CS647: Advanced Topics in Wireless Networks

Basics of Wireless Transmission
Outline

- Frequencies
- Signals
- Antennas
- Signal propagation
- Multiplexing
- Spread spectrum
- Modulation
Types of Wave

- **Transmitter**
- **Receiver**
- **Ground wave**
- **Space wave**
- **Sky wave**

**Troposphere**
- (0 - 12 km)

**Stratosphere**
- (12 - 50 km)

**Mesosphere**
- (50 - 80 km)

**Ionosphere**
- (80 - 720 km)
Speed, Wavelength, Frequency

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

<table>
<thead>
<tr>
<th>System</th>
<th>Frequency</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC current</td>
<td>60 Hz</td>
<td>5,000 km</td>
</tr>
<tr>
<td>FM radio</td>
<td>100 MHz</td>
<td>3 m</td>
</tr>
<tr>
<td>Cellular</td>
<td>800 MHz</td>
<td>37.5 cm</td>
</tr>
<tr>
<td>Ka band satellite</td>
<td>20 GHz</td>
<td>15 mm</td>
</tr>
<tr>
<td>Ultraviolet light</td>
<td>(10^{15}) Hz</td>
<td>(10^{-7}) m</td>
</tr>
</tbody>
</table>
## Radio Frequency Bands

<table>
<thead>
<tr>
<th>Classification Band</th>
<th>Initials</th>
<th>Frequency Range</th>
<th>Characteristics</th>
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<tbody>
<tr>
<td>Extremely low</td>
<td>ELF</td>
<td>&lt; 300 Hz</td>
<td>Ground wave</td>
</tr>
<tr>
<td>Infra low</td>
<td>ILF</td>
<td>300 Hz - 3 kHz</td>
<td></td>
</tr>
<tr>
<td>Very low</td>
<td>VLF</td>
<td>3 kHz - 30 kHz</td>
<td>Ground/Sky wave</td>
</tr>
<tr>
<td>Low</td>
<td>LF</td>
<td>30 kHz - 300 kHz</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>MF</td>
<td>300 kHz - 3 MHz</td>
<td>Ground/Sky wave</td>
</tr>
<tr>
<td>High</td>
<td>HF</td>
<td>3 MHz - 30 MHz</td>
<td>Sky wave</td>
</tr>
<tr>
<td>Very high</td>
<td>VHF</td>
<td>30 MHz - 300 MHz</td>
<td></td>
</tr>
<tr>
<td>Ultra high</td>
<td>UHF</td>
<td>300 MHz - 3 GHz</td>
<td></td>
</tr>
<tr>
<td>Super high</td>
<td>SHF</td>
<td>3 GHz - 30 GHz</td>
<td>Space wave</td>
</tr>
<tr>
<td>Extremely high</td>
<td>EHF</td>
<td>30 GHz - 300 GHz</td>
<td></td>
</tr>
<tr>
<td>Tremendously high</td>
<td>THF</td>
<td>300 GHz - 3000 GHz</td>
<td></td>
</tr>
</tbody>
</table>
Frequencies for communication

- VLF = Very Low Frequency
- LF = Low Frequency
- MF = Medium Frequency
- HF = High Frequency
- VHF = Very High Frequency
- SHF = Super High Frequency
- EHF = Extra High Frequency
- UHF = Ultra High Frequency
- UV = Ultraviolet Light
- infrared
- visible 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></th>
<th>Europe</th>
<th>USA</th>
<th>Japan</th>
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<tbody>
<tr>
<td></td>
<td><strong>UMTS (FDD)</strong> 1920-1980, 2110-2190</td>
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<tr>
<td></td>
<td><strong>UMTS (TDD)</strong> 1900-1920, 2020-2025</td>
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<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>
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<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>**902-928 <strong>IEEE 802.11</strong> 2400-2483 5150-5350, 5725-5825</td>
<td><strong>IEEE 802.11</strong> 2471-2497 5150-5250</td>
</tr>
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<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>
</tbody>
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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 special periodic signal for a carrier:

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

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

ideal periodic signal

real composition (based on harmonics)
Different representations of signals
- amplitude (amplitude domain)
- frequency spectrum (frequency domain)
- phase state diagram (amplitude M and phase $\varphi$ 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
  - 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)

\[
\begin{align*}
\text{side view (xy-plane)} & & \text{side view (yz-plane)} & & \text{top view (xz-plane)} \\
\text{top view, 3 sector} & & \text{top view, 6 sector}
\end{align*}
\]
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

![Diagram of antenna diversity](image)

- 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
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
  \(d = \text{distance between sender and receiver}\)
- 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
Multipath propagation

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

- Time dispersion: signal is dispersed over time
- \( \Rightarrow \) interference with “neighbor” symbols, Inter Symbol Interference (ISI)
- The signal reaches a receiver directly and phase shifted
- \( \Rightarrow \) distorted signal depending on the phases of the different parts
The received signal power at distance $d$:

$$P_r = \frac{A_e G_t P_t}{4\pi d^2}$$

where $P_t$ is transmitting power, $A_e$ is effective area, and $G_t$ is the transmitting antenna gain. Assume that radiated power is uniformly distributed over the surface of the sphere.
Antenna Gain

- The relationship between an effective aperture and received antenna gain $G_r$ can be given by:

\[ G_r = \frac{4\pi A_e}{\lambda^2} \]

where $\lambda$ is the wavelength, and $A_e$ is the effective area covered by the transmitter.

- By substituting $A_e$, in terms of $G_r$ and $\lambda$, we obtain

\[ P_r = G_r G_t P_t / (4\pi d/\lambda)^2 \]

- Free Space path loss is defined as

\[ L_f = P_t / P_r = (1/G_r G_t) (4\pi d/\lambda)^2 \]

$L_f$ indicates power loss in the free space.

- When $G_r = G_t = 1$,

\[ L_f = (4\pi d/\lambda)^2 = (4\pi f_c d/c)^2 \]

where $c = \lambda f_c$ ($c$ is speed of light) and $f_c$ is the carrier frequency.