5. Satellite Systems

History and Orbits
Routing, Localization, and Hand-over
Example Systems
Inter-satellite Communications

History of Satellite Communications (1)
- 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 for mobile phones
  - data communication INMARSAT-C
- 1993 First digital satellite telephone system
- 1998 Global satellite systems for small mobile phones
  - No pole coverage, 9,600 Baud services, 0.32 €/min
- 2000 Globalstar with 48 satellites, 1,414 km (LEO)
- 2001 Commercial re-launch of Iridium Satellite LLC
  - 93 satellites Feb 2002, March 2005 71 operational, 2,400 Baud voice/e-mail service
  - 1 min between 1.50 $US and 0.90 $US per min, with app. 160,000 customers
- 2006 Iridium Next2
  - Including GPS, cameras, environment data services, 10 Mbit/s IP
- 2016 OneWeb foundation, 650 satellites (LEO)
  - Internet for everyone
- 2016 Galileo – Global Navigation Satellite System (GNSS) went live after its 2005 start
  - Accuracy: 1 m (public), 1 cm (encrypted) with 30 satellites (22 usable)
- 2020 Starlink moved forward (started in 2015)
  - 3rd to 6th batch of 60 satellites launched into LEO (by Falcon X)
  - March 2021: 1,325 satellites in total

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) AMPS: Advanced Mobile Phone System

Classic Satellite Systems

Basics
- Satellites in circular orbits
  - Attractive force $F_a = mg(R)^2$ (zentrifugalkraft)
  - Centrifugal force $F_c = mr^2\omega^2$ (zentrifugalkraft)
  - 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/s²)
  - $\omega$: angular velocity ($\omega = 2\pi f$, f: rotation frequency) (Kreisfrequenz)
- Stable orbit
  - $F_a = F_c$
  - $r = \sqrt{\frac{gR^2}{(2\pi f)^2}}$
  - Thus, distance to earth depends on rotation frequency!
Satellite Period and Orbits

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

Elevation

Link Budget of Satellites

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

- Problems
  - Varying strength of received signal due to multi-path propagation
  - Intermittent 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

INMARSAT BGAN Coverage Map

Disclaimer: The maps below depict Inmarsat's expectations of coverage but do not represent a guarantee of service. The availability of service at the edge of coverage area fluctuates depending upon a variety of conditions. Contact a WCC representative for more information.
Atmospheric Attenuation

Example: Satellite systems at 4-6 GHz

Elevation of Satellite

Attenuation of Signal in %

Rain Absorption

Fog Absorption

Orbits

Four different types of satellite orbits identified depending on shape and radius 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 - 12,000 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

Geo-stationary Satellites (GEO)

- 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

GEO Example (Immarsat) (1)

- Owned by British consortium Digital Globe
  - 5th generation to come, 4th generation in operation since 2010/2013 (first global 3G network), 3rd in operation since 1996/98 (spot beams), 2nd in 1990, 1st in 1982
  - Covering oceans (mainly) for pictures and communications for merchant ships to stay in contact and interact in case of emergencies
  - Oceans are NOT covered by radar
  - Coverage does not mean service guarantee
  - 10 satellites at 35,786 km above earth with well-defined positions
  - ITU assigned Immarsat international prefixes for calls as +870 to +874
  - Daily pictures of 2.9 million square km a.o. for Google

GEO Example (Immarsat) (2)

- Very special use case
  - Search operation for MH370
  - Lost Boeing 777 from Malaysian Airlines since March 8, 2014
  - Immarsat tracked Boeing’s automatic and hourly satellite communication system’s signals
  - Incoming signal angle determines 2 possible corridors – still no results

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 in 1999, 48 satellites):
    - Not many customers (2001: 44000, see standby times for mobiles
  - Starlink (start in 2015, > 4,400 satellites)
Emergency Response – Satellite Use

- Thu, April 3, 2014
- The satellite lifted off on a Soyuz rocket from Europe’s Spaceport in Kourou, French Guiana at 21:02 GMT (23:02 CEST). The first stage separated 118 sec later, followed by the fairing (209 sec), stage 2 (287 sec) and the upper assembly (526 sec). After a 617 sec burn, the Fregat upper stage delivered Sentinel into a Sun-synchronous orbit at 693 km altitude.
- 2.31 "sentinel = Wachposten"
- 3 TB data per day
- 1 h for a "full" geo-picture

OneWeb Satellite Constellation

- LEO
  - Low earth orbit at 1,200 km within 18 polar orbit planes
  - K_s band at 12 to 18 GHz ("kurz-unten Band", original lower NATO K band)
  - Internet access 50 Mbit/s downlink bandwidth, uplink less
  - 25 years of operation with subsequent reentering of the Earth’s atmosphere, following the orbital debris-mitigation guidelines
  - Concerns raised here
  - 648 satellites by 2020 (open to add 1,972 additional ones)
    - Airbus Defense and Space
    - 150 kg mass each
    - First satellite launched in February 2019
    - 3 billion USD
    - Cost per satellite will be $1 million or less while industry analysts believe the cost-per-satellite would run between $700,000 to $900,000 in serial production

Starlink Satellite Constellation

- LEO
  - Low Earth orbit at 336 to 1,325 km
  - K_s band at 12 to 18 GHz and K_a band at 26.5 to 40 GHz
  - Receivers attached to flat user terminals (size app. 40-50 cm) with phased array antennas tracking satellites, terminals need LoS
  - Targeting service in the Northern U.S. and Canada in 2020/21
  - Concerns wrt the number of visible satellites, since they will outnumber visible stars such that their brightness in optical and radio wavelengths will severely impact scientific observations
  - 4,045 initial satellites plus 7,518 approved by 2018 (US regulatory)
    - SpaceX
      - App. 227-260 kg mass each
      - First satellite launched in February 2018, recent one in March 24, 2021
      - March 24, 2021: SpaceX has launched 1,385 Starlink satellites (1318 in orbit)
      - US$10 billion for a decade-long project starting in 2015

