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ENGINEERING

Satellite Networks and Standards

Introduction

- The satellite Sputnik 1, to be mentioned for historical reasons, was the first artificial object in Earth orbit. Its success in fact allowed for significant technological advancement, subsequently exploited by all the space agencies in the world.

- Sputnik 1 was a LEO satellite launched in 1957 that communicated with Earth for three weeks and then re-entered the lower layers of the atmosphere, destroying itself in the following two months.

- As for scientific satellites, it is worth mentioning the Chandra and Hubble space telescopes, with the first operating in the X-ray band and the second in the visible and near ultraviolet and infrared ranges.

- Currently, there are many Earth satellites of various sizes in operation, while since the start of the space race in the late 1950s, many other objects have been launched and then decommissioned at the end of their lives.

Satellite networks for telecommunication

Name	Operator	Constellation design	Coverage	Freq.	Services
Broadband Global Area Network (BGAN)	Inmarsat	3 geostationary satellites	82°S to 82°N		Internet access
Global Xpress (GX)	Inmarsat	5 Geostationary satellites		K_a (26.5–40 GHz)	Internet access
Globalstar	Globalstar	48 at 1400 km, 52° (8 planes)	70°S to 70°N	L (1.61-1.63 GHz) S (2.48-2.5 GHz)	Internet access, satellite telephony
Iridium	Iridium	66 at 780 km, 86.4° (6 planes)	Global	L (1.61-1.63 GHz)	Internet access, satellite telephony
O3b	SES	20 at 8062 km, 0° (equatorial orbit)	45°S to 45°N	K_a (26.5–40 GHz)	Internet access
OneWeb	Eutelsat	operational satellites: 654	Global	K_u (12 -18 GHz) K_a (26.5-40 GHz)	Internet access
Orbcomm	ORBCOMM	17 at 750 km, 52° (OG2)	65°S to 65°N		IoT and M2M, AIS
Starlink	SpaceX	LEO in several orbital shells~8000 satellites at 550 km	Global	K_u (12–18 GHz) K_a (26.5–40 GHz) V (40-75 GHz)	Internet access

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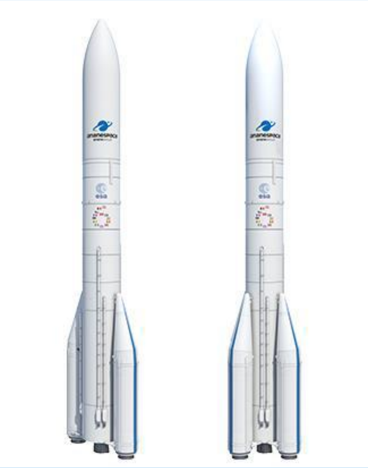
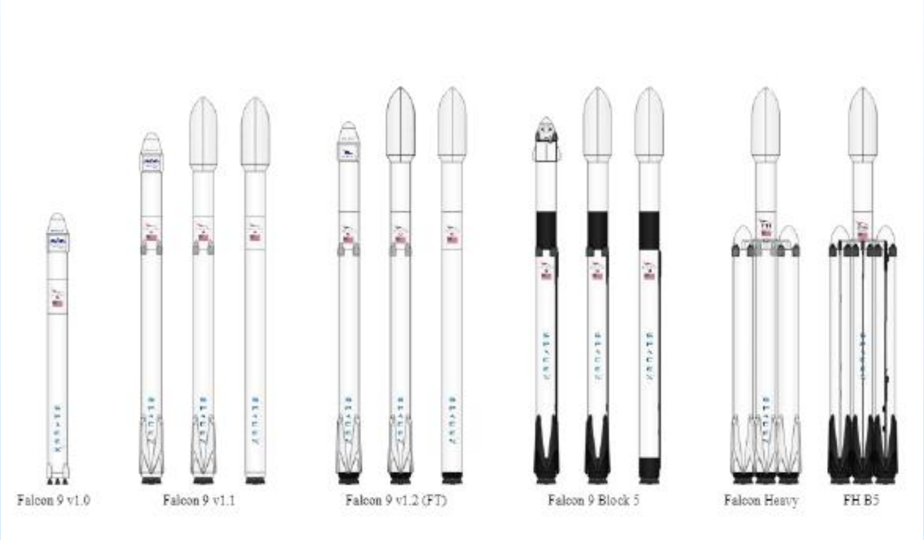
The Launcher Market Evolution

The Launcher Market Evolution

- Europe leadership with Ariane 4-5 launchers has been taken over by SpaceX in US thanks to its unprecedented growth in terms of Falcon 9 launch rates and launch cost reduction also due to booster reuse.
- ESA's Ariane 6 has been launched in July 9 2024 with 4 years delay – 50% less expensive.

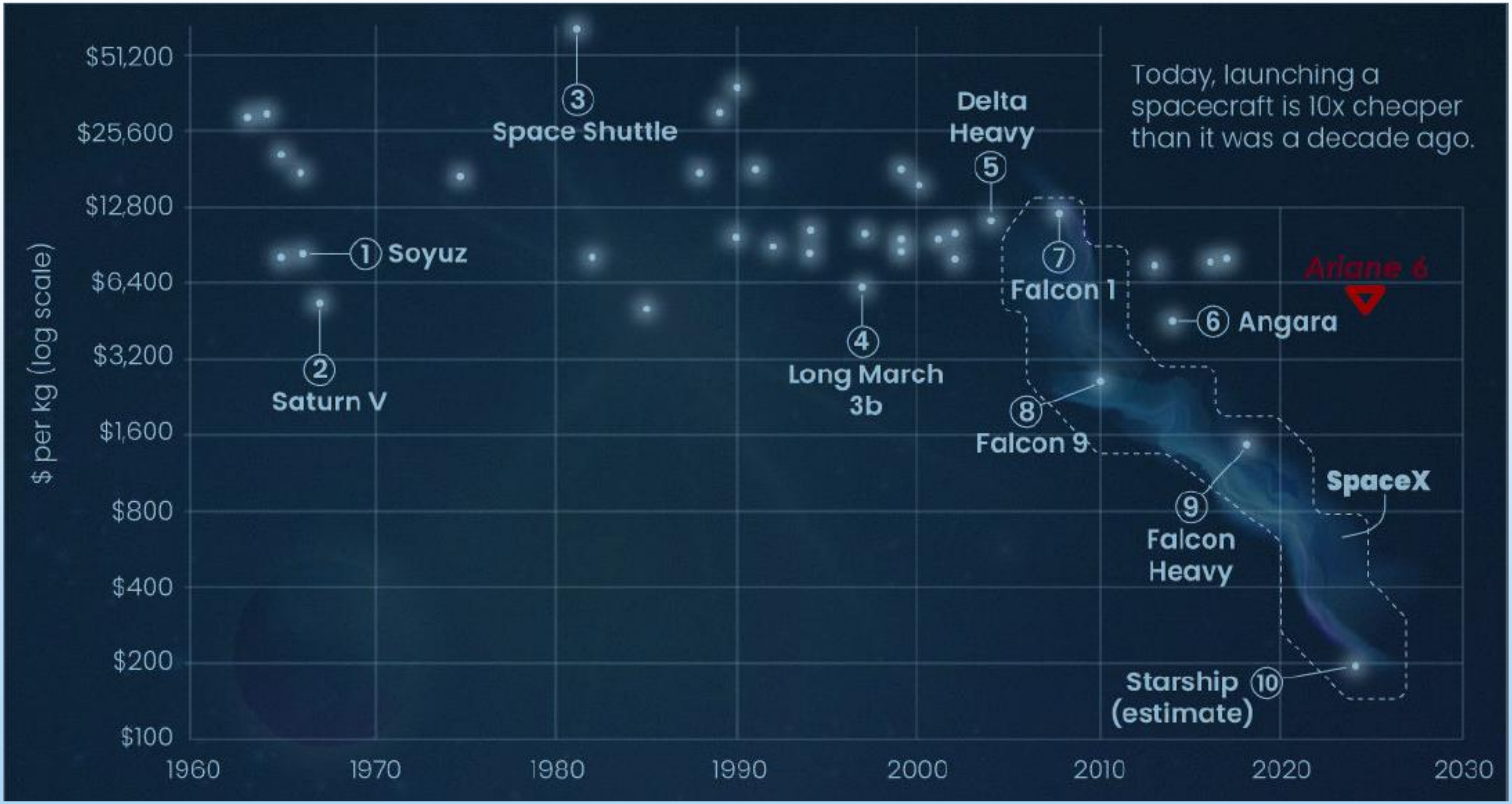




ESA Ariane 1-5 ESA Ariane 6 Space X Falcon family

Source: Riccardo de Gaudenzi - ESA

The Launcher Market Evolution



Non geostationary networks

A comparison

SYSTEM	Iridium	Globalstar	Starlink
Height (h) [km]	780	1400	550,570,560,540
Elevation (θ_{min})	8.2°	10°	
Inclination (λ)	86.4°	52°	53°,70°,97.6°53.2°
Up-link frequencies [MHz]	1616.0-1626.5 (L-Band)	1610.0-1626.5 (L-Band)	
Down-link frequencies [MHz]	1616.0-1626.5 (L-Band)	2483.5-2500.0 (S-Band)	V-band 40-75 GHz
Coverage radium ($R\alpha_v$) [km]	2218	2910	250 (smaller cells of 24 km)
Satellites	66	48	1445,403,233,1566
Orbits	6	8	72,36,12,72
Beams	48	16	

Iridium (1)

- LEO constellation at an altitude of 780 km for mobile telephony and low-rate data services
- Implemented by Motorola (US)
- 66 satellites in quasi polar orbits (86.4 degrees inclination) over 6 planes, 100 min orbit
- Inter-satellite links and on-board regeneration
- 1st generation started service in 1998 and became fully operational in 2002
- Iridium declared bankruptcy in 1999, the largest one at that time

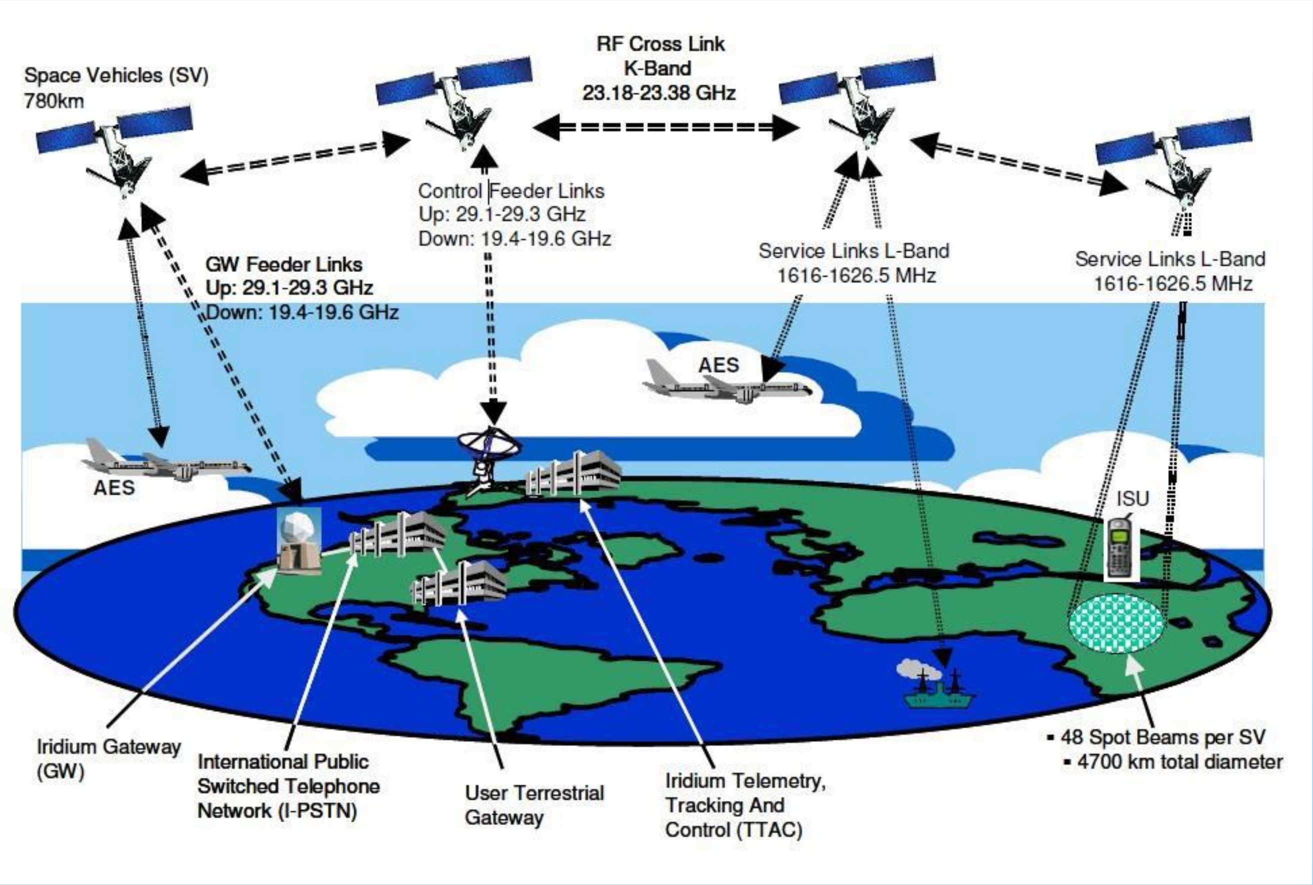
Iridium (2)

- The Iridium spacecraft
  - L-band direct-radiating array with digital regenerative fully reprogrammable payload
  - 2 feeder link antennas with mechanical steering (Ka-band)
  - 4 crosslink antennas (K-band forward/back/left/right, 2 with mechanical steering)
  - Aireon hosted payload for air traffic management (airplanes ADS-B messages reception)

- The Iridium ground segment (user terminal and gateways)
  - Thanks to ISL only few gateways required to provide global coverage
  - From hand-held to compact maritime terminals
  - Powerful paging capability for providing some indoor penetration

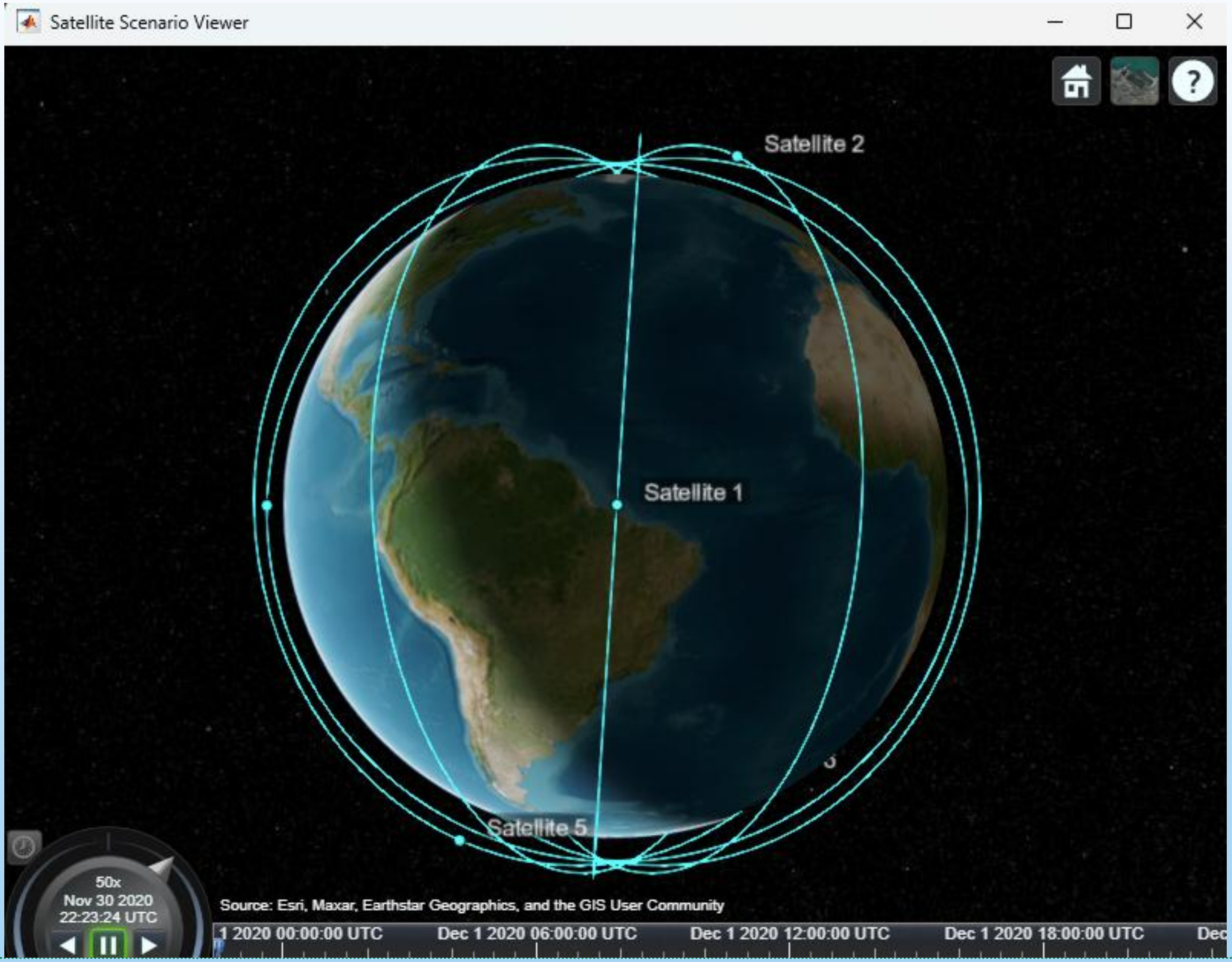
Iridium (3)

- Architecture



Iridium

- Constellation

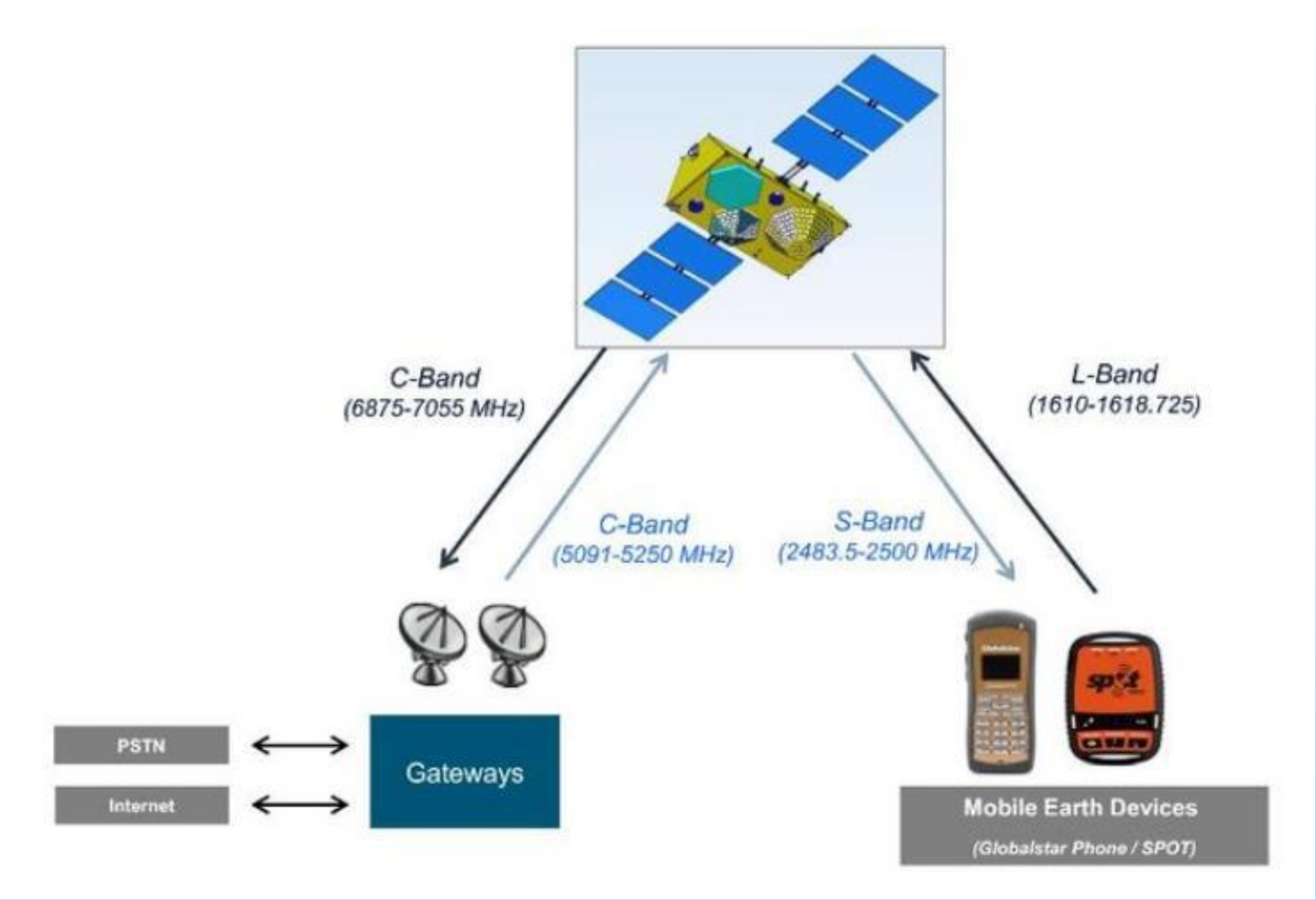


Globalstar (1)

- LEO constellation at an altitude of 1410 km for mobile telephony and low-rate data services.
- Developed by Space System Loral, Qualcomm and Thales Alenia.
- Satellites in inclined orbit (52 degrees inclination) over 8 planes, 114 min orbit.
- Simple bent-pipe satellites (no ISL), several gateways not providing global coverage.
- 1st generation constellation deployment completed in 2000 (48 satellites).
- Globalstar declared bankruptcy in 2002.
- 2nd generation put in operation in 2019 (24 satellites) – 370 M$ debt - 256 KEURO losses in 2022.

