Satellite Communications

15. SatCom Services & Constellations: High Throughput

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PART 1 - THROUGHPUT GSO NETWORKS
High Throughput Satellites (HTS) require a large feeder link bandwidth

- collection of all beams’ useful bandwidth
- typically FWD throughput x 3-4 times RTN

**Example:** Medium HTS requiring 32 GWs

<table>
<thead>
<tr>
<th></th>
<th>FL</th>
<th>RTN</th>
<th>TOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of beams</td>
<td>200</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>Total user bandwidth/polar</td>
<td>500</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>Number of polarizations</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Number of FDMs/polarization</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Number of colours</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Bandwidth/beam/polar</td>
<td>125</td>
<td>62.5</td>
<td>MHz</td>
</tr>
<tr>
<td>Bandwidth/beam</td>
<td>250</td>
<td>125</td>
<td>MHz</td>
</tr>
<tr>
<td>Total user link bandwidth</td>
<td>50</td>
<td>25</td>
<td>GHz</td>
</tr>
<tr>
<td>Avg SE</td>
<td>2.5</td>
<td>1.25</td>
<td>bps/Hz</td>
</tr>
<tr>
<td>Total throughput</td>
<td>125</td>
<td>31.25</td>
<td>156.25</td>
</tr>
</tbody>
</table>

Extending user bandwidth to 1 GHz will double the # GWs required

Need to use non FSS reserved bands or to move to Q/V-band feeder link

Feeder link fading is affecting ALL user links! => ACM not a solution

How to also ensure high FL availability?
- Step 1: uplink power control
- Step 2: spatial GW diversity
- Step 3: smart GW diversity
Classical GW site diversity:

- Each GW has a backup at tenths of km of distance ready to take over in case of heavy fading
- Expensive solution in terms of ground segment
- Abandoned for HTS networks
HTS Architecture – Feeder link aspects

Smart Gateway N+0 concept: No extra GWs in diversity

- Each user beam is served by different GWs (3-4) on different FDMs
- In case of one GW outage the other GWs take over the faded GW traffic
- Easy to implement but impact on the system (beams) throughput
HTS Architecture – Feeder link aspects

Smart Gateway N+P++ concept: P extra GWs in spatial diversity with P << N

- Each user beam is served by different GWs on different FDMs
- In case of one GW outage the other GWs take over the faded GW traffic
- Requires GWs feeder link throughput oversizing and payload flexibility to switch feeder links to beam assignment but no impact on the system throughput
HTS analogue payload supporting Smart GW N+P++ solution

The use of a digital processor is easing the implementation

This architecture also supports progressive gateways deployment

*Increased payload complexity*
After exploitation of Q/V-band (on-going), W-band (R&D stage) optical may be the next frontier for the feeder link.

Pro and contra:
- To achieve a FL availability compared to the current RF’s, several optical ground stations in special “dry” and distant locations will be required (e.g. 9-10 for Europe).
- Each GW will have higher throughput than RF one but the backbone needs to be sized to the FL throughput (up to x Tbps).

Optical GWs for 99.89% availability.
Optical Feeder Link (FL) – Myths and Realities

- **Atmosphere turbulence mitigation**
  - Downlink: adaptive optics
  - Uplink: multiple transmitters at distance of say 0.5 m more BW and power

- **Current FSO satellite links are based on digital binary modulations:**
  - To limit the FL throughput satellite payload has to be regenerative instead of transparent. This may be an issue for GEO HTS easier for LEO constellations already featuring on-board processing.
  - Digital Transparent: the analog signal is sampled / quantized with an increase by a factor ≈16 of the feeder link required throughput

- **RF-over-optical analog modulation being investigated as possible smart optical GWs approach**
  - Use of single/double-sideband modulation to limit the bandwidth occupancy and average power transmitted
The Eutelsat Ka-sat HTS system [launched 2010]:
- Single Ka-band GSO covering Europe, North Africa and Middle East with 70 Gbps
- 82 beams with size of approximately 250 km
- 10 gateways interconnected with multi-protocol label switching (MPLS) high speed terrestrial network