MEO Systems

- Orbit about 6,000 - 12,000 km above earth surface
- Comparison with LEO systems
  - Slower-moving satellites
  - Less satellites needed (12 satellites to cover earth surface)
  - 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

Example 1
- ICo (Intermediate Circular Orbit) started about 2000
  - Bankruptcy, but planning for IP traffic, planned joint ventures with Teledesic, Ixpresso, test operation in 2003 with ~6013 pre-flo (ITU), cancelled again
  - ICo G1 successfully launched from Cape Canaveral on April 14, 2008
    - 13-meter reflector (parabolic), 2 Gbps signals on north America (now owned by EchoStar)

MEO Example 2 (Galileo) (1)

- Galileo: global navigation satellite system (GNSS)
  - Europe: 5.3 billion € project, ending up at 10 billion €
  - Operational by 2016
  - 22 satellites initially (+ 2 testing, 2 unavailable)
- 22 in-orbit satellites (30 planned for)
  - Orbital altitude: 23,222 km
  - 3 orbital planes, 56° inclination, ascending nodes separated by 120° longitude
  - Satellite lifetime: 12 years
  - Satellite mass: 675 kg
  - Satellite body: 2.7 m x 1.2 m x 1.1 m
  - Span of solar arrays: 18.7 m
  - Power of solar arrays: 1,500 W (and of life)
- GIOVE-A 1st GIOVE (Galileo In-Orbit Validation Element) test satellite (12/2005)

Emergency Response – Satellite Use

Iridium-NEXT

- LEO
  - Low earth orbit at 455 km with an inclination of 86.4°
  - K_s band at 26.5 to 40 GHz ("kurz-above Band", original higher NATO K band)
  - Next generation at 128 kb/s to mobile terminals
  - Up to 1.5 Mbit/s to Iridium pilot marine terminals
  - 8 Mbit/s to fixed/transportable terminals
  - Every 8 min hand-over (orbital period of app. 100 min)

- 66 satellites by 2020 (9 in-orbit spares, 6 on-ground spares)
  - Motorola, now Thales Alenia Space
  - App. 689 kg mass each
  - Last satellite launched in January 2019, 95 in space (incl. old generation)
  - 2.1 billion USD + 800 M USD launching
  - First generation at 5 billion USD and lacking market demand (bankruptcy 2002)
MEO Example 2 (Gallileo) (2)

- **Main Services**
  - Open Access Navigation: Free and for use by mass market, simple timing, positioning up to 1 m
  - Commercial Navigation (Encrypted): High accuracy to 1 cm, guaranteed (fees)
  - Safety of Life Navigation: Open service, for applications with essential guaranteed accuracy
  - Public Regulated Navigation (Encrypted): Continuous availability for government agencies even in time of crisis
  - Search And Rescue: Collecting distress beacon locations; feasible for sending feedback, such as "confirming help is on its way"

- 2 rubidium frequency standard, 2 passive hydrogen laser clocks
  - Accurate timing signal for receivers, calculating the time that it takes the signal to reach the target.
  - Used to calculate the position of the receiver by diferentiating the time received signals from multiple satellites.

**Locations of Satellites in Space**

- **Satellites at the Edge of Outer Space**
  - **NASA mission "New Horizons"**
    - Take off on January 19, 2006, destined for Pluto ("dwarf planet" as of 1997)
    - Travel speed on average 48,000 km/h = 48 * 10^9 km/h
    - Compared to speed of light app. 1.08 * 10^10 km/h
    - Passed Pluto June 14, 2015 at 12,600 km/h
    - Travel time app. 9 years, which is app. 4.9 Billion km off Earth
    - Pictures on pairs of 32-Gbit HDs, taking 16 months to send all to Earth
    - IT/CPU: 4 computers – two operational (flight and control) and two backups
    - Processor: Mongoose-V, 12 MHz radiation-hardened version of MIPS R3000
    - Early July 15, 2015 lack of signals ... over-assignment of commanded science operations
    - Gap in communications – no contact for 2 days
    - Communications at X band (7.0–11.2 GHz, micro-wave radio)
      - Via 12 W transmitter (compared to 50 kW for radio stations on Earth)
      - Spacecraft’s radio telecommunications system, a 2.1-meter high-gain antenna
    - Latency at Jupiter app. 33-53 min at 38 kbit/s
    - Travel time app. 4.5 hours at 1 to 2 kbit/s data rate

- **Routing (off Earth)**
  - **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**
    - Inflon 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:**
  - 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/LR 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 call
    - **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 can reach a terrestrial network again which might be cheaper, has a lower latency
## Overview of LEO/MEO Systems

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<th>Iridium</th>
<th>Globstar</th>
<th>ICO</th>
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**Access Method**

- FDM/N: FDM/NIK
- COMA: COMA
- FDM/N: FDM/NIK
- COMA: COMA
- COMA: COMA
- COMA: COMA

**ISL**

- yes
- no
- no
- yes
- no
- yes

**Data Rate**

- 2.1 Gbps
- 5.6 Gbps
- 4.9 Gbps
- 81 Mbps
- 9 Mbps
- 324 kbps
- 1.5 kbps
- 2048 kbps

**Antenna**

- 54 cm
- 7.5 cm
- 12 cm
- 10 cm
- 5 cm
- 3 cm
- 10 cm

**Gains**

- >2.4
- 3.4
- >2.4
- 3.4
- <1.3
- <1.3

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**ISL**: Inter-satellite links  
**ICO**: Intermediate Circular Orbit