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An Evolution of Network Control: from Earth to Space

Overview, Engagement, Research and Standardisation Gaps

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Satellite Communication

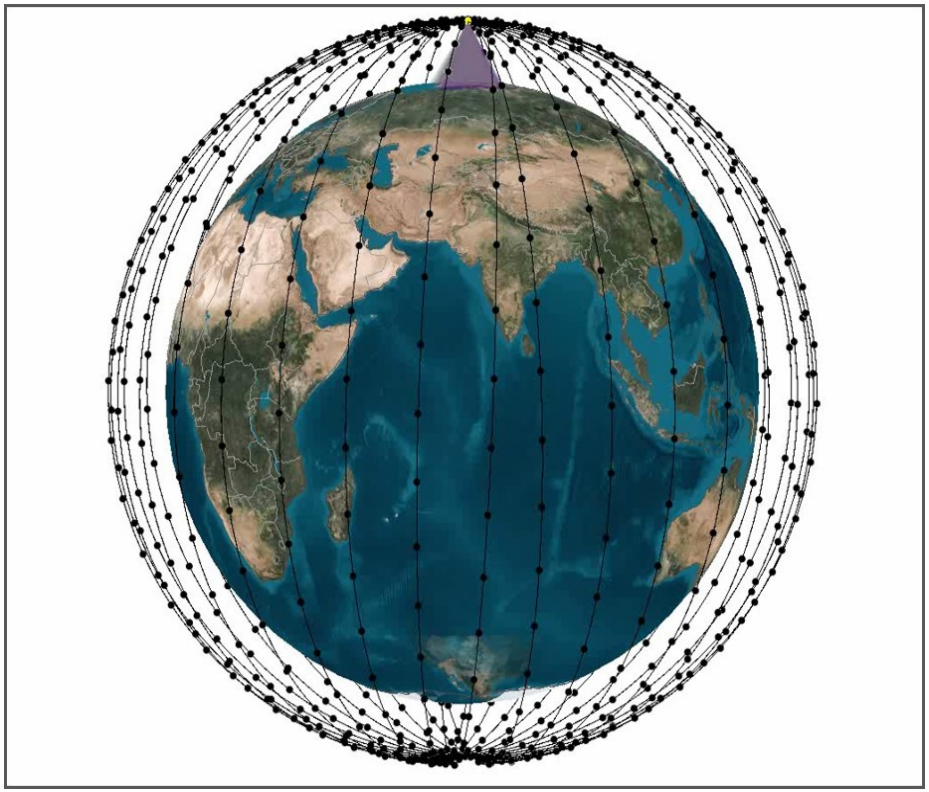
- Consumer-facing satellite networks have existed for decades
- There is abroad spectrum of existing and emerging satellite constellations
  - Currently deployed constellations like HughesNet serve niches like rural coverage for at most a few million subscribers using tens of satellites in geostationary orbit (GEO; 35,786 km) resulting in large latencies of hundreds of milliseconds.
  - Iridium and Iridium NEXT operate in LEO (LEO; ≤ 2,000 km altitude), and target a narrower niche of satellite telephony, operating at lower latencies in order of <50 milliseconds
- New developments differ from these in their goals, their scale, and the technology involved
- The largest "New Space" constellations target cheap, global low-latency Internet coverage using thousands of satellites in low-Earth orbit (LEO; ≤ 2,000 km altitude), such as Space X
- SpaceX stated objective is to carry a significant amount of Internet long-haul traffic

A new Generation of Satellite Constellations

LEO Constellations

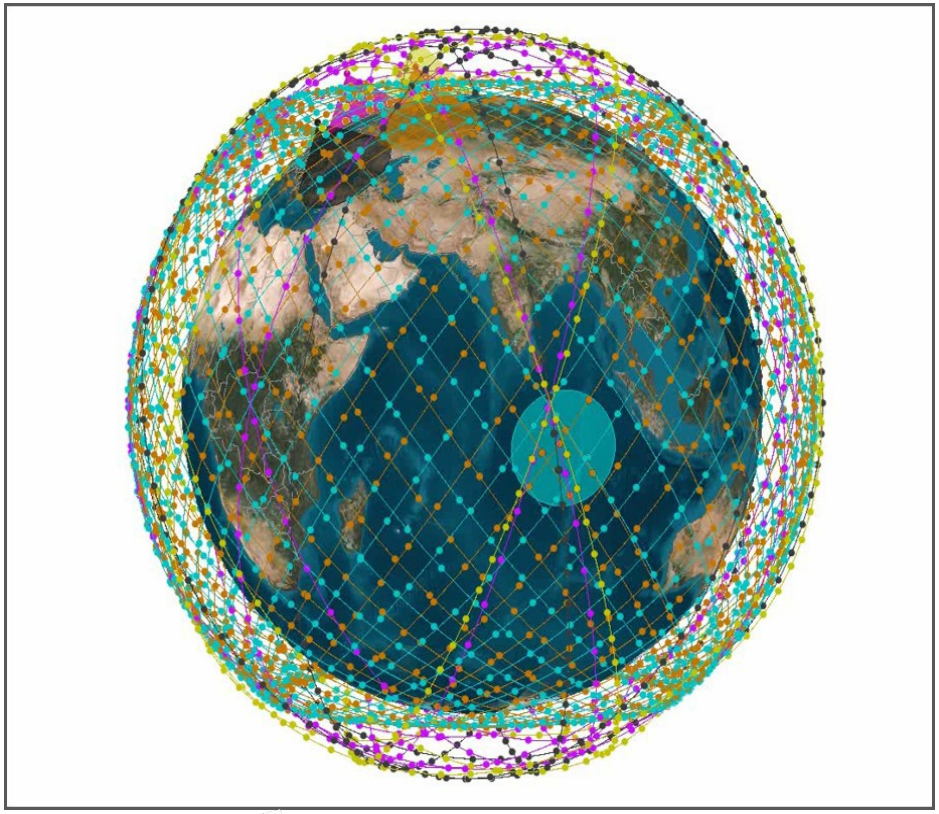
- In the last 3 years there has been a new wave of proposals of LEO mega-constellations to provide broadband Internet
  - 13 Proposals
- LEO satellites orbit the Earth on the order of 100 minutes, traveling at roughly 27,000 kmph
- The objectives of the proposed constellations are to expand coverage to remote areas, as well as provide lower latency than terrestrial networks.
- The potential for lower latency for long-distance connectivity stems from
  - Being able to build nearly-shortest paths (after incurring the overhead for the up-down links) instead of circuitous terrestrial fiber routes
  - Transmitting at the speed of light in instead of that in fiber
- Three of the leading constellations are
  - OneWeb, SpaceX, and TeleSat

