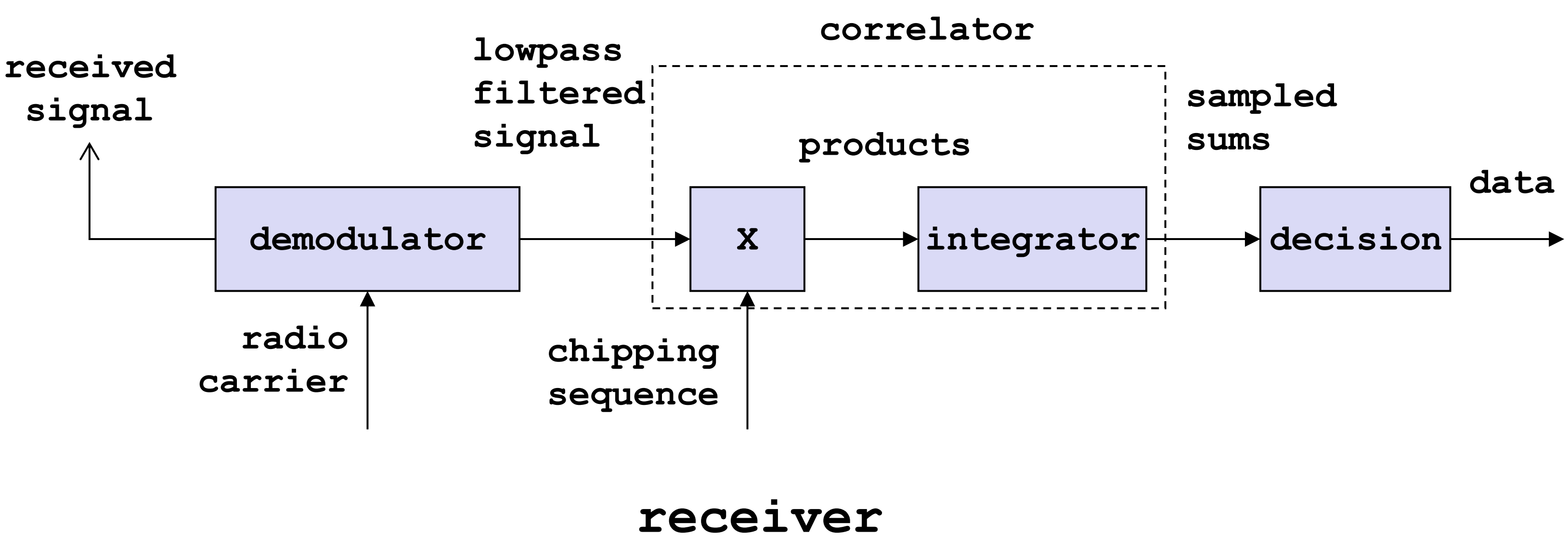
- **XOR of the signal with pseudo-random number** (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal
  - spreading factor
    $s = t_b / t_c$
    - can be 10, 100, 10000, …
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - 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

direct sequence spread spectrum (DSSS)

