Wireless Transmission in Cellular Networks

- Frequencies
- Signal propagation
- Signal to Interference Ratio
- Channel capacity (Shannon)
- Multipath propagation
- Multiplexing
- Spatial reuse in cellular systems
- Antennas
- Spreading
- CDMA
- Modulation
- FDD vs. TDD
- Location management, handover and roaming
Frequencies for communication (spectrum)

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:

$$\lambda = \frac{c}{f}$$

wave length $\lambda$, speed of light $c \approx 300 \times 10^6 \text{ m/s}$, frequency $f$
Frequencies for mobile communication

30 MHz - 3 GHz: VHF-/UHF-ranges for mobile radio
- simple, small antennas
- good propagation characteristics (limited reflections, small path loss, penetration of walls)
- typically used for radio & TV (terrestrial + satellite) broadcast, wireless telecommunication (cordless/mobile phone)

>3 GHz: SHF and higher for directed radio links, satellite communications
- small antenna, strong focus
- larger bandwidth available
- no penetration of walls

Mobile systems and wireless LANs use frequencies in UHF to SHF spectrum
- 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.
Signal propagation & pathloss

Ideal line-of-sight

(d^-2):

1m
1
1:100
1:10000

10m
1:3000 to 1:10 Mio
35-40 dB
1:10000
35-40 dB
1:100 Mio

Realistic propagation (d^-3.5...4):

1
1:3000 to 1:10000
35-40 dB
1:100 Mio
Real world propagation examples
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

Requirements for successful transmission:
- received signal strength \( S \) above threshold
- signal to interference (and noise) ratio \( \text{SINR} \) above threshold

Thresholds depend on radio technology (modulation, coding), HW and signal processing capabilities
Signal to Interference and Noise Ratio (SINR)

(Uplink Situation)

- Ratio of Signal-to-Interference (& noise) power at the receiver

\[ \text{SINR} = \frac{S}{\sum I_j + N} \]

- The minimum required SINR depends on the system and the signal processing potential of the receiver technology

- Typical in GSM: SINR = 15dB (Factor 32)

Quelle: B. Walke, M.P. Althoff, P. Seidenberg, UMTS – Ein Kurs, Weil der Stadt 2001,
Range limited systems (lack of coverage)

- Mobile stations located far away from BS (at cell border or even beyond the coverage zone)

- S at the receiver is too low (below receiver sensitivity) because the path loss between sender and receiver is too high

→ S is too low

→ No signal reception possible
Interference limited systems (lack of capacity)

- Mobile station is within coverage zone
- $S$ is sufficient, but too much interference $I$ at the receiver

$\Rightarrow$ SINR is too low

$\Rightarrow$ No more resources / capacity left
Channel Capacity \((1)\)

- Bandwidth limited Additive White Gaussian Noise (AWGN) channel
- Gaussian codebooks
- Single transmit antenna
- Single receive antenna (SISO)

Shannon (1950):
Channel Capacity \(\leq\)
Maximum mutual information between sink and source

\[
C = B \log_2 \left(1 + \frac{S}{N}\right) \quad \text{[bps]}
\]
Channel Capacity (2)

- For $S/N >> 1$ (high signal-to-noise ratio), approximate

\[ C \approx B \cdot \frac{1}{3} \cdot \frac{S}{N} \text{ dB} \text{ [bps]} \]

- **Observation**: Bandwidth and $S/N$ are reciprocal to each other
- This means:
  - With low bandwidth very high data rate is possible provided
    - $S/N$ is high enough
    - Example: higher order modulation schemes
  - With high noise (low $S/N$) data communication is possible if
    - bandwidth is large
    - Example: spread spectrum
- Shannon channel capacity has been seen as an “unreachable” theoretical limit, for a long time. However:
- Turbo coding (1993) pushes practical systems up to 0.5 dB to Shannon channel bandwidth
The link capacity of current systems is quickly approaching the Shannon limit (within a factor of two).

Future improvements in spectral efficiency will focus on intelligent antenna techniques and/or coordination between base stations.