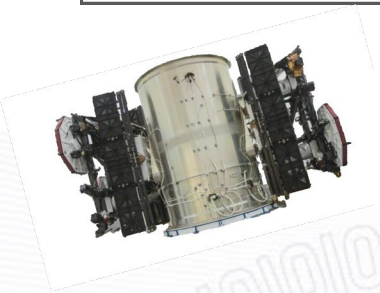
Satellite Deployments
OneWeb Constellation



- OneWeb Characteristics
- 720 satellites in 18 polar planes at 1,200 km @ 86.4°
  - 40 satellites per plane)
- Architecture
  - User links @ Ku-band, gateway links @Ka-band
  - Bent pipe architecture
  - No crosslinks
- Compact satellites 145 kg.
- Service started in 2019

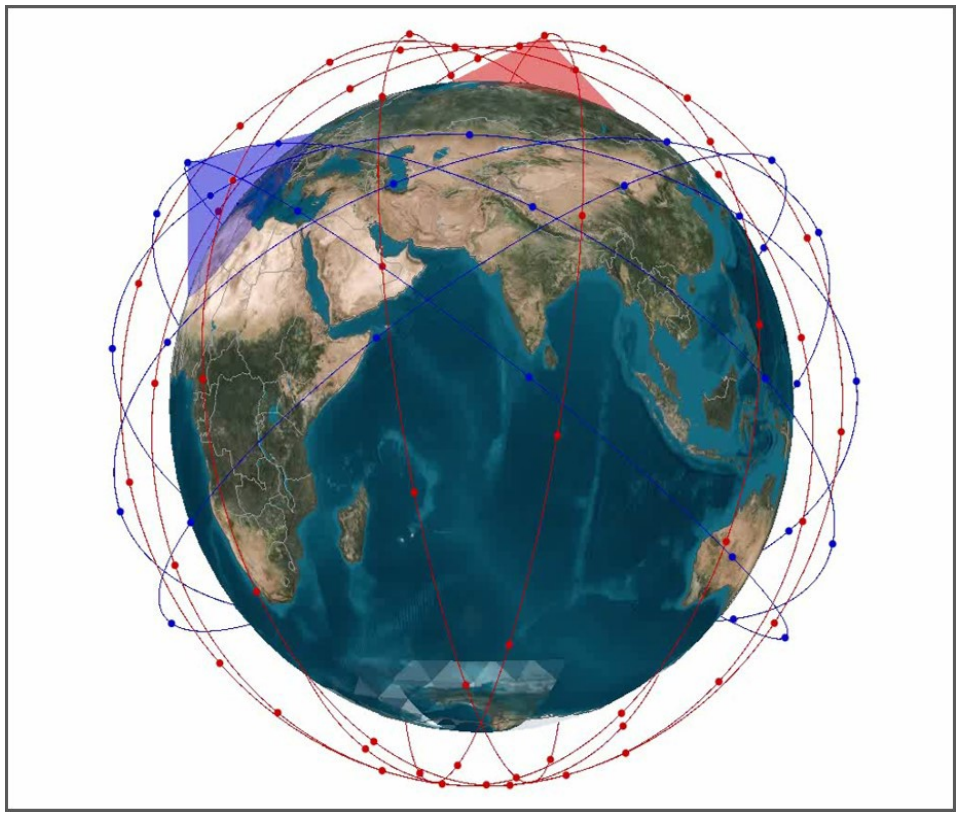
Satellite Deployments
SpaceX Constellation





- 4,425 Satellites in 83 planes. Inclined orbits + polar orbits.
- User links @ Ku-band, gateway links @Ka-band
- Optical crosslinks between satellites
- Digital payload with beam steering and shaping capabilities
- Medium size satellites 386 kg, in house designed.
- First launch in November 2019
- Begun service in 2020

