Radio 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 \( c = 3 \times 10^8 \text{ m/s} \), frequency \( f \)
## Frequencies (MHz) and regulations

<table>
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<tr>
<th></th>
<th>Europe</th>
<th>USA</th>
<th>Japan</th>
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</thead>
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<tr>
<td><strong>Cordless Phones</strong></td>
<td>CT1+ 885-887, 930-932 CT2 864-868 DECT 1880-1900</td>
<td>PACS 1850-1910, 1930-1990 PACS-UB 1910-1930</td>
<td>PHS 1895-1918 JCT 254-380</td>
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<tr>
<td><strong>Wireless LANs</strong></td>
<td>IEEE 802.11 2400-2483 HIPERLAN 2 5150-5350, 5470-5725</td>
<td>902-928 IEEE 802.11 2400-2483 5150-5350, 5725-5825</td>
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<td><strong>Others</strong></td>
<td>RF-Control 27, 128, 418, 433, 868</td>
<td>RF-Control 315, 915</td>
<td>RF-Control 426, 868</td>
</tr>
</tbody>
</table>

Partly adapted from [www.jochenschiller.de](http://www.jochenschiller.de)
Mobile **Phone** coverage

Range and rate

Partly adapted from [www.jochenschiller.de](http://www.jochenschiller.de)

http://www.it.uu.se/edu/course/homepage/datakom3/vt11
Antennas: (Ideal) Isotropic radiator

- Equal radiation in all directions (three dimensional) – (only a theoretical reference antenna)
- Received power: $P_f = K_f 1/d^2$, $d=$distance, $K_f =$ frequency dependent constant
Antennas: simple dipoles

Radiation pattern of a simple Hertzian dipole
Gain: maximum power in the direction of the main lobe

Antennas: directed and sectorized

Directed antenna, e.g. in a valley

Sectorized antenna, e.g. Mobile phone base station
Radio signals

- Parameters of periodic signals:
  - Period $T$
  - Frequency $f = 1/T$
  - Amplitude $A$
  - Phase shift $\varphi$

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

- Function of time, location and phase

Sine Wave

$$s(t) = A_t \sin(2\pi f t + \varphi)$$
Signals II

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

Fourier representation of periodic signals

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

Digital signals need infinite frequencies for perfect transmission => modulation with a carrier frequency for transmission
Modulation and demodulation

Modulation

- **Digital modulation**
  - digital data is translated into an analog signal (baseband)
  - Choice of coding: 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 – allocate different bands
  - medium propagation characteristics – better at higher frequencies.
Digital modulation

- **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
  - more robust against interference

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
Quadrature Amplitude Modulation

- Quadrature Amplitude Modulation (QAM):
  - combines amplitude and phase modulation
  - possible to code \( n \) bits using one symbol
- \( 2^n \) discrete levels, \( n=2 \)
- **BUT - bit error rate increases with** \( n \)
  - Signal To Noise Ratio, SNR, determines \( n \).

Example: 16-QAM (4 bits = 1 symbol)
- used in standard 9600 bit/s modems

Signal propagation ranges

- **Transmission range**
  - communication possible
  - low error rate
- **Detection range**
  - detection of the signal possible
  - no communication possible (too high error rate)
- **Interference range**
  - signal may not be detected
  - signal adds to the background noise
Radio signal propagation

- Propagation in *free space* always a straight line (like light)
- Receiving power influenced by:
  - *attenuation* (frequency dependent) proportional to $distance^2$
  - *shadowing* – some energy may get through/around
  - *reflection* at large obstacles – some energy may get through
  - *refraction* depending on the density of a medium
  - *scattering* at small obstacles
  - *diffraction* at edges of large objects

Real world simulations
Multipath propagation

- Signal can take many different paths between sender and receiver due to reflection, scattering and diffraction
  ➔ interference with “neighbor” symbols, i.e. Inter Symbol Interference (ISI)

Effects of a moving terminal

- Short term, (small scale) fading
  - signal paths change
  - different delay variations of different signal parts
  - different phases of signal parts
  - ➔ quick changes in the power received
- Long term fading
  - distance to sender
  - obstacles further away
  - ➔ slow changes in the average power received
Fading in Ångström corridor