Globalstar (2)

- Globalstar architecture.

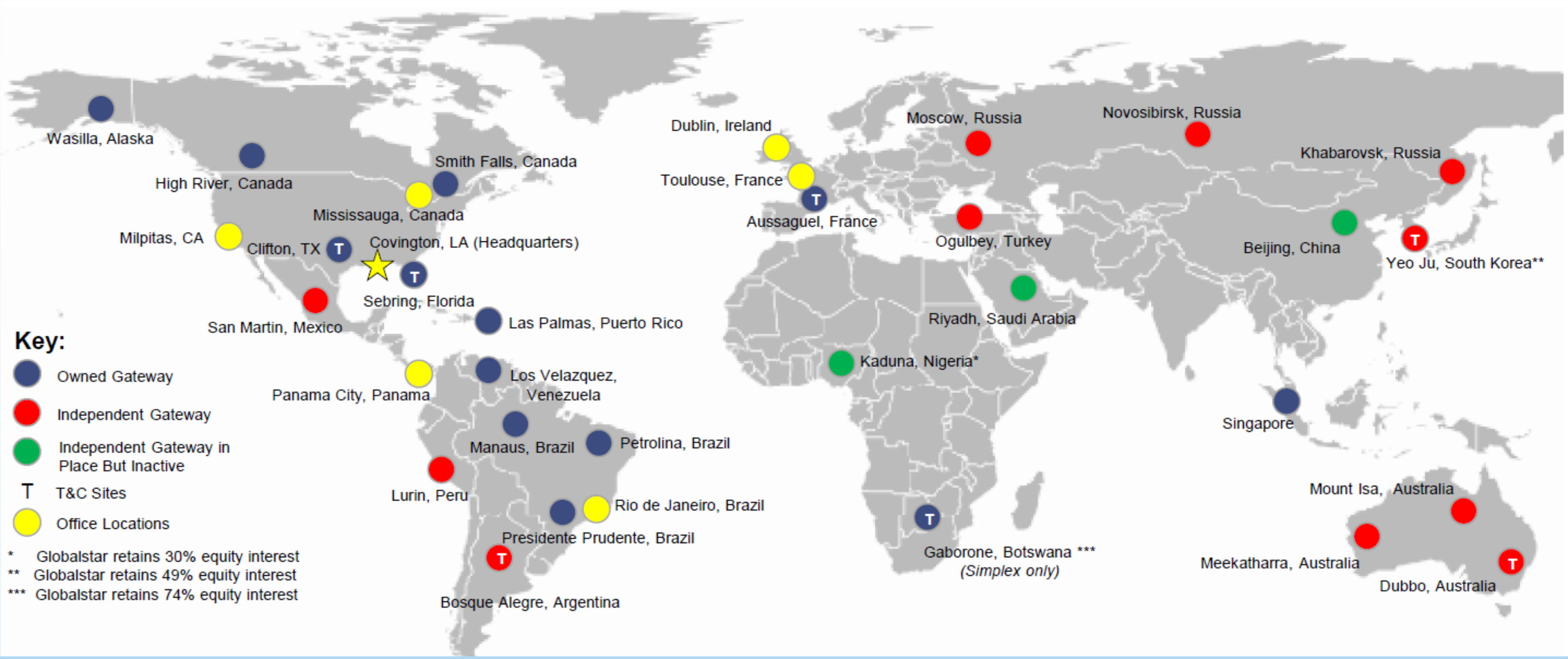


Globalstar (3)

- The Globalstar 2nd generation spacecraft:
  - Bent pipe payload – no regeneration / no ISL as in Iridium.
  - L/S-band separate direct-radiating array with analogue BFN and bent-pipe payload.
  - S-band Tx array split in two conformal DRAs (10+6 beams).
  - L-band Rx array with single flat DRA.
  - 2 feeder link antennas for transmit/receive (C-band).

Globalstar (4)

- The Globalstar ground segment.



AST Mobile

- AST Mobile represents a new paradigm in mobile satcom
  - 243 large LEOs satellites
  - Direct access to terrestrial hand-held mobile phones with services from
  - Use of terrestrial frequency bands to avoid PFD limits affecting MSS bands
  - Very large (30x30 m) deployable phased arrays to support link budgets
  - Solar generators opposite to the phased array antenna
- BlueWalker 3 is AST SpaceMobile’s prototype satellite and is designed to operate directly with standard, unmodified mobile devices. The spacecraft was built with an aperture of 693 square feet to establish connectivity directly with cell phones via 3GPP-standard frequencies. BlueWalker 3 launched to orbit at 9:20 p.m. ET on September 10, 2022, and is a predecessor to planned commercial satellites called BlueBirds.

AST Mobile (2)

- Block 1 BlueBird
  - In March 2022, AST SpaceMobile announced a multi-launch contract with SpaceX to launch its first BlueBird operational satellite. AST SpaceMobile has stated that it plans to produce up to six BlueBird satellites per month at two manufacturing sites in Midland, Texas. On September 12, 2024, the company launched all five satellites with its BlueBird 1–5 mission aboard a SpaceX Falcon 9 rocket. By October 25, the company stated all five satellites had completely unfolded.
- Block 2 BlueBird
  - On November 14, 2024, AST SpaceMobile announced a launch campaign for its next-generation Block 2 BlueBird satellites. The company revealed plans to utilize multiple launch providers, including Blue Origin's forthcoming New Glenn rocket, SpaceX's launch vehicles, and those operated by the Indian Space Research Organization (ISRO). This initiative aims to deploy up to 60 Block 2 BlueBird satellites, each equipped with a communication array spanning approximately 223 square meters. These satellites are designed to achieve data transmission speeds of up to 120 Mbps, enabling voice, data, and video communication capabilities for end users.

Apple/Globalstar

- Apple invested 450 M$ to initiate this new service largely in the Globalstar ground infrastructure
- New more powerful C-band gateways ground antennas
- New ground stations in Nevada and Hawaii, as well as existing facilities in Texas, Alaska, Florida, and Puerto Rico
- Full reuse of the existing Globalstar space segment with proprietary ad-hoc narrowband physical and upper layers – Qualcomm Snapdragon X65 chip
- The service exploits the Globalstar L (Tx) and S (Rx) bands for direct-to-hand-held communications with iPhones 14 & 15.
- Apple satellite features:
  - Emergency SOS
  - Roadside Assistance
  - Messages
  - Location update

Broadband Global Area Network (BGAN)

- Used to connect a laptop computer to Internet in remote locations.
- A BGAN terminal is about the size of a laptop.
- Downlink speeds of high-end BGAN terminals are up to 492 kbit/s, and upload speeds are up to 492 kbit/s - Best Effort as BGAN Background IP (BIP) is a contended (shared) channel.
- Typical latency is 0.6–1.5 seconds round trip for the Background IP service, and 0.8–1 seconds for the Streaming services.
- BGAN user is often assigned a non-routable IP address and routed through a NAT server; this increases security and helps control usage costs.
- The BGAN terminal needs to find its position using GPS before it can negotiate with the satellite, so a clear view of the sky is necessary, to begin with. Once the GPS position is obtained, it does not need to do that again unless it is moved to a different region. Getting the initial GPS position can take a few minutes.

O3b

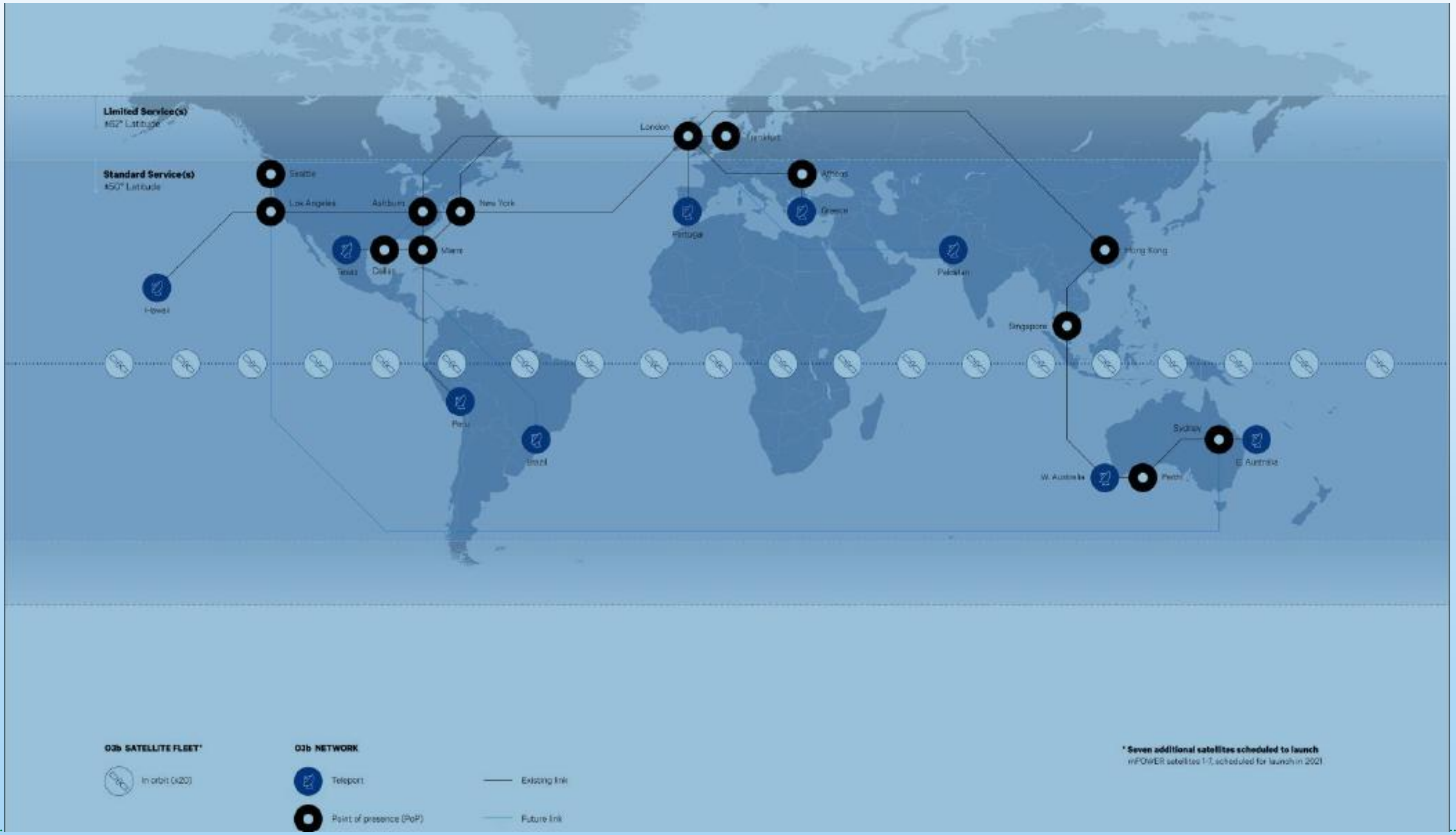
- 20 satellites operating at Ka-band. The satellites are deployed in a circular orbit along the equator at an altitude of 8063 km (MEO) at a velocity of approximately 18918 km/h, each making 5 orbits a day.
- Each satellite is equipped with twelve fully steerable Ka-band antennas (two beams for gateways, ten beams for remotes) that use 4.3 GHz of spectrum (2 × 216 MHz per beam) with a proposed throughput of 1.6 Gbit/s per beam (800 Mbit/s per direction), resulting in a total capacity of 16 Gbit/s per satellite.
- Each beam's footprint measures 700 km in diameter.
- O3b claims a mouth-to-ear one-way latency of 179 milliseconds for voice communication, and an end-to-end round-trip latency of 140 ms for data services.
- The maximum throughput per TCP connection is 2.1 Mbit/s.
- For maritime applications, O3b claims a round-trip latency of 140 ms, and connectivity speeds of over 500 Mbit/s.

O3b (2)

- 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 started service in 1998 and became fully operational in 2002
- 2nd generation deployment started service in 2023 and expected to be operational in 2024

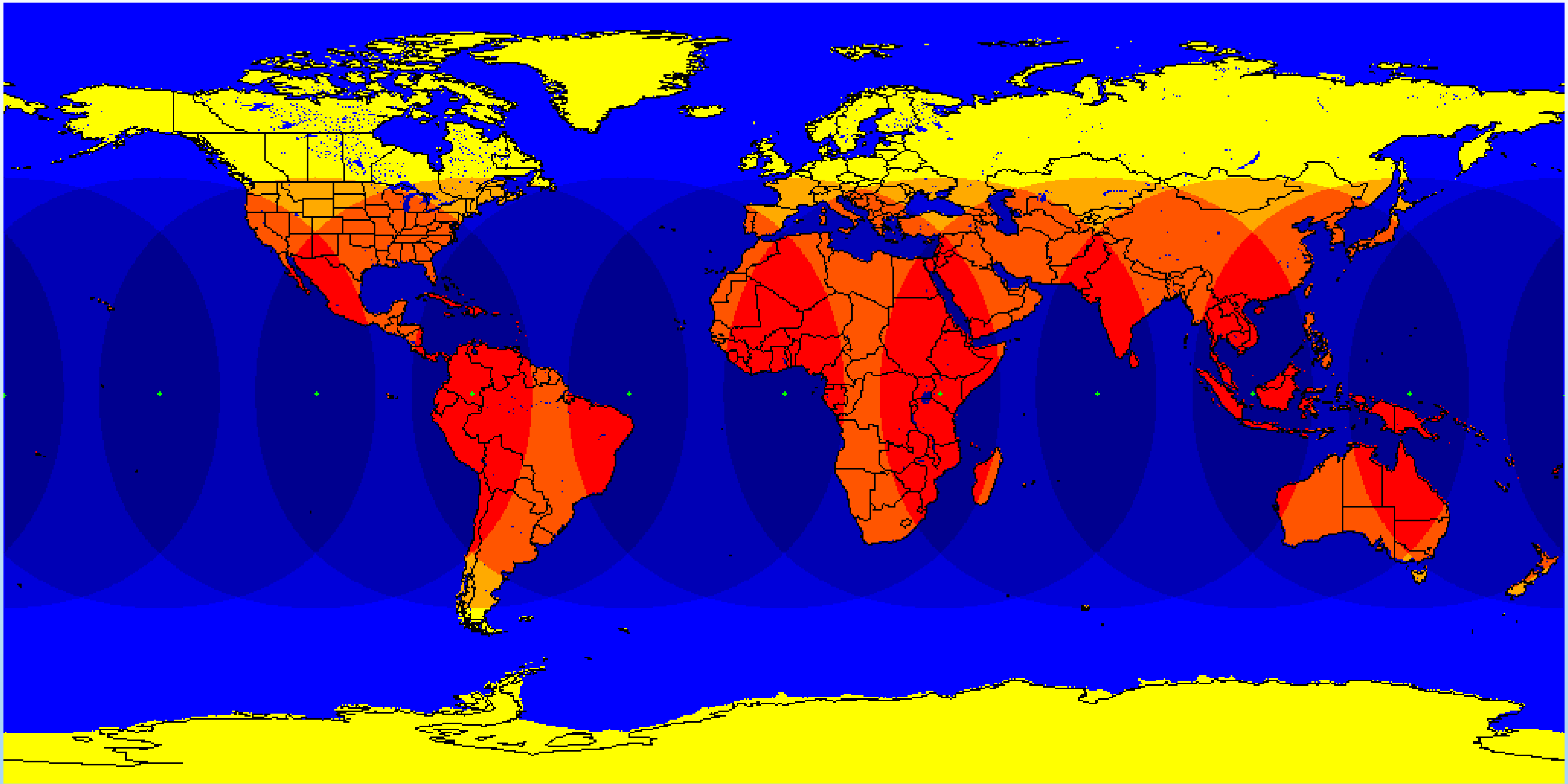
O3b (3)

- The O3B system architecture:
  - gateways serving 20 satellites, DVB-S2 air interface with ACM
  - Make-before-break handover with two satellites active during handover phase



O3b (4)

- Coverage



OneWeb (1)

- First LEO megaconstellation at an altitude of 1200 km for global broadband access.
- 654 satellites (some are spares) in 12 orbital planes with 49 satellites each, 109 minutes orbital period.
- 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.
- 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.
- Low latency (50 ms)
- Services:
  - Mobility (maritime, aviation, land mobility, IoT).
  - Satellite broadband (corporate enterprise, small and medium business, consumer residential).

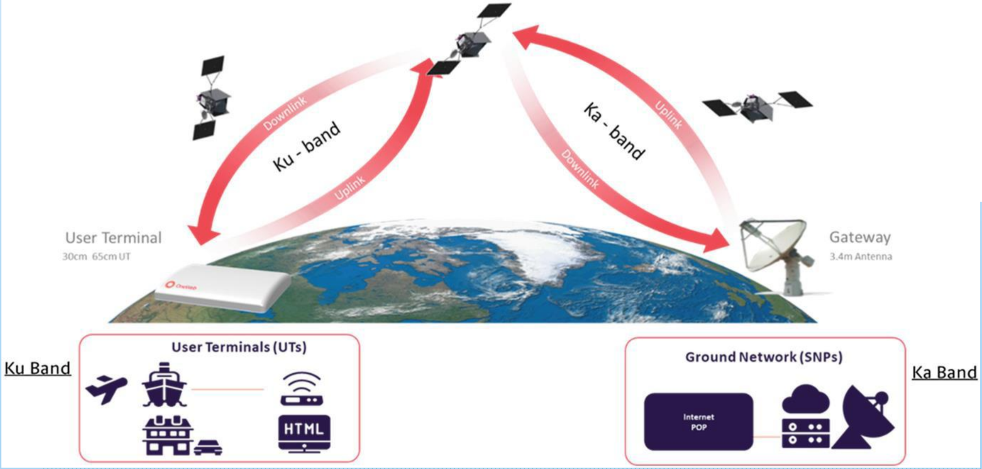
OneWeb constellation

Inclination	Max Number of Planes	Max Number satellites per plane
87.9°	36	49
40	32	720
55	32	720

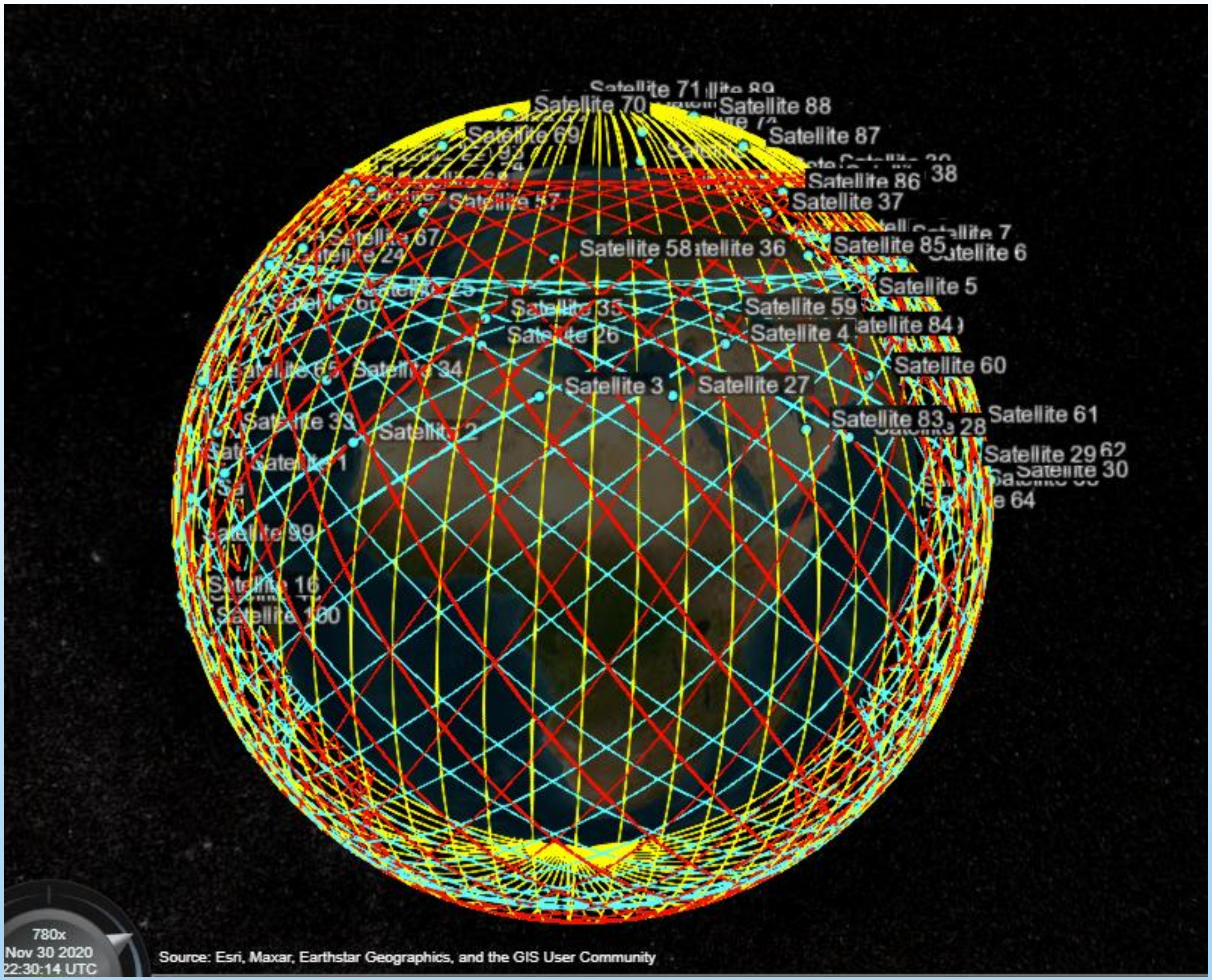
- OneWeb satellites operate at an approximate elevation of 1200 km.
- Transparent (derived from Globalstar)

