5. Satellite Systems

History and Orbits
Routing, Localization, and Hand-over
Systems

History of Satellite Communications

- 1945 Arthur C. Clarke about “Extra Terrestrial Relays“
- 1957 First satellite SPUTNIK
- 1960 First reflecting communication satellite ECHO
- 1963 First geo-stationary satellite SYNCOM
- 1965 First commercial geo-stationary satellite “Early Bird”
  - INTELSAT I: 240 duplex telephone channels or
    1 TV channel, 1.5 years lifetime
- 1976 Three MARISAT satellites (maritime communication)
- 1982 First mobile satellite telephone system INMARSAT-A
- 1988 First satellite system for mobile phones and
data communication INMARSAT-C
- 1993 First digital satellite telephone system
- 1998 Global satellite systems for small mobile phones
Applications

- **Traditional:**
  - Weather satellites
  - Radio and TV broadcast satellites
  - Military satellites
  - Satellites for navigation and localization (e.g., GPS)

- **Telecommunication:**
  - Global telephone connections
  - Backbone for global networks
  - Connections for communication in remote places or underdeveloped areas
  - Global mobile communication

→ Satellite systems extend cellular phone systems (e.g., GSM or AMPS)

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Classic Satellite Systems

- Mobile User Link (MUL)
- Inter Satellite Link (ISL)
- Gateway Link (GWL)
- Footprint: Small Cells (Spotbeams)
- Base Station or Gateway

PSTN: Public Switched Telephone Network

User Data

ISDN

PSTN

GSM

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Basics

- Satellites in circular orbits:
  - Attractive force \( F_g = m \cdot g \cdot \left( \frac{R}{r} \right)^2 \)
  - Centrifugal force \( F_c = m \cdot r \cdot \omega^2 \)
  - \( m \): mass of the satellite
  - \( R \): radius of the earth (\( R = 6370 \) km)
  - \( r \): distance to the center of the earth
  - \( g \): acceleration of gravity (\( g = 9.81 \) m/s\(^2\))
  - \( \omega \): angular velocity (\( \omega = 2 \pi f \), \( f \): rotation frequency)

- Stable orbit:
  - \( F_g = F_c \)

\[
r = 3 \sqrt{\frac{gR^2}{(2\pi f)^2}}
\]
Terms and Definitions

- Elliptic or circular orbits
- Complete rotation time depends on distance satellite-earth
- Inclination: angle between orbit and equator
- Elevation: angle between satellite and horizon
- LOS (Line of Sight) to the satellite necessary for connection:
  - High elevation needed, less absorption due to, e.g., buildings
- Up-link: connection base station to satellite
- Down-link: connection satellite to base station
- Typically separated frequencies for up-link and down-link:
  - Transponder used for sending/receiving and shifting of frequencies
  - Transparent transponder: only shift of frequencies
  - Regenerative transponder: additionally signal regeneration

Inclination

[Diagram showing satellite orbit with perigee and inclination angle δ]

- Plane of Satellite Orbit
- Satellite Orbit
- Perigee
- Inclination δ
- Equatorial plane
Elevation

Angle $\epsilon$ between center of satellite beam and surface

Minimal elevation:
Elevation needed at least to communicate with the satellite

Link Budget of Satellites

- Parameters like attenuation or received power determined by four parameters:
  - Sending power
  - Gain of sending antenna
  - Distance between sender and receiver
  - Gain of receiving antenna

- Problems:
  - Varying strength of received signal due to multi-path propagation
  - Interruptions due to shadowing of signal (no LOS)

- Possible solutions:
  - Link Margin to eliminate variations in signal strength
  - Satellite diversity (usage of several visible satellites at the same time) helps to use less sending power

$$L = \left( \frac{4\pi rf}{c} \right)^2$$

$L$: Loss
$f$: carrier frequency
$r$: distance
$c$: speed of light
Atmospheric Attenuation

Example: Satellite systems at 4-6 GHz

<table>
<thead>
<tr>
<th>Elevation of Satellite</th>
<th>Attenuation of Signal in %</th>
</tr>
</thead>
<tbody>
<tr>
<td>5°</td>
<td>50</td>
</tr>
<tr>
<td>10°</td>
<td>40</td>
</tr>
<tr>
<td>20°</td>
<td>30</td>
</tr>
<tr>
<td>30°</td>
<td>20</td>
</tr>
<tr>
<td>40°</td>
<td>10</td>
</tr>
<tr>
<td>50°</td>
<td>0</td>
</tr>
</tbody>
</table>

- **Rain Absorption**
- **Fog Absorption**
- **Atmospheric Absorption**

Orbits

- Four different types of satellite orbits identified depending on shape and diameter of orbit:
  - **GEO**: Geo-stationary orbit, about 36,000 km above earth surface
  - **LEO (Low Earth Orbit)**: About 500 - 1,500 km
  - **MEO (Medium Earth Orbit) or ICO (Intermediate Circular Orbit)**: About 6,000 - 20,000 km
  - **HEO (Highly Elliptical Orbit)**: elliptical orbits
- **Van-Allen-Belts**:
  - Ionized particles at 2,000 - 6,000 km and 15,000 - 30,000 km above earth surface
Routing

- One solution:
  - Inter-satellite links (ISL)
  - Reduced number of gateways needed
  - Forward connections or data packets within the satellite network as long as possible
  - Only one uplink and one downlink per direction needed for the connection of two mobile phones

- Problems:
  - More complex focusing of antennas between satellites
  - High system complexity due to moving routers
  - Higher fuel consumption
  - Thus shorter lifetime

- Examples:
  - Iridium and Teledesic planned with ISL
  - Other systems use gateways and additionally terrestrial networks