**Ka-sat services:**

- **B2B2C**
  - **Tooway™**
  - **Consumer**

- **Professional Data Network**
  - **Enterprises and Institutions**

- **Satellite News Gathering**
  - **News agencies**
  - **Enterprises**

- **Broadcasting**
  - **National, regional TV**
  - **Enterprises**
High Throughput Satellite Network Example – Eutelsat Ka-sat

User Terminals within Beams

- 18.2 – 19.7 GHz
- 28 – 29.5 GHz

« FWD »
19.7 – 20.2 GHz

« RTN »
29.5 – 30 GHz

10 antennas of 9m

User Terminals within Beams
High Throughout Satellite Network Example – Eutelsat Ka-sat

Eutelsat Ka-sat coverage
High Throughout Satellite Network Example – Eutelsat Ka-sat

Eutelsat Ka-sat spacecraft

Power
- Spacecraft Power <14kW
- Payload DC power 11kW
- Solar Array Power up to 16kW

Mass
- Payload mass ~1000 kg
- Spacecraft dry mass ~3170 kg
- Satellite launch mass 5.7t -6.1t

Orbital Maneuver lifetime
- 16 years
Eutelsat Ka-sat core network interconnecting the 10 gateways

The GWs terrestrial interconnection is a key requirement for HTS with non negligible cost impact for both CAPEX and OPEX.
High Throughout Satellite Network Example – Eutelsat Ka-sat

Ka-sat footprint

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High Throughput Satellite Network Example – Eutelsat Ka-sat

Ka-sat ground segment (user terminal and gateways)

Gateway

User Equipment
### FY 2022-23 REVENUES BY APPLICATION

<table>
<thead>
<tr>
<th>Service Type</th>
<th>Revenue Contribution</th>
<th>Revenue (€m)</th>
<th>Like-for-Like YOY Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>VIDEO</td>
<td>62%</td>
<td>705</td>
<td>-8.3%</td>
</tr>
<tr>
<td>GOVERNMENT SERVICES</td>
<td>12%</td>
<td>143</td>
<td>-7.2%</td>
</tr>
<tr>
<td>MOBILE CONNECTIVITY</td>
<td>10%</td>
<td>110</td>
<td>+26.8%</td>
</tr>
<tr>
<td>FIXED CONNECTIVITY</td>
<td>16%</td>
<td>178</td>
<td>-2.3%</td>
</tr>
<tr>
<td><strong>TOTAL OPERATING VERTICALS</strong></td>
<td></td>
<td><strong>1,136</strong></td>
<td><strong>-4.8%</strong></td>
</tr>
<tr>
<td>OTHER REVENUES</td>
<td></td>
<td>-5</td>
<td>-€8m³</td>
</tr>
</tbody>
</table>

The fixed connectivity is losing customers: the Ka-sat Tx/Rx user terminal head is gone – a real case observed in Corsica mountains.
- HTS covering North-Central America and Oceanic routes to Europe
- Boeing H720P platform 6.5 tons 18 kW
- 300 Gbps throughput operating at Ka-band
- Launched mid-2017
Viasat 3: first Terabps HTS GSO system announced in 2015 has been launched in 2023 with large delay

- The global ViaSat-3 constellation is expected to deliver unprecedented capacity to individuals, businesses, and governments — on the ground, in the air, at sea, and beyond.
- **Spectrum**: The ViaSat-3 constellation operates on Ka-band
- **Coverage**: The ViaSat-3 constellation is designed to cover North and South America, Europe, Africa, and Asia Pacific
- **Speed**: Each ViaSat-3 satellite is planned to have the ability to deliver download speeds of up to 100's of Mbps
- **Capacity**: Each satellite is anticipated to deliver at least 1 Terabit of data per second (1Tbps)
- **Weight**: Each satellite is expected to weigh approximately 6 metric tons
- **Payload**: Innovative payload solutions aiming at flexibility with reduced complexity 

video [https://www.viasat.com/space-innovation/satellite-fleet/viasat-3/](https://www.viasat.com/space-innovation/satellite-fleet/viasat-3/)
Viasat 3 planned global coverage with 3 GEOs
Viasat 3 satellite: very large Ka-band reflector and solar generators
Risky business – It happens...