OneWeb architecture

- The 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 orbits

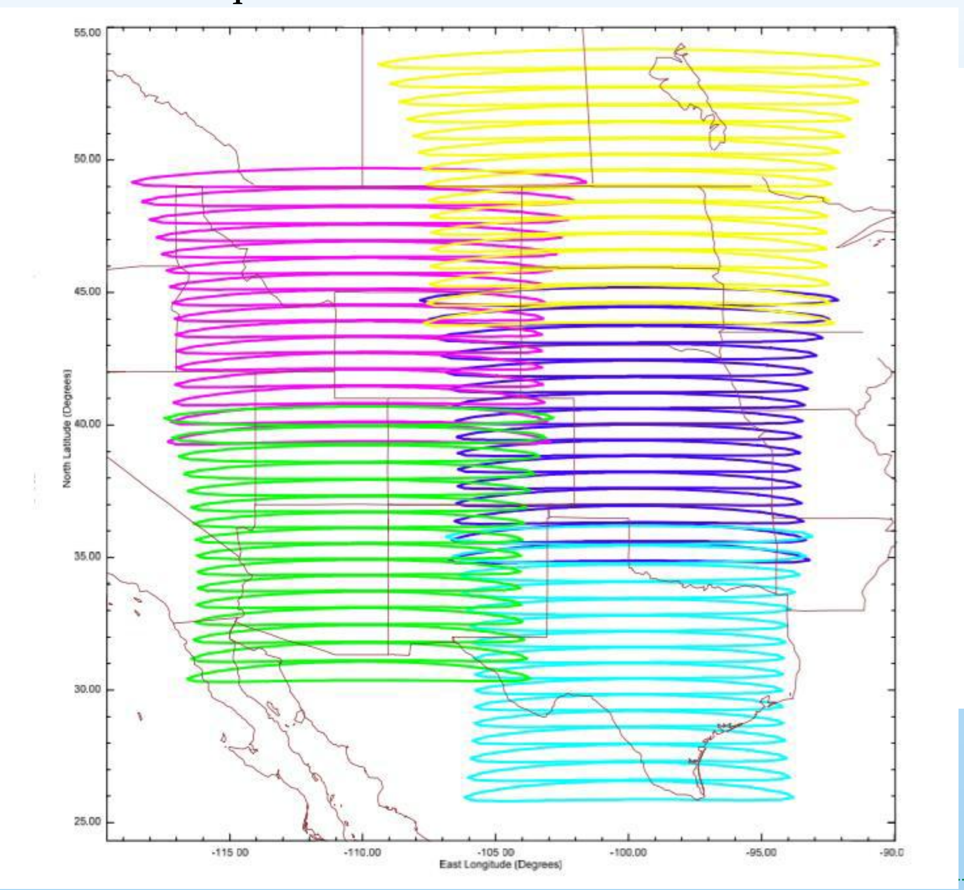


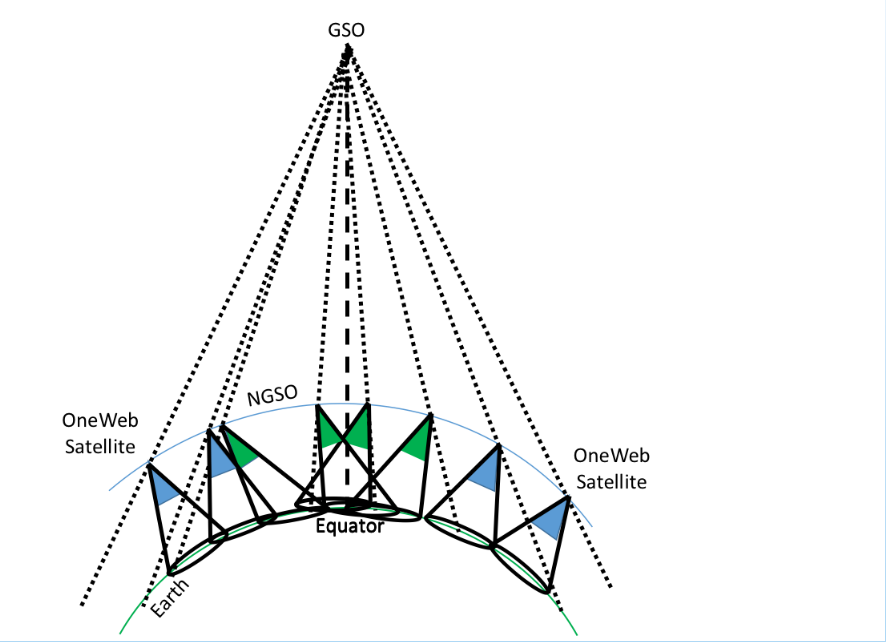
The OneWeb payload

- Simple 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 in 2023

OneWeb GEO interference avoidance approach

- Progressive pitching the satellite to avoid GEO arc interference
- Banana shaped beams to better cope with the beam squinting operation at the equator





Starlink (1)

- Starlink is a satellite network operated by the US aerospace company SpaceX aiming at internet access provisioning to terrestrial subscribers.
- The owner of SpaceX is Elon Musk, its headquarters is in Hawthorne, California.
- The FCC notification allows Starlink to deploy about 11 927 LEO satellites up to 2027.
- The satellites are deployed in different orbital planes with altitudes ranging between 540 km to 1300 km.
- Characteristic of the Starlink constellation is that the latitudes of interest are served by multiple satellites.
- In a first trial, Starlink achieves data throughputs up to 93 Mbps for individual users, approximately 16 Gbps capacity per satellite and latency values of 31 ms with the drawback that the terrestrial coverage area does not exceed 60° latitude in the northern hemisphere.

Starlink (2)

- Future objectives are terrestrial coverage beyond those latitudes and data rates up to 300 Mbps.
- As user terminal, Starlink provides a stationary VSAT with about 60 cm phased-array antenna.
- SpaceX Starlink uses the Ku-band 10.7 GHz to 12.7 GHz in downlink direction and 14 GHz to 14.5 GHz in uplink direction.
- In addition to that, frequency bands in the Ka-band are also allocated below Kuiper and frequencies from the V-band around 37 GHz to 50.4 GHz are allocated.

[] I. del Portillo, B. Cameron, E. Crawley, "A Technical Comparison of Three Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband",, Acta Astronautica, Vol 159, June 2019

Starlink operative constellation (October 2023)

Inclination	Planes	Altitudes [km]	Satellites in position
53°	72	550	1665
53.2	72	540	1542
70	36	570	301
97.6	10	560	230

- The majority of Starlink's operational 4000 satellites lie within the 53° shell, which only covers parts of the globe.
- The 70° and 97.6° orbits allow serving regions near the poles. These other shells however have fewer satellites

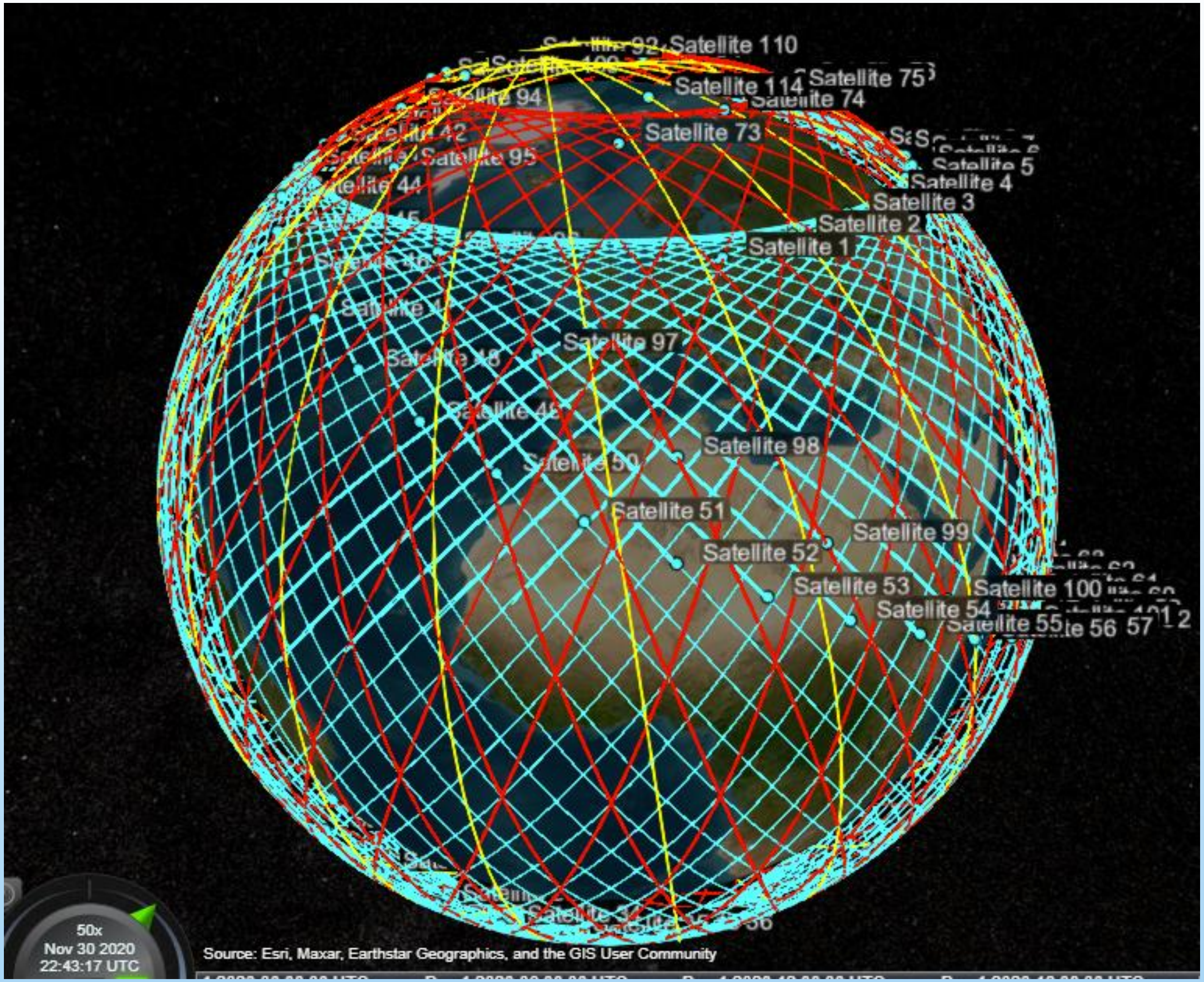
Identified Starlink orbital shells and satellite generation breakdown (end of 2025)

Inclination	Altitudes [km]	v1	v1.5	v2 mini	Satellites
53°	552	557	18		575
53.2	540		1376		1376
53.2	484		2	1846	1848
53.2	354		2	313	315
43	559		625	595	1220
43	489			1380	1380
43	355			321	321
70	570		352	238	590
97.6	557		208	303	511

Starlink update

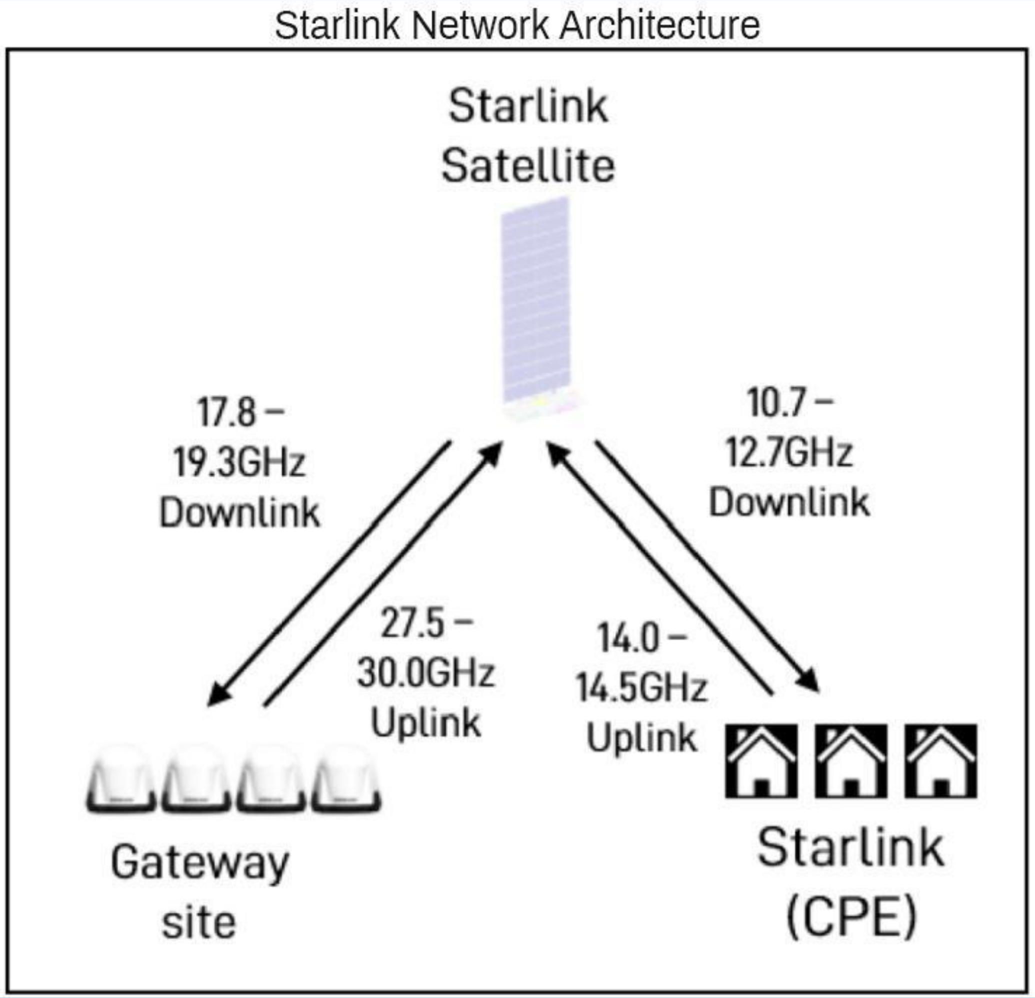
- Steps 1-5: 4108 satellites @ 550 km in 72 orbital planes with 54, 70, 74, 81 degrees inclination
- operating at Ku-band for the user link, Ku/Ka-band for the feeder link (6500 already in orbit of which 6000 operational @ August 24)
- Step 6: 7518 satellites at 340 km with V-band addition for user/gateways
- 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 orbits



Starlink architecture

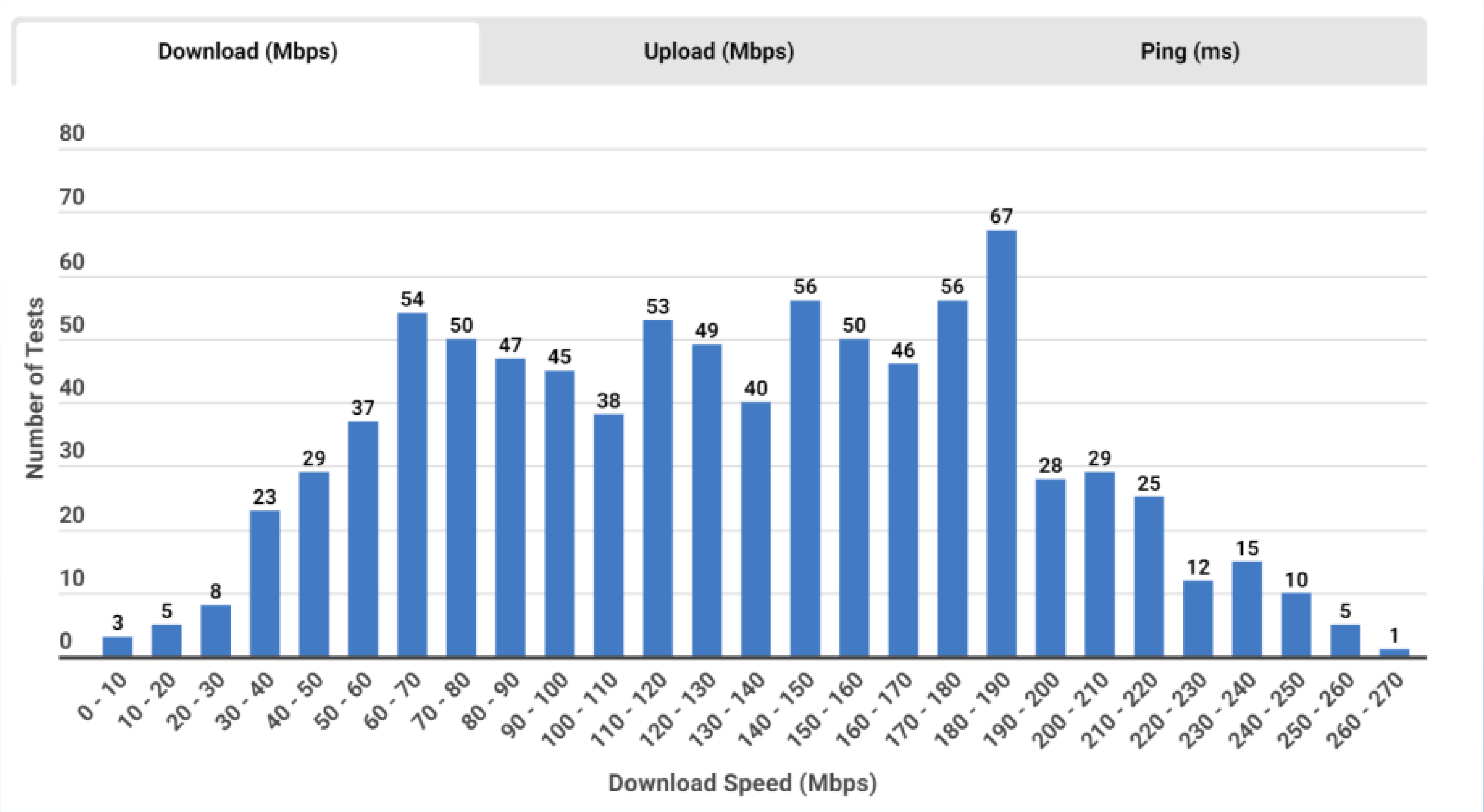
- 32 gateways filed in USA, unclear number worldwide



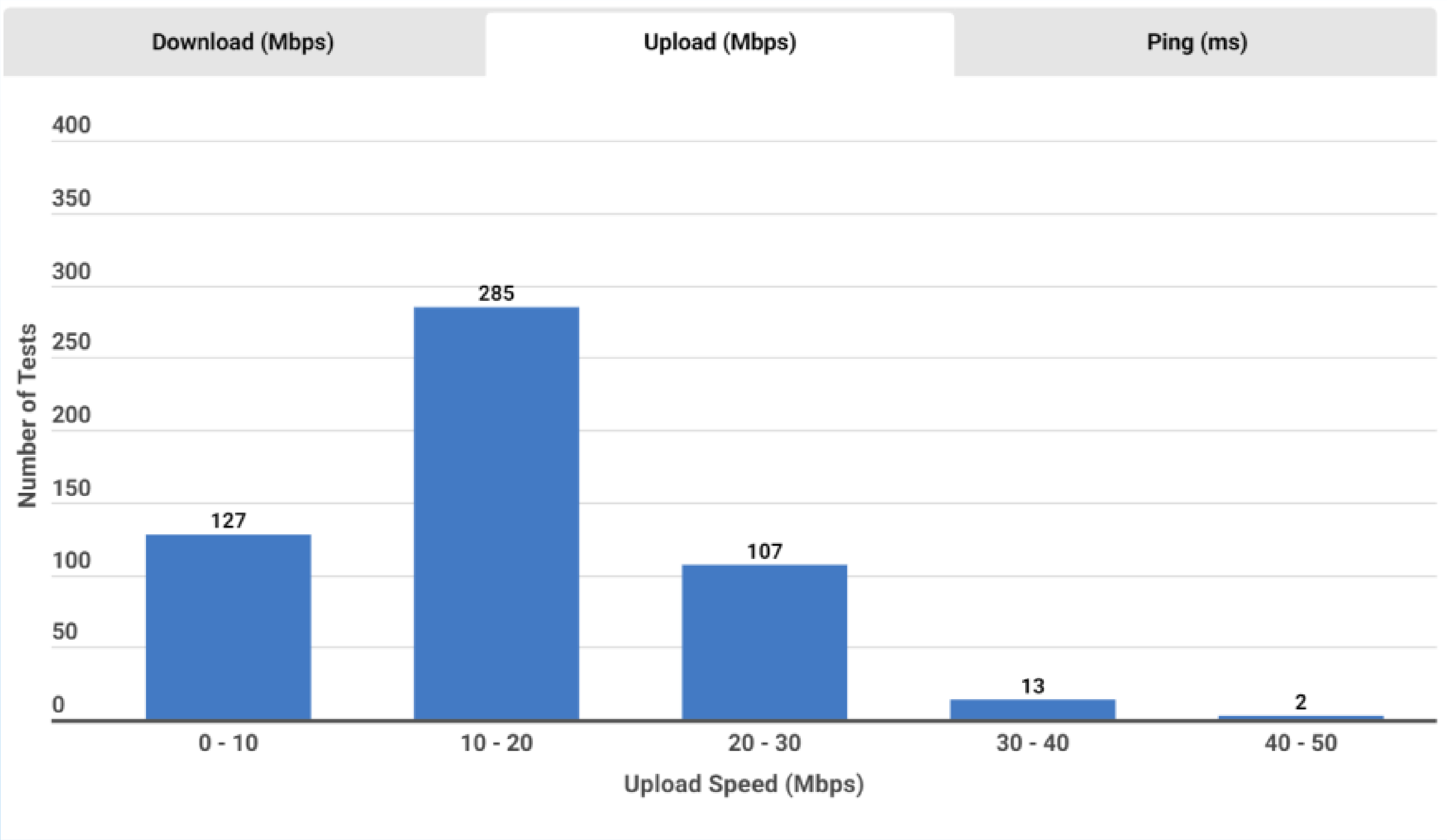
Starlink performance (1)

