Mobile Communication: Basics

Dominic Duggan
Based on materials by Jochen Schiller

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WAVES AND FREQUENCIES

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Physics Basics

- Wireless signals travel in waves
  - Electromagnetic
  - Infrared
  - Visible light, UV
- Speed is limited by the speed of light, c
- Signal characteristics:
  - Wavelength, λ
  - Frequency, $f = c/\lambda$
  - Amplitude

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Wavelength and Frequency

- Wavelength measured in distance, km to μm
- Frequency measured in Hz/kHz/MHz/GHz/THz
- Antenna size proportional to wavelength
- Long waves (low frequency)
  - Easier to penetrate physical objects e.g. submarines
- Short waves (high frequency)
  - Better for mobile devices (antenna)
  - High frequency $\Rightarrow$ high bandwidth
  - Subject to interference (e.g. visible light)

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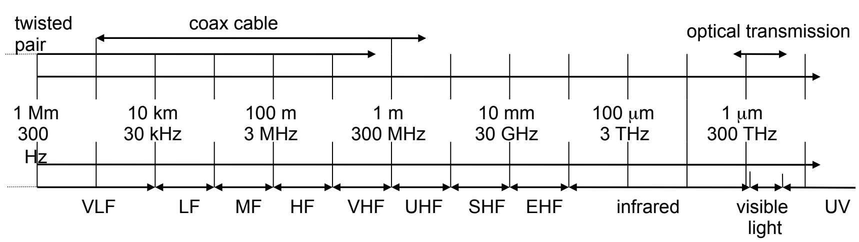
Frequencies for communication

- 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 $c \cong 3x10^8$m/s, frequency f



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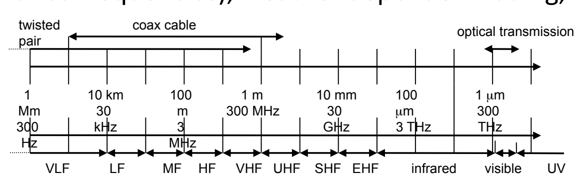
Frequencies for Mobile Communication

- MF/HF ranges for radio stations
  - AM, short wave (SW), FM
- VHF-/UHF-ranges for television, telephone, mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellites
  - small antenna, beam forming, large bandwidth available
- Wireless LANs use frequencies in UHF to SHF range
  - limitations due to absorption by water and oxygen molecules (resonance frequencies), weather dependent fading, rainfall…



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Frequencies and Regulations

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

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

SIGNALS

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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

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Periodic Signals

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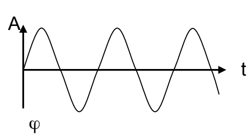
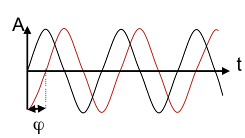
- Periodic signals (esp sine waves) of particular interest for radio transmission





Phase shift used to represent data

- 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:

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

Parameters may change over time

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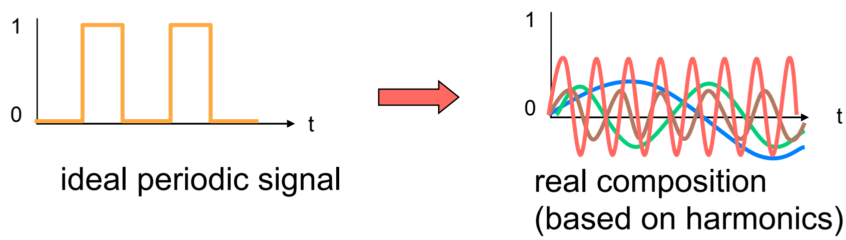
Fourier representation of periodic signals (sampling)

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



f is the **fundamental frequency**

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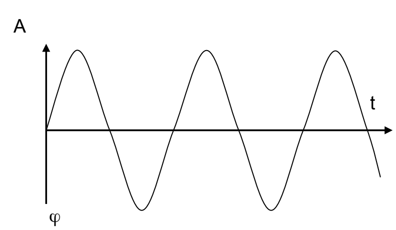
Representation of Signals

- Representations of Signals: Amplitude domain



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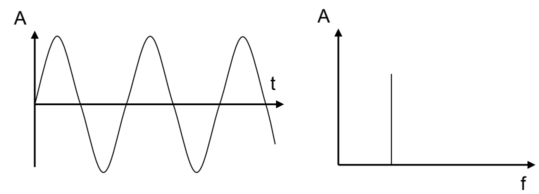
Representation of Signals

- Representations of Signals: Frequency domain



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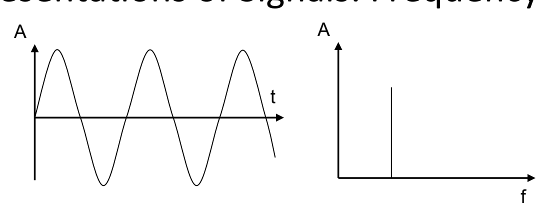
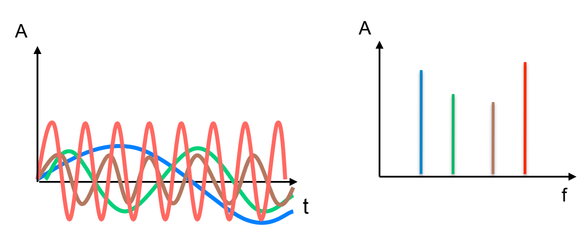
Representation of Signals

- Representations of Signals: Frequency domain



- Composed signals transferred into frequency domain using Fourier transformation



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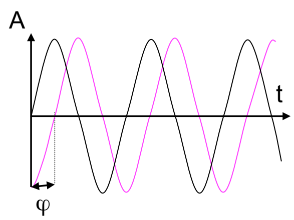
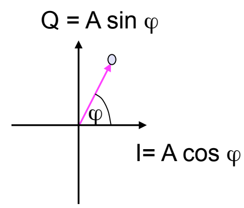
Representation of Signals

- Representations of Signals: phase state
  - amplitude M and phase φ in polar coordinates





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Representation of Signals

- Recall Fourier representation:

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

- Digital signals need
  - infinite frequencies for perfect transmission
    - But in practice limited bandwidth and frequencies
    - Only need to sample at some finite number of frequencies
  - modulation with a carrier frequency for transmission (analog signal)

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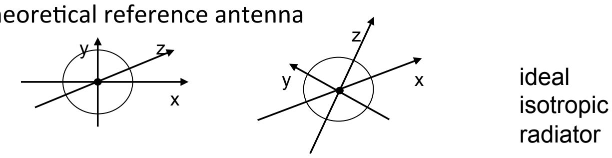
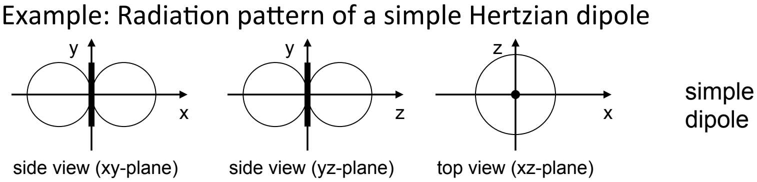
SIGNAL PROPAGATION

Antennas

- Isotropic radiator: equal radiation in all directions
  - only a theoretical reference antenna



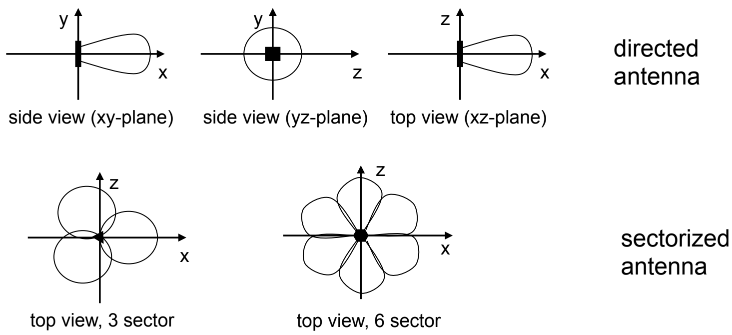
- Real antennas always have directive effects (vertically and/or horizontally)
- Radiation pattern: measurement of radiation around an antenna
- Example: Radiation pattern of a simple Hertzian dipole



