Key enabling technologies, applications and open research topics in 6G networks

2023-11-20

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POLYTECHNIQUE FACTS AND FIGURES

- Over 10,000 students as of Fall 2022
  - 29% women
  - 29% international students
  - 24% graduate students
- 2,150 diplomas awarded in 2021-2022
  - 57,106 graduates since 1873
- Over 120 programs
- Over 300 professors
  - 19% women
- 1,500 employees
- Annual institutional budget of $300 million

Outline

- Satellite Networks - Now
- Satellite Networks - Towards 6G
- Helper Layer: High Altitude Platform Stations
- What else?
- Open Research Topics
- Conclusions

POLYTECHNIQUE MONTRÉAL

UNIVERSITÉ D'INGÉNIERIE

Satellite Networks - Now

Satellites

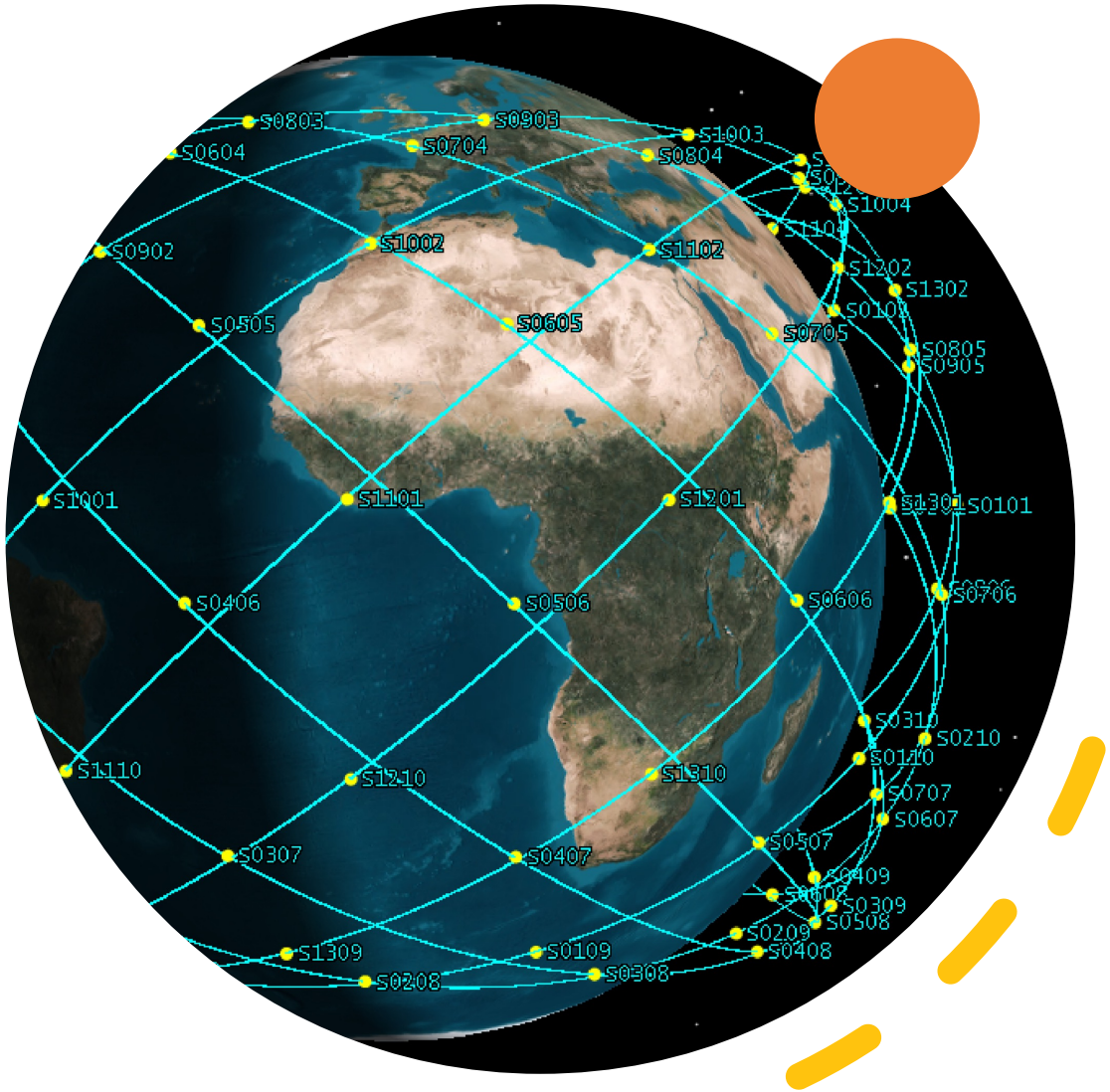
- A satellite is a human-made object that is placed into orbit around Earth
  - There are also satellites around other celestial bodies, such as Mars ☺
- Satellites are used for :
  - Communication
  - Navigation/localization (e.g. GPS -Global Positioning System)
  - Earth observation/remote sensing
    - To gather data about the Earth and its environment
    - This application included weather monitoring satellites
  - Scientific/radioastronomy
  - Military applications
- Overall, there are many different types of satellites that serve a variety of purposes, from communication and navigation to scientific research and military applications.