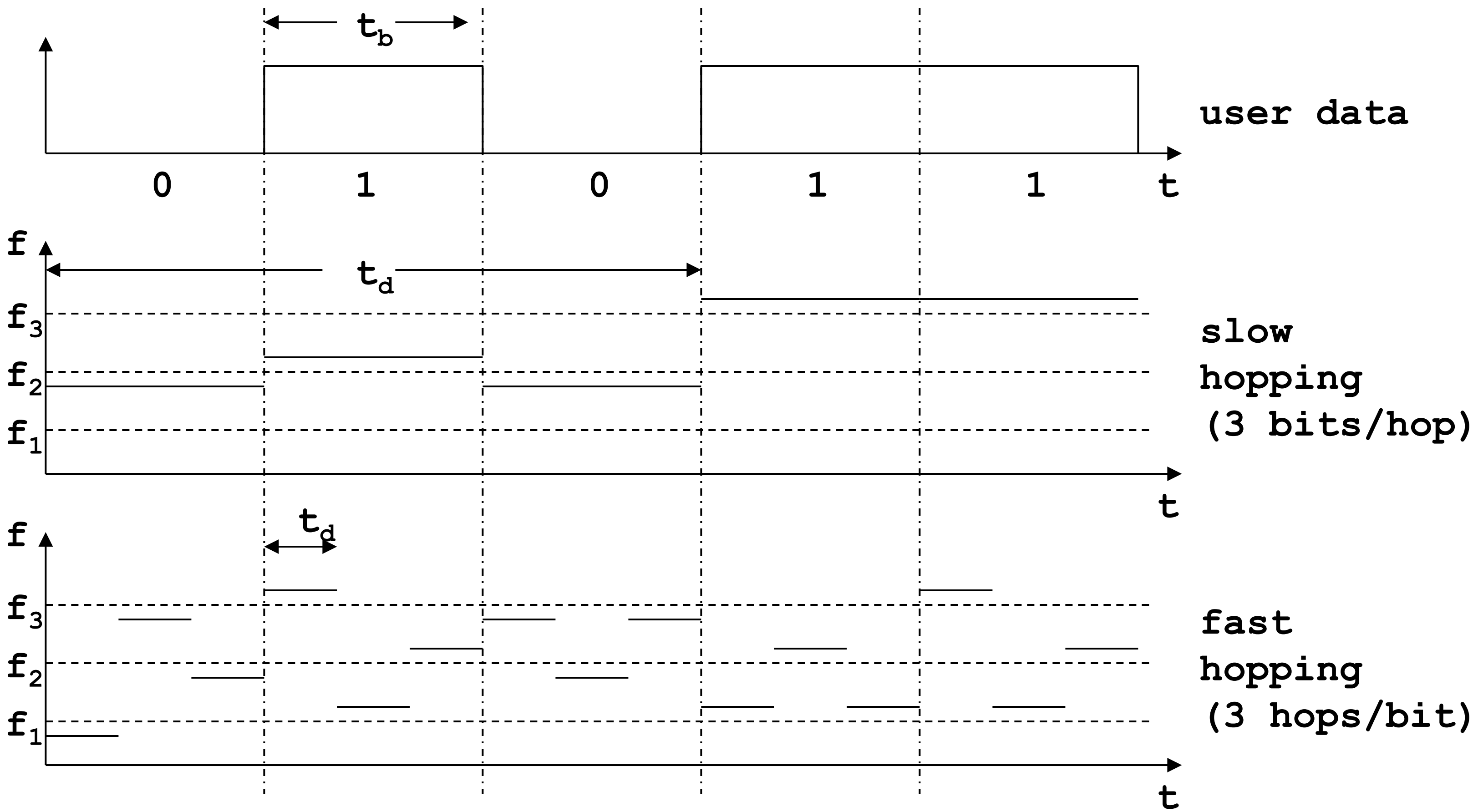




frequency hopping spread spectrum (FHSS)