- The Starlink current service:
  - The data rate effectively provided is highly variable lower than what advertised (300 Mbps)
  - Latency is also time dependent
  - Dropouts in video applications observed

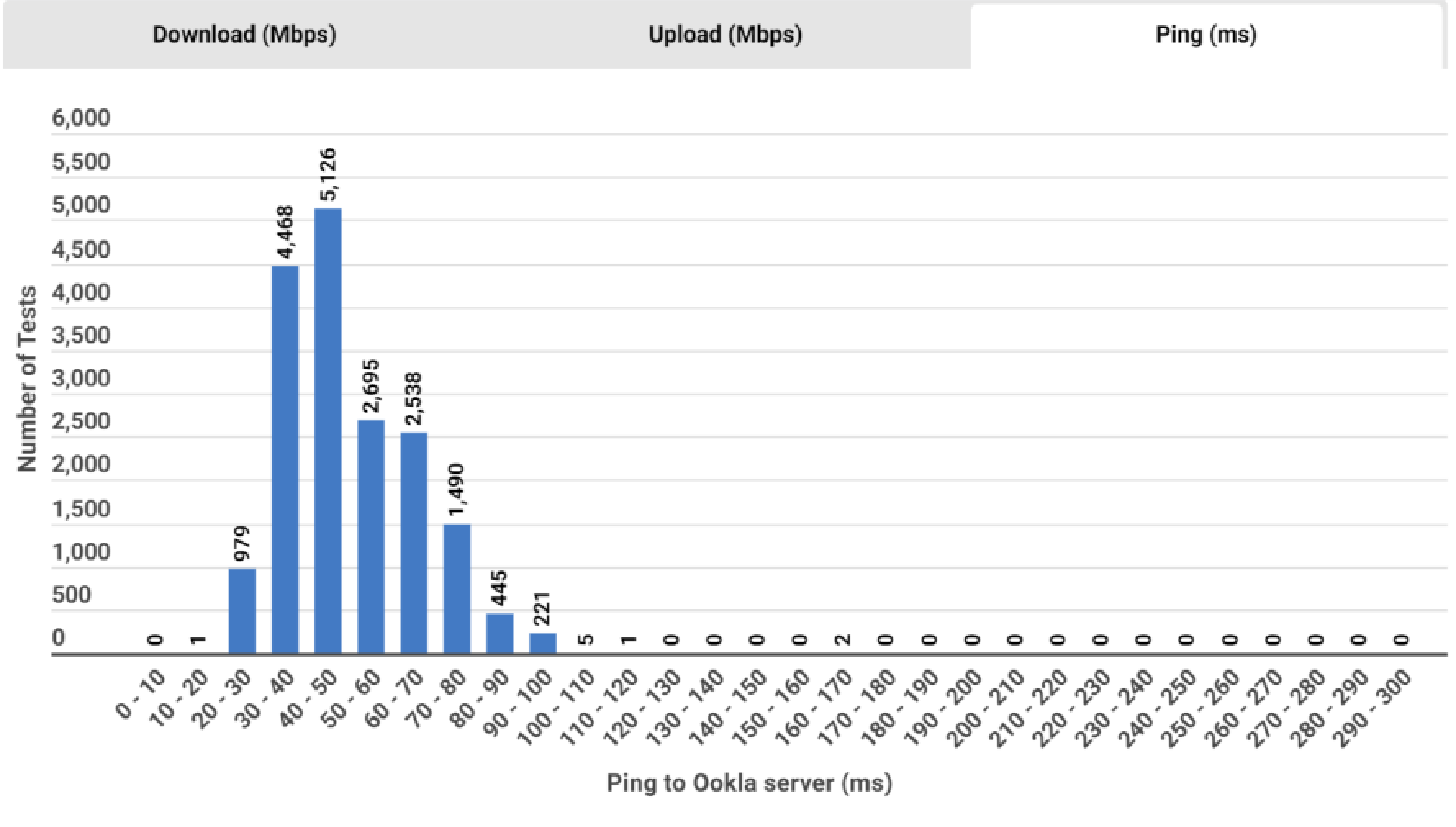
Starlink performance (2)



Starlink performance (3)



Starlink performance (4)



Starlink OFDM parameters

- Bandwidth single channel: $W=F_s=240$ MHz
  - $N_{\mathrm{FFT}}=1024$
  - $\Delta f=F=F_s/N_{\mathrm{FFT}}=3\cdot 5^7=234375$ Hz
  - $T=1/F=64/15=4.27$ μs (useful symbol duration)
  - $T_s=T/N_{\mathrm{FFT}}=4.27$ ns (sampling interval)
  - $N_{\mathrm{CP}}=32$ (cyclic prefix samples)
  - $T_{\mathrm{CP}}=N_{\mathrm{CP}}T_s=0.13$ ns
  - $T_{\mathrm{SYM}}=T+T_{\mathrm{CP}}T_s=4.40$ μs (total symbol duration)
  - Symbols per frame: 301
  - The frame ends with a slightly longer guard slots of duration $T_{\mathrm{G}}=68/15=4.53$ μs. It follows that the total frame duration is $T_f=302T_{\mathrm{SYM}}+T_{\mathrm{G}}=1/750$ s$=1.333$ ms.
  - In a frame, 298 symbols and 1020 carriers are used for transmitting information, obtaining a total bit rate given by: $R_{\mathrm{S}}=b\cdot 1020\cdot 298\cdot 750$, where b are the bits of the used modulation.
  - For QPSK ($b=2$), $R_{\mathrm{S}}=455.94$ Mbit/s, r$=R_{\mathrm{S}}/W=1.90$ bit/s/Hz.

Starlink OFDM frame layout

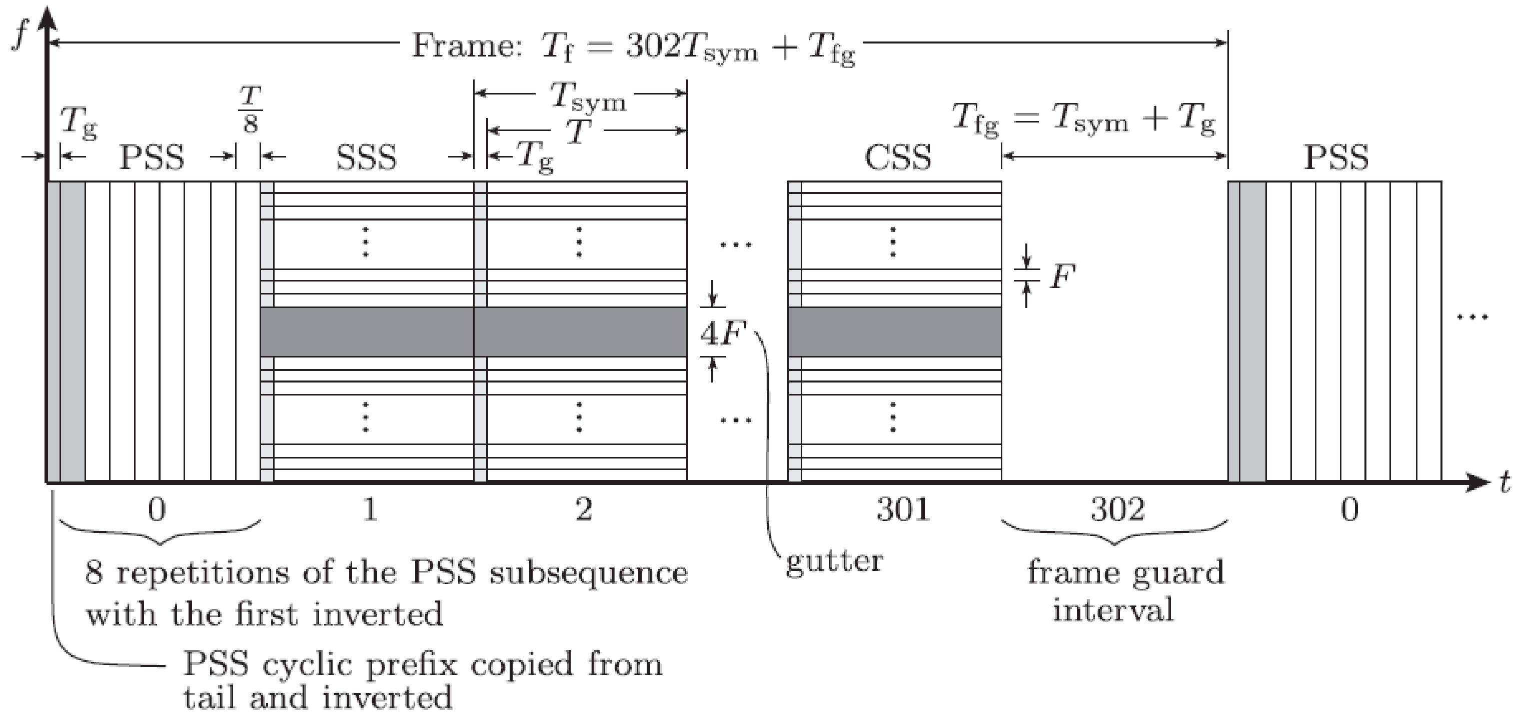


Fig. 6. Frame layout for the Ku-band Starlink downlink along time-frequency dimensions.

- T. E. Humphreys, P. A. Iannucci, Z. M. Komodromos and A. M. Graff, "Signal Structure of the Starlink Ku-Band Downlink,“ *IEEE Transactions on Aerospace and Electronic Systems*, vol. 59, no. 5, pp. 6016-6030, Oct. 2023

Starlink OFDM channels

Frequencies: $F_{ci} = 10.7 + F/2 + 0.25\ (i\text{-}1/2)$ GHz.

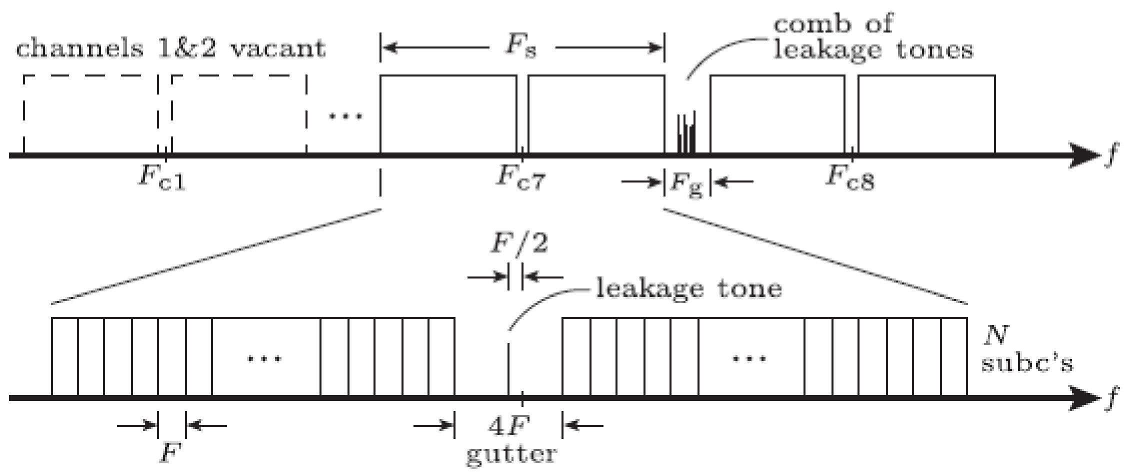


Fig. 5. Channel layout for the Ku-band Starlink downlink.

- A total of eight channels, each with bandwidth of F_s = 240 MHz and 10 MHz of guard, span the band allocated for Starlink's Ku-band downlink. The lower two channels, those centered at F_{c1} and F_{c2}, are currently vacant.

More considerations on architecture

- To offer Internet services, the current Starlink satellites work as standalone “mirrors” to redirect signals between terminals and ground stations (Figure 3a). This mode’s network coverage is constrained by the geographic ground station distributions, since both the ground station and terminal should reside within each satellite’s coverage. So Starlink is progressively adopting optical inter-satellite links (ISLs) to form a networked LEO mega-constellation.

- Y. Li, H. Li, W. Liu, L. Liu, W. Zhao, Y. Chen, J. Wu, Q. Wu, J. Liu, Z. Lai et al., “A networking perspective on Starlink’s self-driving LEO mega-constellation,” in Proceedings of the 29th Annual International Conference on Mobile Computing and Networking, 2023.

Networks under development

Constellat.	Manufact.	Number	Weight	Avail.	Altitude	Offer	Band
O3b mPOWER, (SES)	Boeing	13	1700 kg	Q2 2024	8,000 km	50 Mbit/s – 10 Gbit/s, each user[1]	K_a (26.5-40 GHz)
Project Kuiper	Amazon	3236		2024	590–630 km		

O3b mPOWER

- O3b mPOWER is a communications satellite system owned and operated by SES.
- The system uses high-throughput and low-latency satellites in a medium Earth orbit (MEO), along with ground infrastructure and intelligent software, to provide multiple terabits of global broadband connectivity for applications including cellular backhaul and international IP trunking, cruise line connectivity, disaster recovery, and military communications.
- The system became operational in April 2024 with 6 satellites. The system's capacity will be increased by a further 7 satellites launched by 2026.
- The O3b mPOWER satellites use fully shapable and steerable spot beams that can be shifted and scaled in real time to suit individual users. The satellites join SES' existing constellation of 20 first-generation O3b satellites in MEO and operate in conjunction with them and the SES fleet of geostationary satellites.

Project Kuiper

- Project Kuiper System is planned to consist of 3236 satellites operating in 98 orbital planes in three orbital shells, one each at 590 km, 610 km, and 630 km orbital altitude.
- Phase 1 of deployment will be 578 satellites at 630 km altitude and an orbital inclination of 51.9 degrees. A total of five phases of constellation development are planned.
- Kuiper is planned to work in concert with Amazon's previously announced large network of 12 satellite ground station facilities (the "AWS Ground Station unit") announced in November 2018.
- In addition to connecting to ground stations to connect to the ground-based internet, satellites will interconnect via optical infrared laser connections. Amazon refers to this technology as OISL (optical inter-satellite link). These lasers are capable of maintaining 100 Gbps over distances up to 2600 km among two satellites moving at 25000 km/h. Current in-space tests have demonstrated this speed up to a distance of 1000km.

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High throughput geostationary networks

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
- https://www.viasat.com/space-innovation/satellite-fleet/viasat-3/.

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: Ka-band, Q- and V-band for gateways
- Coverage: North & South America Speed: Up to 100 Mbps
- Capacity: More than 500 Gbps
- Total maritime mobility Spot beams: 300
- Each beam carries 500 MHz or more, providing more than 1 Gbps/beam

Comments

- GSO HTS are trying to fill the gap of the GSO broadcasting satellite decline
  - Even using Ka-band high frequency reuse (hence small beams) is a must to get high throughput
  - ACM (Adaptive Code and Modulation) 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 (TV Receiving only) 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

A new area of concern - RF spectrum pollution

- NGSO (LEO/MEO) Megaconstellations of hundreds/thousands of satellite are rapidly building up
  - Is this creating a new type of space pollution? Yes, Radio Frequency spectrum cleanliness is impacted

- For mm-wave bands the main issue is related to:
  - GSO to NGSO interference – countermeasures are in place and enforced by ITU
  - NGSO to NGSO interference – FCC calls to avoid in-line interference (10 degrees 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

COMPUTER & ELECTRONIC ENGINEERING

Interactive Mobile Broadband Broadcast Standard

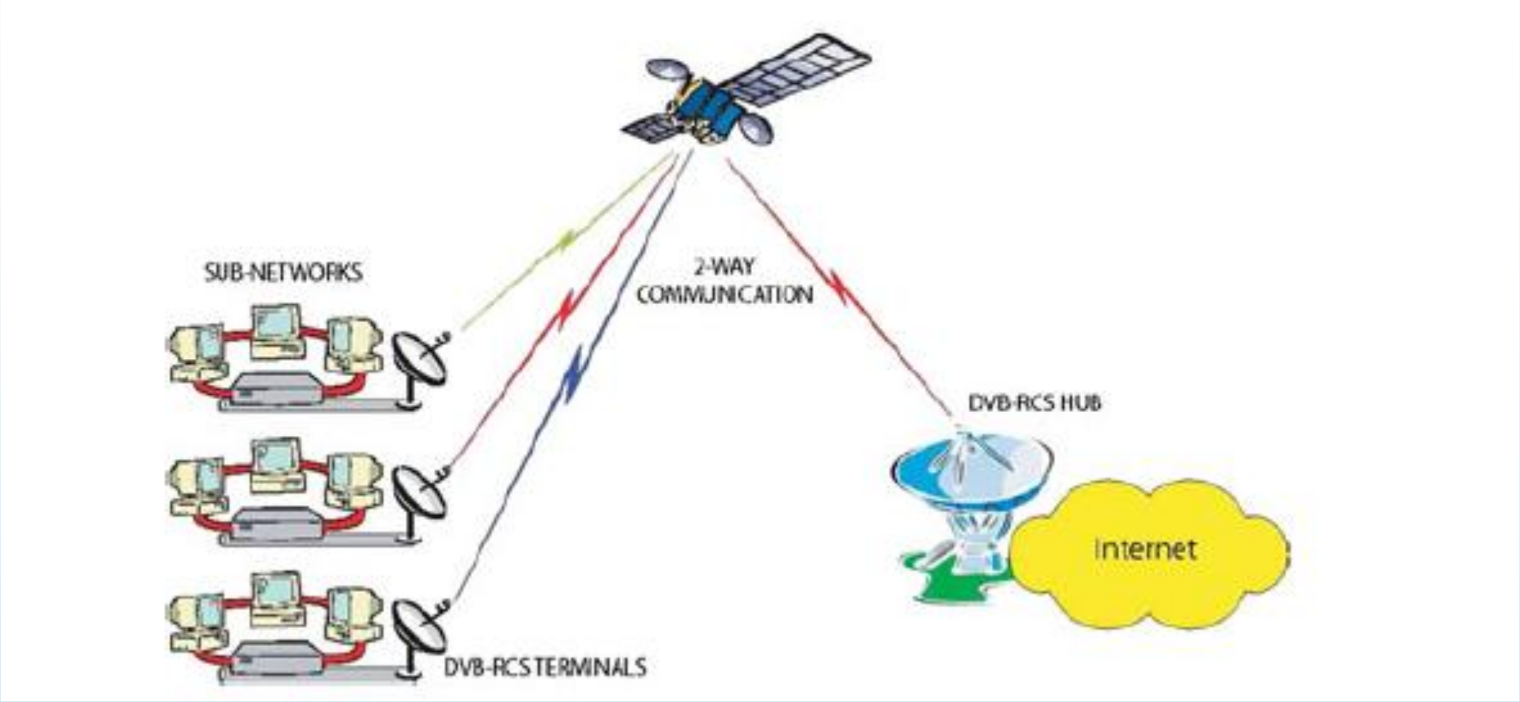
Interactive Mobile Broadband Broadcast Standard

- Digital Video Broadcasting (DVB) is a family of technology standards defining digital broadcasting and designed to facilitate broadcasting of audio, images and multimedia to allow a large degree of user interaction.
- These standards are designed to use existing satellite, cable and terrestrial infrastructures for broadcasting.
- DVB-S (DVB-Satellite) is the standard for delivery of television/video via satellite. The modulation schemes used in DVB-S (SHF) are QPSK, 8PSK or 16-QAM.
- DVB-S2 (DVB-Satellite Second Generation) is the standard for the second generation of DVB services via satellite. The modulation schemes used for DVB-S2 are QPSK, 8PSK, 16APSK and 32APSK.
- DVB-RCS (DVB-Return Channel Satellite) provides satellite DVB services with a return channel to facilitate interactivity.
- DVB-RCS2: Second generation DVB-RCS standard.