- In addition to the sizeable development delay Viasat 3 had a major issue after April 23 launch in deploying the large Ka-band reflector in July (Northrop Grumman’s Astro Aerospace) probably leading to the completed satellite operational loss

- Insurance coverage expected to be 420 M US$ but not fully compensating for the mission cost > 700 M US$

- Stocks falling after July news....
Hughes Network Systems Jupiter 3 (Echostar XXIV)

- Jupiter 3 HTS made by Maxar has been launched in July 2023 is the heaviest communication satellite launched so far (9 tons vs 5.6 tons of Viasat 3 with a solar array wingspan of 39 m vs 44)
- In service in 4Q 2023, with user download speed up to 100 Mbps
- Spectrum: 18 gateways exploiting Ka-band, Q- and V-band
- Coverage: North & South America
- Speed/Throughput: Up to 100 Mbps/ More than 500 Gbps
- Total maritime mobility Spot beams: 300 - Each beam carries 500 MHz or more, providing more than 1 Gbps/beam
GSO HTS are trying to fill the gap of the GSO broadcasting satellite decline

- High throughput is a must but challenging even using Ka-band high frequency reuse (hence small beams)
- ACM is a key technique for the efficient exploitation of Ka-band
- Smart gateway diversity to mitigate the number of ground stations required
- Q/V-band starts to be adopted for the feeder link
- User terminal like TVRO equipment, no tracking antenna
- Long satellite lifetime
• **Key challenges:**
  
  – Larger number of beams means more and more non uniform traffic and payload complexity plus larger antenna aperture calling for deployable reflectors with associated risks
  
  – Large (semi)-active antennas to allow coverage and traffic request flexibility
  
  – Radio resource management challenging considering the uneven traffic
  
  – Interconnected gateways number cost is high – shift towards higher feeder link RF frequencies or optical space-to-ground links
  
  – User segment equipment and service cost is still an issue
  
  – GSO latency it is still representing an issue for certain applications requiring low-latency
  
  – Traffic distribution is very uneven -> requires high antenna spatial discrimination and smart radio resource management
The uneven traffic challenge for the system design

- The traffic distribution is very uneven -> requires high antenna spatial discrimination
- Smart radio resource management solution is key

Gray bar=requested throughput
Green bar=offered throughput

Estimated potential user population distribution
Forward link SNIR distribution

3D view of the MB+QVD SNIR dB
PART 2 - HIGH THROUGHPUT NGSO NETWORKS
A new area of concern – RF spectrum pollution
A new area of concern – RF spectrum pollution 1/2

NGSO (LEO/MEO) Megaconstellations of hundreds/thousands of satellite are rapidly building up - Radio Frequency spectrum cleanliness is endangered

For mm-wave bands the main interference issues are related to:

- GSO to NGSO – countermeasures are in place and enforced by ITU
- NGSO to NGSO – FCC calls to avoid in-line interference (10 deg min sat angle separation)
  - Without operators' coordination there will be a large waste of spectrum resources in mm-wave bands
  - For mobile direct access a single global constellation will block the worldwide usage of the selected band – divide et impera approach?
NGSO (LEO/MEO) Megaconstellations

Should We Worry About Interference in Emerging Dense NGSO Satellite Constellations?

(a) Look-aside  (b) GSO protection

Throughput degradation $\Delta R [%]$
MEO O3B Broadband Constellation

- MEO constellation at an altitude of 8062 km for broadband access to unserved equatorial regions started by SES
- 20 satellites in equatorial orbit, 6 hours orbital period, operating at Ka-band
- Services:
  - Tier 1: national telecom operators and Internet providers, 3.5 m dish, 600 Mbps
  - Tier 2: cellular operators linking base stations, ships, 1-2 m dish, up to 155 Mbps
  - Tier 3: consumers and small business, 0.5-1 m dish and up to 155 Mbps
- 1st generation operational in 2002, 2nd generation expected in operation for 2024
O3B system architecture:

- 9 gateways serving 20 satellites, DVB-S2 air interface with ACM
- Make-before-break handover with two satellites active during handover phase
O3B coverage
The O3B 1G spacecraft payload (20 launched):
- Simple bent-pipe architecture connecting the 2 gateway(s) beams to the 10 user beams through mechanically steerable 27 cm antennas; TAS-F made

The O3B 2G spacecraft (4 launched, 11 planned in total):
- Designed with Boeing, software-defined satellites respond dynamically to user demand
- Electronically steered phased-array antennas support thousands of beams per satellite, each scaling from 50 Mbps to 10 Gbps
MEO O3B Broadband Constellation

- 2\textsuperscript{nd} generation (mPower) satellites being produced by Boeing in USA
- 11 satellites in MEO orbit planned
- Deployment initiated in December 2022 (2) with 2 more in Q2 2023, third launch being delayed due to some issue identified on the first fours satellites power modules
- Boeing's multi-orbit BSS-702X satellite bus with an all-electric propulsion system and a payload that can be reprogrammed from the ground to reallocate resources “on the fly”
- Electronically steered phased array antennas can provide up to 5000 spot beams per satellite each shaped and pointed as required to specifically distribute power and bandwidth to individual user’s and, using the full Ka-band spectrum, enable uncontended speeds from 50 Mbit/s up to 10 Gbit/s
MEO O3B Broadband Constellation

The O3B ground segment (user terminal and gateways)

User Equipment

Gateway

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LEO OneWeb Broadband Constellation

• First LEO megaconstellation at an altitude of 1200 km for global broadband access
• 648 (588+spares) satellites in 12 orbital planes with 49 satellites each, 109 minutes orbital period, operating at Ku-band for the user link, Ka-band for the feeder link, no ISL
• Small satellites 150 kg, 50 W DC power each
• Constellation deployment started on February 2019, 634 satellites launched at May 23
• Services:
  – Mobility (maritime, aviation, land mobility, IoT)
  – Satellite broadband (corporate enterprise, small and medium business, consumer residential)
OneWeb system architecture:

- 55-75 gateways serving the satellites with large number of antennas/gateway
- Make-before-break handover with two satellites active during handover phase
OneWeb constellation

- 12 near polar orbit planes at 1,200 km (750 mi) altitude, at 86.4° orbital inclination
- Approaching the poles, beams are progressively switched off to avoid overlaps

Multi-satellite launch: spacecrafts stowed in fairing
OneWeb payload

- Bent-pipe transponder single polar user link and dual polar feeder link (no ISL)
- Two Ka-band gateway feeder link steerable antennas with downlink power control
- 16 Ku-band venetian-blind fixed antenna for the user links with elliptical shape
- Attitude control allows adjusting the satellite pointing to avoid GEO interference
- Second generation satellite bids expected in 2023
OneWeb GEO interference avoidance approach:
- Progressive pitching of the satellite to avoid GEO arc interference
- Banana-shaped beams to better cope with the beam squinting operation at the equator

Venetian blind beam shape to ease the progressive pitching process
• With “progressive pitching” the satellite (patent pending)
OneWeb production facility in Florida – 2 satellites/day

See video:
https://vimeo.com/529924820
LEO OneWeb Broadband Constellation

OneWeb ground segment (user terminal and gateways)
Starlink LEO Broadband Constellation

- LEO megaconstellation at an altitude of 335-550 km for global broadband access
- Steps 1-5: 4108 satellites @ 550 km in 72 orbital planes with 54, 70, 74, 81 degrees inclination operating at Ku-band for the user link, Ku/Ka-band for the feeder link (4519 already in orbit of which 4487 operational @ July 23)
- Step 6: 7518 satellites at 340 km with V-band addition for user/gateways
- Small satellites 260-290 kg, optical ISLs (4) being deployed in most recent satellites
- Services:
  - Satellite broadband (corporate enterprise, small and medium business, consumer residential)
  - Military and mobility support?
Starlink LEO Broadband Constellation

Starlink system architecture:

