Mobile Communications
Chapter 2: Wireless Transmission

- Frequencies
- Signals, antennas, signal propagation
- Multiplexing
- Spread spectrum, modulation
- Cellular systems
Frequencies for communication

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

- Frequency and wave length
  - $\lambda = \frac{c}{f}$
  - wave length $\lambda$, speed of light $c \approx 3 \times 10^8 \text{m/s}$, frequency $f$
Frequencies for mobile communication

- VHF-/UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
- SHF and higher for directed radio links, satellite communication
  - small antenna, beam forming
  - large bandwidth available
- Wireless LANs use frequencies in UHF to SHF range
  - some systems planned up to EHF
  - limitations due to absorption by water and oxygen molecules (resonance frequencies)
    - 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)

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

- **JCT** 245-380
Signals I

- physical representation of data
- function of time and location
- signal parameters: parameters representing the value of data
- classification
  - continuous time/discrete time
  - continuous values/discrete values
  - analog signal = continuous time and continuous values
  - digital signal = discrete time and discrete values
- signal parameters of periodic signals: period $T$, frequency $f = 1/T$, amplitude $A$, phase shift $\varphi$
  - 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

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

ideal periodic signal

real composition (based on harmonics)
Signals II

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

- Composed signals transferred into frequency domain using Fourier transformation

- Digital signals need
  - infinite frequencies for perfect transmission
  - modulation with a carrier frequency for transmission (analog signal!)
Antennas: isotropic radiator

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

- 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](xy-plane)  ![Directed Antenna](yz-plane)  ![Directed Antenna](xz-plane)  
side view (xy-plane)  side view (yz-plane)  top view (xz-plane)

![Sectorized Antenna](xy-plane)  ![Sectorized Antenna](yz-plane)  
top view, 3 sector  top view, 6 sector
Antennas: diversity

- Grouping of 2 or more antennas
  - multi-element antenna arrays

- Antenna diversity
  - switched diversity, selection diversity
    - receiver chooses antenna with largest output
  - diversity combining
    - combine output power to produce gain
    - cophasing needed to avoid cancellation
MIMO

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

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

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

Diagram:
- Sending time:
  1: $t_0$
  2: $t_0 - d_2$
  3: $t_0 - d_3$
- Time of flight:
  $t_2 = t_1 + d_2$
  $t_3 = t_1 + d_3$
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
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 ($d =$ 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
Real world example
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
  - $\Rightarrow$ quick changes in the power received (short term fading)

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

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

- Goal: multiple use of a shared medium

- Important: guard spaces needed!
Frequency multiplex

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Advantages
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible
Time multiplex

- A channel gets the whole spectrum for a certain amount of time

**Advantages**
- only one carrier in the medium at any time
- throughput high even for many users

**Disadvantages**
- precise synchronization necessary
Time and frequency multiplex

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

- Advantages
  - better protection against tapping
  - protection against frequency selective interference
- but: precise coordination required
Cognitive Radio

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

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

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

- Each channel has a unique code

- All channels use the same spectrum at the same time

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

- Disadvantages
  - varying user data rates
  - more complex signal regeneration

- Implemented using spread spectrum technology
Modulation

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

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

• Motivation
  • smaller antennas (e.g., \( \lambda/4 \))
  • Frequency Division Multiplexing
  • medium characteristics

• Basic schemes
  • Amplitude Modulation (AM)
  • Frequency Modulation (FM)
  • Phase Modulation (PM)
Modulation and demodulation

Digital data 101101001 is input to the digital modulation block. The output is an analog baseband signal. This signal is then modulated to an analog carrier signal, which is transmitted to the radio transmitter.