Interactive Mobile Broadband Broadcast Standard

- More precisely, DVB-RCS2 extends the scope of the DVB-RCS specifications from being physical-layer and link-layer specifications to a full interactive satellite communications solution for native IP.
- DVB-RCS2 retains all the functionality of the first generation, including provisions for mobile terminals and mesh networks.
- The lower layers are also optimized for Ka-band (and higher) frequencies, via technologies such as adaptive coding and modulation in both forward and return links.
- A very substantial amount of effort in the standardization process was directed towards defining efficient and scalable ways of translating IP-level QoS to satellite resource management, as well as to define interfaces for equipment and service management.

DVB-RCS2

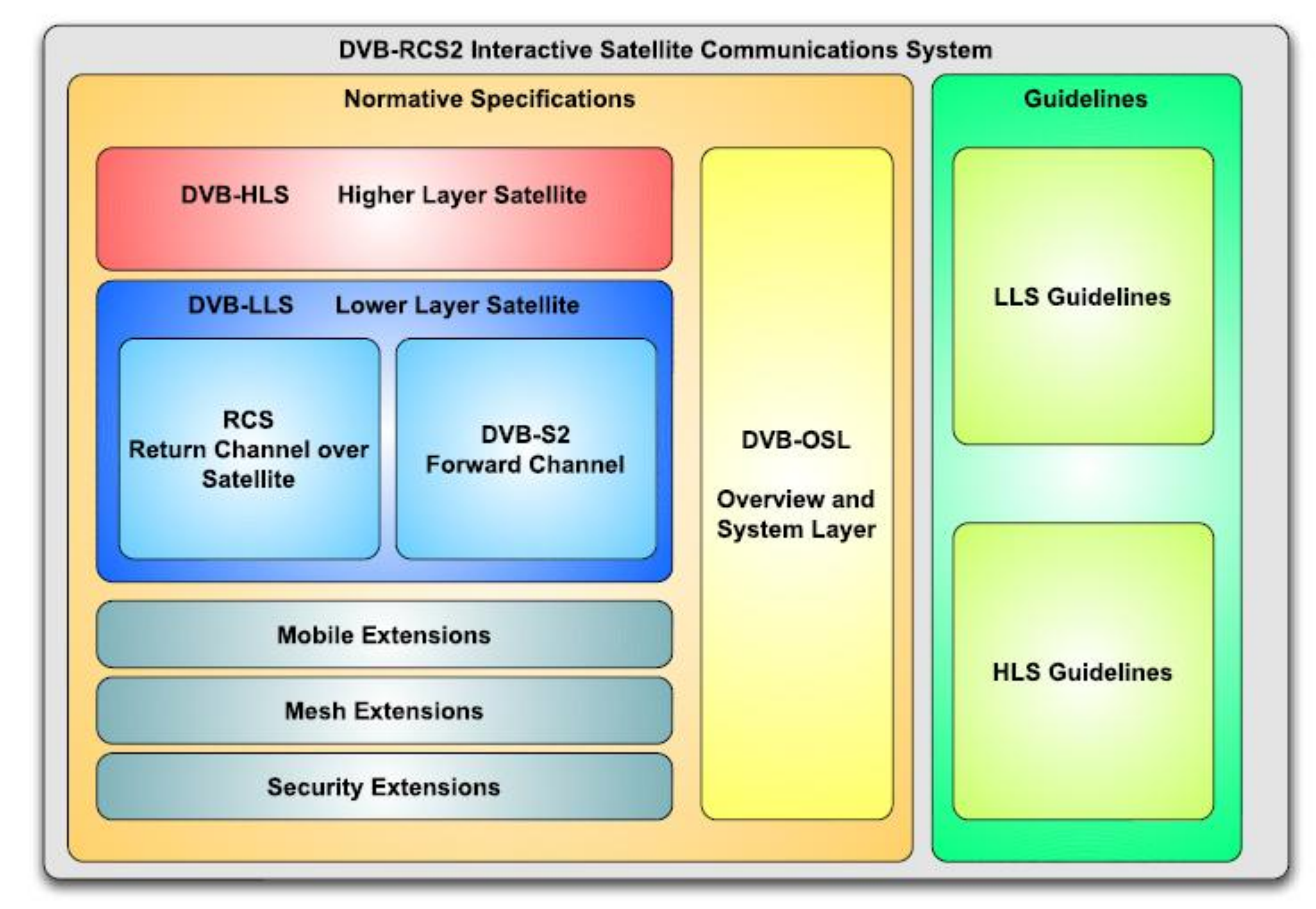


- H. Skinnemoen, C. Rigal, A. Yun, L. Erup, N. Alagha and A. Ginesi, DVB-RCS2 overview, Int. J. Satell. Commun. Network. (2013).

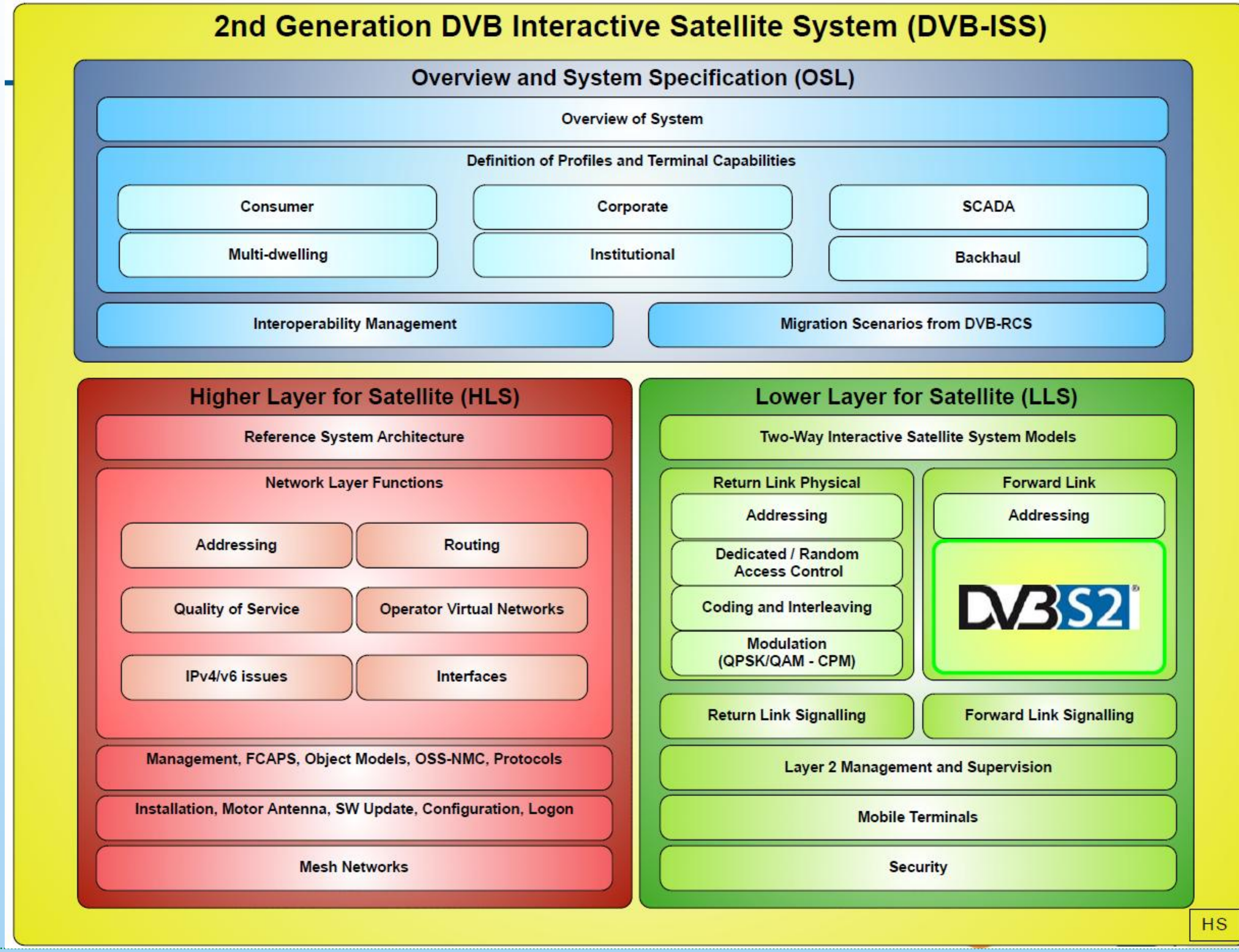
DVB-RCS2

- Produced by Joint Technical Committee (JTC) Broadcast of the European Broadcasting Union (EBU), Comité Européen de Normalisation ELECtrotechnique (CENELEC) and the European Telecommunications Standards Institute (ETSI).
- Specified in the following documents
  - TS 101 545-1: "Overview and System Level specification; V1.3.1 (2020-07).
  - EN 301 545-2: "Lower Layers for Satellite standard"; V1.4.1 (2024-01).
  - TS 101 545-3: "Higher Layers Satellite Specification"; V1.3.1 (2020-07).
  - TR 101 545-4: "Guidelines for Implementation and Use of EN 301 545-2“.
  - TR 101 545-5: "Guidelines for the Implementation and Use of TS 101 545-3".
- The standard allows one to provide the best possible interoperability between terminals and hubs, thus defining not only the lower layers of the system (up to layer 2) but also network functions as well as management and control capabilities.
- As these requirements combined together may end up in a very complex terminal design; a subsets of capabilities known as profiles may be used together to address a given market segment.

DVB-RCS2


DVB-RCS2 Interactive Satellite Communications System
Normative Specifications
Guidelines
DVB-HLS Higher Layer Satellite
DVB-LLS Lower Layer Satellite
RCS
Return Channel over Satellite
DVB-S2
Forward Channel
Mobile Extensions
Mesh Extensions
Security Extensions
DVB-OSL
Overview and System Layer
LLS Guidelines
HLS Guidelines

DVB-RCS2



2nd Generation DVB Interactive Satellite System (DVB-ISS)
Overview and System Specification (OSL)
Overview of System
Definition of Profiles and Terminal Capabilities
Consumer
Corporate
SCADA
Multi-dwelling
Institutional
Backhaul
Interoperability Management
Migration Scenarios from DVB-RCS
Higher Layer for Satellite (HLS)
Reference System Architecture
Network Layer Functions
Addressing
Routing
Quality of Service
Operator Virtual Networks
IPv4/v6 issues
Interfaces
Management, FCAPS, Object Models, OSS-NMC, Protocols
Installation, Motor Antenna, SW Update, Configuration, Logon
Mesh Networks
Lower Layer for Satellite (LLS)
Two-Way Interactive Satellite System Models
Return Link Physical
Addressing
Dedicated / Random Access Control
Coding and Interleaving
Modulation (QPSK/QAM - CPM)
Forward Link
Addressing
DVB S2
Return Link Signalling
Forward Link Signalling
Layer 2 Management and Supervision
Mobile Terminals
Security
HS

DVB-RCS2


Lower Layer for Satellite (LLS)
Two-Way Interactive Satellite System Models
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Security

DVB-RCS2

Some key technological improvements from DVB-RCS to DVB-RCS2

	RCS1	RCS2
Harmonized management and control	None	Yes (optional)
Harmonized IP-level QoS	None	Yes
Multiple virtual network support	None	Yes
Security	Single solution	Support for multiple security systems, for applications with widely different requirements
Return link access scheme for traffic	TDMA, continuous carrier	TDMA, continuous carrier, random access
Modulation schemes	QPSK	Linear: BPSK, QPSK, 8PSK, 16QAM Constant-envelope: CPM
Channel coding	RS/convolutional, 8-state PCCC turbo code	16-state PCCC turbo code (linear modulation), SCCC (CPM)
Burst spread spectrum	Burst repetition	Direct sequence
Return link adaptivity	Limited support	Inherent in air interface (TDMA and continuous carrier)
Bandwidth efficiency	Improved about 30% from DVB-RCS to DVB-RCS2	

BPSK, Binary Phase Shift Keying; QPSK, Quaternary Phase Shift Keying; 8PSK, 8-ary Phase Shift keying; PCCC, Parallel Concatenated Convolutional Codes; SCCC, Serially Concatenated Convolutional Codes.

Some technical characteristics

- Adaptive coding and modulation
  - The possibility to adapt coding and modulation (ACM) provides an efficient way of adapting transmission to the maximum capacity possible, rather than adjusting to a possibly conservative, worst-case scenario. This will be able to increase the overall capacity in most current systems. It is an essential technology for Ka and higher frequency band systems, where the effect of rain fading is much more severe than at Ku-band.
  - A combination of dynamic rate adaptation, as well as ACM may also be exploited to optimize the user QoS when in the presence of strong intra-system interference.

- Support for Continuous Phase Modulation (CPM)
  - A key improvement is the introduction of support for continuous phase modulation (CPM), where amplifiers can be run in saturation (non-linear) mode.
  - For a RCS2 terminal it is mandatory to support both linear and CPM modulations

Some technical characteristics

- Improved Random access
  - Slotted Aloha
  - CRDSA
- IP over satellite
- QoS management
- Forward Error correction coding
  - The modulation schemes are CPM, 8PSK and 16QAM, in addition to QPSK
  - The FEC for QPSK, 8PSK and 16QAM is a 16-state turbo code, commonly called Turbo-phi.
  - The FEC for CPM is Convolutional Coding.
- Antenna alignment
- Improved Security

ETSI EN 301 545-2 V1.4.1 (2024-01)

- A typical DVB-RCS2 Network will utilise a satellite with multi or single beam coverage. In most networks, the satellite carrying the forward link signal will also support the return link.
- The forward link carries signalling from the NCC and user traffic to RCSTs. The signalling from the Network Control Centre (NCC) to RCSTs that is required to operate the return link system is called "Forward Link Signalling".
- A Network Management Centre (NMC) provides overall management of the system elements and manages the Service Level Agreement (SLA) assigned to each RCST.
- The following network topologies are addressed by the standard:
  - Transparent star network system.
  - Transparent star network system with contention access.
  - Transparent mesh overlay network system.
  - Regenerative mesh network system.
  - NGSO (non-Geosynchronous Orbit) constellations of satellites.

Transparent mode (1)

- Transparent system description shows both transparent star and mesh overlay network topologies and has the following components:
  - Transparent satellite(s). One or more transparent satellites provide the link between terminals and the Hub, or among terminals for the transparent mesh system. Digital Transparent Processor (DTP) payloads can also give multi-beam connectivity.
  - Hub/NCC. Performs the control (NCC), management (NMC) functions and interfaces user plane (traffic gateway) functions.
  - Star terminals (RCSTs).The star transparent terminal complies with the requirements of the DVB-RCS2 standard, providing star connectivity, or mesh connectivity with a double satellite hop.

Transparent mode (2)

- Mesh overlay transparent terminals (RCSTs). The mesh overlay transparent terminals comply with the requirements of the DVB-RCS2 standard, providing star connectivity, mesh connectivity with a double satellite hop, and also mesh connectivity with a single satellite hop. The transparent mesh overlay terminal is more complex, it includes two or more demodulators adapted to DVB-S2(X) or RCST-TX waveforms as defined in DVB-RCS2.

- Gateway RCST (GW-RCST). This a mesh RCST with SLA enforcement functions that takes the GW role. A GW-RCST provides mesh RCST users with access to terrestrial networks. There may be one GW-RCST giving service to a small number of terminals, or to a large number of terminals. Essentially, each comprise one RCST, plus an SLA Enforcer and an access router, but may also include VoIP telephony servers, traffic acceleration servers, and backhaul modules.

- DVB BlueBook A155-1r3 (September 2024)

Transparent mode (3)

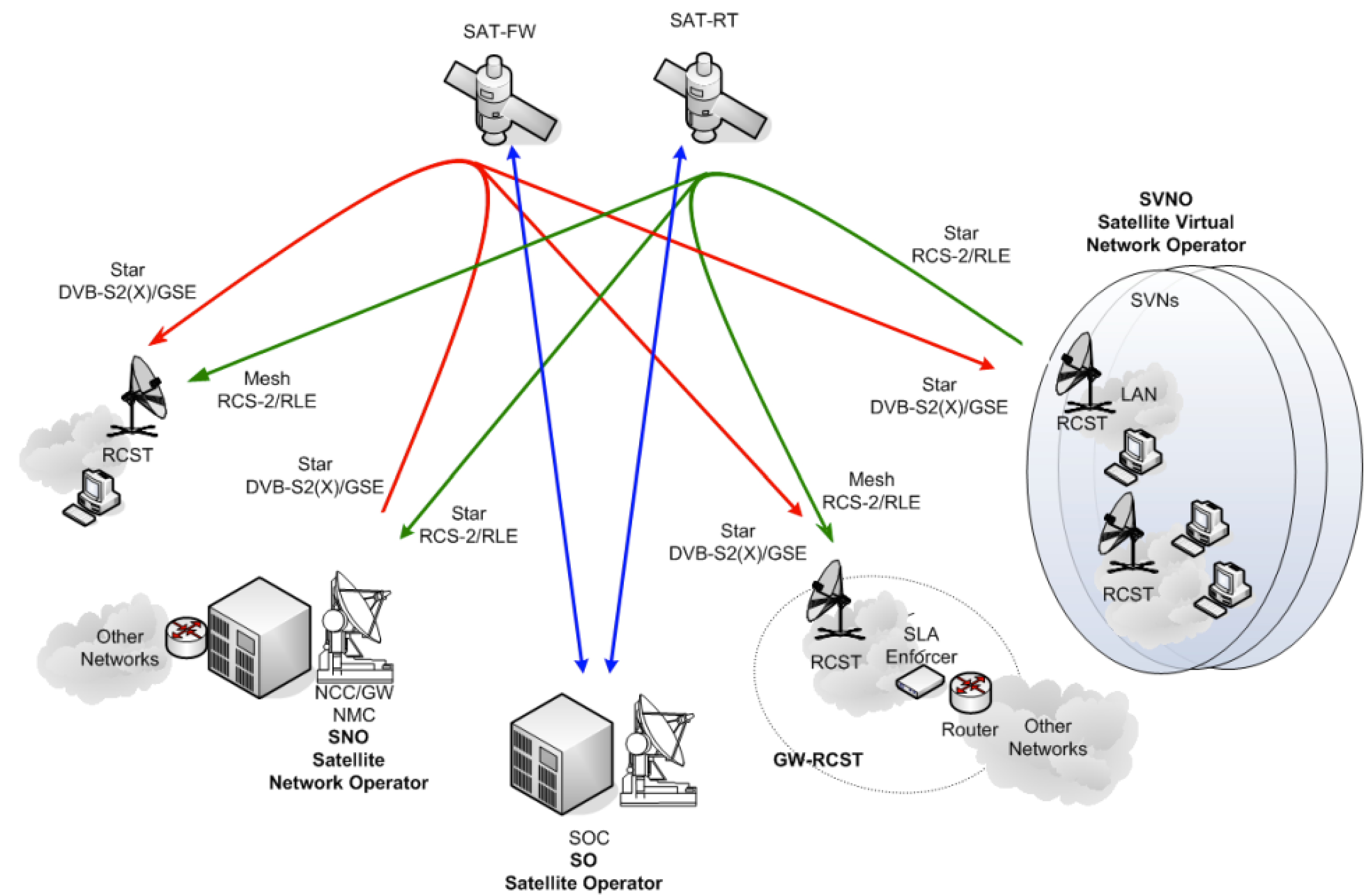


Figure 1: Main roles in a DVB-RCS2 transparent satellite interactive network

Regenerative mode (1)

- Regenerative system DVB-RCS2 satellite interactive network which supports mesh topology:
  - Regenerative satellite. Performs demodulation, demultiplexing, decoding (and possibly decapsulation) functions at the receiver side, on-board switching (at layer 2 or 3) for multi-beam systems, and the corresponding transmission functions after signal regeneration. The regenerative satellite payload embeds an on board processor (OBP). This OBP behaves as a router, switch or multiplexer in the sky for mono or multi-beam systems. Its regeneration functions allow to use an uplink (UL) air interface format different from the downlink (DL) (by demodulation, decoding and new modulation and coding, and possibly des-encapsulation and new encapsulation functions). The air interface formats are DVB-RCS2 TX on the uplink and DVB-S2(X) on the downlink, depending on the topology scenario.

Regenerative mode (2)

- Management Station. It provides the management (NMC) and control (NCC) plane functions to the satellite network users.

- Regenerative Satellite Gateway (GW-RCST). The GW-RCST is a satellite terminal that provides regenerative RCST users with access to terrestrial networks. There may be one GW-RCST giving service to a small number of terminals, or to large number of them. Essentially, a GW-RCST comprises one RCST, plus an SLA Enforcer and an access router, but may also include VoIP telephony servers, traffic acceleration servers, and backhaul modules.

- Regenerative mesh terminals. The regenerative mesh terminal complies with the requirements of the DVB-RCS2 standard, providing mesh connectivity with a single satellite hop. These RCSTs are identical in terms of hardware to the star transparent terminals, but their software includes additional functionalities to support dynamic mesh connectivity. These functions are not exclusive of making these terminals capable of being operated in star transparent or mesh overlay topologies.