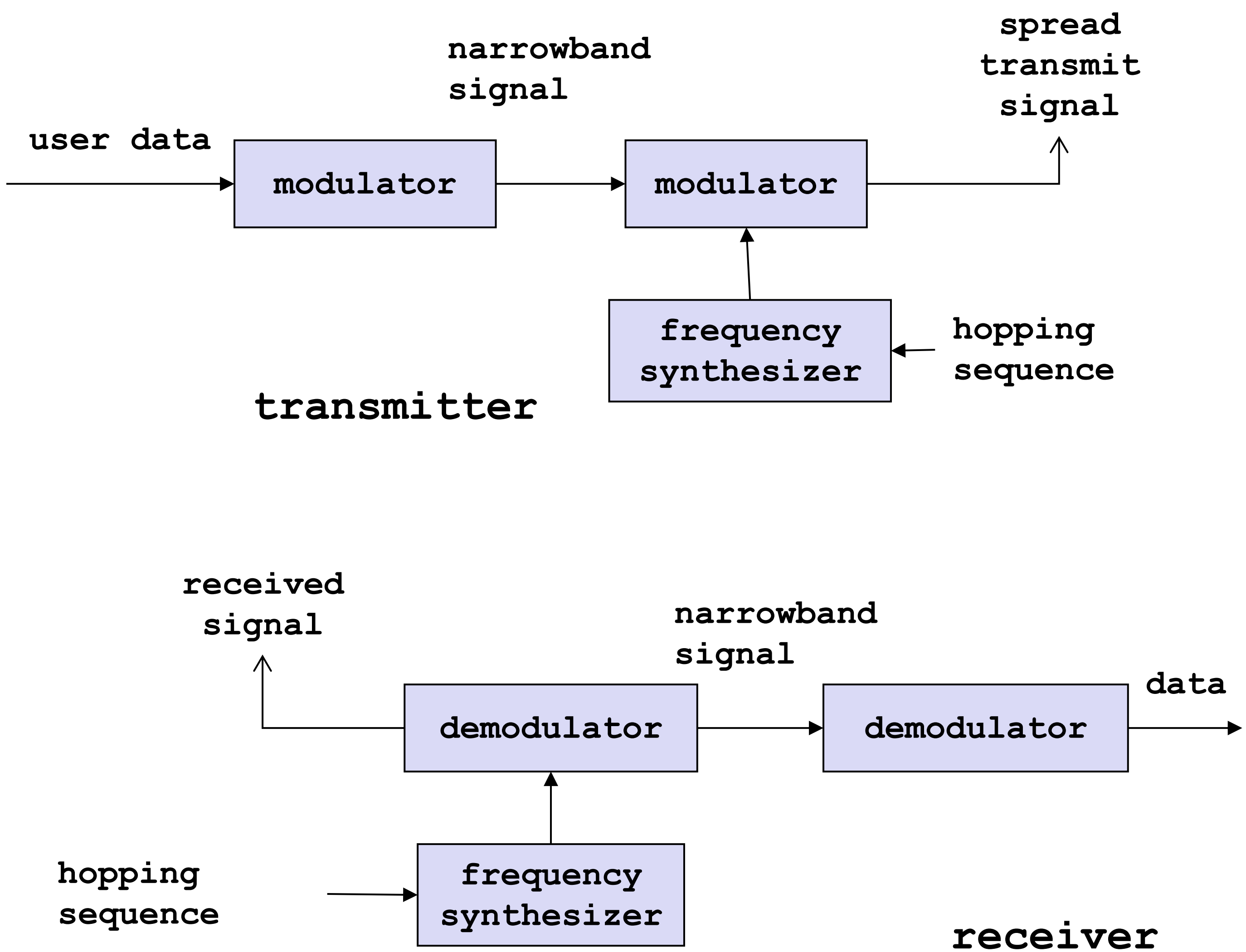
- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence (hopping seq.)
- Two versions
  - Fast Hopping
    - several frequencies per user bit
  - Slow Hopping
    - several user bits per frequency
- Advantages
  - frequency selective fading 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

frequency hopping spread spectrum (FHSS)



t_b: bit period t_d: dwell time

frequency hopping spread spectrum (FHSS)



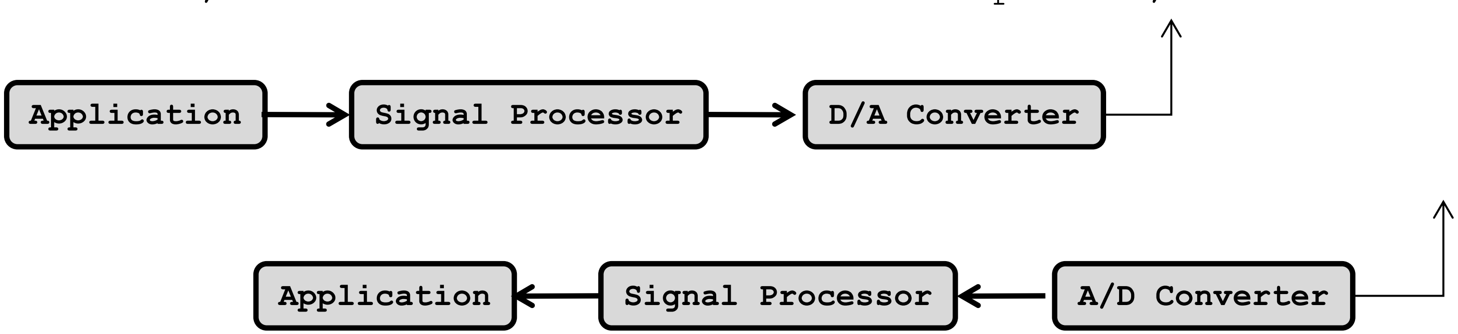
frequency hopping spread spectrum (FHSS)

- Typical example of an FHSS system
  - Bluetooth
    - performs 1.600 hops per second
    - uses 79 hop carriers
      - equally spaced with 1 MHz in the 2.4 GHz ISM band

** ISM: Industrial, Scientific and Medical radio bands defined by the ITU-R in 5.138, 5.150, and 5.280 of the Radio Regulations*

software defined radio

- Basic idea (ideal world)
  - Full flexibility with regard to 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 (US military)
  - GNU Radio, Universal Software Radio Peripheral, …