At the radio receiver, the analog carrier signal is demodulated to an analog baseband signal. This signal is then input to the synchronization decision block. The output is digital data 101101001.
Digital modulation

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

- Frequency Shift Keying (FSK):
  - needs larger bandwidth

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

- bandwidth needed for FSK depends on the distance between the carrier frequencies
- special pre-computation avoids sudden phase shifts ➔ MSK (Minimum Shift Keying)
  - bit separated into even and odd bits, the duration of each bit is doubled
  - depending on the bit values (even, odd) the higher or lower frequency, original or inverted is chosen
  - the frequency of one carrier is twice the frequency of the other
  - Equivalent to offset QPSK

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

- Even bits:
  - Bit sequence: 0 1 0 1
  - Signal values:
    - Original signal: +
    - Inverted signal: -

- Odd bits:
  - Bit sequence: 0 0 1 1
  - Signal values:
    - Original signal: +
    - Inverted signal: -

- Low frequency
- High frequency

No phase shifts!
Advanced Phase Shift Keying

- **BPSK (Binary Phase Shift Keying):**
  - bit value 0: sine wave
  - bit value 1: inverted sine wave
  - very simple PSK
  - low spectral efficiency
  - robust, used e.g. in satellite systems

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

- Often also transmission of relative, not absolute phase shift: DQPSK - Differential QPSK (IS-136, PHS)
Quadrature Amplitude Modulation

- Quadrature Amplitude Modulation (QAM)
  - combines amplitude and phase modulation
  - it is possible to code \( n \) bits using one symbol
  - \( 2^n \) discrete levels, \( n=2 \) identical to QPSK
- Bit error rate increases with \( n \), but less errors compared to comparable PSK schemes
  - Example: 16-QAM (4 bits = 1 symbol)
  - Symbols 0011 and 0001 have the same phase \( \phi \), but different amplitude \( a \).
  - 0000 and 1000 have different phase, but same amplitude.

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![Diagram of QAM modulation](image)
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
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

i) $\frac{dP}{df}$

ii) $\frac{dP}{df}$

iii) $\frac{dP}{df}$

iv) $\frac{dP}{df}$

v) $\frac{dP}{df}$

sender

receiver

user signal

broadband interference

narrowband interference
Spreading and frequency selective fading

narrowband channels

spread spectrum channels
DSSS (Direct Sequence Spread Spectrum) I

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

- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - base stations can use the same frequency range
    - several base stations can detect and recover the signal
    - soft handover

- Disadvantages
  - precise power control necessary

\[ \text{user data} \]
\[ \begin{array}{cccccccccccc}
0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \\
\end{array} \]
\[ \xor \]
\[ \begin{array}{cccccccccccc}
0 & 1 & 1 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 \end{array} \]
\[ = \]
\[ \begin{array}{cccccccccccc}
0 & 1 & 1 & 0 & 1 & 0 & 1 & 1 & 0 & 1 & 0 & 1 \\
\end{array} \]

- \( t_b \): bit period
- \( t_c \): 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)

- **Symbols**
  - \( t_b \): bit period
  - \( t_d \): dwell time
FHSS (Frequency Hopping Spread Spectrum) III

user data → modulator → spread transmit signal

freq. synthesizer → hopping sequence

transmitter

received signal → demodulator → data

freq. synthesizer → hopping sequence

receiver
Software Defined Radio

- **Basic idea (ideal world)**
  - Full flexibility wrt modulation, carrier frequency, coding...
  - Simply download a new radio!
  - Transmitter: digital signal processor plus very fast D/A-converter
  - Receiver: very fast A/D-converter plus digital signal processor

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

- **Examples**
  - Joint Tactical Radio System
  - GNU Radio, Universal Software Radio Peripheral, ...
Cell structure

- Implements space division multiplex
  - base station covers a certain transmission area (cell)
- Mobile stations communicate only via the base station

- Advantages of cell structures
  - higher capacity, higher number of users
  - less transmission power needed
  - more robust, decentralized
  - base station deals with interference, transmission area etc. locally

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

- Cell sizes from some 100 m in cities to, e.g., 35 km on the country side (GSM) - even less for higher frequencies
Frequency planning I

- Frequency reuse only with a certain distance between the base stations
- Standard model using 7 frequencies:
  - Fixed frequency assignment:
    - certain frequencies are assigned to a certain cell
    - problem: different traffic load in different cells
  - Dynamic frequency assignment:
    - base station chooses frequencies depending on the frequencies already used in neighbor cells
    - more capacity in cells with more traffic
    - assignment can also be based on interference measurements
Frequency planning II

3 cell cluster

7 cell cluster

3 cell cluster with 3 sector antennas
Cell breathing

- CDM systems: cell size depends on current load
- Additional traffic appears as noise to other users
- If the noise level is too high users drop out of cells