Regenerative mode (3)

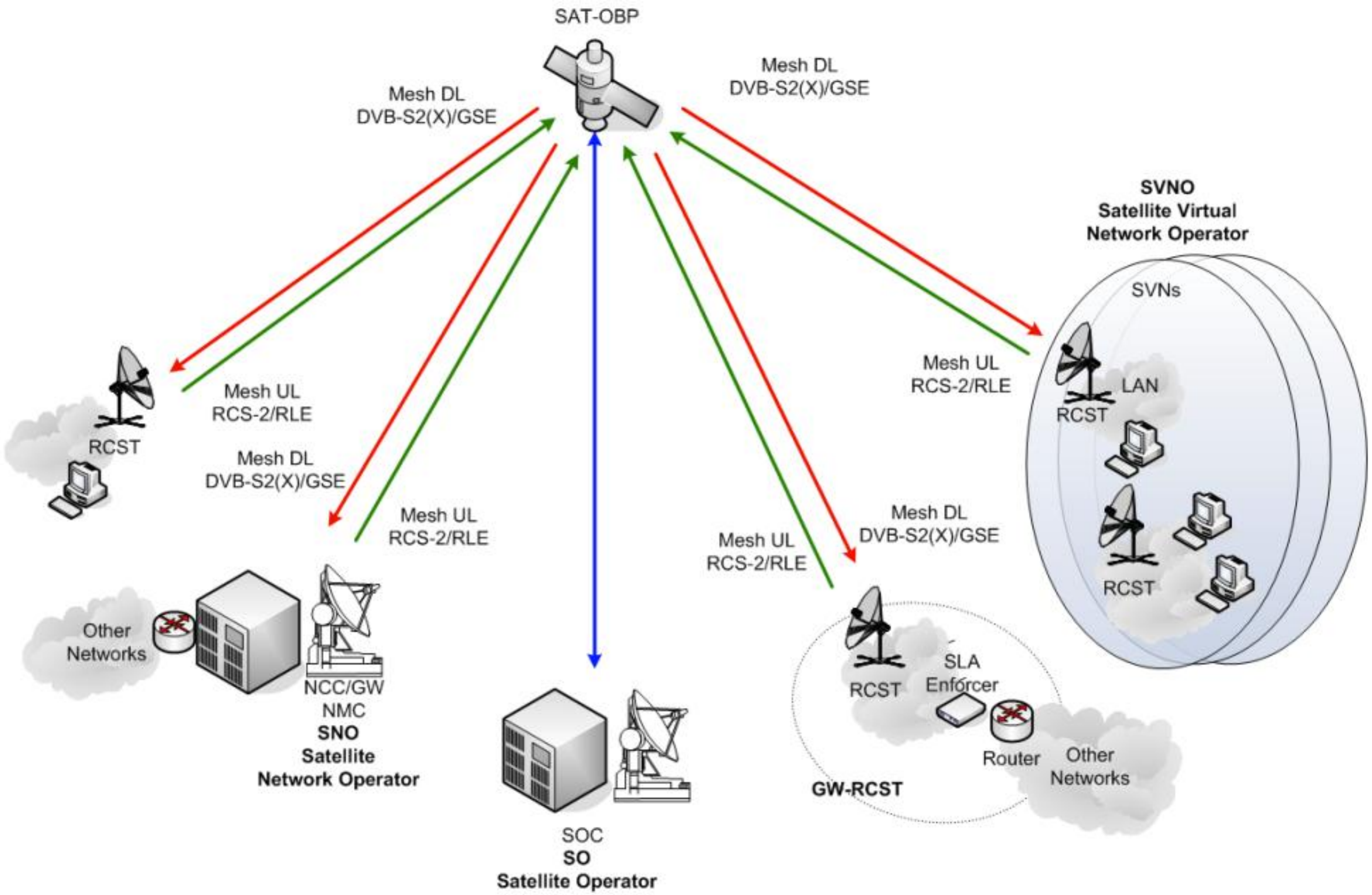


Figure 2: Main roles in a DVB-RCS2 regenerative satellite network implementing mesh topology

NGSO (non-Geosynchronous Orbit)

- A reference scenario for an NGSO scenario is given in figure below. NGSO satellite systems might use either reference architectures (typically a regenerative system), with the premise that a connection between any two ground entities (RCST, GW, GW-RCST) may be established by a single satellite or by a number of satellites connected by Inter Satellite Links (ISL). Unlike GSO satellites, the NGSO satellites orbit the earth and thus a given RCST is served by different satellites in time. From the point of view of the RCST or the SVNO which serves a group of RCST’s the satellite constellation, which is shown above the red line in the figure, can be viewed as a virtual satellite server.

NGSO (non-Geosynchronous Orbit)

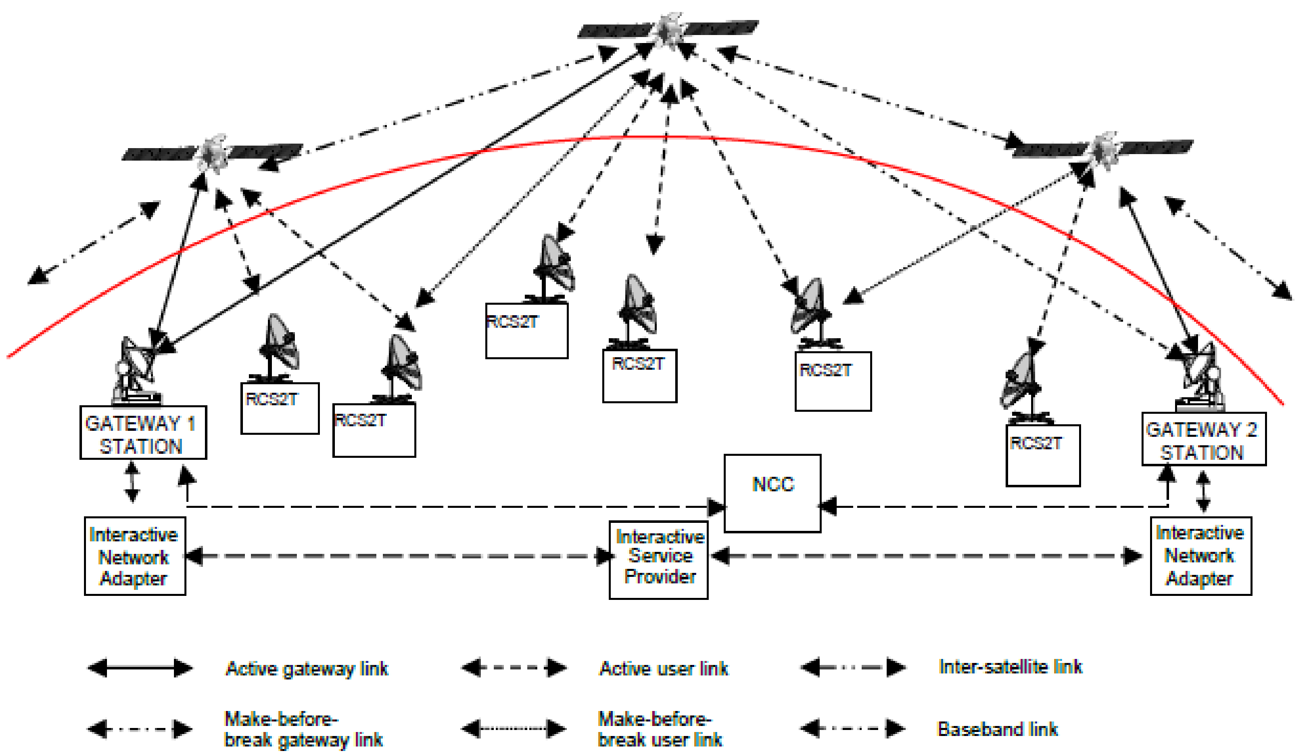


Figure 3 Reference Scenario of a DVB-RCS2 NGSO satellite network

System Roles (1)

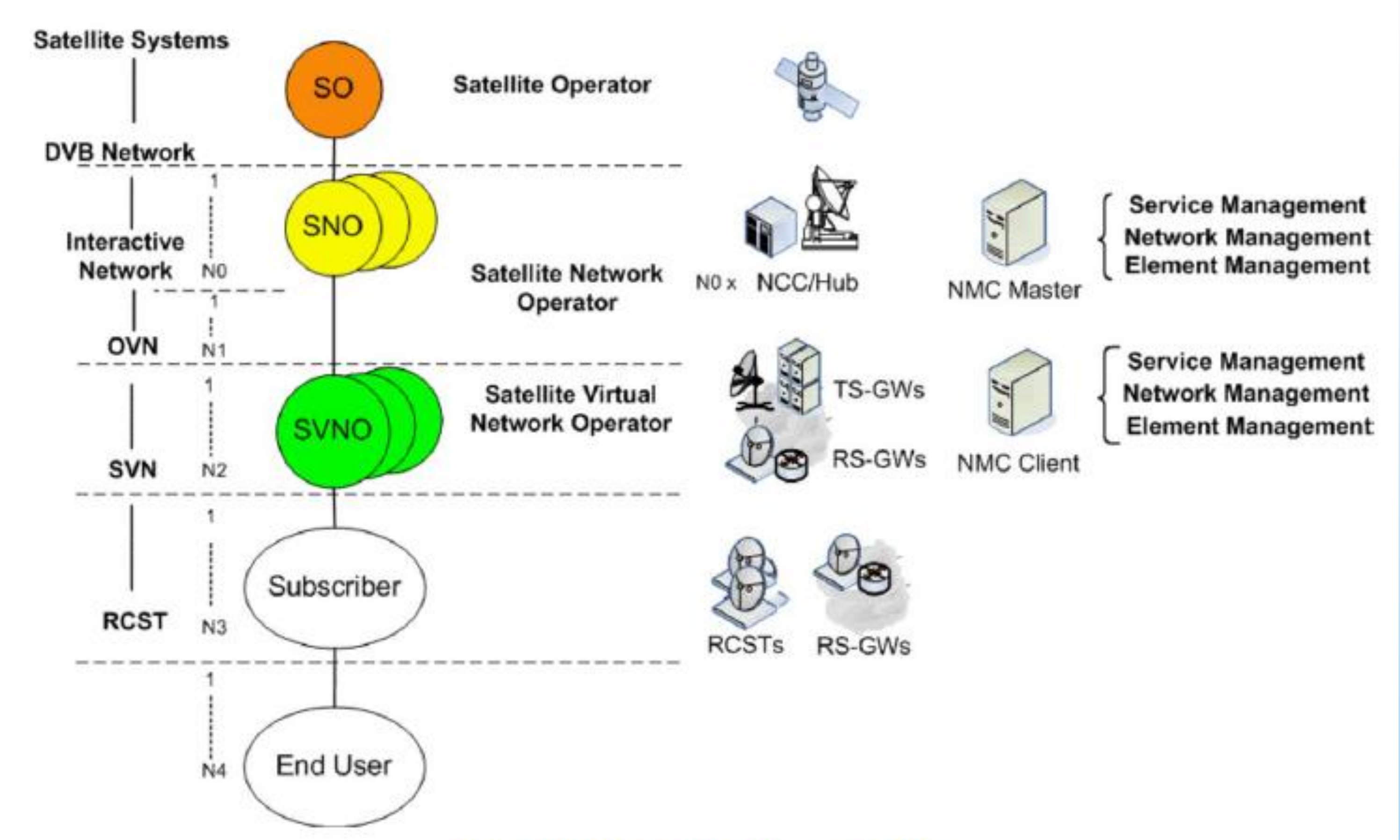


Figure 4: DVB-RCS2 actors and roles

System Roles (2)

- Satellite Operator (SO), who manages the whole satellite, or satellite constellation, and sells capacity at transponder level to one or several SNOs.
- Satellite Network Operators (SNO), are assigned one or more satellite transponders. Each SNO owns one or more Network Control Center/Network Management Center (NCC/NMC), and configures the time/frequency plan. Each SNO is responsible for one Interactive Network (IN), corresponding to one DVB network (identified by the Network_ID), controlling their own capacity. The SNO may divide the interactive network into one or more Operator Virtual Networks (OVN). Each OVN is an independently managed higher layer network, and is managed by a Satellite Virtual Network Operator (SVNO). SNOs distribute their own physical and logical resources among OVNs. In the transparent architecture the SNO owns the Transparent Satellite GateWay (TS-GW).
- For NGSO constellations, an SNO may be assigned all or part of the capacity of the satellites as they pass over a region being served by an SNO.

System Roles (3)

- Satellite Virtual Network Operators (SVNO), are assigned one or more Operator Virtual Networks (OVN), each being given some physical and logical resources. An active Return Channel Satellite Terminal (RCST) can only be a member of one OVN, This is assigned at logon to the DVB-RCS2 Network. Each OVN is assigned a pool of SVN numbers from which it can allocate SVN-MAC addresses. The SVN concept is used to logically divide the addressing space controlled by the operator. SVNOs sell connectivity services to their subscribers and for the regenerative architecture may also manage one or several RSGWs.
- Subscriber (RCST), are the user stations, which they contract to the SVNOs.
- End-user are the final actors enjoying the satellite services, connected to the RCST LAN interface.

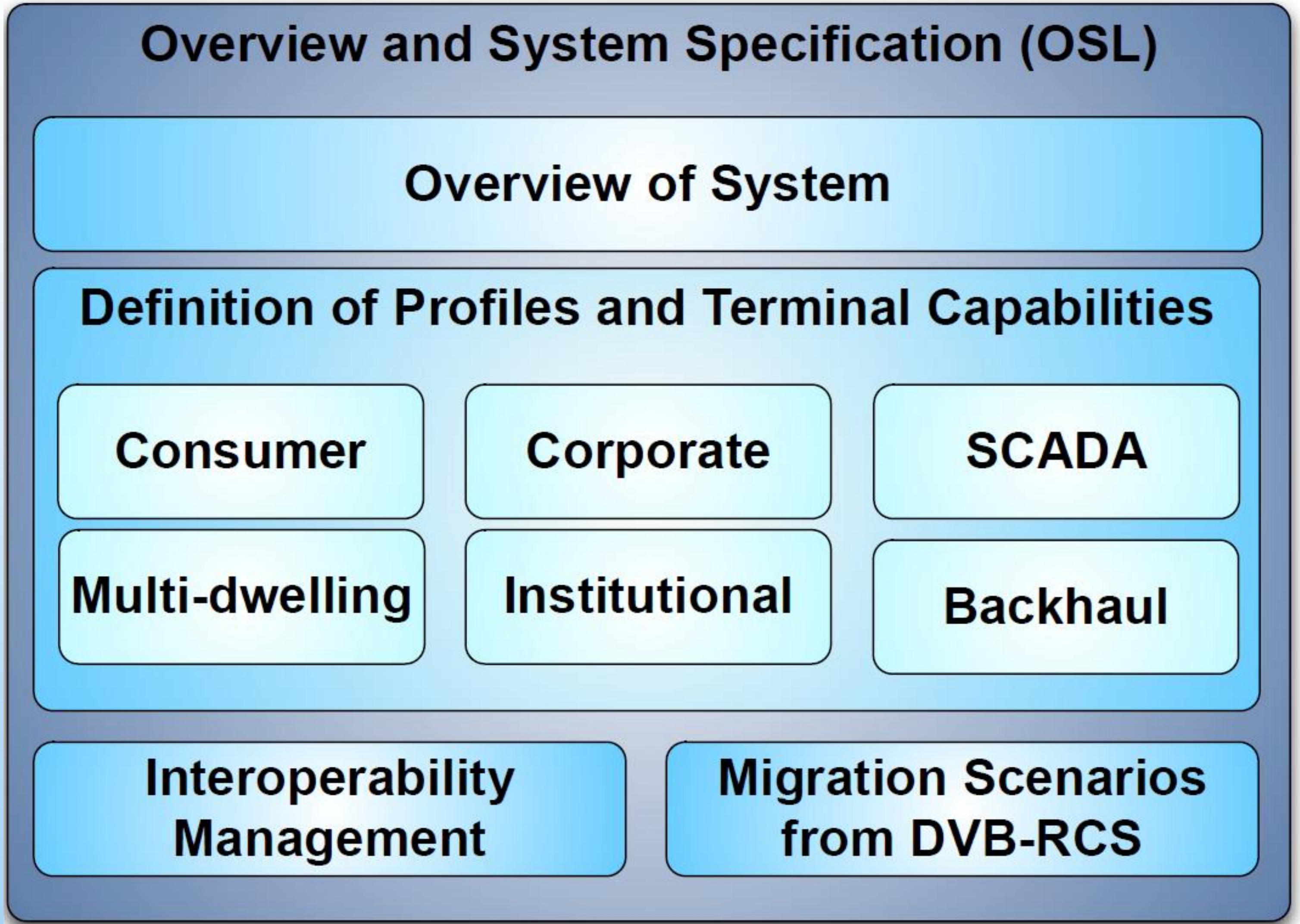
Profiles (1)

- Systems implementing DVB-RCS2 standard are not mandated to implement all features defined in the lower layers and higher layer satellite specifications documents. In order to better match DVB-RCS2 systems with their potential uses, a set of terminal profiles and features is defined.
- Terminal optional features are defined as a set of capabilities that a terminal can implement or not depending on its design. Implementation of these features depends on the manufacturer decision and represents a competitive differentiation with respect to other designs. Normative features shall be implemented by all DVB-RCS2 terminals.
- The fact that these features are implemented or not does not prevent the terminal to be interoperable with hubs as the hub should be aware of the implementation of these features via signalling.
- In the particular case of mobile DVB-RCS2 terminals, some capabilities may be implemented to improve their capacity or their suitability when used in a mobile environment. Actually, no specific feature is mandated to support mobility.

Profiles (2)

- DVB-RCS2 terminals implementing no option can be mobile. Anyway, some features like hand-over management or spread spectrum support will improve significantly the exploitation of terminals in a mobile system by allowing smooth transitions between coverages or small aperture terminals.
- This does not create a specific terminal profile as any terminal can be mobile and no specific feature is linked to mobility either. Eventually, mobility implementation for a DVB-RCS2 terminal is a feature that is tied to its supporting platform and antenna system.
- Similarly, any terminal can be connected to a NGSO system. Although as of this version optional means supporting NGSO are added, NGSO implementation is still considered a feature that is tied to its supporting platform and antenna system.

Profiles (3)


Overview and System Specification (OSL)
Overview of System
Definition of Profiles and Terminal Capabilities
Consumer
Corporate
SCADA
Multi-dwelling
Institutional
Backhaul
Interoperability Management
Migration Scenarios from DVB-RCS

Profiles (4)

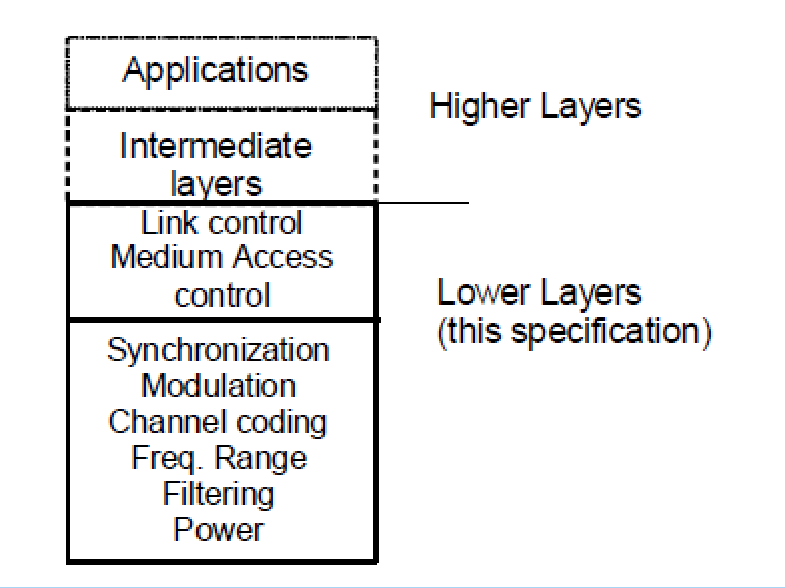
	Consumer	Multi-dwelling	Corporate	SCADA	Backhaul	Institutional
Physical layer						
16QAM return link modulation	O	O	M	O	M	M
32APSK forward link modulation	O	O	O	O	M	M
Essential waveform flexibility	O	O	M	O	M	M
Fast carrier switching	O	O	M	O	M	M
Lowest carrier switching class	1	1	2	1	2	2
MAC layer						
Minimum number of supported traffic SVN	1	4	4	1	4	4
Minimum number of layer 2 traffic classes (request classes and allocation channels)	3	3	7	3	3	7
Slotted Aloha traffic	O	O	O	M	O	O
TRANSEC hooks support	O	O	O	O	O	M
Network layer						
Minimum number of simultaneous traffic multicast streams reception	16	64	64	16	16	64
Dynamic IP routing via OSPF support	O	M	M	O	M	M
Firewall capability	O	O	M	M	O	M
Multicast forwarding on the return link	O	O	O	O	O	M
Management layer						
SNMP v3 support (*)	O	M	M	O	M	M
Multi SVNO support	O	M	O	O	O	O

M: Mandatory capability required for this profile.
O: Optional capability not required for this profile.
(*) SNMP V2c is required as a minimum for all terminals profiles while SNMP V3 should be normative unless specified optional.

OSPF, Open Shortest Path First.