- 32 gateways filed in USA, unclear number worldwide
- Make-before-break handover with two satellites active during handover phase

Starlink Network Architecture

- 17.8 – 19.3GHz Downlink
- 27.5 – 30.0GHz Uplink
- 10.7 – 12.7GHz Downlink
- 14.0 – 14.5GHz Uplink

Map data ©2022 Google, INEGI, Imagery ©2022 NASA, TerraMetric
Starlink LEO Broadband Constellation

Starlink coverage: https://www.youtube.com/watch?v=bKj4GDNhH0Q
Starlink LEO Broadband Constellation

Starlink satellite/payload

- Phased-array Ku-band antenna, on-board processing, ISL
- Two Ka-band gateway feeder link steerable antennas
- Likely use of beam hopping with 4 simultaneously active beams/satellite
Starlink Launch

- Stacked satellites allowing 60 satellites/launch on Falcon 9
- 400/launch planned with Starship
- 45 satellites/week produced
Starlink V2 mini satellites

- Intermediate version of V2 satellites requiring Starship launcher
- 4 times the throughput of V1 satellites, bigger and heavier (800 kg vs GEN 1 295 kg)
- Stacked satellites allowing 22 satellites/launch on Falcon 9, 4.1 m wide satellite
- 99% reliability, lower brightness, operations below 600 km, advanced collision avoidance, 100% dismissible
- V2 will also include a mobile payload for direct to hand-held communications
Starlink LEO Broadband Constellation

Starlink ground segment

User Equipment

Gateway
Starlink LEO Broadband Constellation

UE v1 mechanical/electronic steering antenna: sold at 499$, production cost 5 times as high – v2 has reduced the production cost, million samples produced

Beautiful engineering but complex active antenna
• Big effort in reducing cost and size of the user terminal:
  – Reduction in the number of beamformer ICs power consumption and cost!
  – Very large number of IPs protecting the technology
The use of FDD/TDD allows to greatly simplify the user terminal:

- The terminal is not receiving and transmitting at the same time
- When not transmitting/receiving the beam hopped satellite can serve other beams
- No duplexer filters required
- Hybrid analogue/digital BFN with ST designed/produced chips
Starlink LEO Broadband Constellation

Starlink service cost/performance (2022):

- Monthly fee private user: $135/month plus $599 for the UE with 1 TB data cap during peak hours
- Monthly fee business user: $2500/month
- The data rate effectively provided is highly variable lower than what advertised (300 Mbps)
Starlink LEO Broadband Constellation

Starlink service cost/performance (2022):

- Latency is also time dependent
- Dropouts in video applications observed

<table>
<thead>
<tr>
<th>Ping (ms)</th>
<th>Download (Mbps)</th>
<th>Upload (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Download (Mbps)</td>
<td>Upload (Mbps)</td>
</tr>
<tr>
<td>0 - 10</td>
<td>979</td>
<td>4,468</td>
</tr>
<tr>
<td>20 - 30</td>
<td>2,695</td>
<td>2,538</td>
</tr>
<tr>
<td>40 - 50</td>
<td>2,126</td>
<td>1,490</td>
</tr>
<tr>
<td>60 - 70</td>
<td>2,211</td>
<td>445</td>
</tr>
</tbody>
</table>

Ping to Ookla server (ms)
Starlink Mobile Service Offer

Starlink for Land Mobility
Reliable high-speed internet while in-motion.
Starting at €239/mo with a hardware cost of €2,355.

Starlink for Maritime
High-speed internet around the globe.
Starting at €239/mo with a hardware cost of €2,355.

Starlink for Aviation
Reliable high-speed internet in-flight.
$25,000/yr with a hardware cost of $69,000.

Starlink Direct to Cell
Starlink satellites with Direct to Cell capabilities enable ubiquitous access to texting, calling, and browsing wherever you may be on land, lakes, or coastal waters.