Link performance of OFDM & 3G systems are similar and approaching the (physical) Shannon bound.
Signal propagation

Propagation in free space always like light (straight line, line of sight)

Receving power proportional to
\[ \frac{1}{d^2} \text{ (ideal),} \]
\[ \frac{1}{d^\alpha} \text{ (} \alpha = 3...4 \text{ realistically)} \]
\( (d = \text{distance between sender and receiver}) \)

Receving power additionally influenced by
- fading (frequency dependent)
- shadowing
- reflection at large obstacles
- scattering at small obstacles
- diffraction at edges
Multipath propagation

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

Delayed signal rec’d via longer path

Signal received by direct path
Effects of mobility - Fading

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

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

- simulation showing time and frequency dependency of Rayleigh fading (model for urban environments, non-line-of-sight)

\[ V = 110 \text{km/h} \ 900 \text{MHz} \]
## Interference

<table>
<thead>
<tr>
<th>Interference</th>
<th>Problem</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersymbol Interference (ISI)</td>
<td>Multipath; superposition of same radiated data symbol transmitted via different paths</td>
</tr>
<tr>
<td>Multiple Access Interference (MAI)</td>
<td>Different user signals interfere dependent on the access scheme used (T/F/CDMA)</td>
</tr>
<tr>
<td>Intra-Cell Interference</td>
<td>Interference caused by users belonging to same cell</td>
</tr>
<tr>
<td>Inter-Cell Interference</td>
<td>Interference caused by users belonging to neighbor cells</td>
</tr>
</tbody>
</table>
Lessons learned: Key issues in infrastructure-based networks

**Interference limited systems**
- (spatially distributed) radio resource is the limiting factor!

=> increase of resource use (power) results in
  + increase of individual throughput (Shannon)
  - decrease of throughput of others due to increase of interference (Shannon)

=> reuse of resource results in
  + increase of capacity (due to reuse)
  - decrease in capacity due to increased interference!

**Channel quality** (S, I variations)
- S & I are influenced by the cell layout, sectorization, antenna (radiation pattern) by influencing pathloss & degree of multipaths
- fast variations are caused by the movement of mobiles in multipath environments (fast fading)

**Parameters to play with to maximize system capacity**
- cell layout: degree of reuse of radio resources
- dynamic resource reuse (allocation & scheduling)
- transmit power
- modulation & coding
- frame size
- exploitation of space and direction (beamforming)
- ...

Complex interdependence between S and I is controlled by the infrastructure to
- maximize system capacity &
- control individual throughput & QoS
Goal: multiple use of shared radio resource

Multiplexing in 4 dimensions
- space ($s_i$)
- time ($t$)
- frequency ($f$)
- code ($c$)

Channels $k_i$

Image showing three spheres representing different dimensions: space, time, and frequency, with codes $k_1$ to $k_6$. Each sphere is divided into sections showing the overlap of these dimensions.
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 needed
- applicable to analog signals

Disadvantages:
- waste of bandwidth if the traffic is distributed unevenly
- inflexible
- guard space
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 needed
Time and frequency multiplex

Combination of both methods
A channel gets a certain frequency band for a certain amount of time
Example: GSM (frequency hopping)

Advantages:
- some (weak) protection against tapping
- protection against frequency selective interference

but: precise coordination required
Code multiplex

Each channel has a unique code
All channels use the same spectrum at the same time

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

Disadvantages:
- complex receivers (signal regeneration)

Implemented using spread spectrum technology
Spreading and frequency selective fading

narrowband interference without spread spectrum

spread spectrum to limit narrowband interference
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 needed

\[
\text{user data (data rate)} \times \frac{1}{T_s} = \text{code sequence (chip rate)} \times \frac{1}{T_c} = \text{resulting signal (chip rate)}
\]
DSSS (Direct Sequence Spread Spectrum) II

**Transmitter**

- User data
- Code sequence
- Spread spectrum signal
- Radio carrier
- Modulator
- Transmit signal

**Receiver**

- Received signal
- Radio carrier
- Code sequence
- Received signal
- Baseband signal
- Correlator
- Products
- Sums
- Demodulator
- X
- Integrator
- Data

Cellular Communication Systems
Andreas Mitschele-Thiel, Jens Mückenheim
Oktober 2017
CDMA (Code Division Multiple Access)

- all terminals send on the same frequency probably at the same time and can use the whole bandwidth of the transmission channel
- each sender has a unique random number, the sender XORs the signal with this random number
- the receiver can “tune” into this signal if it knows the pseudo random number, tuning is done via a correlation function

Advantages:
- all terminals can use the same frequency, less planning needed
- huge code space (e.g. $2^{32}$) compared to frequency space
- interference (e.g. white noise) is not coded
- forward error correction and encryption can be easily integrated

Disadvantages:
- higher complexity of a receiver (receiver cannot just listen into the medium and start receiving if there is a signal)
- all signals should have the same strength at a receiver (power control)
CDMA Principle

sender (base station)