Satellites according to altitudes

- Low-Earth Orbit (LEO)
  - 300 – 1500 km
- Medium-Earth Orbit (MEO)
  - 7000 – 25000 km
- Geostationary Earth Orbit (GEO) satellite
  - 35 786 km
- High Elliptical Orbit (HEO)
  - 400 – 50000 km

Transformation in Satellite Industry (1/2)

- The momentum behind the satellite communications and networking area is substantial.
- The ambitious plans about satellite mega-constellations with thousands of low Earth orbit (LEO) satellites clearly demonstrate the rejuvenated interest in satellite communications and networking by the industry ecosystems and standardization organizations.
- These developments are further fueled by technological innovations in ;
  - advanced payload architectures
  - active antenna systems,
  - microwave, digital and optical technologies,
  - solar panels and batteries
  - ground segment technologies

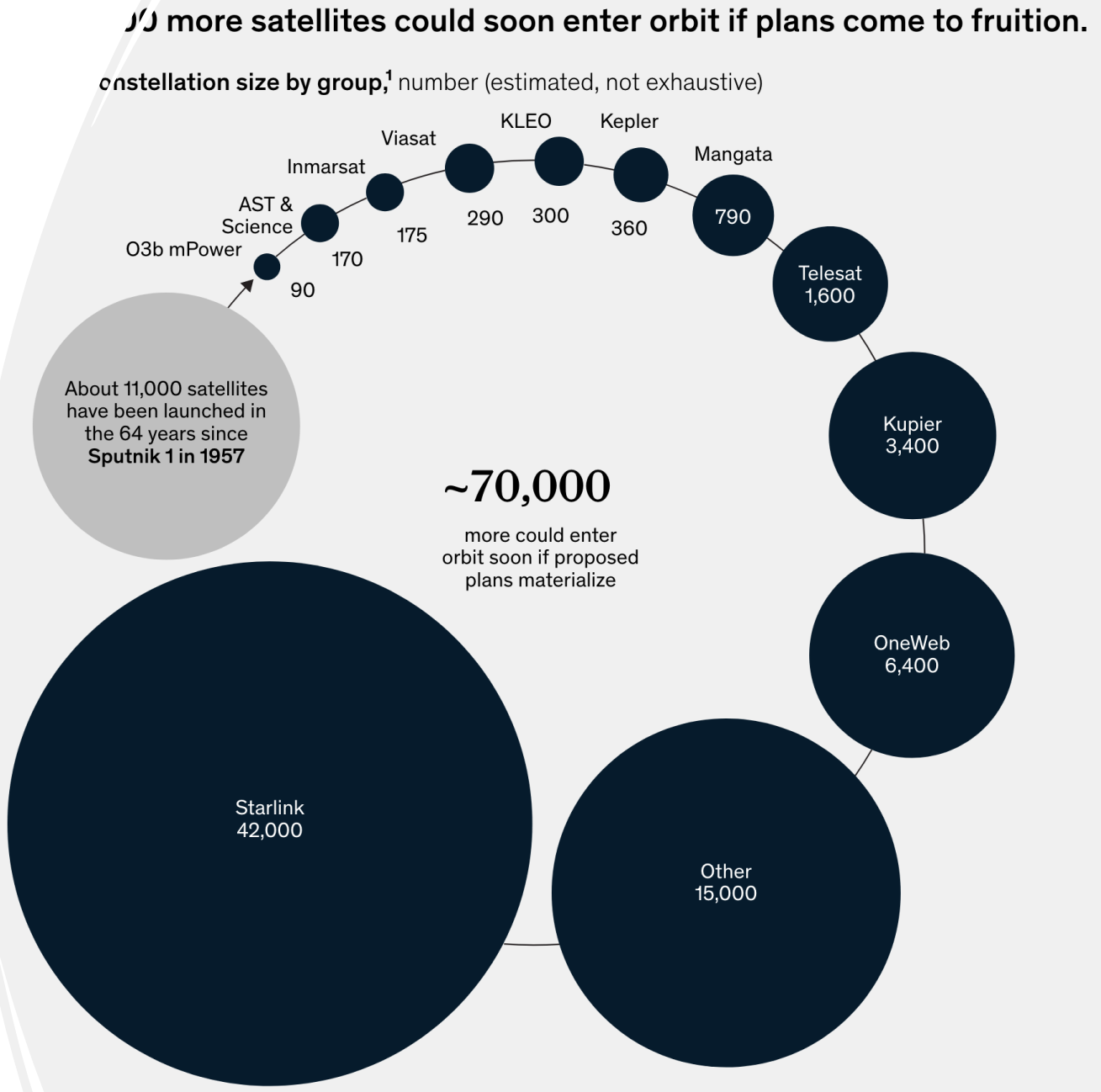


Transformation in Satellite Industry (2/2)

- One main difference between the legacy satellite systems and the mega-constellations of the 6G era satellite systems is the networking complexity.
- Next-generation satellite networks have very high-speed inter-satellite links in addition to highly flexible resource allocation.
  - For efficient operation, the networks are expected to be autonomous, intelligent, resilient, self-organizing and self-controlling as much as possible to reduce the cost of human intervention in highly complicated settings.

Satellite Networks (SatNets)

- Many countries and companies have launched numerous satellites
- Forecasts of dense LEO networks:
  - Starlink ~ 42,000 LEO
  - OneWeb ~6,300
  - Kuiper ~ 3,200
  - Telesat ~ 1,600