- Gain: maximum power in the direction of the main lobe compared to the power of an isotropic radiator

Antennas: Directed and Sectorized

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



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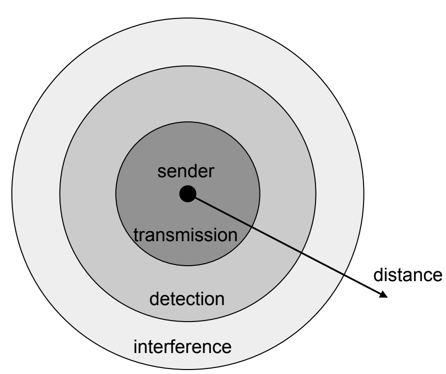
Signal Propagation Ranges

- Transmission range
  - communication possible
  - low error rate
- Detection range
  - no communication possible
- Interference range
  - signal may not be detected
  - signal adds to the background noise



Motivation for cells

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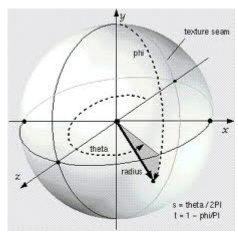
Signal Propagation

- Propagation in free space in straight line
- Receiving power proportional to $1/d^2$ in vacuum (d = distance between sender and receiver)
  - Recall: area of sphere = $4\pi d^2$ where d = radius



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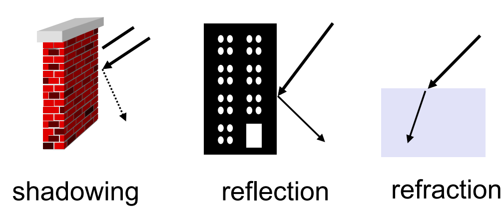
Signal Propagation

- Receiving power additionally influenced by
  - fading (frequency dependent)
  - shadowing
  - reflection at large obstacles
  - refraction (depends on density of medium)



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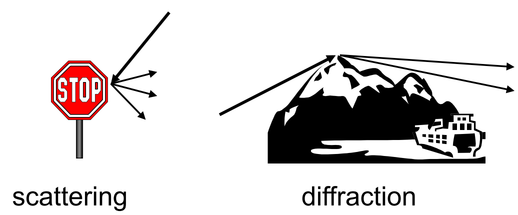
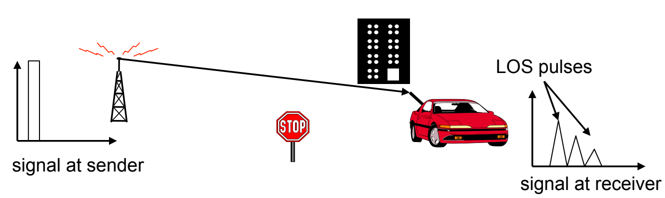
Signal Propagation

- Receiving power additionally influenced by
  - scattering at small obstacles
  - diffraction at edges

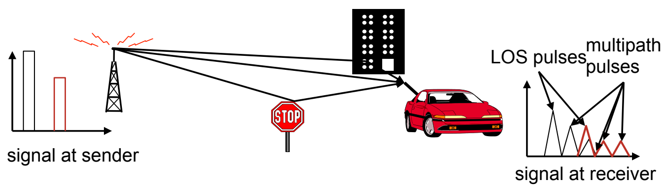


Multipath propagation



Multipath propagation

- Signal can take many different paths due to reflection, scattering, diffraction



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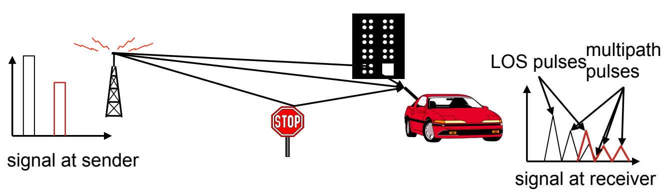

- Signal is dispersed over time
  - Inter Symbol Interference (ISI)
- Signal reaches a receiver directly and phase shifted

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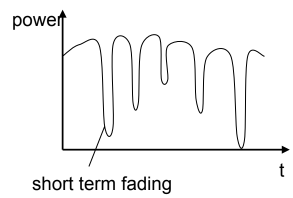
Effects of Mobility

- 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)



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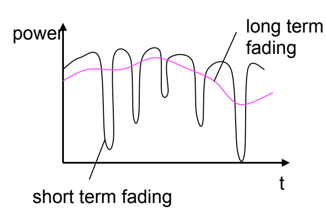
Effects of Mobility

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



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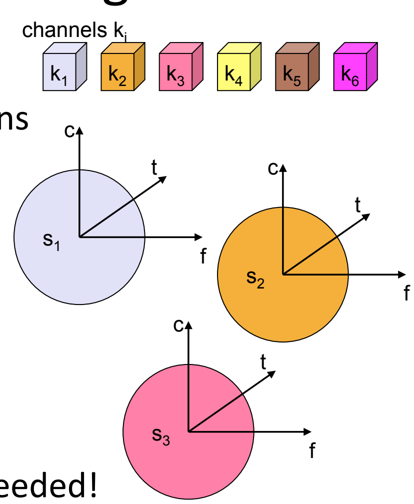
MULTIPLEXING

Multiplexing

Analog telephone
FM radio stations

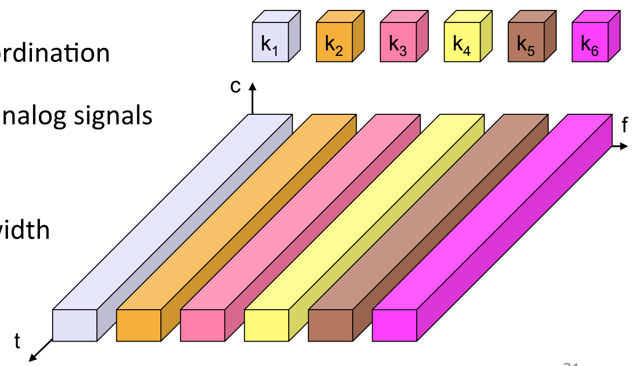


- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)
- Goal: multiple use of a shared medium
- Important: guard spaces needed!

Radio stations

Frequency Multiplexing

- 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



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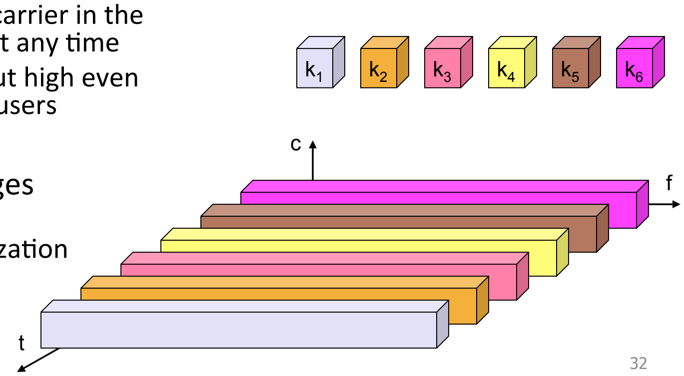
Cars on a highway