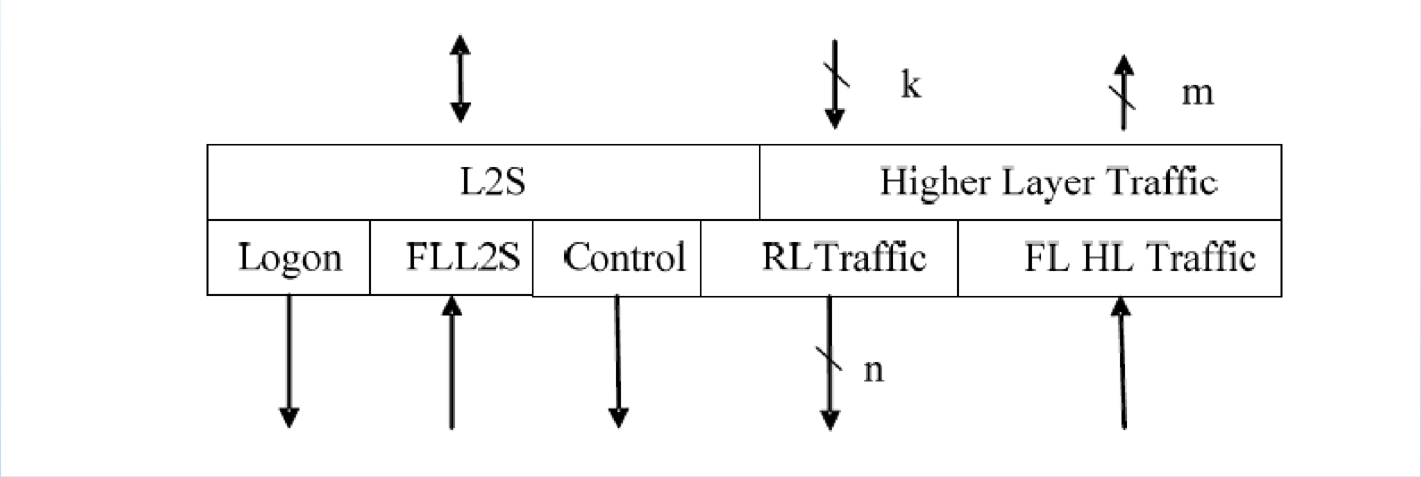
Protocol Stack

- The protocol stack consists of the following layers:
  - Physical layer: part of the lower layers where the transmission parameters and transmission frame constructions are defined.
  - Data link layer: part of the lower layers that defines the logical link control and the medium access control protocols.
  - Intermediate layers: the higher layer protocols connecting to the lower layers.
  - Applications layer: the interactive application software and runtime environment (e.g. home shopping application, script interpreter, etc.).



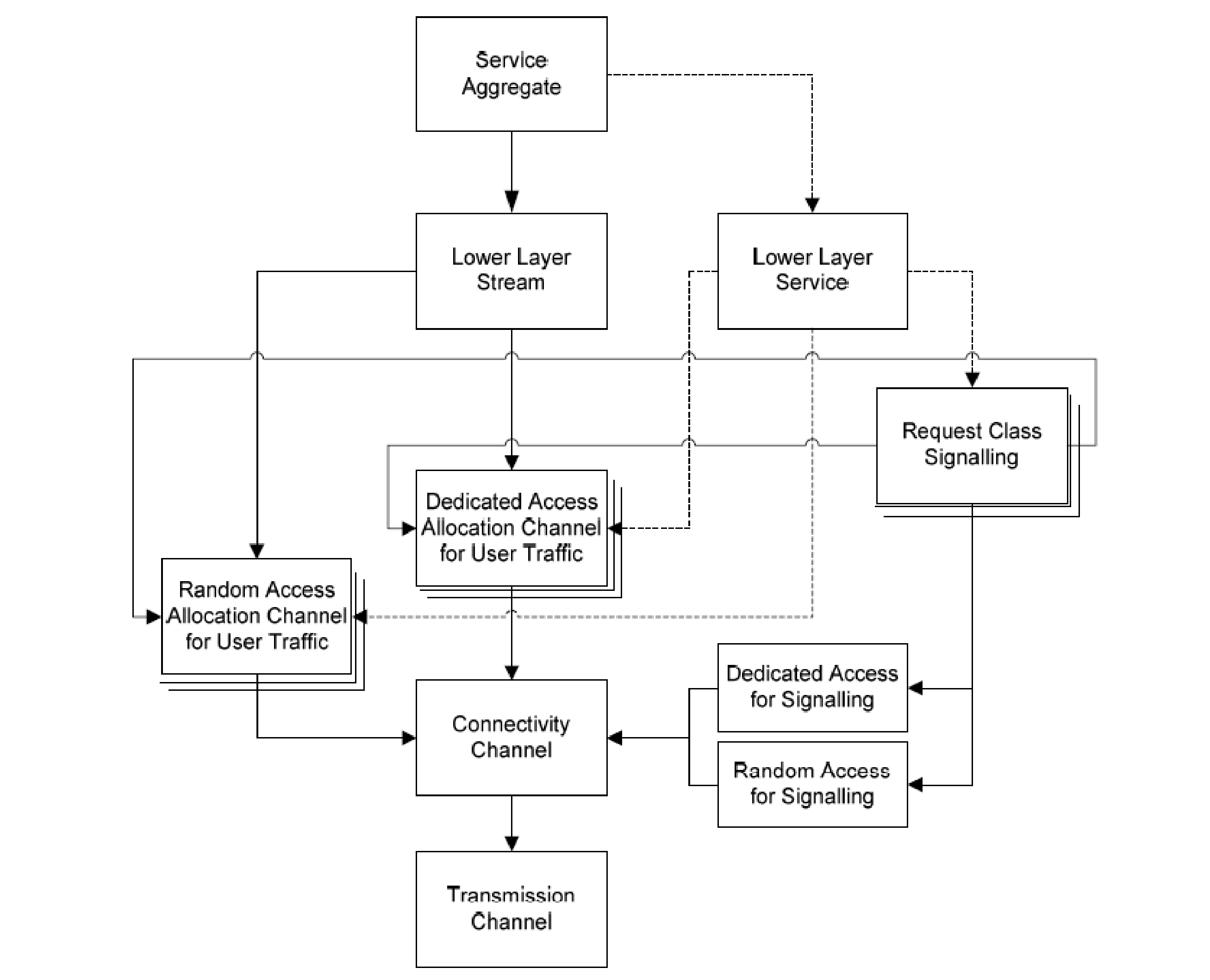
The lower layers

- Four layer 1 content types are defined for the return link: logon, control, traffic and traffic/control.
- The logon and control content types are for L2S, the traffic content type is for higher layer traffic, and the traffic/control content type is for higher layer traffic and L2S, at RCS Terminal (RCST) discretion.



- The RCST may be assigned satellite transmission resources for '*n*' layer-1 allocation channels useful for transmission of the traffic frames. The lower layers may support transmission of '*k*' layer-2 service aggregates mapped into the '*n*' layer-1 allocation channels.

Lower Layer Services



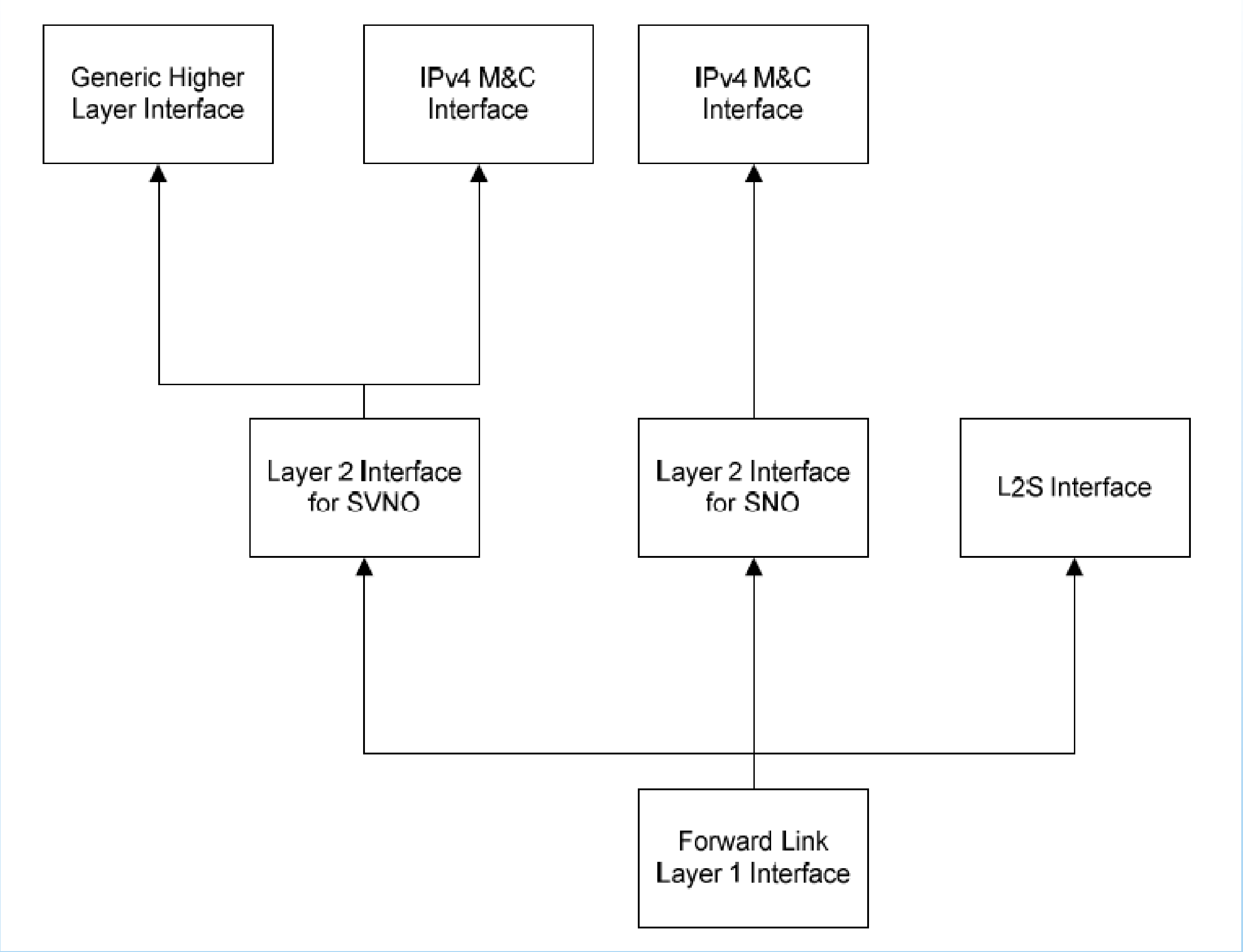
Return channel fragmenting

- An example of how a sequence of SDUs is mapped into a sequence of PDUs fitting into a sequence of transmission frame payloads is shown in figure.

Higher layers	SDU1	SDU2		SDU3
LLC	Link PDU 1	Link PDU 2		Link PDU 3
MAC	Addressed LPDU 1	Addressed LPDU 2		Addressed LPDU 3
	Payload adapted PDU 1	Payload adapted PDU 2	Payload adapted PDU 3	Payload adapted PDU 4
	Frame PDU 1		Frame PDU 2	
PHY	Transmission Frame 1		Transmission Frame 2	

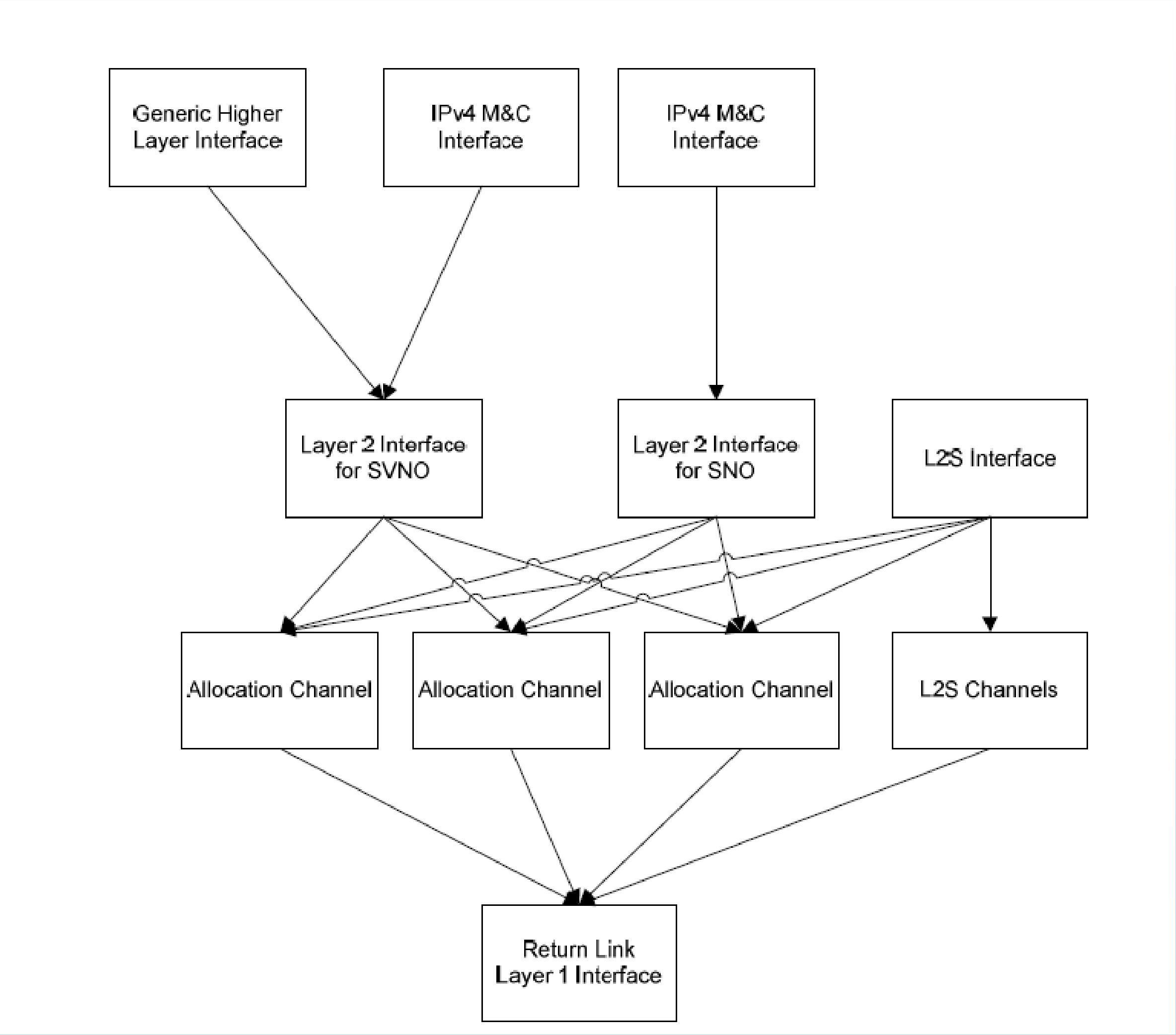
Forward Link Intrfaces

- SVN: Satellite Virtual Network
- SVNO: SVN Operator

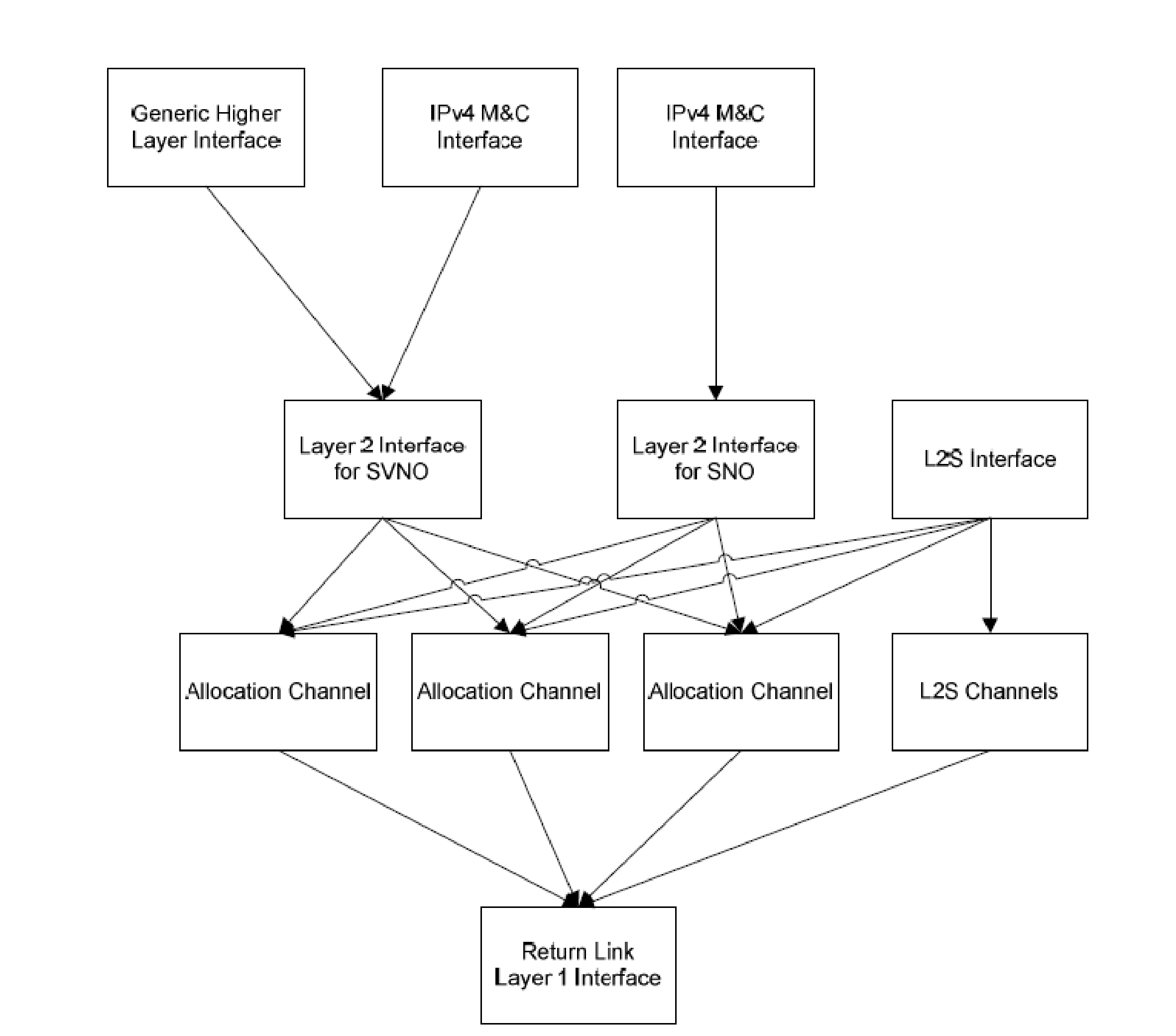


Return Link Interfaces

- SVN: Satellite Virtual Network
- SVNO: SVN Operator



Forward Link Interfaces



Return Link

- The Return Link access is based on the Multi-Frequency Time Division Multiple Access (MF-TDMA) scheme.
- MF-TDMA allows a group of RCSTs to communicate with the NCC and a gateway sharing a set of carrier frequencies, each of which is divided into timeslots for burst transmission,
- Mesh Link access is based on the same type of MF-TDMA transmission aimed not necessarily at a gateway but directly towards another RCST.
- RCST support of Mesh Link access is an option.
- The return link can optionally use a Continuous Carrier (CC) instead of MF-TDMA
- The NCC may allocate timeslots for return link bursts for dedicated access, as well as for random access, and indicate the type of burst and content to be transmitted. The resulting Burst Time Plan (BTP) shall be distributed to the RCSTs via broadcast of the SCT, the FCT2 (Frame Configuration Table 2), the BCT (RL Broadcast Configuration Table) and the TBTP2 (Terminal Burst Time Plan 2) service information tables, and via TIM-U (Terminal Information Message Unicast), as applicable.

Return Link Logical Link Control

- The RCST shall support transmission and reception of IPv4 PDUs as SDUs and shall also support transmission and reception of IPv6 PDUs as SDUs. The RCST may support a mix of IPv4 and IPv6 PDUs as SDUs.

- The Maximum Transmission Unit (MTU) used for the return link shall be:
  - a) 512 for lower layer signalling unless bound to a lower value by the specific transmission format;
  - b) for other traffic either 1 500 bytes or as indicated by administrative means, if this is larger than 1 500 bytes.