https://www.mckinsey.com/featured-insights/the-next-normal/space

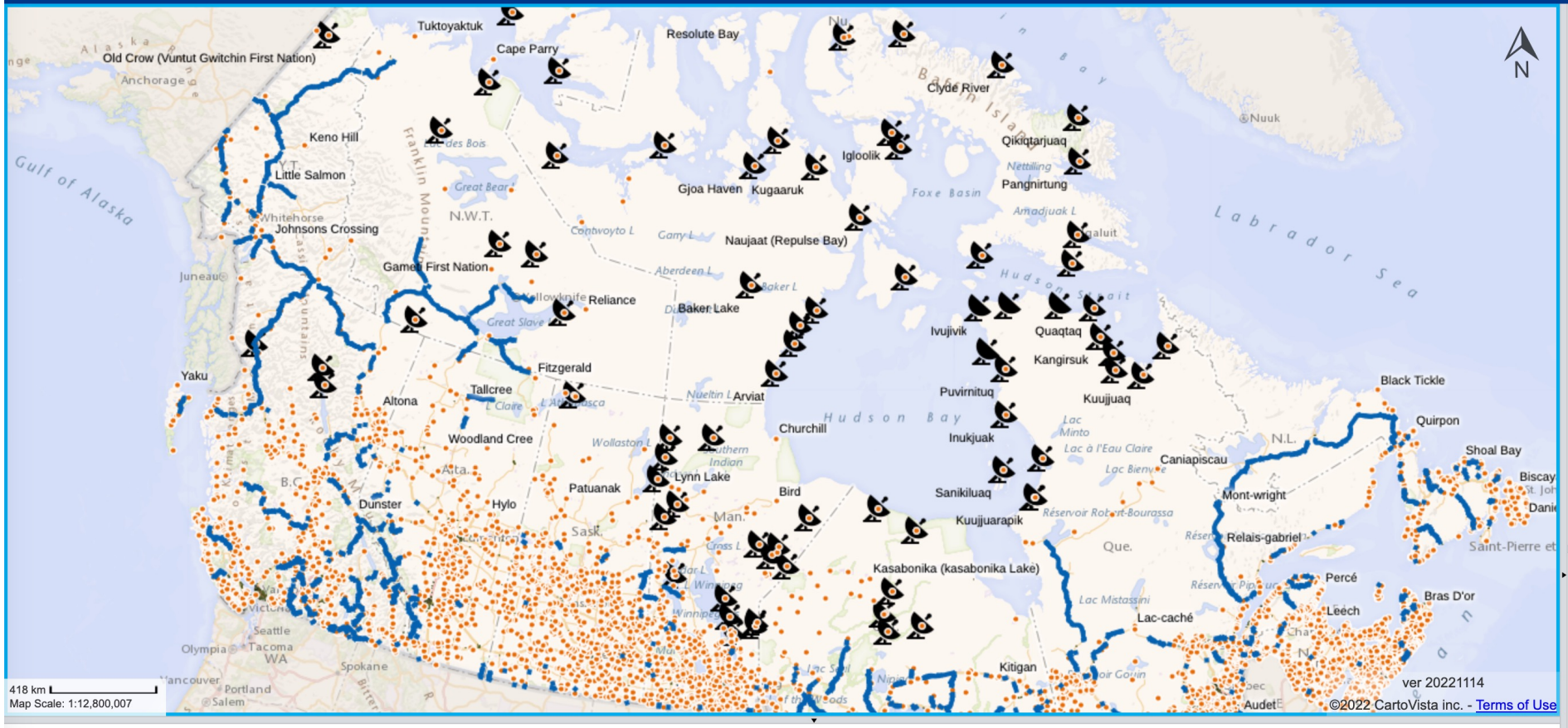
Transition to LEO Mega-Constellations

- When orbital period decreases as satellites move from GEO to LEO and very low earth orbit (VLEO), there are several consequences (in terms of communications) for a ground station:
  - There will be gaps in coverage unless a proliferated constellation of the same satellite is in orbit.
  - Observation time per satellite decreases significantly as orbit altitude is reduced.
  - The required complexity of earth station antennas decreases.
  - There is reduced signal delay with decreasing altitude.

Call 3 Eligibility Map

EN

CartoVista



Eligible Roads

1099838 - 2
1099844 - 2
1122281 - Principale
1122388 - Principale
1127312 - Principale
1131196 - Grande Ligne
1131804 - Principale
1132163 - 293
1132451 - 232
1138788 - 289
1138934 - Principale
1143241 - Route 17
1143732 - Route 17
1143735 - Route 17
1143739 - Route 17
1143744 - Route 17

Eligible Roads

Eligible Transport Communities

Satellite Dependent Communities

Population Centres

large urban population centres, with a population of 100,000 or more (35)

medium population centres, with a population between 30,000 and 99,999 (59)

small population centres, with a population between 1,000 and 29,999 (936)

Eligible Roads

Eligible Road ID	Road Name	Length of segment (km)	Road Rank	Class
1956060	66	0.84	1	12
5138439	11	1.51	1	12
6006900	1	0.07	1	12
2801065	11	0.29	1	12
4096646	Trans Canada	0.53	1	12
4437748	Yellowhead	0.03	1	12
5138063	17	1.30	1	12
3259014	Dempster	21.68	2	12

2023-11-20

https://crtc.gc.ca/cartovista/Call_3_Eligibility_map_en/index.html

Data(5,520)

Selection

Can mega-constellations bridge the digital divide?

GALAXUS

Wonach suchst du?