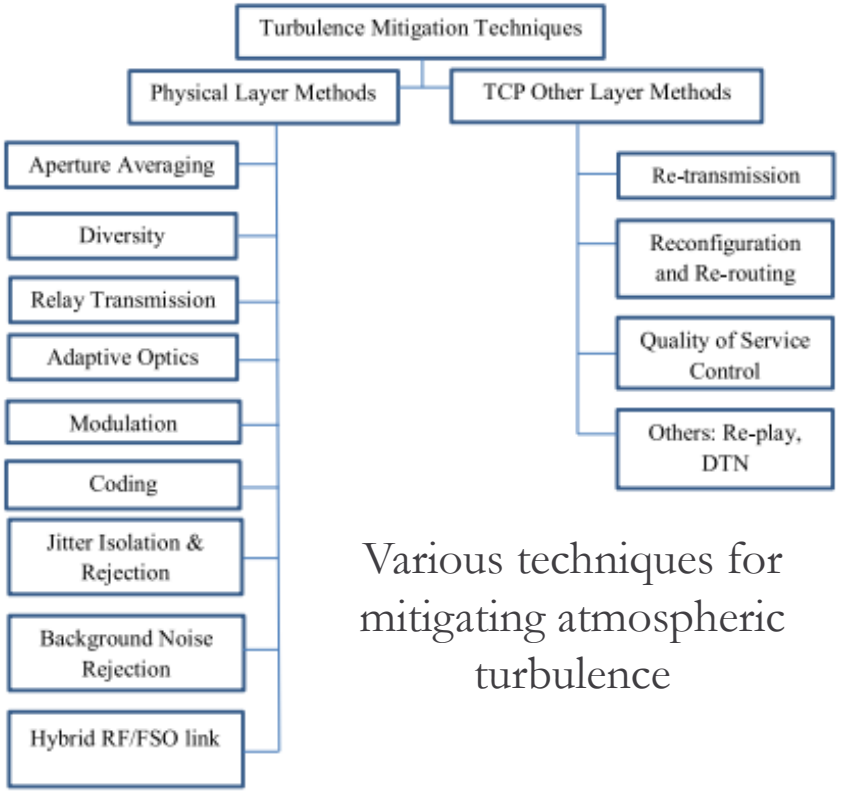
Satellite Deployments
Telesat Constellation



- 117 Satellites in 11 planes
  - Polar: 6 planes x 12 satellites at 1,000 km @ 99.5°
  - Inclined: 5 planes x 9 satellites at 1,200 km @ 37.4
- User and gateway links @Ka-band
- Optical crosslinks between satellites
- Demodulation + modulation + IP-Routing
- Planned Launch 2021
- Beginning of service 2022

Satellite Constellation Architecture
Free Space Optics (FSO) Basics

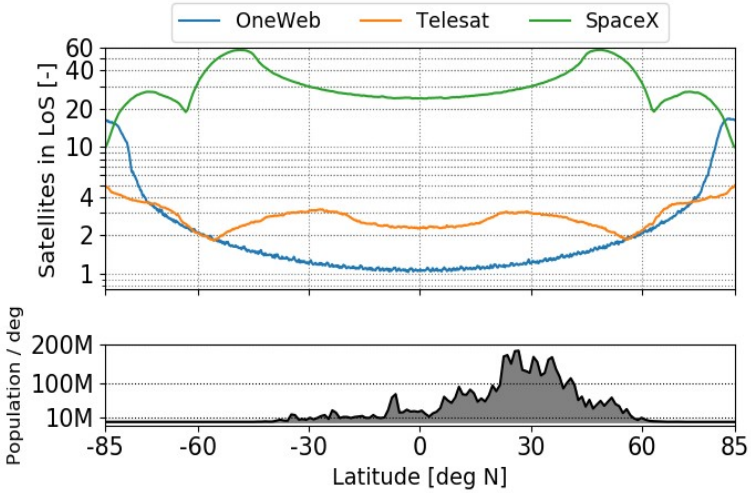
- Free Space Optical (FSO) communication benefits include:
  - high data rates, small terminal sizes, low transmit power, high data-security and no bandwidth regulation issues
- Prone to atmospheric effects for Space-to-Earth Communication
  - Atmospheric-turbulence
  - Clouds/Fog
  - Snow/Rain
- For inter-satellite FSO links, various limiting factors include pointing, background noise and link availability

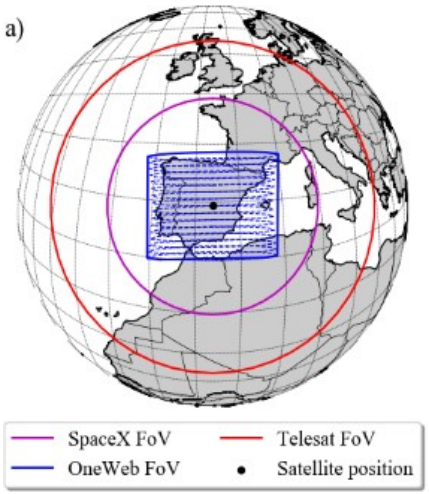


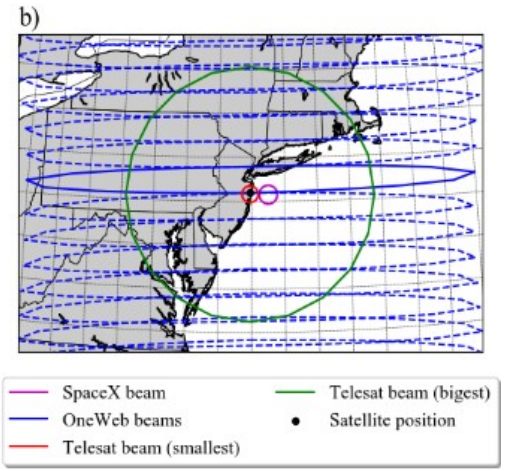
Various techniques for mitigating atmospheric turbulence

Satellite Constellation Architecture

Line of Sight and Beam Characteristics







- Significant differences in beam footprint and field-of-view areas.
- SpaceX and Telesat have steerable and shapeable user beams. One web has fixed beams.

