Wireless Transmission:

Physical Layer Aspects and Channel Characteristics

- Frequencies
- Signals
- Antenna
- Signal propagation
- Multiplexing
- Modulation
- Spread spectrum
- Cellular systems
Frequencies for communication

VLF = Very Low Frequency
LF = Low Frequency
MF = Medium Frequency
HF = High Frequency
VHF = Very High Frequency
UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

Frequency and wave length:
\[ \lambda = \frac{c}{f} \]

Wave length \( \lambda \), speed of light \( c \approx 3 \times 10^8 \) m/s, frequency \( f \)
Electromagnetic spectrum

- **100 MHz**: FM Radio, VHF TV
- **400 MHz**: UHF TV
- **450 MHz**: C-Netz
- **900 MHz**: GSM900
- **1800 MHz**: GSM1800
- **1900 MHz**: DECT
- **2000 MHz**: UMTS (3G)
- **2400 MHz**: WLAN, Bluetooth
- **2450 MHz**: Microwave oven
- **3500 MHz**: WiMax
Frequencies for mobile communication

VHF/UHF-ranges for mobile radio
- simple, small antennas
- good propagation characteristics (limited reflections, small path loss, penetration of walls)

SHF and higher for directed radio links, satellite communication
- small antenna, strong focus
- larger bandwidth available
- no penetration of walls

Wireless LANs use frequencies in UHF to SHF spectrum
- some systems planned up to EHF
- limitations due to absorption by water and oxygen molecules (resonance frequencies) resulting in weather dependent fading, signal loss caused by heavy rainfall etc.
**Frequencies and regulations**

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

Examples of assigned frequency bands (in MHz)

<table>
<thead>
<tr>
<th></th>
<th>Europe</th>
<th>USA</th>
<th>Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cordless Phones</strong></td>
<td><strong>CT1</strong>+ 885-887, 930-932 <strong>CT2</strong> 864-868 <strong>DECT</strong> 1880-1900</td>
<td><strong>PACS</strong> 1850-1910, 1930-1990 <strong>PACS-UB</strong> 1910-1930</td>
<td><strong>PHS</strong> 1895-1918 <strong>JCT</strong> 254-380</td>
</tr>
<tr>
<td><strong>Wireless LANs</strong></td>
<td><strong>IEEE 802.11</strong> 2400-2483 <strong>HIPERLAN 2</strong> 5150-5350, 5470-5725</td>
<td><strong>902-928</strong> <strong>IEEE 802.11</strong> 2400-2483 5150-5350, 5725-5825</td>
<td><strong>IEEE 802.11</strong> 2471-2497 5150-5250</td>
</tr>
<tr>
<td><strong>Others</strong></td>
<td><strong>RF-Control</strong> 27, 128, 418, 433, 868</td>
<td><strong>RF-Control</strong> 315, 915</td>
<td><strong>RF-Control</strong> 426, 868</td>
</tr>
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**Abbreviations:**
- AMPS Advanced Mobile Phone System
- CDMA Code Division Multiple Access
- CT Cordless Telephone
- DECT Digital Enhanced Cordless Telecommunications
- GSM Global System for Mobile Communications
- HIPERLAN High-Performance LAN
- IEEE Institute of Electrical and Electronics Engineers
- JCT Japanese Cordless Telephone
- NMT Nordic Mobile Telephone
- PACS Personal Access Communications System
- PACS-UB PACS- Unlicensed Band
- PDC Pacific Digital Cellular
- PHS Personal Handyphone System
- TDMA Time Division Multiple Access
Signals in general

- 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 $\phi$
  - sine wave as special periodic signal for a carrier:

$$s(t) = A_t \sin(2\pi f_t t + \phi_t)$$
Fourier representation of periodic signals

Every periodic signal \( g(t) \) can be constructed by

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

ideal periodic signal

real composition
(based on harmonics)
Signal representations

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

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

Real antennas are not isotropic radiators but, e.g.
- dipoles with lengths $\lambda/4$ on car roofs or
- $\lambda/2$ as Hertzian dipole

$\Rightarrow$ shape of antenna proportional to wavelength

Example: Radiation pattern of a simple Hertzian dipole

Antenna 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)

directed antenna

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

\[
\begin{align*}
\lambda/4 & - \lambda/2 & \lambda/4 \\
\lambda/2 & - \lambda/2 & \lambda/2
\end{align*}
\]

ground plane
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
Real world examples
Signal propagation: received power due to pathloss

Ideal line-of sight (\(d^2\)):
- 1 m: 1
- 10 m: 1:100
- 100 m: 1:10000

Realistic propagation (\(d^{-3.5\ldots4}\)):
- 1 m: 1
- 10 m: 1:3000 to 1:10000
- 100 m: 1:10 Mio to 1:100 Mio

35-40 dB
Signal to Interference Ratio (SINR, CIR, C/I)

(Uplink Situation)

- Ratio of Carrier-to-Interference 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: \( \text{SINR} = 15\text{dB} \) (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, 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