Ubiquitous Coverage
Direct to Cell will also connect IoT devices with common LTE standards.
Amazon Kuiper Broadband Constellation

Project Kuiper system architecture

Satellites

Customer downlink: 17.7-18.6 / 18.8-19.4 / 19.7-20.2 GHz

Gateway downlink: 17.7-18.6 / 18.8-20.2 GHz

Gateway uplink: 27.5-30.0 GHz

Customer uplink: 28.35-29.1 / 29.5-30.0 GHz

Customer Terminals

Residential

Business

Agriculture

Transportation

Telecom

Infrastructure

Gateway Stations
Tracking, Telemetry, and Command (TT&C) Terminals

Points of presence (PoP) / traffic interchange

Fiber links

Third-party enterprise/service provider networks

Internet

Cloud services

Satellite Communications

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15. SatCom Services & Constellations: High Throughput

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Project Kuiper

is a constellation of 3,236 low earth orbit (LEO) satellites delivering high-speed, low-latency broadband services on a global scale – planned system availability end of 2024 (TBC)

Orbital altitudes and service coverage

- Deployed in 98 orbital planes shells 590 km/610 km/630 km & 3 inclinations (33.0°/42.0°/51.9°, figure refers to shell 2, 42.0°)
- Service coverage reaches 56 degrees North and South Latitudes
Satellite System

- Ka-band customer links offering better performance than C and Ku-bands
- Phased array antennas communicate with customer terminals on the ground

Customer Terminals

- Single aperture, 12 in. diameter, Ka-band phased array
- Maximum throughput 400-1000 Mbps

Networking and Infrastructure

- Hundreds of gateway Earth stations around the world
- Software-defined networking to coordinate beams and allocate bandwidth
- End-to-end encryption between customer and administrative endpoints
Amazon Kuiper Broadband Constellation

First two Kuiper experimental satellites launched in October 2023 with ULA

- The series of tests will add real-world data from space to years of data collected from lab and field testing, providing additional insight into how the end-to-end Project Kuiper network performs across ground and space.
- Learnings from the mission to help refine hardware, software, and infrastructure.
- First production satellites are on track for launch in the first half of 2024, expected to be in beta testing with early commercial customers by the end of 2024.
Amazon Kuiper Broadband Constellation

- Ultra compact 18x18 cm, 100 Mbps,
- High performance antenna 28x28 cm, 400 Mbps, 400$
- High bandwidth antenna 48x48 cm, 1000 Mbps
- Custom made chips for UE and GWs
Amazon Kuiper Broadband Constellation

Project Kuiper Launch & Deployment

Project Kuiper has secured a minimum of 77 – and up to 92 – launches to support its ambitious deployment plan for Project Kuiper.

Project Kuiper Launch Lineup

- Secured up to 92 launches across three launch providers – Arianespace, Blue Origin and United Launch Alliance (ULA).
- Heavy-lift vehicles will provide enough capacity to enjoy vast majority of our 3,236-satellite constellation.
- Amazon is investing billions of dollars across the three agreements, making it the single-largest commercial procurement of launch vehicles in history.

Industry Impact

- Contracts will support thousands of suppliers and highly skilled jobs in 49 states in the U.S. and 13 countries across Europe.
- Partnership with ULA includes investments in launch infrastructure and service upgrades at Cape Canaveral Space Force Station.
• New space approach is revolutionizing the HTS satellite ecosystem
  – New big players (SpaceX, Amazon...) on top of more conventional operators (SES, Eutelsat, Intelsat...)
  – Constellations of thousand of satellites with optimized geometry
  – Very Low-Earth Orbiting Satellites, low latency, global coverage
  – Active antennas on-board with regeneration and ISL becoming a must
  – Satellites are produced in series at a pace and cost unthinkable few years ago
  – Tenths to hundreds of satellites / launch – many launches
  – First mass market production of electronically steerable active antennas for the user terminal
  – Starlink web-based marketing approach with DIY installation appears a promising approach
Key challenges:

- The spectrum is a scarce resource, very difficult to share the spectrum among different LEO constellations -> risk of “dividi et impera” approach reducing the performance of the single system
- Regulatory and licensing aspects at national level may hamper the system penetration
- Radio resource management challenging considering the uneven traffic
- Potential issue with space debris management
- User segment equipment cost is still an issue