2.4 GHz, IEEE 802.15.4

High resolution of fading
Multiplexing

• Goal: Accept multiple users of a shared medium (i.e. radio spectrum)
• Multiplexing/sharing in 4 dimensions
  – frequency (f)
  – space (s_i)
  – time (t)
  – code (c)

Frequency multiplexing

• A user/channel gets a certain frequency band of the spectrum. A reservation.
• Advantages:
  – Easy - no dynamic coordination necessary.
  – works also for analog signals
• Disadvantages:
  – waste of bandwidth if the traffic is unevenly distributed
  – Inflexible
    • Can not redistribute bands
  – Need “guards” (i.e. spaces between bands) to avoid disturbing each other
Space Division Multiplexing

User gets frequency/channel $k_i$

Allocate frequencies in a regular pattern to avoid overlap with same frequency in same geographical area.

Transmission ranges of base stations

Spatial Guard

Frequency planning

- Frequency reuse only within a certain distance between the base stations
- Standard model uses 7 frequencies. Distance=3.
- Fixed frequency assignment
  - Also allow dynamic frequency planning
Space Division Cell structure

Mobile stations communicate only via the base station

- **Advantages** of cell structures:
  - to get higher capacity, decrease cell sizes and increase density
    - Cell sizes: City > 100m radius. Country side < 35km radius.
  - adaptive transmission power – only needs to reach to the base station.
  - Robust against misbehaving clients - centralized control
    - base station deals with interference, transmission area, etc

- **Consequences** of cell structures:
  - fixed network needed for interconnecting base stations
  - handover (changing from one cell to another, one frequency to another) is necessary
  - interference with and between other cells. Requires careful planning.

Time multiplexing

- A user/channel gets the whole allocated band for an agreed time-slot \( t \), repeated every \( nt \).

- **Advantages**:
  - only one user/channel/carrier in the medium at any time
  - utilization high also for many users

- **Consequences**:
  - precise synchronization between distributed nodes necessary
Combination of time and frequency multiplexing

• A user gets a *certain frequency band for a certain amount of time*

• Advantages:
  – protection against frequency interference
  – better protection against eaves listening

• Consequence:
  – Precise co-ordination required


Code multiplexing

• Each user transmits according to their own *unique code* on the whole frequency band.
  – All channels use the same band *at the same time* but with different underlying codes.

• Advantages:
  – no coordination and synchronization necessary
  – good protection against interference and eaves tapping (code is protected)
  – bandwidth efficient – degrades gracefully

• Consequences:
  – lower user data rates
  – more complex signal generation
Spreading and frequency wrt selective fading

Effects of spreading and interference

\[ dP/df = \text{dPower/dfrequency} \]

\[ \text{user signal} \]
\[ \text{broadband interference} \]
\[ \text{narrowband interference} \]
Direct Sequence Spread Spectrum

- XOR the transmission bits with an assigned “code”, called the chipping sequence
  - Use many chips per bit (e.g., 128), which results in a wider bandwidth of the total signal.

- Advantages
  - Reduces selective fading and interference
  - in cellular networks:
    A base stations can use the same frequency range but with different chipping sequence for different users

- Disadvantages
  - precise power control necessary
    - A nearby user may drown a distance user

\[
\begin{align*}
\text{user data} & \quad \text{XOR} \\
\begin{array}{cccccccc}
0 & 1 & 0 & 1 & 0 & 1 & 0 & 1 \\
\end{array} & \quad \begin{array}{cccccccc}
0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 \\
\end{array} \\
\end{align*}
\]

\[t_b: \text{bit period} \quad t_c: \text{chip period}\]

Frequency Hopping Spread Spectrum

- slow hopping (3 bits/hop)
- fast hopping (3 hops/bit)

\[
\begin{align*}
\text{fast hopping} & \quad \text{slow hopping} \\
\begin{array}{cccccccc}
0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 \\
\end{array} & \quad \begin{array}{cccccccc}
0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 \\
\end{array} \\
\end{align*}
\]

\[t_b: \text{bit period} \quad t_d: \text{dwell time}\]