Code 0

data 0

Code 1

data 1

Code 2

data 2

receiver (terminal)

Code 0

data 0

Code 1

data 1

Code 2

data 2

Transmission via air interface
CDMA by example

data stream A & B

spreading

spreaded signal
CDMA by example

Overlay of signals

Transmission and distortion (noise and interference)

decoding and despreading

Sum of Sources Spread

Sum of Sources Spread + Noise
Spatial reuse in cellular systems

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

Disadvantages:

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

Cell sizes vary from 10s of meters in urban areas to many km in rural areas (e.g. maximum of 35 km radius in GSM)
Cellular systems: Frequency planning I

Frequency reuse only with a certain distance between the base stations

Typical (hexagon) model:

- **reuse-3 cluster:**
- **reuse-7 cluster:**

Other regular pattern: **reuse-19**

⇒ **the frequency reuse pattern determines the experienced SINR**

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
Cellular systems: frequency planning II

3 cell cluster

7 cell cluster

3 cell cluster
with 3 sector antennas
Cellular Communication Systems

Andreas Mitschele-Thiel, Jens Mückenheim

Oktober 2017

Cellular systems: coverage and capacity

Application: Coverage of system

Legend: red indicates high signal level, yellow indicates low level

Coverage map

Application: Capacity planning

Legend: color indicates cell with highest signal level (best serving cell)

Best server map (capacity/area)
Antennas for spatial reuse: directed and sectorized antennas

Often used for microwave connections (narrow directed beam) or base stations for cellular networks (sectorized cells)
Antenna 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
Antenna examples

3-sectorized
downtilt
## Comparison SDMA/TDMA/FDMA/CDMA

<table>
<thead>
<tr>
<th>Approach</th>
<th>SDMA</th>
<th>TDMA</th>
<th>FDMA</th>
<th>CDMA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idea</td>
<td>segment space into cells/sectors</td>
<td>segment sending time into disjoint time-slots, demand driven or fixed patterns</td>
<td>segment the frequency band into disjoint sub-bands</td>
<td>spread the spectrum using orthogonal codes</td>
</tr>
<tr>
<td>Terminals</td>
<td>only one terminal can be active in one cell/one sector</td>
<td>all terminals are active for short periods of time on the same frequency</td>
<td>every terminal has its own frequency, uninterrupted</td>
<td>all terminals can be active at the same place at the same moment, uninterrupted</td>
</tr>
<tr>
<td>Signal separation</td>
<td>cell structure, directed antennas</td>
<td>synchronization in the time domain</td>
<td>filtering in the frequency domain</td>
<td>code plus special receivers</td>
</tr>
<tr>
<td>Advantages</td>
<td>very simple, increases capacity per km²</td>
<td>established, fully digital, flexible</td>
<td>simple, established, robust</td>
<td>flexible, less frequency planning needed, soft handover</td>
</tr>
<tr>
<td>Dis-advantages</td>
<td>inflexible, antennas typically fixed</td>
<td>guard space needed (multipath propagation), synchronization difficult</td>
<td>inflexible, frequencies are a scarce resource</td>
<td>complex receivers, needs more complicated power control for senders</td>
</tr>
<tr>
<td>Comment</td>
<td>only in combination with TDMA, FDMA or CDMA useful</td>
<td>standard in fixed networks, together with FDMA/SDMA used in many mobile networks</td>
<td>typically combined with TDMA (frequency hopping patterns) and SDMA (frequency reuse)</td>
<td>still faces some problems, higher complexity, lowered expectations; will be integrated with TDMA/FDMA</td>
</tr>
</tbody>
</table>
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- transmit power
- modulation & coding
- frame size
- exploitation of space and direction (beamforming)
- ...

Complex interdependence between S and I is controlled by the infrastructure to
- maximize system capacity &
- control individual throughput & QoS
Modulation

“The shaping of a (baseband) signal to convey information”.

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

Digital modulation
- digital data is translated into an analog signal (baseband)
- ASK, FSK, PSK
- differences in spectral efficiency, power efficiency, robustness

Motivation for modulation
- smaller antennas (e.g., \(\lambda/4\))
- medium characteristics
- Frequency Division Multiplexing
- spectrum availability
Modulation and demodulation

Example: ASK

11001101000…

digital modulation

binary data

baseband signal

analog modulation

carrier signal

transmitter

analog demodulation

carrier signal

digital demodulation

baseband signal

binary data

receiver

11001101000…
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
- used in UMTS and EDGE (8-PSK)
- often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK (IS-136, PHS)

