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
  \[ \lambda = \frac{c}{f} \]
  \( \lambda \) = wave length, \( c \approx 3 \times 10^8 \text{ m/s} \), frequency \( f \)

Frequencies for Mobile Communication

- VHF-UHF-ranges for mobile radio
  - simple, small antenna for cars
  - deterministic propagation characteristics, reliable connections
  - 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)

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Radio Spectrum

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 $\phi$
  - sine wave as a special periodic signal for a carrier:
    $s(t) = A \sin(2\pi ft + \phi)$
Fourier Representation of Periodic Signals

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

ideal periodic signal \hspace{1cm} \rightarrow \hspace{1cm} \text{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 Radiators

- 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

ideal isotropic radiator
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 ➔ 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)

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
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cophasing needed to avoid cancellation

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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
- Path loss (attenuation)
- Fundamental propagation behaviors:
  - ground wave (<2MHz): follow earth's surface, long distances (submarine communication, AM radio)
  - sky wave (2-30MHz): reflected at ionosphere, around the world (intl. broadcasts, amateur radio)
  - line-of-sight (>30MHz): LOS, straight line, waves are bent by atmosphere due to refraction (mobile phones, satellite, cordless)
- Most systems we will discuss work with >100MHz: LOS (question: so how do mobile phones work then??)

Other propagation effects
- 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
  - quick changes in the power received (short term fading)
- Additional changes in
  - distance to sender
  - obstacles further away
  - slow changes in the average power received (long term fading)
Multiplexing

- Multiplexing in 4 dimensions: space ($s$), time ($t$), frequency ($f$), code ($c$)

- Goal: multiple use of a shared medium

- Important: guard spaces needed!

Frequency division multiplexing (FDM)

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

- Advantages
  - no dynamic coordination necessary
  - works also for analog signals

- Disadvantages
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible

Time division multiplexing (TDM)

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

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

- Disadvantages
  - precise synchronization necessary
Time and frequency multiplex
- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM
- Advantages
  - better protection against tapping
  - protection against frequency selective interference
- but: precise coordination required

Code division multiplexing (CDM)
- Each channel has 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 here
  - 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., λ/4)
  - Frequency Division Multiplexing
  - medium characteristics
- Basic schemes
  - Amplitude Modulation (AM)
  - Frequency Modulation (FM)
  - Phase Modulation (PM)
Modulation and demodulation

- Digital 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

- FSK can cause sudden changes in phase (which can cause high 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
Example of MSK

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

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.
Spread spectrum technology

- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code
  - protection against narrow band interference

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

- Alternatives: Direct Sequence, Frequency Hopping

Effects of spreading and interference

- Spreading and frequency selective fading

- Narrowband channels
- Spread spectrum channels

Spreading and frequency selective fading
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

\[
\begin{array}{c}
\text{user data} \quad 0 \quad 1 \\
\text{chipping sequence} \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \\
\text{resulting signal} \quad 0 \quad 1 \quad 0 \quad 1 \quad 0 \quad 1 \\
\end{array}
\]

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

DSSS (Direct Sequence Spread Spectrum) II

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

FHSS (Frequency Hopping Spread Spectrum) III

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
Key Points to Take Away

- Regulation and harmonization of frequencies is a big challenge.
- Many things can happen to electromagnetic waves: affects system design, frequency choice, modulation choice, user experience, ...
- Multiplexing is key to being efficient and minimize interference (SDM, FDM, TDM, CDM)
- Spread spectrum allows us to implement several features, e.g., security, robustness
- Cellular systems implement SDM to raise overall capacity of mobile phone systems