- Major differences in the number of satellites within line of sight for different latitudes between constellations.
- Telesat and SpaceX concentrate their satellites within the ±60 latitude band by using inclined and polar orbits.

Satellite Constellation Architecture

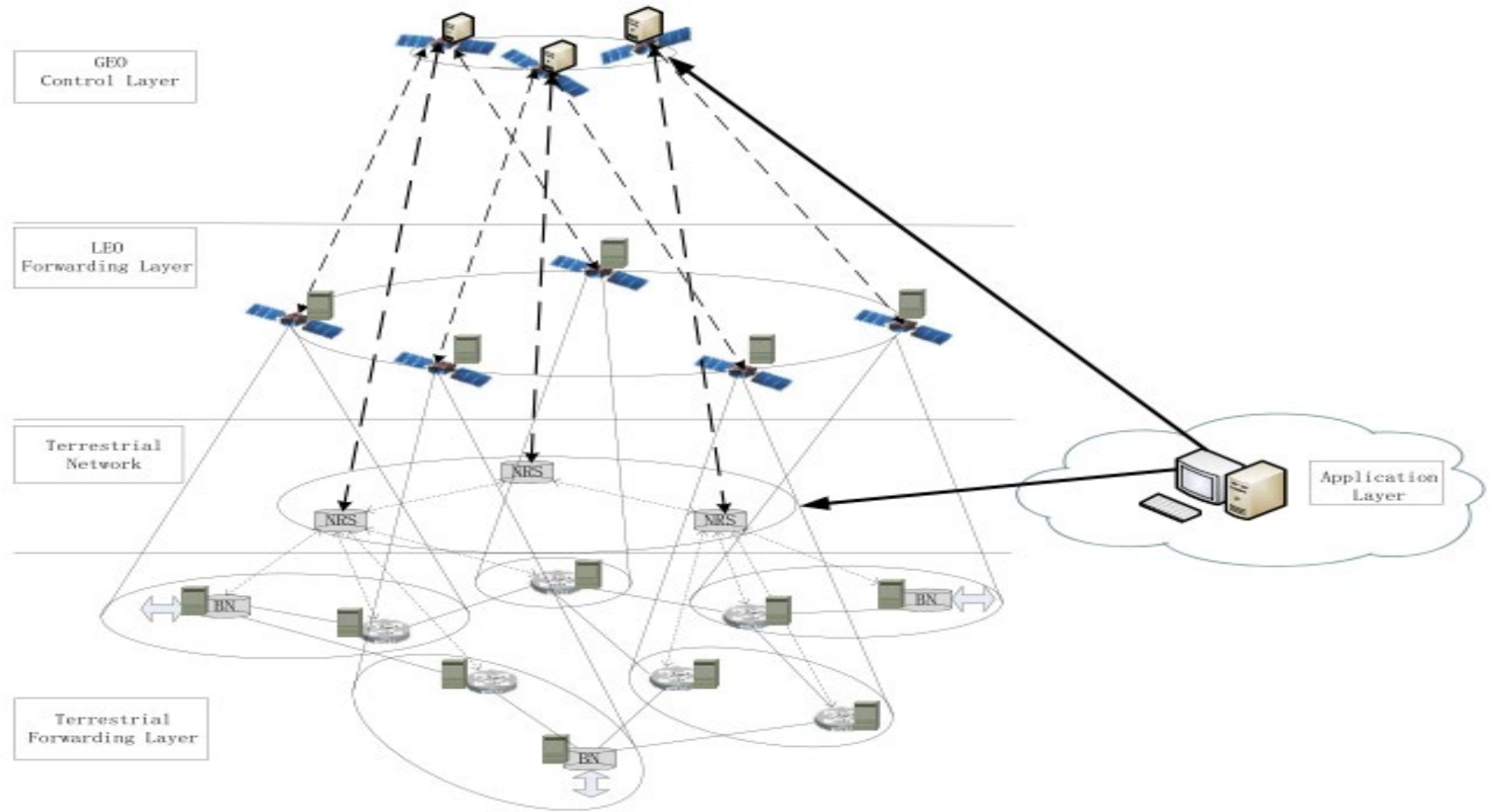
Traffic types and Characteristics

- Immense increase in the capability and capacity requirements of earth observation (EO) sensors attached to satellites
  - High resolution optical and infrared cameras and Synthetic-Aperture Radar (SAR)
    - These require gigabits and terabits per second
  - Broadband Internet
    - >100Mbps Residential Internet
    - >1Gbps Enterprise Internet
  - Telesat
    - More than 4x SpaceX and 10x OneWeb
  - SpaceX
    - Need to deploy a very large number of ground stations for maximum capacity
  - OneWeb
    - Space segment is the limiting factor