Localization of Mobile Stations

- Mechanisms similar to GSM
- Gateways maintain registers with user data:
  - HLR (Home Location Register):
    - Static user data
  - VLR (Visitor Location Register):
    - (Last known) location of the mobile station
  - SUMR (Satellite User Mapping Register):
    - Satellite assigned to a mobile station
    - Positions of all satellites

- Registration of mobile stations:
  - Localization of the mobile station via the satellite’s position
  - Requesting user data from HLR and updating VLR and SUMR

- Calling a mobile station:
  - Localization using HLR/VLR similar to GSM
  - Connection setup using the appropriate satellite
Hand-over in Satellite Systems

- Additional situations for hand-over in satellite systems compared to cellular terrestrial mobile phone networks caused by the movement of the satellites
  - Intra-satellite hand-over
    - Hand-over from one spot beam to another
    - Mobile station still in the footprint of the satellite, but in another cell
  - Inter-satellite hand-over
    - Hand-over from one satellite to another satellite
    - Mobile station leaves the footprint of one satellite
  - Gateway hand-over
    - Hand-over from one gateway to another
    - Mobile station still in the footprint of a satellite, but gateway leaves footprint
  - Inter-system hand-over
    - Hand-over from the satellite network to a terrestrial cellular network
    - Mobile station can reach a terrestrial network again which might be cheaper, has a lower latency

Geo-stationary Satellites

- Orbit 35,786 km distance to earth surface, orbit in equatorial plane (inclination 0°)
  - Complete rotation exactly one day, satellite is synchronous to earth rotation
  - Fixed antenna positions, no adjusting necessary
  - Satellites typically have a large footprint (up to 34% of earth surface!), therefore, difficult to reuse frequencies
  - Bad elevations in areas with latitude above 60° due to fixed position above the equator
  - High transmission power needed
  - High latency due to long distance (about 275 ms)

- Not useful for global coverage for small mobile phones and data transmission
- Typically used for radio and TV transmission
LEO Systems

- Orbit about 500 - 1,500 km above earth surface
- Visibility of a satellite about 10 - 40 minutes
- Global radio coverage possible
- Latency comparable with terrestrial long distance connections, ca. 5 - 10 ms
- Smaller footprints, better frequency reuse
- But now handover necessary from one satellite to another
- Many satellites necessary for global coverage
- More complex systems due to moving satellites
- Examples:
  - Iridium (start 1998, 66 satellites):
    - Bankruptcy in 2000, deal with US DoD (free use, saving from "de-orbiting")
  - Globalstar (start 1999, 48 satellites):
    - Not many customers (2001: 44000), low stand-by times for mobiles

MEO Systems

- Orbit about 5,000 - 12,000 km above earth surface
- Comparison with LEO systems:
  - Slower moving satellites
  - Less satellites needed
  - Simpler system design
  - For many connections no hand-over needed
  - Higher latency, ca. 70 - 80 ms
  - Higher sending power needed
  - Special antennas for small footprints needed
- Examples:
  - ICO (Intermediate Circular Orbit, Inmarsat) start about 2000
    - Bankruptcy, but planning for IP traffic
    - Planned joint ventures with Teledesic, Ellipso – cancelled again,
      initial components planned for 2003, full new start planned for 2005
## Overview of LEO/MEO Systems

<table>
<thead>
<tr>
<th></th>
<th>Iridium</th>
<th>Globalstar</th>
<th>ICO</th>
<th>Teledesic</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong># Satellites</strong></td>
<td>66 + 6</td>
<td>48 + 4</td>
<td>10 + 2</td>
<td>288</td>
</tr>
<tr>
<td><strong>Altitude (km)</strong></td>
<td>780</td>
<td>1414</td>
<td>10390</td>
<td>ca. 700</td>
</tr>
<tr>
<td><strong>Coverage</strong></td>
<td>global</td>
<td>±70° latitude</td>
<td>global</td>
<td>global</td>
</tr>
<tr>
<td><strong>Min. Elevation</strong></td>
<td>8°</td>
<td>20°</td>
<td>20°</td>
<td>40°</td>
</tr>
<tr>
<td><strong>Frequencies [GHz (about)]</strong></td>
<td>1.6 MS ↑</td>
<td>1.6 MS ↑</td>
<td>2 MS ↑</td>
<td>19 ↓</td>
</tr>
<tr>
<td></td>
<td>29.2 ↑</td>
<td>2.5 MS ↓</td>
<td>2.2 MS ↓</td>
<td>28.8 ↑</td>
</tr>
<tr>
<td></td>
<td>19.5 ↓</td>
<td>5.1 ↑</td>
<td>5.2 ↑</td>
<td>62 ISL</td>
</tr>
<tr>
<td></td>
<td>23.3 ISL</td>
<td>6.9 ↓</td>
<td>7 ↓</td>
<td></td>
</tr>
<tr>
<td><strong>Access Method</strong></td>
<td>FDMA/TDMA</td>
<td>CDMA</td>
<td>FDMA/TDMA</td>
<td>FDMA/TDMA</td>
</tr>
<tr>
<td><strong>ISL</strong></td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td><strong>Bit Rate</strong></td>
<td>2.4 kbit/s</td>
<td>9.6 kbit/s</td>
<td>4.8 kbit/s</td>
<td>64 Mbit/s ↓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2/64 Mbit/s ↑</td>
</tr>
<tr>
<td><strong># Channels</strong></td>
<td>4000</td>
<td>2700</td>
<td>4500</td>
<td>2500</td>
</tr>
<tr>
<td><strong>Lifetime [years]</strong></td>
<td>5-8</td>
<td>7.5</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td><strong>Cost Estimation</strong></td>
<td>4.4 B$</td>
<td>2.9 B$</td>
<td>4.5 B$</td>
<td>9 B$</td>
</tr>
</tbody>
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