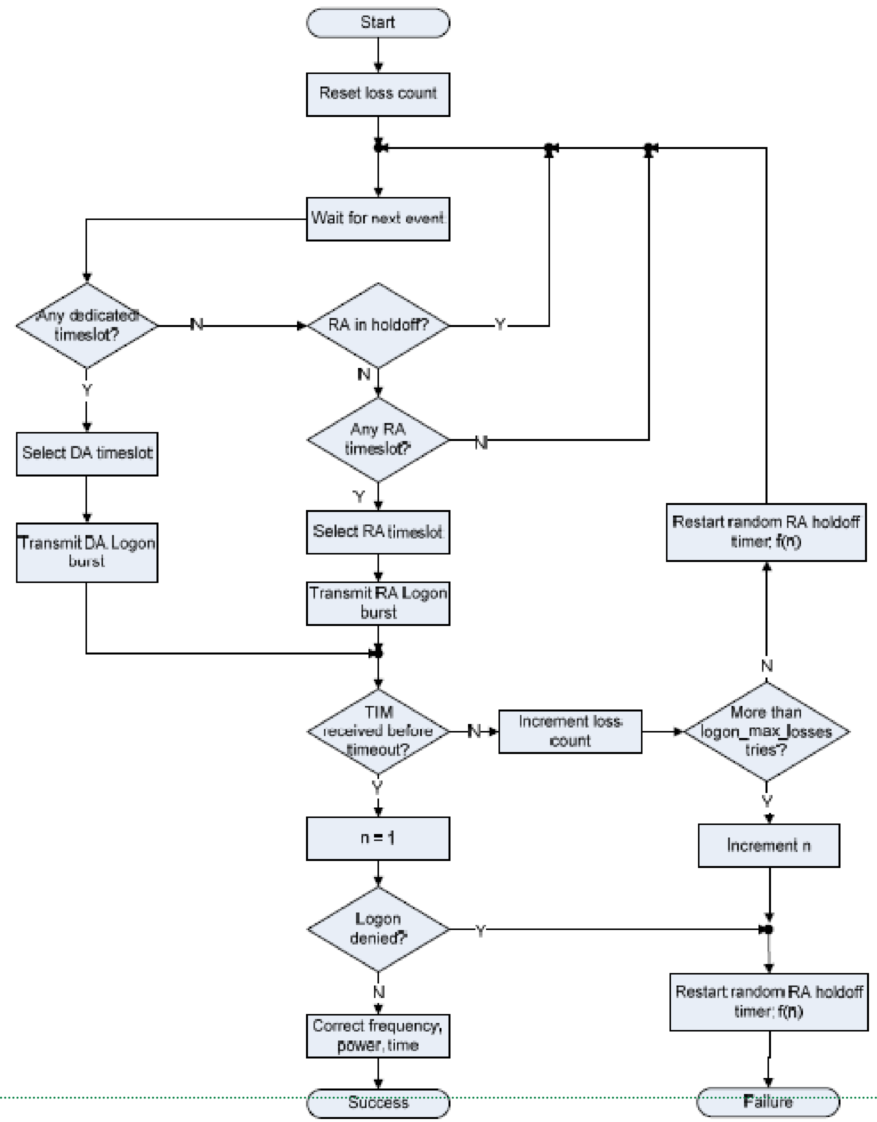
Return Link MAC: Random Access

- The NCC may provide the RCST with timeslots for random access. Segments of an SDU shall not be sent using RA ifat least one segment of the same SDU has been sent or will be sent using Dedicated Access (DA).
- Timeslots may be allocated for random access logon bursts as indicated by the SCT/FCT2/BCT and by these in combination with the TBTP2. The RCST shall be capable of utilizing these timeslots.
- Timeslots may be optionally allocated for random access control bursts as indicated by the SCT/FCT2/BCT and by these in combination with the TBTP2. The RCST may make use of these timeslots.
- Timeslots may optionally be allocated for random access user traffic as indicated by the SCT/FCT2/BCT, or by these in combination with the TBTP2. The RCST may optionally be capable of making use of such timeslots.
- The RCST shall by default not transmit in contention timeslots for traffic, but may do this when explicitly allowed by indication in the Lower Layer Service Descriptor or by other administrative means.

Return Link MAC: Random Access

- Two methods are considered for random access, one called Slotted Aloha and another called Contention Resolution Diversity Slotted Aloha (optional).
- An RCST shall support use of slotted aloha logon timeslots.
- An RCST may optionally support use of slotted aloha control timeslots.
- An RCST may optionally support use of slotted aloha timeslots for user traffic and may be assigned one or more random access allocation channels for such access.
- Retransmission by RA is to be done after a random interval.
- The RA hold-off interval shall in the initial iteration of the logon procedure be a uniformly distributed random variable in the range from now up to a programmable maximum [0, max_time_before_retry], provided by the NCC in the Logon Contention Descriptor sent in TIM-B.
- If the logon procedure fails without response, further RA re-transmission of logon request shall take place in a random access logon timeslot occurring after a random interval being a uniformly distributed random variable in the interval $[0, n^2 \cdot \text{max\_time\_before\_retry}]$ where n is one more than the number of consecutive iterations of the logon procedure completed with failure.

Lower layer logon procedure



CRDSA

- Contention Resolution Diversity Slotted ALOHA (CRDSA) is based on the transmission of a chosen number of replicas of each burst payload by using slotted aloha in a specific transmission scheme.
- There are two possible variants of CRDSA transmitter operation:
  - Constant Replication Ratio CRDSA (CR-CRDSA): using a constant number of replicas of each burst;
  - Variable Replication Ratio CRDSA (VR-CRDSA): using a varying number of replicas for the different bursts, where the number of replicas is determined according to a pre-defined probability distribution.
- The type of CRDSA scheme (CR-CRDSA vs. VR-CRDSA) that is best to use may be chosen on the basis of a trade-off between throughput and burst loss rate. While CR-CRDSA allows low burst loss rate, VR-CRDSA allows larger peak throughput.

CRDSA (2)

- The following essential configuration shall be supported for a CRDSA implementation:

1) Support for CR-CRDSA is required. Support for VR-CRDSA is implementation dependent.
2) The RCST shall support single-carrier RA blocks when *nofInstances* ≥ 2.
3) The RCST shall be able to support *nofInstances* = {1,2,3}.
4) If the configuration is *nofInstances* = 1 then only the unique payload shall be transmitted and the access method shall be SA, and operation shall be according to the scheme for SA.
5) If the configuration is nofInstances ≥ 2 then the indicated number of instances shall be transmitted and the access method shall be CRDSA, and operation shall be according to the scheme for CRDSA.
6) The RCST shall support RA block duration less than or equal to 150 ms.
7) The RCST shall support RA blocks with number of slots from 64 to 128.
8) The RCST shall support RA blocks that are submultiples of the superframe duration.

CRDSA (3)

9) The RCST shall support RA blocks that are entirely contained in one superframe only and that do not overlap the boundary between two superframes.
10) The RCST shall support operation with equal-sized RA blocks with respect to the number of timeslots.
11) The RCST shall be able to support transmission of a minimum of one unique payload per RA block.
12) The RCST shall support CRDSA random access allocation channel when using the same transmission_type for all the timeslots.
13) The RCST shall be able to support minimum one CRDSA random access allocation channel.
14) The RCST shall be able to support CRDSA allocation channels without assignment of timeslots to the channel by TBTP2 signalling.

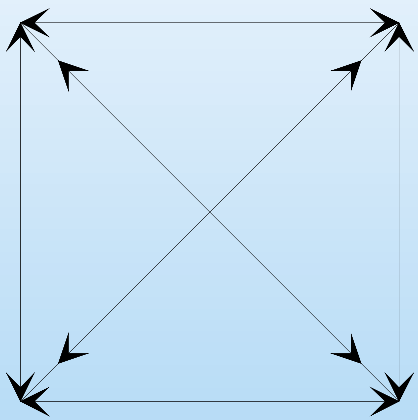
MSK Modulation

- Q-PSK / 4-PSK Modulation
- Generic waveform: $u_m(t) = g_T(t)\cos(2\pi f_c t + \varphi_m),\ 0 \le t \le T,\ \varphi_m = \pi(2m+1)/4,\ m = 0 \div 3$
- Message: $u(t) = \sum_n u_{m_n}(t - nT) = I(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t)$
  where $I(t) = \sum_n \cos\varphi_{m_n} g_T(t - nT)$ and $Q(t) = \sum_n \sin\varphi_{m_n} g_T(t - nT)$
- For simplicity, let's assume that we use a rectangular pulse of duration T,
  $$g_T(t) = \Pi\left(\frac{t}{T} - \frac{1}{2}\right)$$
  and that the information is represented by binary random variables that can take the values -1, 1.
- Results: $I(t) = \sum_n \xi_{2n-1}\Pi(t/T - 1/2 - n)$, $\quad Q(t) = \sum_n \xi_{2n}\Pi(t/T - 1/2 - n)$
- Transitions between all phases are possible. Due to the abrupt phase changes, the QPSK system would tend to have out-of-band lobes. The signal is, however, filtered, which tends to eliminate the out-of-band lobes, but also produces an alteration of the signal envelope, a highly undesirable effect.
- Objective: To identify a modulation that has the performance of QPSK but does not have abrupt phase transitions.

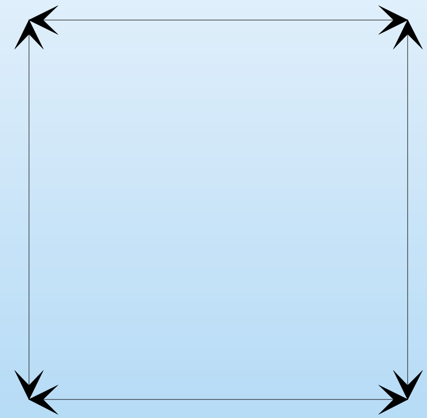
Offset QPSK Modulation

- The two binary sequences are phase shifted by T_b=T/2. In this way the phase transitions concern only one binary variable at a time, and they are all by π/2.

- Results: $I(t) = \sum_n \xi_{2n-1} \Pi(t/2T_b - n) \quad Q(t) = \sum_n \xi_{2n} \Pi(t/2T_b - 1/2 - n)$.



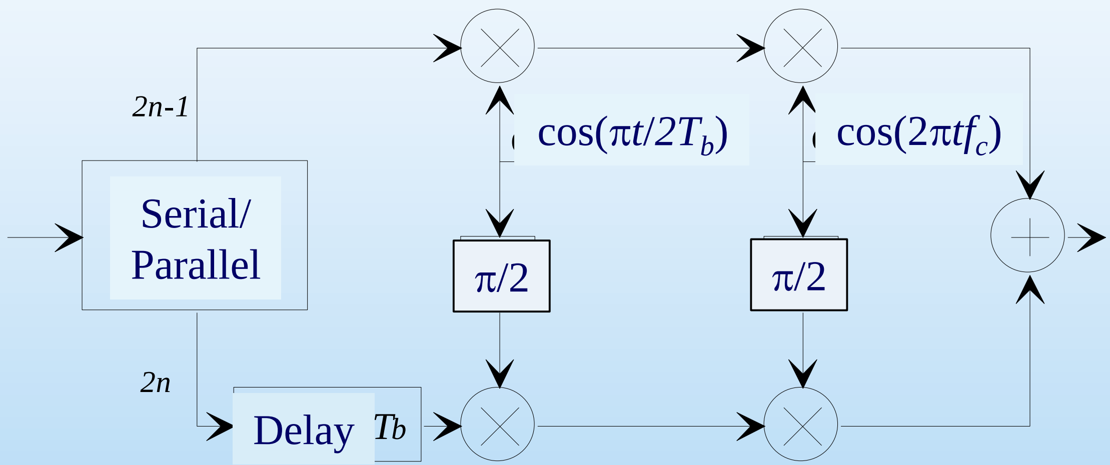
Phase diagram QPSK



Phase diagram O-QPSK

MSK Modulation

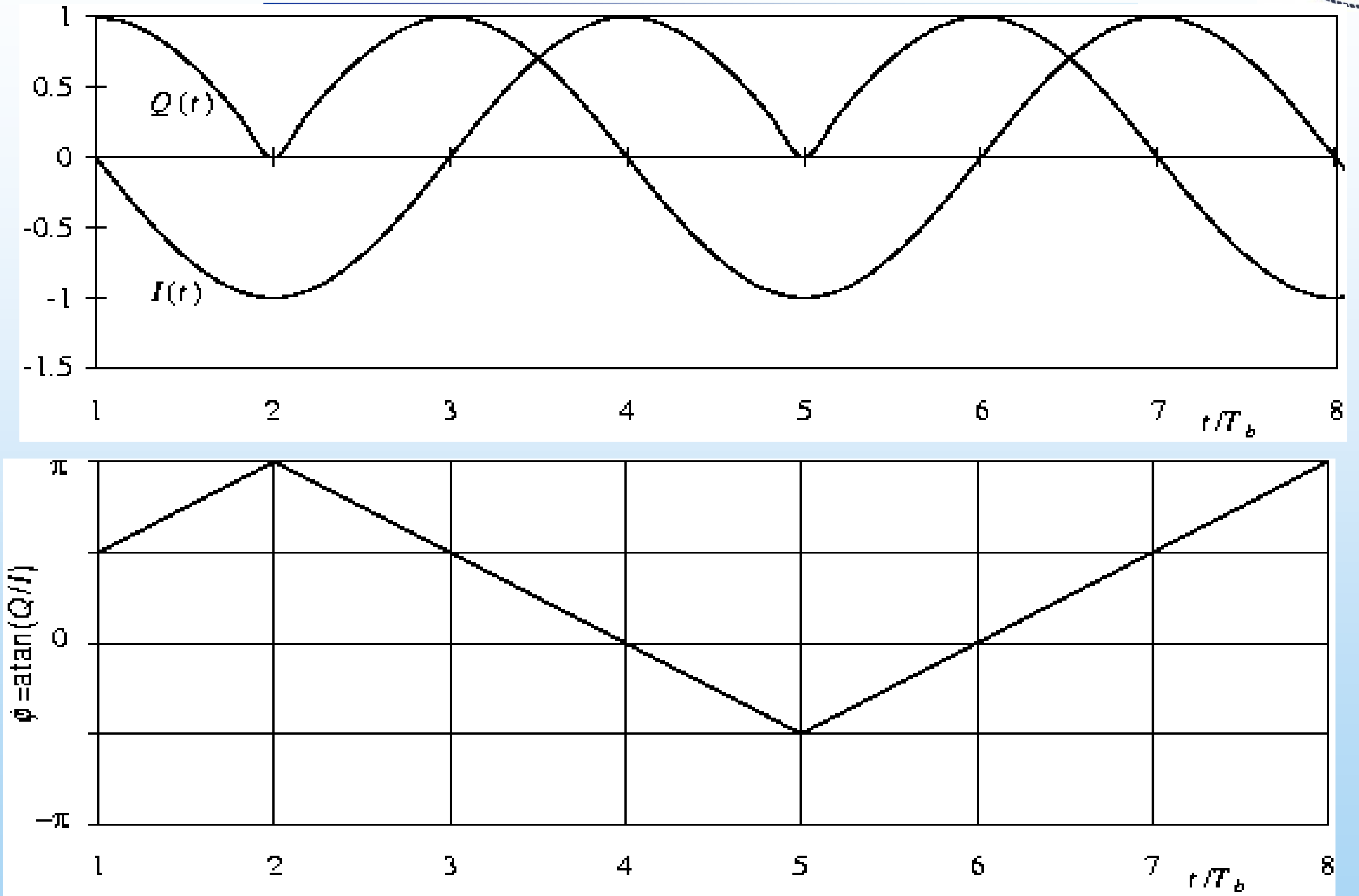
- The rectangular pulse is replaced by a sinusoidal pulse of period $2T$.
- Results $I(t) = \sum_n \xi_{2n-1} \Pi\left(\frac{t}{2T_b} - n\right) \cos\left(\frac{2\pi t}{4T_b}\right)$ $Q(t) = -\sum_n \xi_{2n} \Pi\left(\frac{t}{2T_b} - n - \frac{1}{2}\right) \sin\left(\frac{2\pi t}{4T_b}\right)$



The functions $I(t)$ and $Q(t)$ vary continuously; therefore, the phase also varies continuously, and varies linearly.

- In even multiples of T_b (where $I(t)$ varies), the phase can be $\pi/2$ or $3\pi/2$. In odd multiples, the phase can be 0 or π. Over the bit period, the phase varies by a total of $\pi/2$. Therefore, the phase transition is a process with memory, of which the initial phase is the state.

MSK Modulation



- Functions $Q(t)$ and $I(t)$ associated with the numerical sequences -1,1,1,1 and 1,1,-1,-1 and related phase evolution.

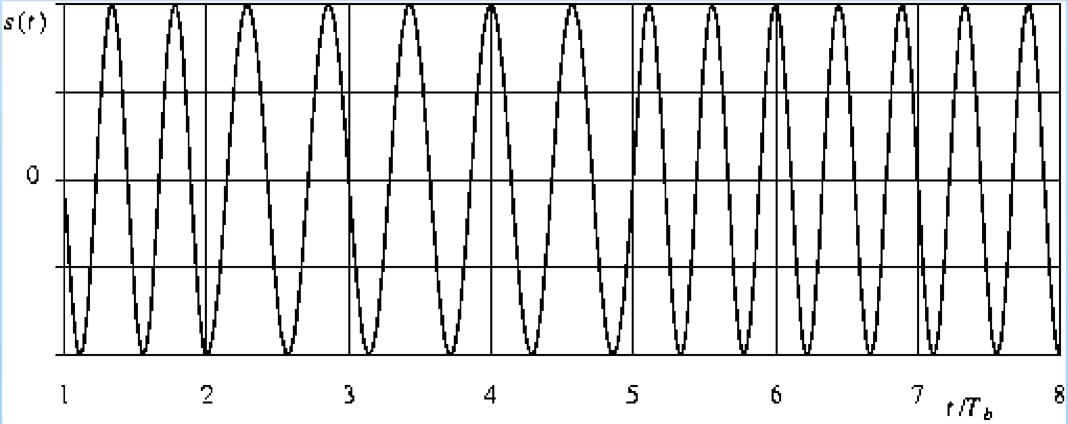
MSK Modulation

- Let $f_1 = f_c + 1/4T_b$ and $f_2 = f_c - 1/4T_b$. Substituting into the previous equations gives

$$u(t) = \sum_n \xi_{2n-1}\Pi\left(\frac{t}{2T_b} - n\right)\frac{1}{2}\left(\cos 2\pi f_2 t + \cos 2\pi f_1 t\right) + \\ + \sum_n \xi_{2n}\Pi\left(\frac{t}{2T_b} - n - \frac{1}{2}\right)\frac{1}{2}\left(\cos 2\pi f_2 t - \cos 2\pi f_1 t\right)$$

.

- Introducing the binary variable $b_n = -\xi_{2n} \cdot \xi_{2n-1}$, if $b_n = 1$, $u(t)$ is a sinusoid with frequency f_1 while if $b_n = -1$, $u(t)$ is a sinusoid with frequency f_1.
- With respect to the binary variable b_n, which changes value every T_b, the MSK modulation turns out to be a continuous-phase FSK modulation, with $\Delta f = 1/2T_b$, which is the minimum frequency difference that satisfies the orthogonality condition.

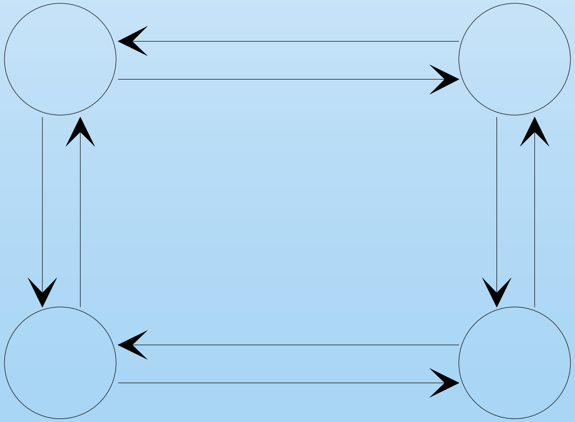


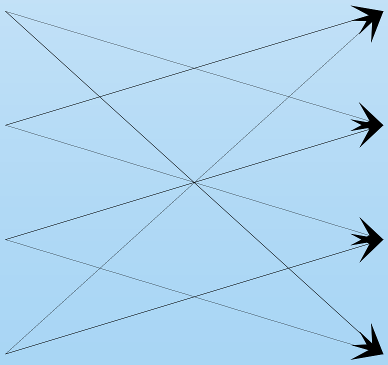
MSK Modulation: Key Features

- MSK modulation is an OQPSK modulation with a sinusoidal-shaped signal.
- The phase of the MSK signal varies linearly, changing its value by π/2 at each bit period.
- With the introduction of the binary variable $b_n = -\xi_{2n} \cdot \xi_{2n-1}$, MSK can be viewed as a continuous-phase orthogonal frequency modulation, whose generic waveform is expressed by

$$u_m\left(t-nT_b\right)=\cos\left(2\pi f_0 t+\frac{b_n\pi}{2T_b}\left(t-nT_b\right)+\varphi_n\right),\quad nT_b\le t\le (n+1)T_{b,}\ b_n\in\{-1,1\},\ \varphi_n\in\left\{0,\frac{\pi}{2},\pi,\frac{3\pi}{2}\right\}$$

- Phase continuity can be represented with a state diagram or a trellis diagram.





MSK: demodulation

- Coherent
  - QPSK (optimal receiver): $P(e) = 2p - p^2$ where $p = Q\left(\sqrt{2E_b / N_0}\right)$
  - CPM (Viterbi algorithm): $P(e) < 2Q\left(\sqrt{2E_b / N_0}\right)$
  - Orthogonal FSK: performance 3 dB lower.

- Non-Coherent
  - Discriminator: 6.6 dB lower than the optimal receiver (partially recoverable using partial response pulses and the Viterbi algorithm).

- Differential
  - Performance falls between that of DECPSK and DPSK.

MSK power spectrum

$$G(f) = \frac{8T_b}{\pi^2} \frac{1 + \cos 4\pi f T_b}{\left(1 - 16 f^2 T_b^2\right)^2}$$