	Telesat	OneWeb	SpaceX	
Num. satellites	117	720	4,425	-
Max. total system FWD capacity	2.66	1.56	23.7	Tbps
Number of ground locations for max. FWD capacity	42	71	123	-
Number of gateway antennas for max FWD capacity	221	725	~3,500	-
Required number of gateways per ground station	5-6	11	30	-
Average data-rate per satellite (real)	22.74	2.17	5.36	Gbps
Max. data-rate per satellite	38.68	9.97	21.36	Gbps
Satellite efficiency	58.8	21.7	25.1	%

Optical Space Communication Networks

Multi-layer Networking



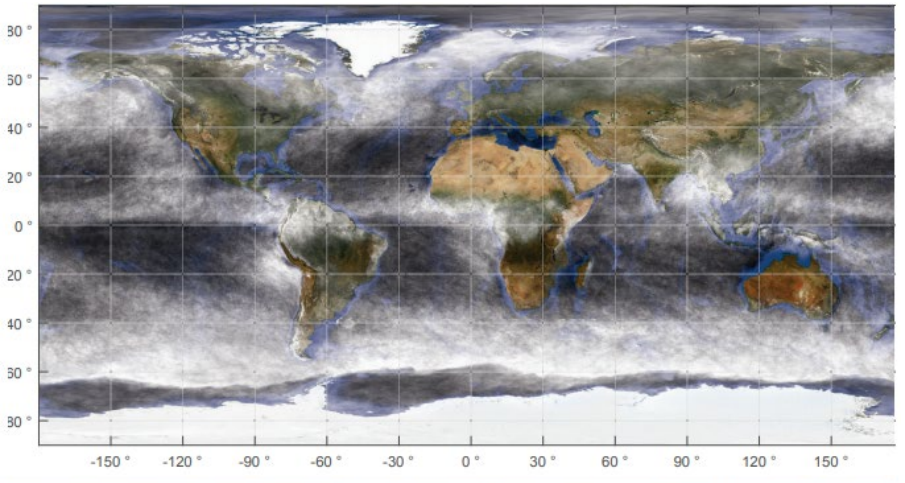
Optical Space Communication Networks
Building the Network Graph

- Given
  - constellation's satellite trajectories,
  - small to medium number of inter-satellite connection units at each satellite
  - a target traffic matrix between terrestrial endpoints
- Our goal is to decide which satellite-satellite connections to build, we must:
  - minimize latency and hop-count in end-end paths
  - Consider fixed and static variants (satellite motion and Earth's rotation)
  - Utilise links efficiently and attach to gateways based on optimal delivery of traffic

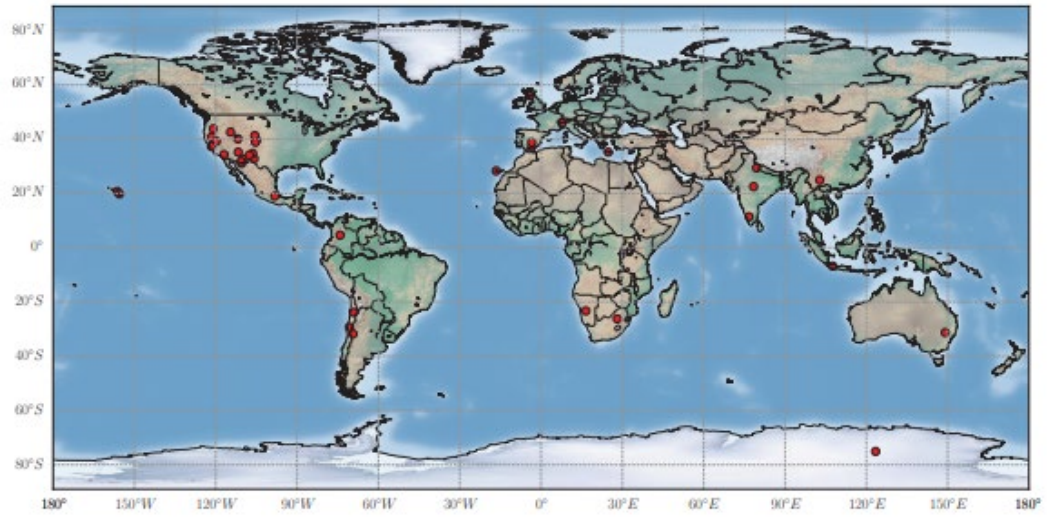
Optical Space Communication Networks

Architecting the space-to-ground segment

- Significant challenges for direct Free-Space Optical (FSO) include:
  - downlinks from satellites are affected by cloud cover, air turbulence and external object occlusion, which all determines the availability and speed of the downlinks.