Time Multiplexing

- 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



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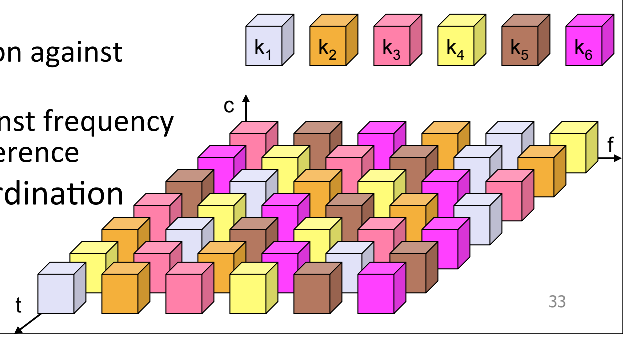
Time and Frequency Multiplexing

- 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
- but: precise coordination required



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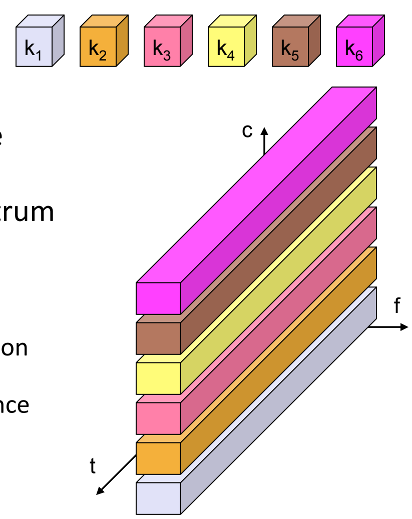
Code Multiplexing

Simultaneous conversations in different languages



- 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

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MODULATION

Digital Modulation

- Digital modulation
  - digital data is translated into an analog signal (baseband)
  - E.g. shift 1 Mb/s bit stream to 1 MHz baseband signal
- Techniques
  - Amplitude shift keying (ASK)
  - Frequency shift keying (FSK)
  - Phase shift keying (PSK)
  - differences in spectral efficiency, power efficiency, robustness

Analog Modulation

- Analog modulation
  - shifts center frequency of baseband signal up to the radio carrier
  - e.g. shift 1 MHz signal to 1 GHz (otherwise need an antenna hundreds of meters high)
- Motivation
  - smaller antennas (e.g., $\lambda/4$)
  - Frequency Division Multiplexing
  - medium characteristics
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)

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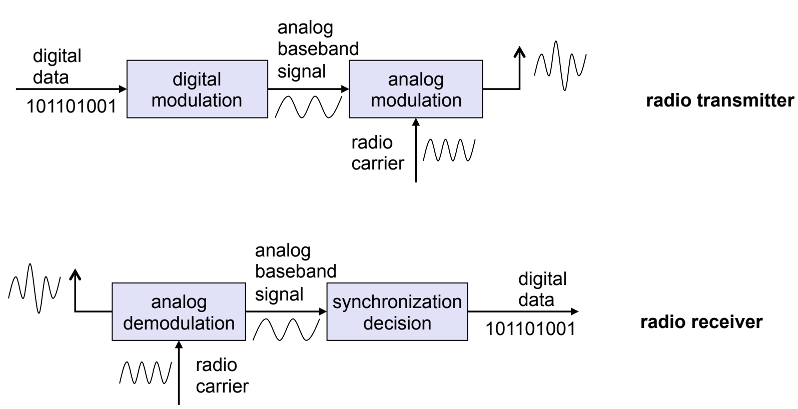
Modulation and demodulation



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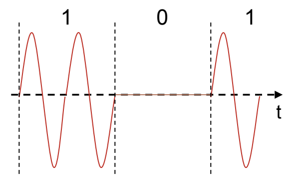
Digital modulation

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



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Digital modulation

- Modulation of digital signals known as Shift Keying
- Amplitude Shift Keying (ASK):
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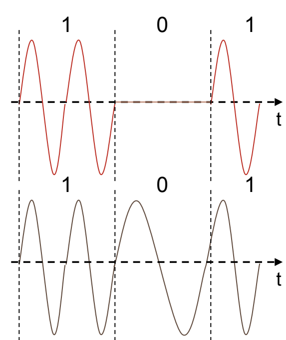
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - needs larger bandwidth



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Digital modulation

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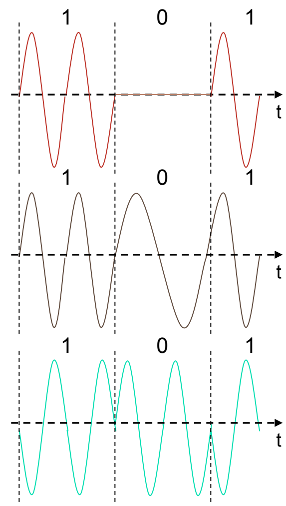
  - very susceptible to interference
- Frequency Shift Keying (FSK):
  - needs larger bandwidth
- Phase Shift Keying (PSK):
  - more complex
  - robust against interference



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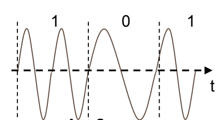
Advanced Frequency Shift Keying



- Bandwidth needed for FSK depends on distance between 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
  - Two frequencies f_1 and $f_2 = 2f_1$
  - Both bits 1 ⇒ send on f_2, both bits 0 ⇒ send on f_2 inverted
  - Odd bit 1, even bit 0 ⇒ send on f_1
  - Odd bit 0, even bit 1 ⇒ send on f_1 inverted
  - Key point: no abrupt phase changes
- Even higher bandwidth efficiency using a Gaussian low-pass filter ⇒ GMSK (Gaussian MSK), used in GSM

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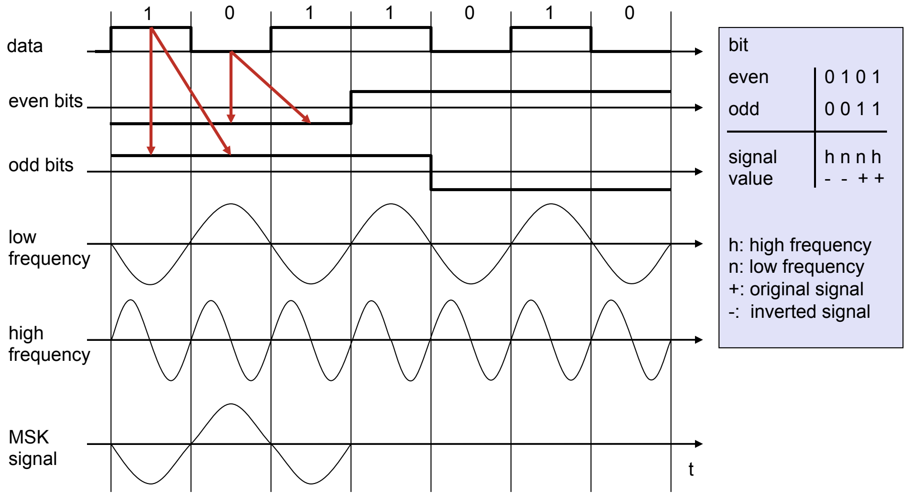
Example of MSK



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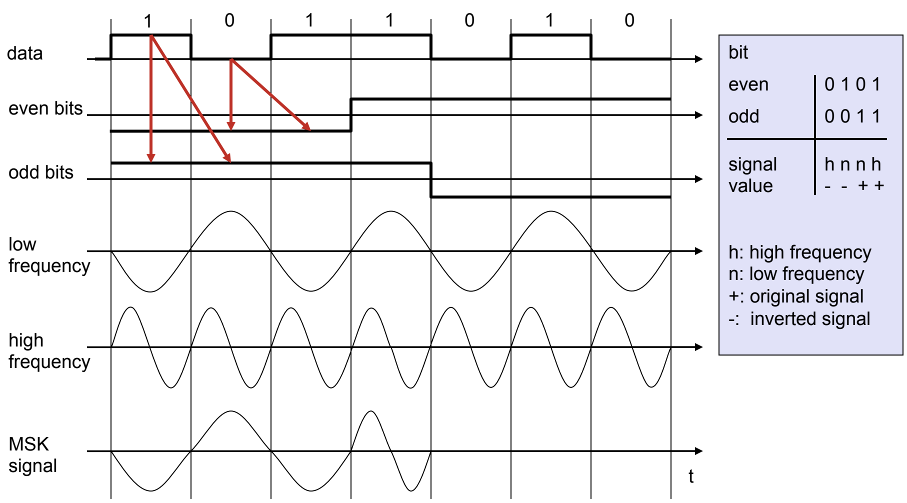
Example of MSK



No phase shifts!