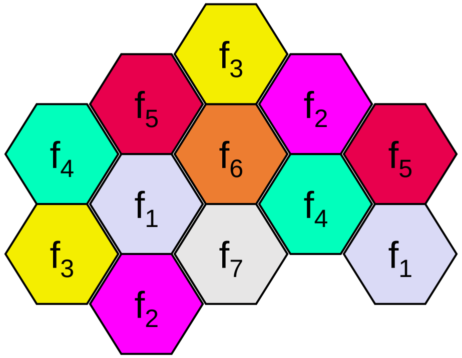


cellular systems

- Implement **space-division multiplexing** (i.e. MIMO)
  - 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 100m in cities to, e.g., 35km on the country side (GSM)
  - even less for higher frequencies

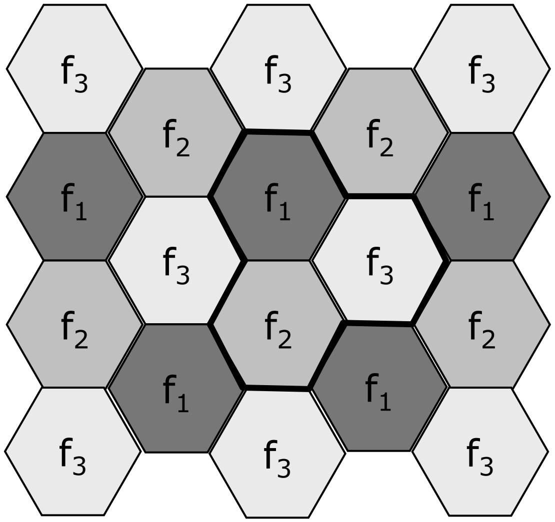
frequency planning

- Frequency **reuse only with a certain distance** between the base stations
- Standard model using 7 frequencies

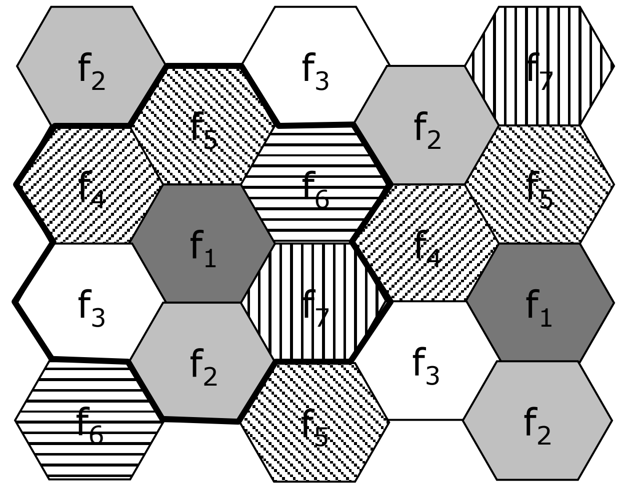


- **Fixed** frequency assignment
  - certain frequencies are assigned to a certain cell
  - problem: different traffic load in different cells
- **Dynamic** frequency assignment
  - base station chooses frequencies depending on the frequencies already used in neighbor cells
  - more capacity in cells with more traffic
  - assignment can also be based on interference measurements

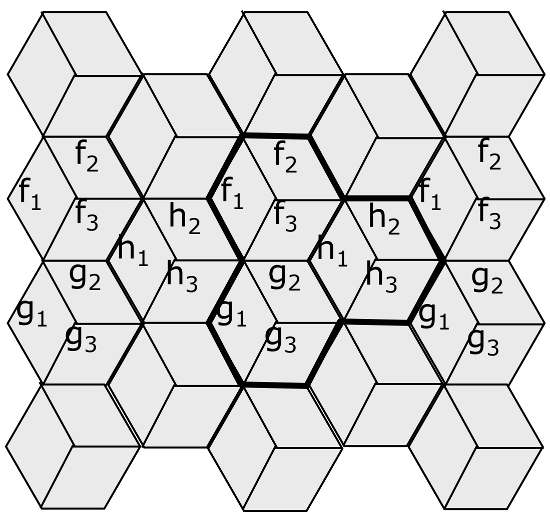
frequency planning



3 cell cluster



7 cell cluster



3 cell cluster
with 3 sector antennas

cell breathing

- **CDM systems** (instead of FDM)
  - do not need complex frequency planning
  - each user is assigned a code
  - **cell size depends on current load**
  - **CDM cells are commonly said to 'breathe'**
- Additional traffic **appears as noise** to other users
- If the noise level is too high users **drop out of cells**
  - similar to trying to talk to someone far away at a
  - crowded party