Puls filtering of baseband to avoid sudden phase shifts
=> reduce bandwidth of modulated signal
Phase Shift Keying

QPSK for different noise levels (low to high)
Quadrature Amplitude Modulation (QAM)

- combines amplitude and phase modulation
- it is possible to code \( n \) bits using one symbol
- \( 2^n \) discrete levels: e.g. 16-QAM, 64-QAM
  \( n=2: \ 4\text{-QAM identical to QPSK} \)
- bit error rate increases with \( n \), but less errors compared to comparable PSK schemes

Example: 16-QAM (1 symbol = 16 levels = 4 bits)
Symbols 0011 and 0001 have the same phase, but different amplitude
0000 and 1000 have different phase, but same amplitude

also: 64-QAM (1 symbol = 64 levels = 6 bits)

QAM is used in
- UMTS HSDPA (16-QAM)
- LTE (64-QAM)
- standard 9600 bit/s modems
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Frequency Division Duplex (FDD)

Separate frequency bands for up- and downlink

+ separation of uplink and downlink interference

- no support for asymmetric traffic

Examples: UMTS, GSM, IS-95, AMPS

Time Division Duplex (TDD)

Separation of up- and downlink traffic on time axis

+ support for asymmetric traffic

- mix of uplink and downlink interference on single band

Examples: DECT, UMTS (TDD)
FDD/FDMA - general scheme, example GSM

- **f**
- **t**

- **f**
  - 960
  - 935.2
  - 915
  - 890.2

- **t**

- **200 kHz**

- **20**

- **124**
  - 1

- **Example GSM**
TDD/TDMA - general scheme, example DECT
Basic Lower Layer Model for Wireless Transmission

<table>
<thead>
<tr>
<th>Transmit direction</th>
<th>Receive direction</th>
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</thead>
<tbody>
<tr>
<td><strong>Data link layer</strong></td>
<td>Protocol Processing</td>
</tr>
<tr>
<td>– media access</td>
<td>– reassembly</td>
</tr>
<tr>
<td>– fragmentation</td>
<td>– frame error detection</td>
</tr>
<tr>
<td>– frame error protection</td>
<td>– demultiplex</td>
</tr>
<tr>
<td>– multiplexing</td>
<td>– decryption</td>
</tr>
<tr>
<td><strong>Physical layer</strong></td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>– encryption</td>
<td>– decoding, bit error correction</td>
</tr>
<tr>
<td>– coding, forward error protection</td>
<td>– deinterleaving</td>
</tr>
<tr>
<td>– interleaving</td>
<td>– demodulation</td>
</tr>
<tr>
<td>– modulation</td>
<td>– A/D conversion; (signal equalization)</td>
</tr>
<tr>
<td>– D/A conversion, signal generation</td>
<td>– receive</td>
</tr>
<tr>
<td>– transmit</td>
<td></td>
</tr>
</tbody>
</table>

### Wireless Channel (path loss)

- Intersymbol-Interference (distortion of own signal)
- Intercell-Interference (multiple users)
- Intracell-Interference (multiple users)
- Thermal Noise
Location Management, Handover and Roaming

The problem:
locate a mobile user from the network side (mobile-terminated call)

Two extreme solutions:

- Mobile registers with each visited cell
  (e.g. direct call to the hotel room to reach a person)
  - signaling traffic to register mobile when cell is changed
  - network has to maintain detailed location information about each mobile
  + low signaling load to page mobile (i.e. in one cell only)

- Page mobile using a network- or worldwide broadcast message
  (e.g. broadcast on TV or radio to contact a person)
  - heavy signaling load to page the mobile (i.e. in all cells)
  + no signaling traffic while mobile is idle
Location Management

The issue: Compromise between

◆ minimizing the area where to search for a mobile
◆ minimizing the number of location updates

Solution 1: Large paging area

Solution 2: Small paging area

TOTAL Signalling Cost =

∑ Paging Signalling Cost

+ ∑ Paging Area Update Signalling Cost
Handover

The problem:
Change the cell while communicating

Reasons for handover:
- Quality of radio link deteriorates
- Communication in other cell requires less radio resources
- Supported radius is exceeded (e.g. Timing advance in GSM)
- Overload in current cell
- Maintenance

![Diagram of handover process]
Roaming

The problem:

Use a network not subscribed to

Roaming agreement needed between network operators to exchange information concerning:

- Authentication
- Authorisation
- Accounting

Examples of roaming agreements:

- Use networks abroad
- Use of T-Mobile network by O₂ (E2) subscribers in area with no O₂ coverage