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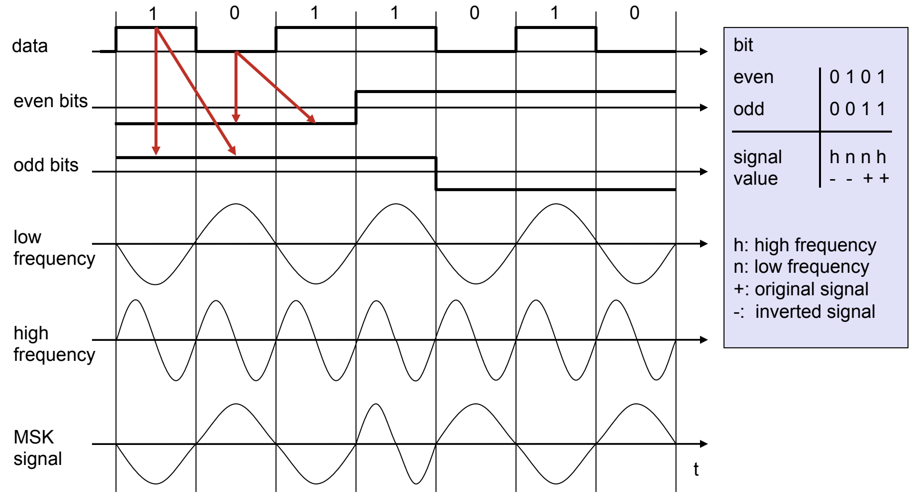
Example of MSK



No phase shifts!

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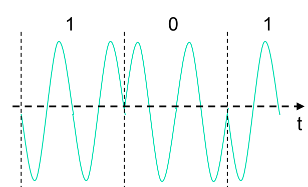
Advanced Phase Shift Keying

- 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 satellites



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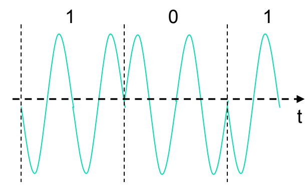

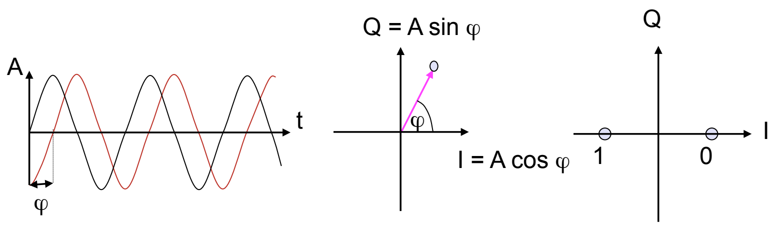

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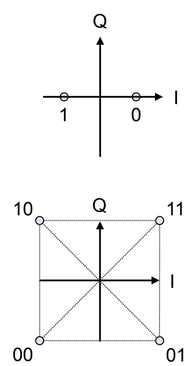
- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - needs less bandwidth compared to BPSK
  - more complex



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Advanced Phase Shift Keying

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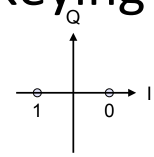
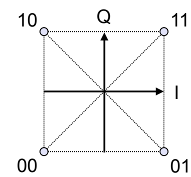
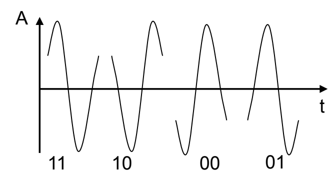
  - robust, used e.g. in satellite s
- QPSK (Quadrature Phase Shift Keying):
  - 2 bits coded as one symbol
  - symbol determines shift of sine wave
  - needs less bandwidth compared to BPSK
  - more complex
- Often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK (IS-136, PHS)







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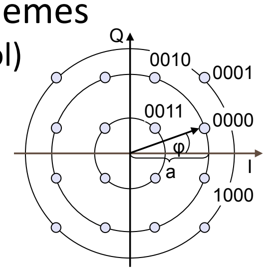
Quadrature Amplitude Modulation

- 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)



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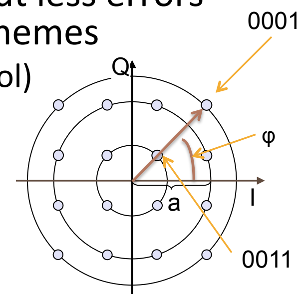
Quadrature Amplitude Modulation

- 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.



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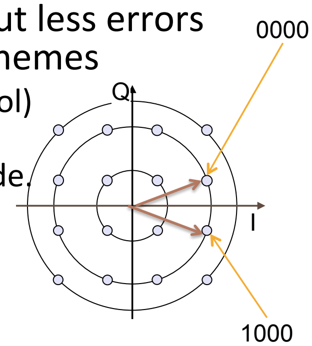
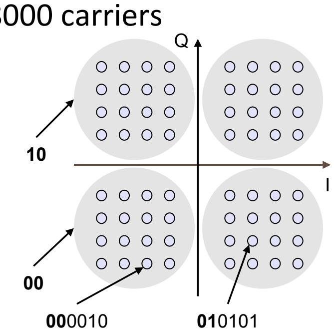
  - Symbols 0000 and 1000 have different phase, but same amplitude.



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
- 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



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SPREAD SPECTRUM

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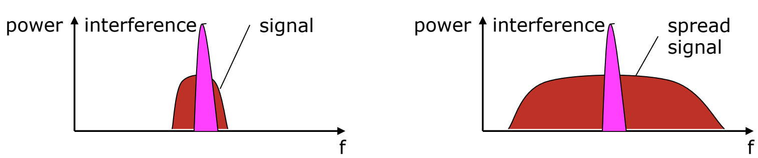
Spread Spectrum

- Problem: frequency dependent fading
  - Can wipe out narrow band signals
- Solution: spread the narrow band signal into a broad band signal using a code



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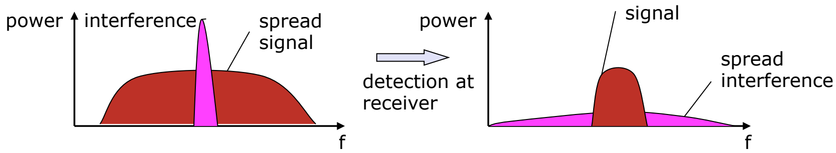

- Side effects:
  - coexistence of several signals without dynamic coordination
  - tap-proof
- Alternatives: Direct Sequence, Frequency Hopping

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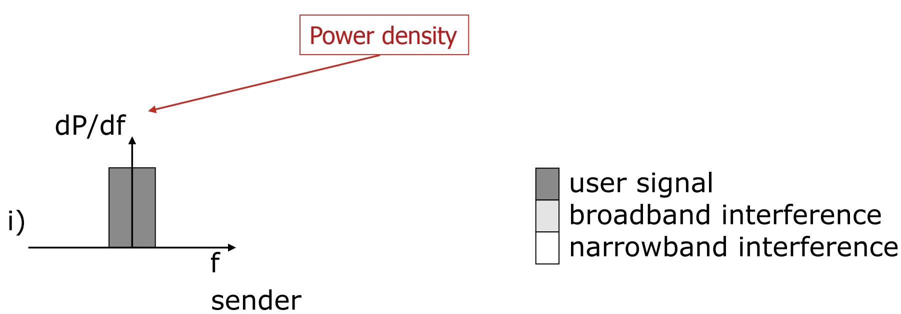
Effects of Spreading and Interference