Information Theory: 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

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

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

$$C \approx \frac{1}{3} \frac{S}{N_{dB}} \text{ [bps]}$$

- **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
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)

Receiving power proportional to $1/d^2$
(d = distance between sender and receiver)

Receiving 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, 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 – 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)

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

Goal: multiple use of a shared medium

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

Important: guard spaces needed!
Frequency multiplex

Separation of the whole spectrum into smaller frequency bands
A channel gets a certain band of the spectrum for the whole time

Advantages:
- no dynamic coordination 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
Modulation

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

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

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

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

1. Digital data (101101001) enters a digital modulation process.
2. The digital modulation output is an analog baseband signal.
3. This signal is then modulated to create an analog radio carrier.
4. The radio carrier is transmitted by the radio transmitter.

5. The radio receiver receives the radio carrier.
6. The radio carrier is demodulated to an analog baseband signal.
7. The analog baseband signal is synchronized for decision-making.
8. The decision output is then converted back into digital data (101101001).

Digital modulation and analog modulation processes are illustrated in the diagram.
Digital modulation

Modulation of digital signals known as Shift Keying

Amplitude Shift Keying (ASK):
- very simple
- low bandwidth requirements
- very susceptible to interference

Frequency Shift Keying (FSK):
- needs larger bandwidth

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

- bandwidth needed for FSK depends on the distance between the carrier frequencies
- special pre-computation avoids sudden phase shifts  
  ➔ Continuous Phase Modulation (CPM)  
  e.g. MSK (Minimum Shift Keying)
- bit stream is 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, eliminating abrupt phase changes

- even higher bandwidth efficiency using a Gaussian low-pass filter  
  ➔ GMSK (Gaussian MSK), used for GSM and DECT
Example of MSK

<table>
<thead>
<tr>
<th>Bit</th>
<th>Even</th>
<th>Odd</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0 1 0 1</td>
<td>0 0 1 1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>h l l h</td>
<td>- - + +</td>
</tr>
</tbody>
</table>

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

No sudden 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
- used in UMTS
- often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK (IS-136, PHS)

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

QPSK for different noise levels (low to high)
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, but different amplitude
0000 and 1000 have different phase, but same amplitude
⇒ used in standard 9600 bit/s modems
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 broadband signal using a special code

⇒ protection against narrow band interference

Side effects:
- coexistence of several signals without dynamic coordination
- tap-proof

Alternatives:
- Direct Sequence (UMTS)
- Frequency Hopping (slow FH: GSM, fast FH: Bluetooth)
Spreading and frequency selective fading

narrowband interference without spread spectrum

spread spectrum to limit narrowband interference
Effects of spreading and interference

i) narrow band signal

ii) spreaded signal (broadband signal)

iii) addition of interference

iv) despreaded signal

v) application of bandpass filter

sender

receiver

dP/df

user signal

broadband interference

narrowband interference

f

f

f
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
  - all base stations can use the same frequency range
  - several base stations can detect and recover the signal
- soft handover

Disadvantages
- precise power control needed

\[ \begin{align*}
0 & \quad 1101010101101011 \\
\oplus & \quad 1101011100101010 \\
\hline
\text{resulting signal:} & \quad 0 \quad 1110101010101010 \\
\hline
\end{align*} \]

\[ t_b: \text{bit period} \]
\[ t_c: \text{chip period} \]
DSSS (Direct Sequence Spread Spectrum) II

**Transmitter**
- User data
- Chipping sequence
- Radio carrier
- Spread spectrum signal
- Modulator
- Transmit signal

**Receiver**
- Received signal
- Radio carrier
- Chipping sequence
- Lowpass filtered signal
- Correlator
- Products
- Sampled sums
- Integrator
- Decision
- Data
FHSS (Frequency Hopping Spread Spectrum) I

- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence
- Two versions
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency
- Advantages
  - frequency selective fading and interference limited to short period
  - simple implementation
  - uses only small portion of spectrum at any time
- Disadvantages
  - not as robust as DSSS
  - simpler to detect
FHSS (Frequency Hopping Spread Spectrum) II

user data

slow hopping
(3 bits/hop)

fast hopping
(3 hops/bit)

"t_b": bit period
"t_d": dwell time
FHSS (Frequency Hopping Spread Spectrum) III

User data input to the modulator, which modulates the signal and transmits it. The spread signal is then received by the receiver, which demodulates it and outputs the data. The hopping sequence is used by the frequency synthesizer to switch between different narrowband signals.
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

Problems:
- 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

Standard (hexagon) 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
Cellular systems: frequency planning II

3 cell cluster

7 cell cluster

3 cell cluster with 3 sector antennas
Cellular systems: example of coverage and best server map

Application: Coverage of system
Legend: red indicates high signal level, yellow indicates low level

Application: Capacity planning
Legend: color indicates cell with highest signal level (best serving cell)
References

Jochen Schiller: Mobile Communications (German and English), Addison-Wesley, 2000
(most of the material covered in this chapter is based on the book)