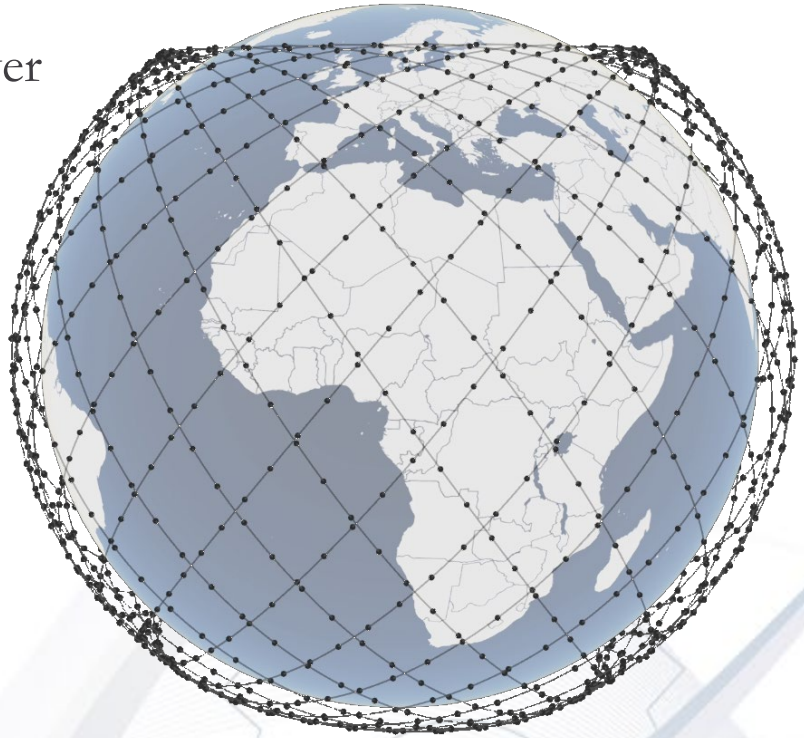
Some FSO ground stations will be mobile



Optical Space Communication Networks

Architecting the space-to-space segment

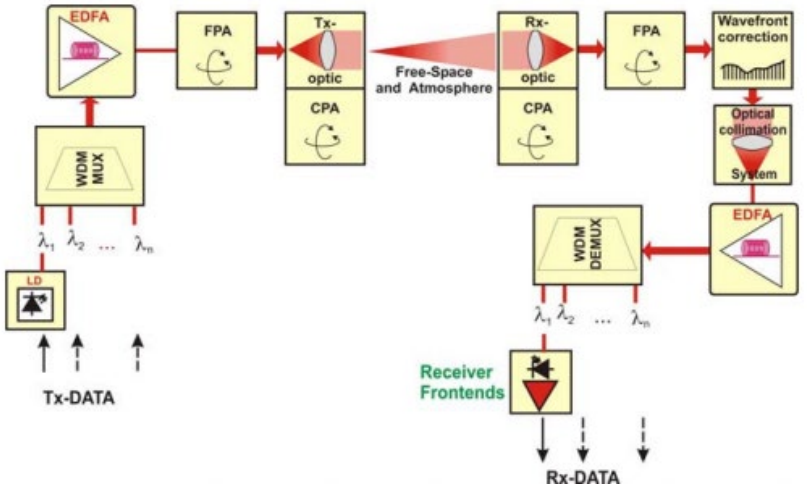
- Acquisition and tracking of satellites as they move, and calculating relative velocity
- Inter-satellite or inter-orbital links have to cover larger distances, therefore the transmission scheme has to be power-efficient with good sensitivity at the receiver
- Need to consider power versus transmission costs, and path viability
- Emerging technology of Steered Laser Transceiver (SALT)s that would need remote control capabilities

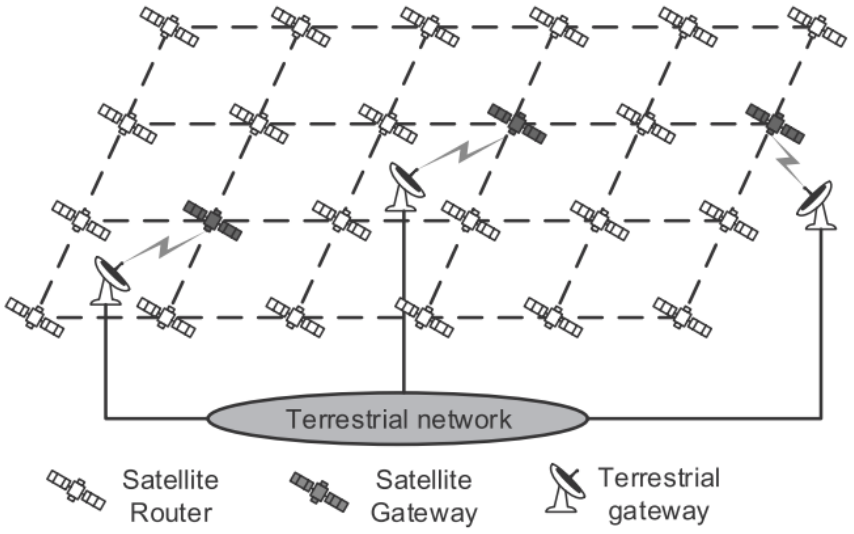


Optical Space Communication Network

Architecting the space-to-ground segment

- Future broadband free-space optical DWDM system for simplex EO-Sat downlinks
- In order to cut down transmission hops, significant numbers of gateways are required in the ground segment
  - Gateways are the interface of satellite network and terrestrial network
- Often Gateways will also manage of LEO satellites.
- The location and the number of ground gateways may change over time