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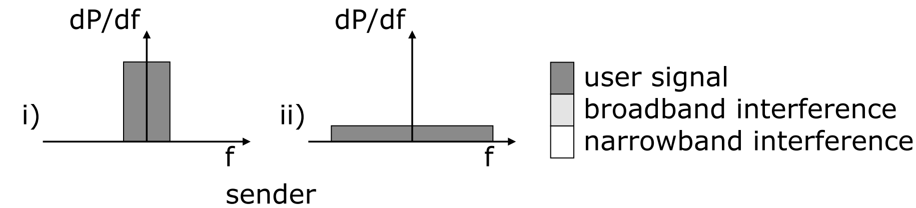
Effects of Spreading and Interference



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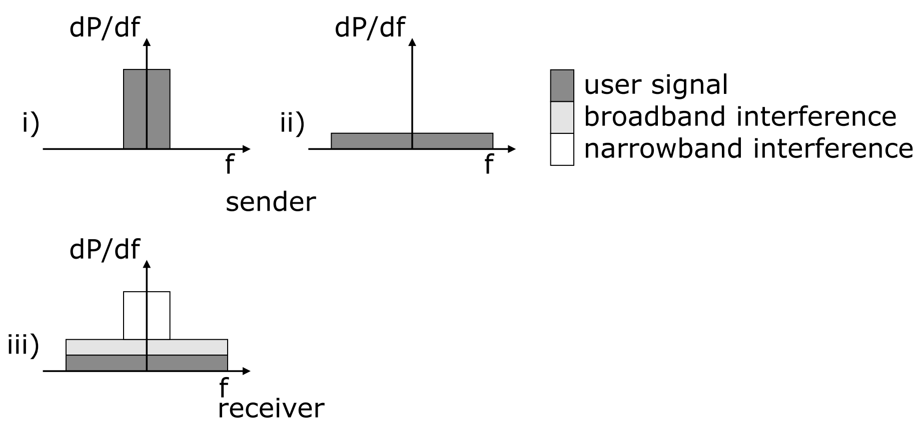
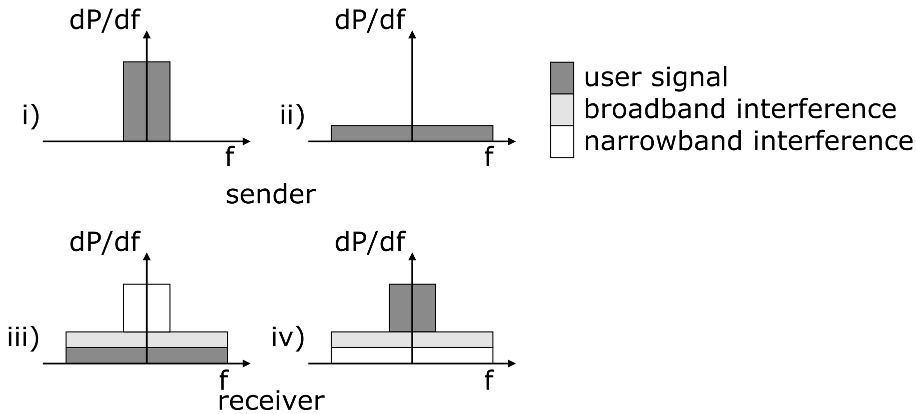


Effects of Spreading and interference



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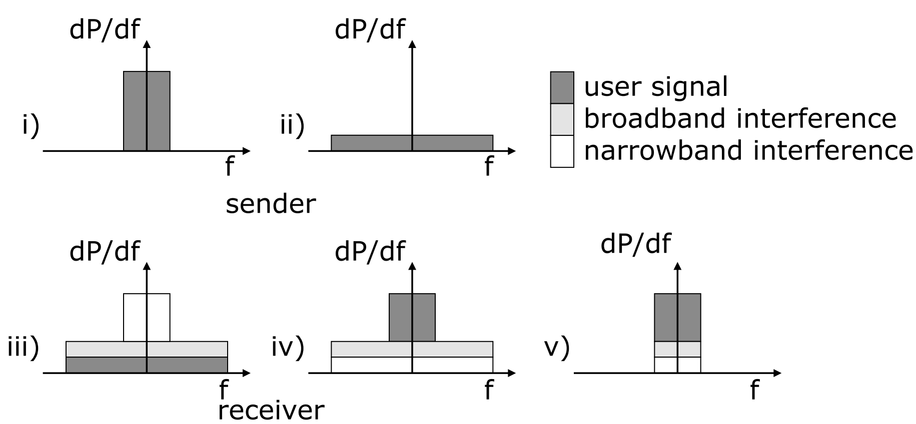
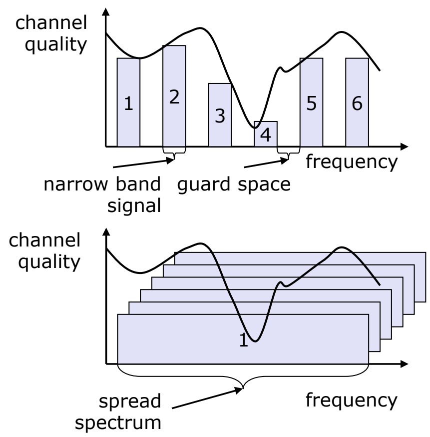


Spreading and frequency selective fading



narrowband channels

spread spectrum channels

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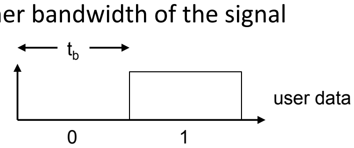
DSSS (Direct Sequence Spread Spectrum)

- XOR of the signal with pseudo-random number (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal



t_b: bit period

64

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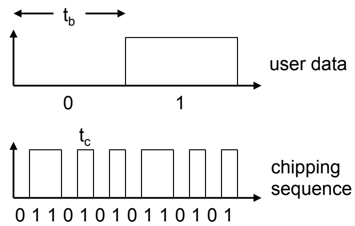

t_b: bit period
t_c: chip period

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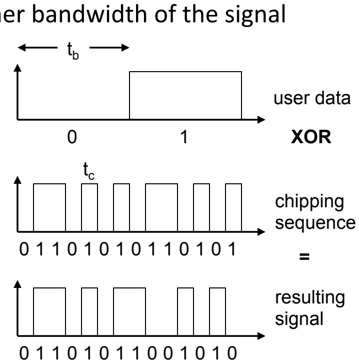

t_b: bit period
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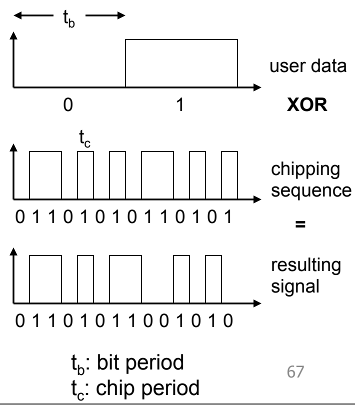
DSSS (Direct Sequence Spread Spectrum)

- 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



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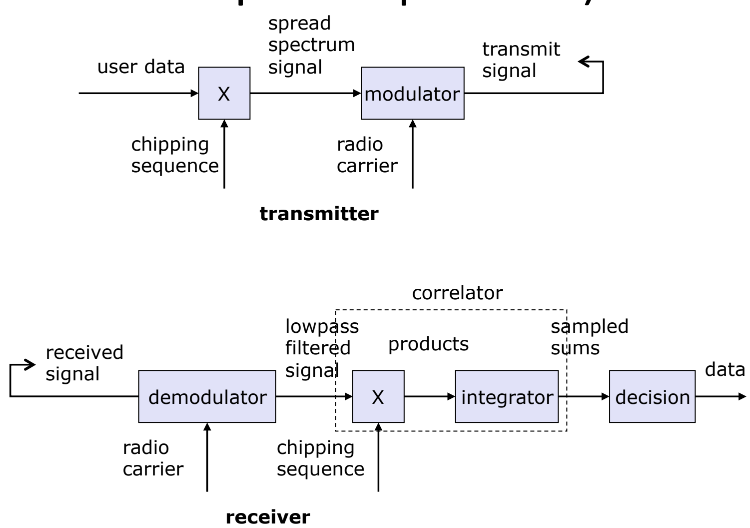

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FHSS (Frequency Hopping Spread Spectrum)

- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence
  - Implements FDM and TDM
- 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

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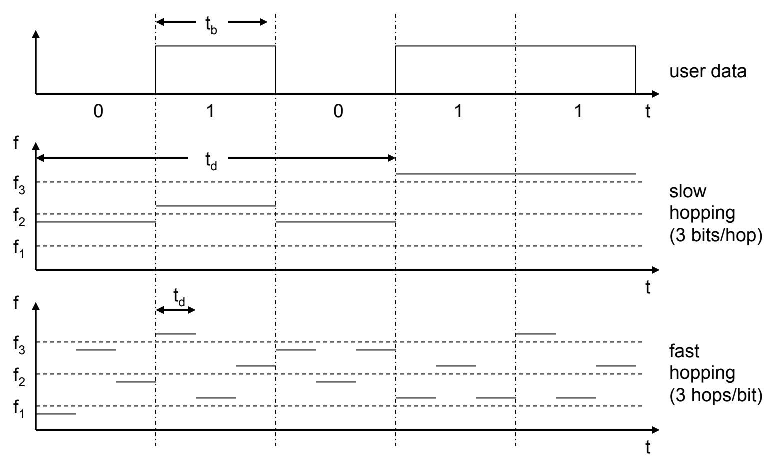
FHSS (Frequency Hopping Spread Spectrum)



t_b: bit period t_d: dwell time

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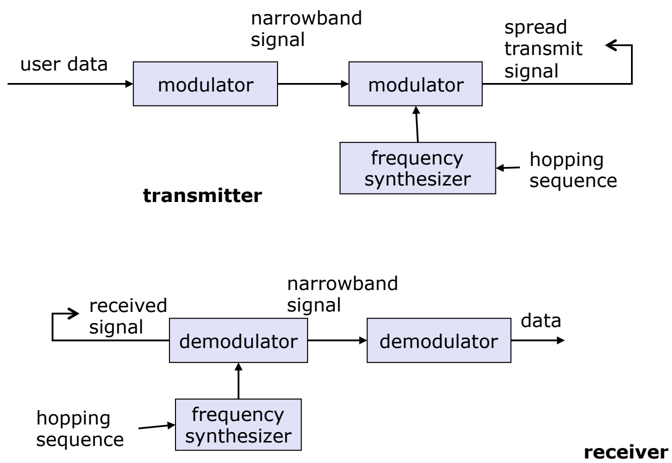
FHSS (Frequency Hopping Spread Spectrum)



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CELL DESIGN

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Cell Structure

- Implements space division multiplex (SDM)
- Mobile stations communicate only via the base station

- Advantages of cell structures (compared to e.g. radio stations)
  - higher capacity, higher number of users due to frequency reuse
  - 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

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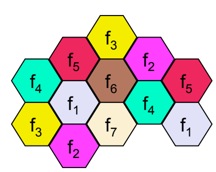
Frequency planning

- 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

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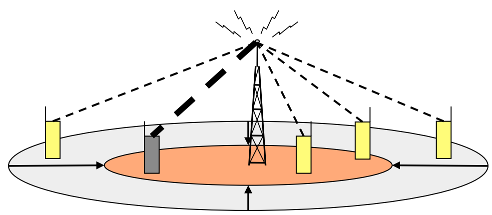
Cell Breathing

- 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



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MEDIUM ACCESS CONTROL

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Motivation

- Can we apply media access methods from fixed networks?
- Example from Ethernet: CSMA/CD
  - **C**arrier **S**ense **M**ultiple **A**ccess with **C**ollision **D**etection
  - send as soon as the medium is free, listen into the medium if a collision occurs (legacy method in IEEE 802.3)
- Problems in wireless networks
  - signal strength decreases proportional to the square of the distance
  - collisions happen at the receiver
  - sender cannot "hear" the collision
  - furthermore, CS might not work if, e.g., a terminal is "hidden"

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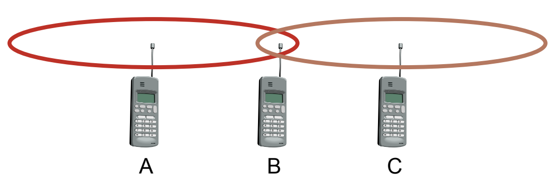
Motivation: hidden terminals

- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B, C senses a "free" medium (CS fails)
  - collision at B, A cannot receive the collision (CD fails)
  - A is "hidden" for C



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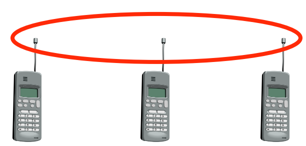
Motivation: exposed terminals

- Exposed terminals
  - B sends to A, C wants to send to another terminal (not A or B)
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary
  - C is "exposed" to B



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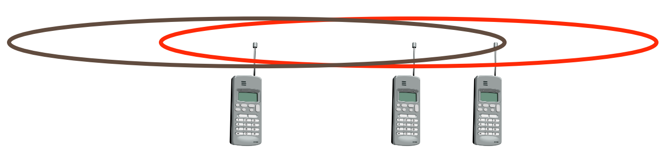
Motivation: Near and far terminals

- Terminals A and B send, C receives
  - signal of terminal B drowns out A's signal (recall signal strength proportional to $1/d^2$)
  - C cannot receive A



- If C for example was an arbiter for sending rights, terminal B would drown out terminal A already on the physical layer
- Problem for CDM-networks—precise power control needed!

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ACCESS METHODS SDMA/FDMA/TDMA

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- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - cell structure

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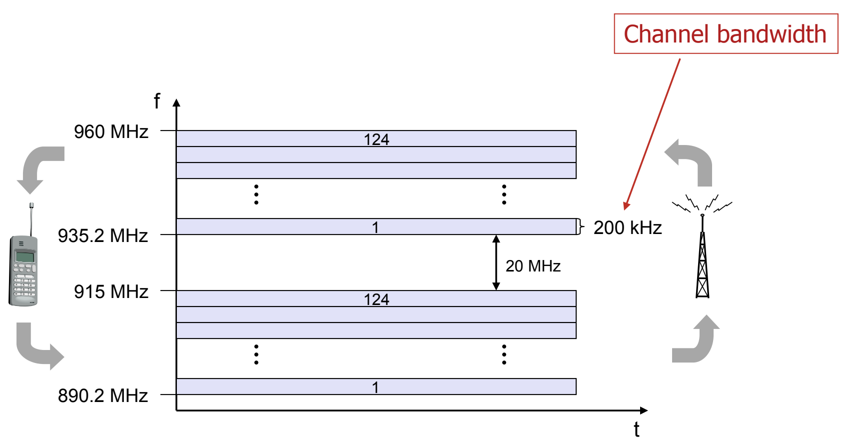
- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - cell structure
- FDMA (Frequency Division Multiple Access)
  - assign a certain frequency to a transmission channel
  - **permanent** (e.g., radio broadcast), **slow hopping** (e.g., GSM), **fast hopping** (FHSS, Frequency Hopping Spread Spectrum)
  - **Frequency division duplex (FDD):** different frequencies for uplink and downlink

FDD/FDMA – General scheme, example GSM



f_d = 935.2 + n*0.2 MHz, f_u = f_d + 45 MHz
Ex: f_d = 935.2 MHz, f_u = 890.2 MHz

Access Methods SDMA/FDMA/TDMA

- SDMA (Space Division Multiple Access)
  - segment space into sectors, use directed antennas
  - cell structure
- FDMA (Frequency Division Multiple Access)
  - assign a certain frequency to a transmission channel
  - permanent (e.g., radio broadcast), slow hopping (e.g., GSM), fast hopping (FHSS, Frequency Hopping Spread Spectrum)
  - Frequency division duplex (FDD): different frequencies for uplink and downlink
- TDMA (Time Division Multiple Access)
  - assign the fixed sending frequency to a transmission channel for a certain amount of time
- The multiplexing schemes presented previously are now used to control medium access!