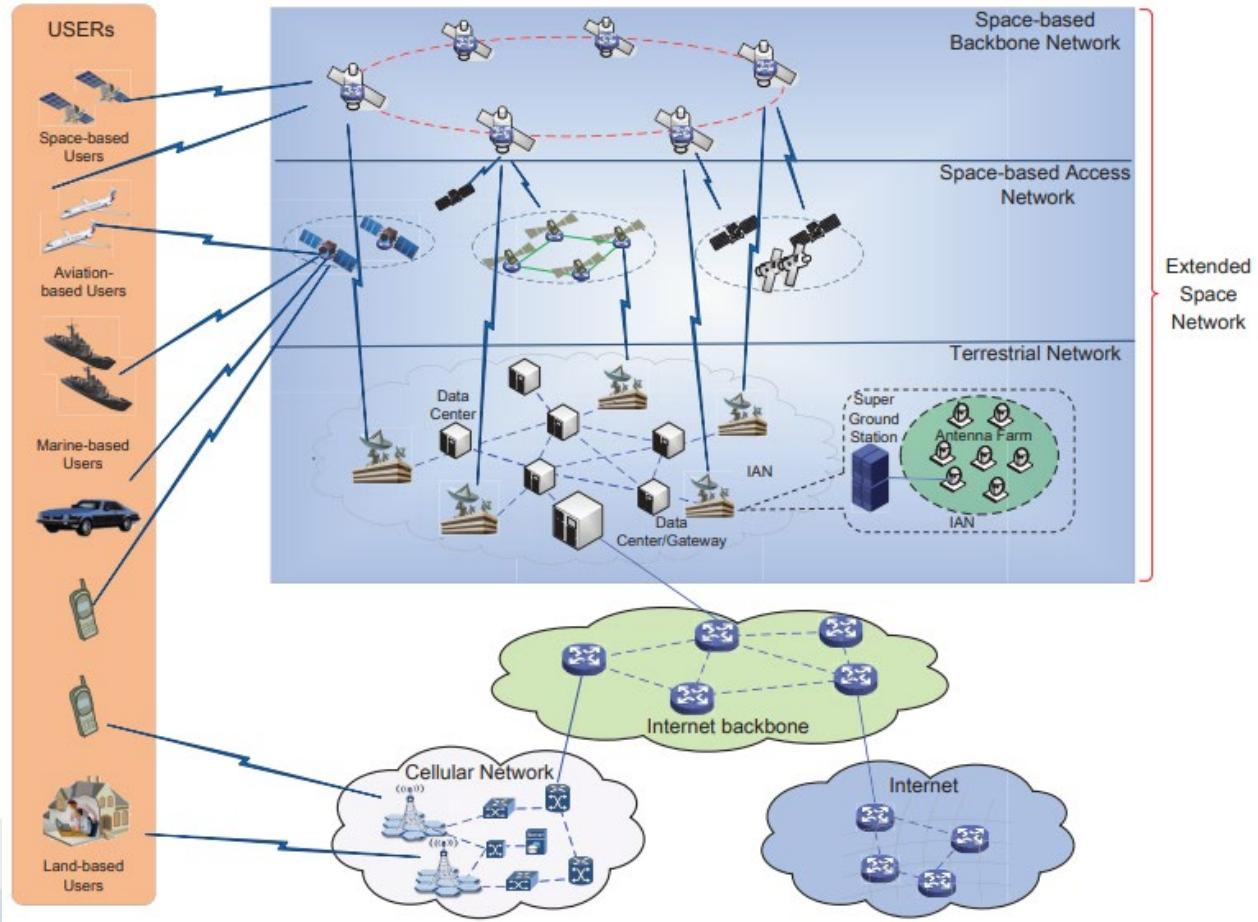


Optical Space Communication Networks
Control Plane and Management Plane Requirements

- Routing
  - The network is not static. Satellite most directly overhead changes frequently, the laser links between space-based satellites change frequently, and link latencies for links that are up change constantly
  - Time-varying topology of the space network may necessitate frequent routing updates
  - Need to avoid routing oscillation between space and ground networks
- Multi-layer networking
  - Layers include systems that are Earth-based, GEO, LEO, HEO, Lunar, and Deep-Space
  - A variety of communication techniques covering laser and radio technologies
- Control of Reconfigurable Optics
  - Both Space-based and Earth-based Transceivers
  - Separated Control and Forwarding?
- Disruption Tolerant Networking
  - Capable of tolerating latencies or disruptions from milliseconds to several hours
- QoS and Path Selection
  - Constellation networks will need to support multiple gateways based on environmental conditions and traffic types
  - Seam location has remarkable effects on satellite network performance
  - Priority paths and load balancing for congestion avoidance
- **Security, Trust and Reliance notably missing**