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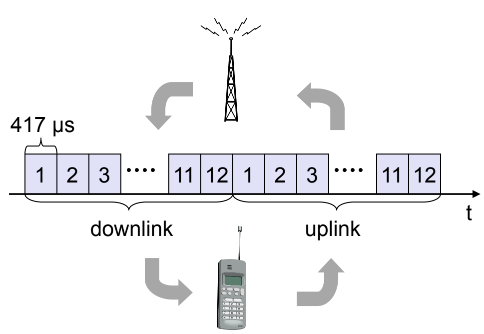
TDD/TDMA – General Scheme, example DECT



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Back up

- How do these schemes handle hidden terminals?

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  - They don't
  - Central base station means that they do not face that problem
  - If terminal is hidden from base station, it cannot communicate

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- How do these schemes handle hidden terminals?
  - They don't
  - Central base station means that they do not face that problem
  - If terminal is hidden from base station, it cannot communicate
- In less centralized cases e.g. ad hoc networks, use MACA…

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COLLISION AVOIDANCE

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MACA - collision avoidance

- MACA (Multiple Access with Collision Avoidance) uses short signaling packets for collision avoidance
  - RTS (request to send): control packet from sender to receiver
  - CTS (clear to send): control packet from receiver to sender
- Signaling packets contain
  - sender address
  - receiver address
  - packet size
- Variants of this method can be found in IEEE802.11 as DFWMAC (Distributed Foundation Wireless MAC)

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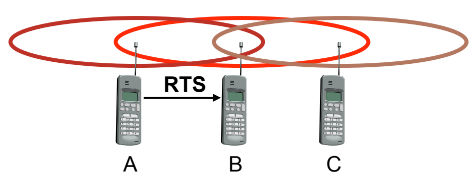
MACA Examples

- MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first



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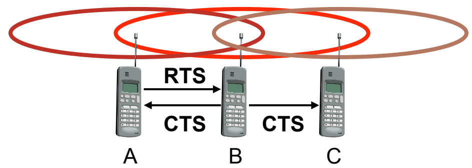
MACA Examples

- MACA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - C waits after receiving CTS from B



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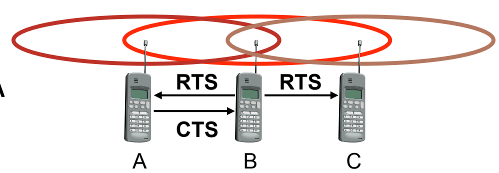
MACA Examples

- MACA avoids the problem of exposed terminals
  - B wants to send to A
  - C wants to send to another terminal
  - C does not have to wait, since it cannot receive CTS from A



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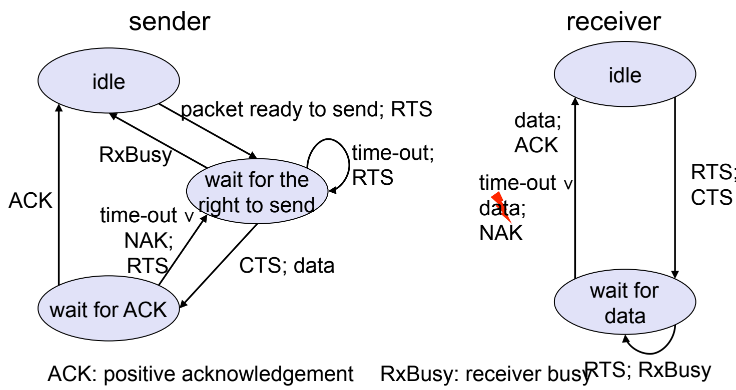
MACA variant: DFWMAC in IEEE802.11



ACK: positive acknowledgement
NAK: negative acknowledgement
RxBusy: receiver busy

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LTE: LONG TERM EVOLUTION (AND BEYOND)

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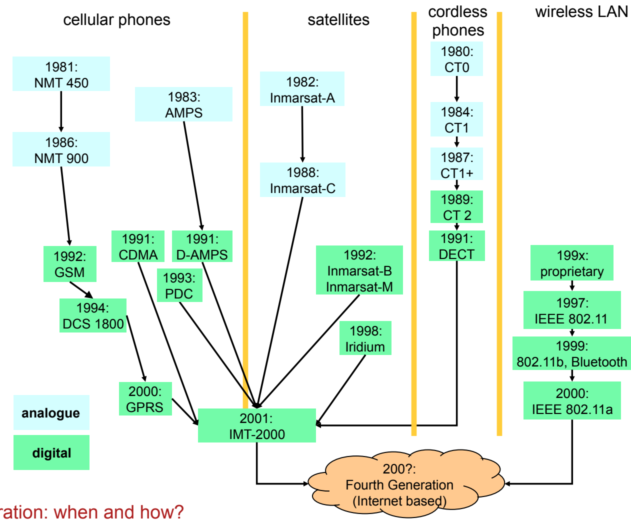
Evolution of networks



4G – fourth generation: when and how?

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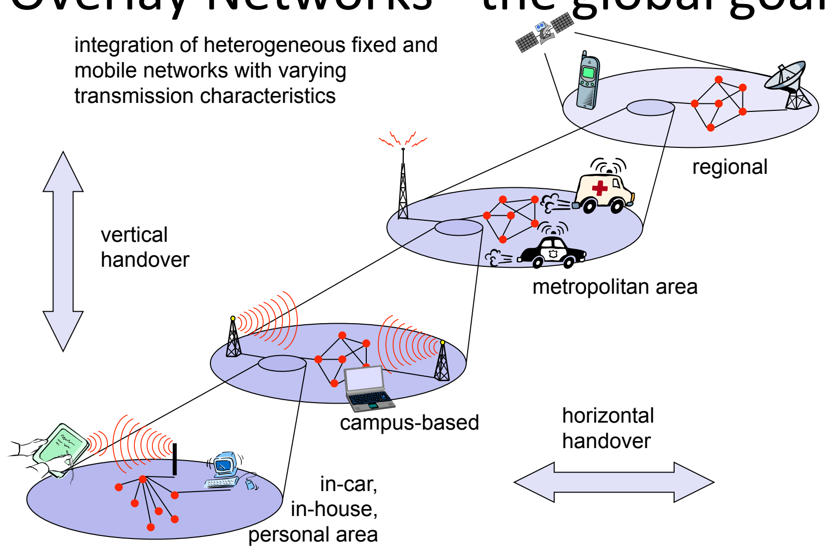
Overlay Networks - the global goal

integration of heterogeneous fixed and mobile networks with varying transmission characteristics



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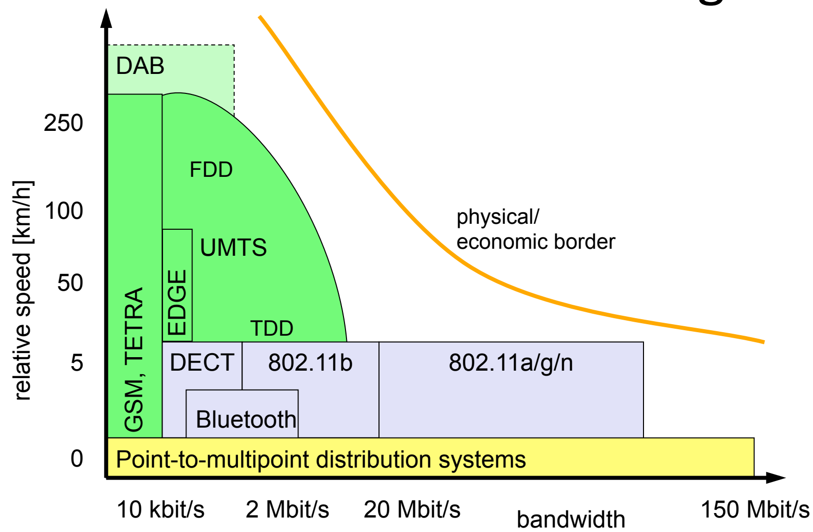
Wireless access technologies



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Key features of future mobile and wireless networks

- Improved radio technology and antennas
  - smart antennas, beam forming, multiple-input multiple-output (MIMO)
    - space division multiplex to increase capacity, benefit from multipath
  - software defined radios (SDR)
    - use of different air interfaces, download new modulation/coding/...
  - dynamic spectrum allocation
    - spectrum on demand results in higher overall capacity
- Core network convergence
  - IP-based, quality of service, mobile IP
- Ad-hoc technologies
  - spontaneous communication, power saving, redundancy
- Simple and open service platform
  - intelligence at the edge, not in the network (as with IN)
  - more service providers, not network operators only

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Long Term Evolution (LTE)

- Initiated in 2004, focus on enhancing the Universal Terrestrial Radio Access (UTRA) and optimizing 3GPP's radio access architecture.
- Targets: Downlink 100 Mbit/s, uplink 50 Mbit/s
- Downlink: OFDM, QPSK, 16QAM, and 64QAM
- Uplink: SC-FDMA, BPSK, QPSK, 8PSK and 16QAM
- Channel bandwidths between 1.25 and 20 MHz
- 4 x Increased Spectral Efficiency, 10 x Users Per Cell (MIMO), reduced RTT
- FDD and TDD supported, co-existence with earlier 3GPP standards incl. handover
- Core network: System Architecture Evolution (SAE), optimizing it for packet mode and in particular for the IP-Multimedia Subsystem (IMS)

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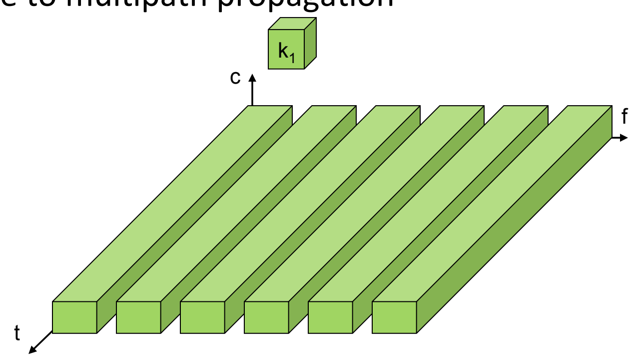
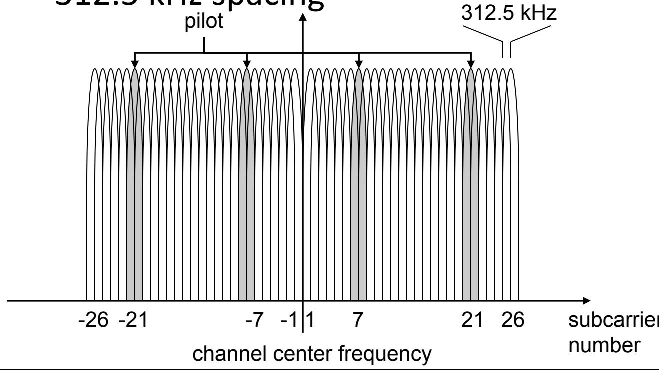
Multi-channel Modulation

- MCM: take a high symbol rate signal on one carrier and turn it into several lower symbol rate signals on multiple subcarriers
- Advantage: Less prone to inter-symbol interference due to multipath propagation



OFDM in IEEE 802.11a

- OFDM with 52 used subcarriers
  - 48 data + 4 pilot
  - 312.5 kHz spacing



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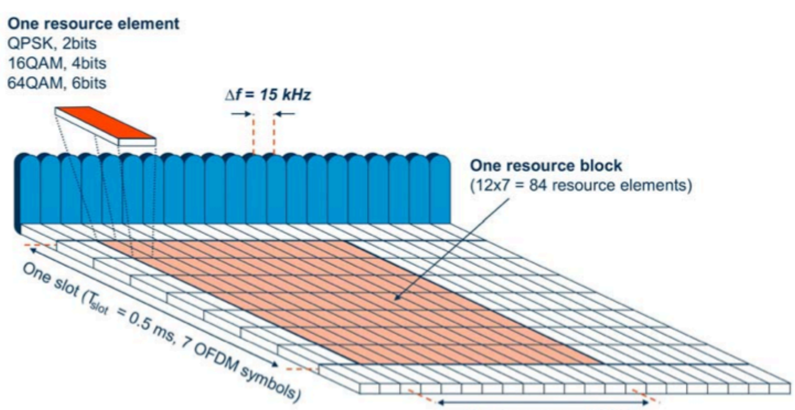
LTE Downlink with OFDM



LTE advanced

- GSM – UMTS - LTE
  - LTE advanced as candidate for IMT-advanced
- Worldwide functionality & roaming
- Compatibility of services
- Interworking with other radio access systems
- Enhanced peak data rates to support advanced services and applications (100 Mbit/s for high and 1 Gbit/s for low mobility)
- 3GPP will be contributing to the ITU-R towards the development of IMT-Advanced via LTE-Advanced.

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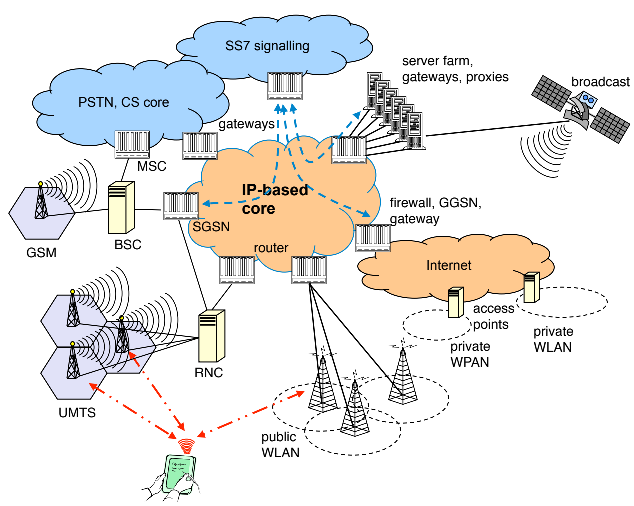
Example IP-based 4G/Next G/... network



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Potential problems

- Quality of service
  - Today's Internet is best-effort
  - Integrated services did not work out
  - Differentiated services have to prove scalability and manageability
  - What about the simplicity of the Internet? DoS attacks on QoS?
- Security of the network
- Reliability, maintenance
  - Is Internet technology really cheaper as soon as high reliability (99.9999%) is required plus all features are integrated
- Missing charging models
  - Charging by technical parameters (volume, time) is not reasonable
  - Pay-per-application may make much more sense

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