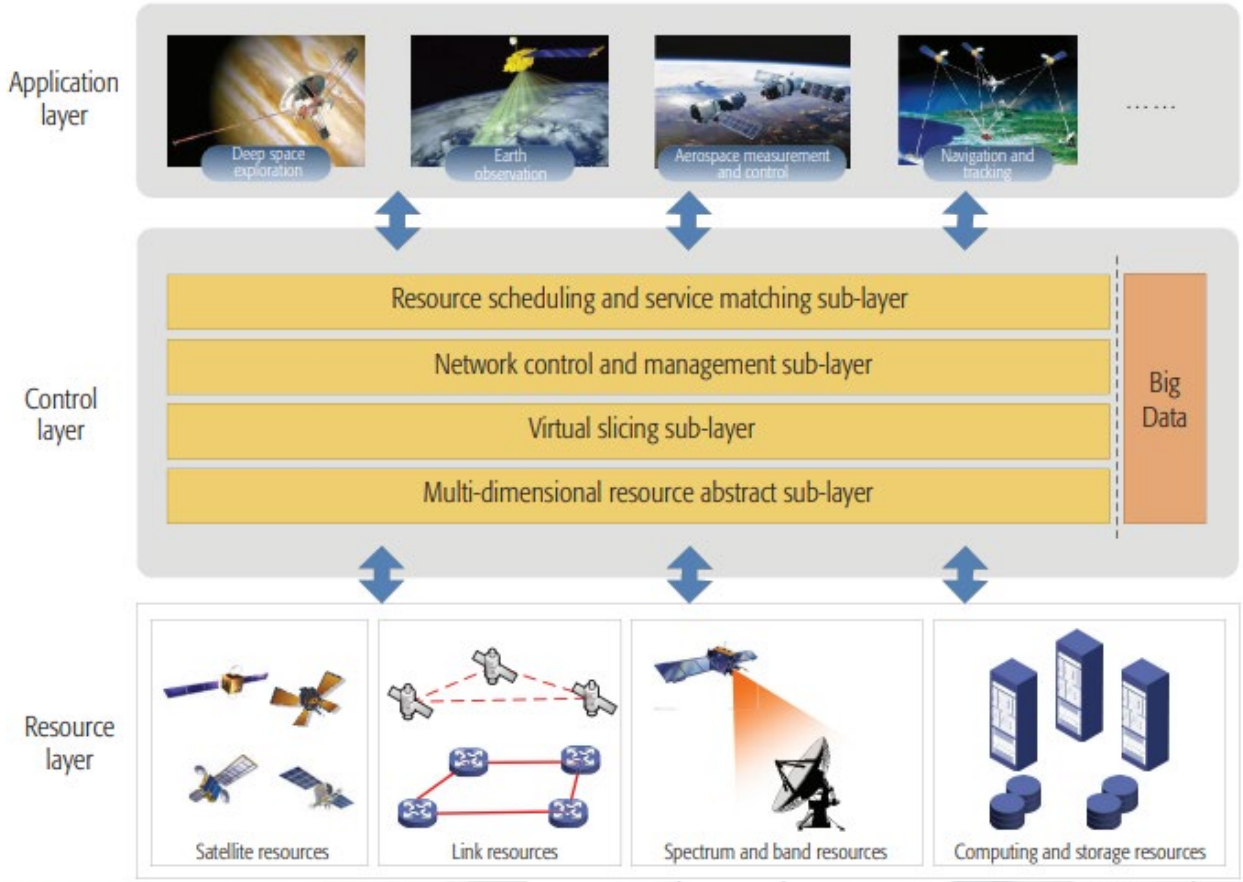
Optical Space Communication Networks
User Types

- Control mechanisms would also need to apply to different network users
  - Space-based
  - Aviation
  - Marine
  - Vehicles
  - Mobile



Optical Space Communication Networks
Need for a logical framework

- A logical framework for hybrid FSO networks
  - Integrating traffic engineering and bandwidth management via an network control layer , supporting both offline and online computation
  - Use data at ingress routers for traffic engineering and routing when the network is online
  - Virtual network slicing
  - Multi-dimensional resource management



F. Song, Y. Zhou, L. Chang and H. Zhang, "Modeling Space-Terrestrial Integrated Networks with Smart Collaborative Theory," in *IEEE Network*, vol. 33, no. 1, pp. 51-57, January/February 2019.

Optical Space Communication Networks
Role of SDOs

Org Website	www.aiaa.org	www.iso.org	www.ccsds.org
Stds Library	Click Here	Click Here	http://public.ccsds.org/publications/
# of Standards	~75 published, 12 in work	~206 published, 42 in work	160 published; 89 in work
Standards costs	Free for AIAA members Others pay (~page count based)	Pay per document (Sampling, $50 to $180)	Free
Organization Structure	**US-based** non-profit professional organization but encourages international participation.	**International body** composed of representatives from many national standards bodies.	**International body** Led by 11 government space agencies, but with commercial, industrial, academic participants.
General scope and topic focus	► Aerospace professional standards ► Broad range of topics: Hardware, processes, data. ► Guides, practices and standards.	► Space Systems & Ops ► Operations and quality processes ► System standardization other than data/comm (HW, etc.)	► Space Data and Comm Systems ► Interfaces and data exchange. ► Focused on interoperability between organizations

Optical Space Communication Networks
Role of SDOs

- IRTF
  - Global Access to the Internet for All (gaia)
  - Delay-Tolerant Networking Research Group DTNRG – **Concluded**
    - Published "Delay-Tolerant Networking Architecture" RFC 4838
  - Interplanetary Internet Research Group (IPNRG) - **Concluded**
  - Network Complexity Research Group NCRG - **Concluded**
  - Routing Research Group RRG - **Concluded**
- ITU-T
  - FG Network 2030
    - Focus Group on Technologies for Network 2030 https://www.itu.int/en/ITU-T/focusgroups/net2030/Pages/default.aspx

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Questions?

Thank you

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