- Gesamtsortiment
- IT + Multimedia
- Netzwerk
- Bridges + Router
  - Access Point
  - Netzwerk Switch
  - Powerline
  - **Router**
  - WLAN Repeater

Angebote

Sale Router %

Verwandte Kategorien

Access Point
Netzwerk Zubehör
Netzwerkadapter
WLAN Repeater

Gesamtsortiment > IT + Multimedia > Netzwerk > Bridges + Router > Router > Starlink Standard Kit

8 Bilder

-33%

299,– statt 449,–

Starlink Standard Kit

Preis in EUR inkl. MwSt., kostenloser Versand

Bewertungen
★★★½☆ 44

Marke
Mehr von Starlink

Vorbestellung ohne bestätigten Liefertermin
Mehr als 10 Stück bestellt

Benachrichtigen, wenn lieferbar

In den Warenkorb

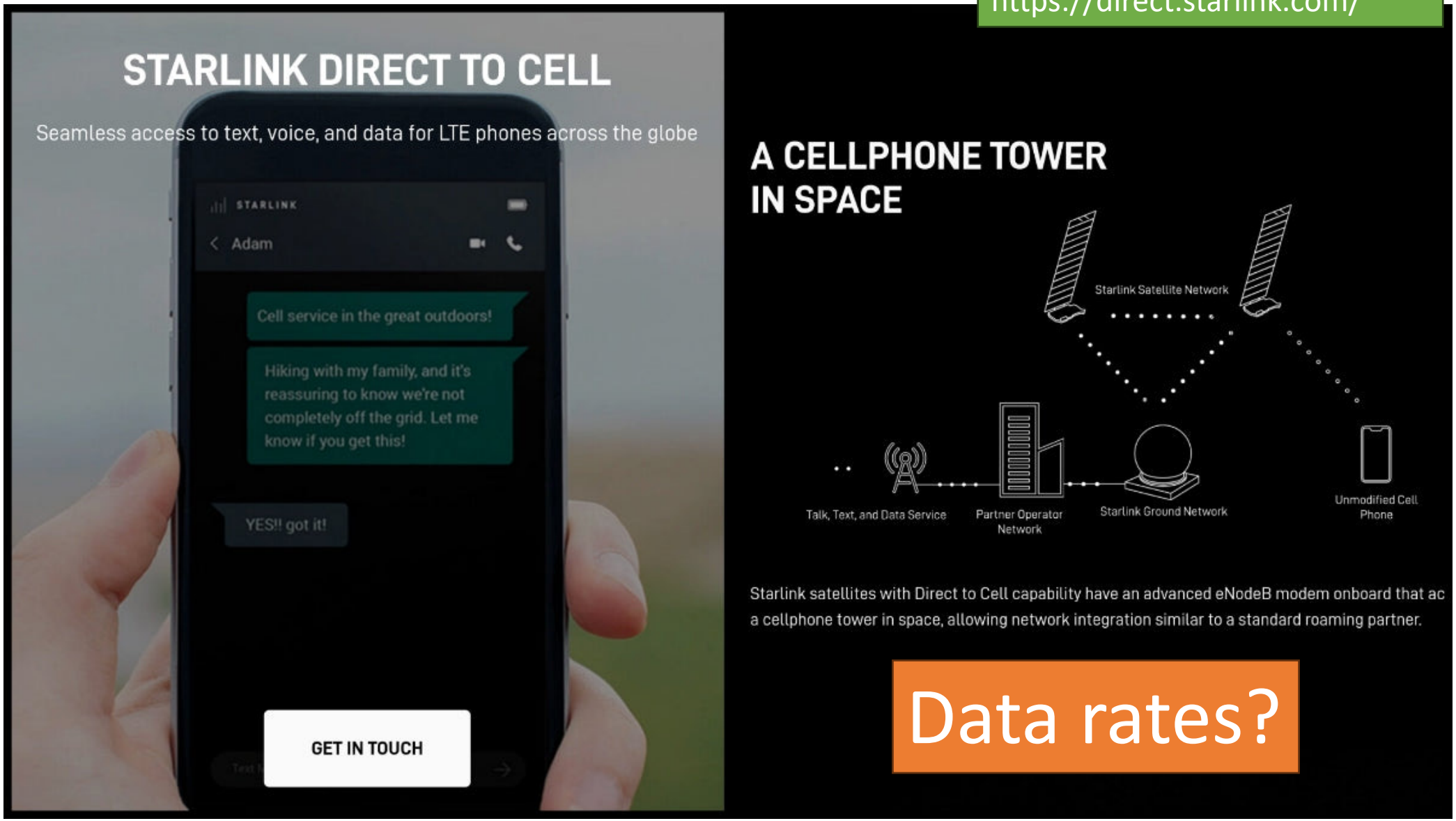
Vergleichen

Merken

2023-11-20

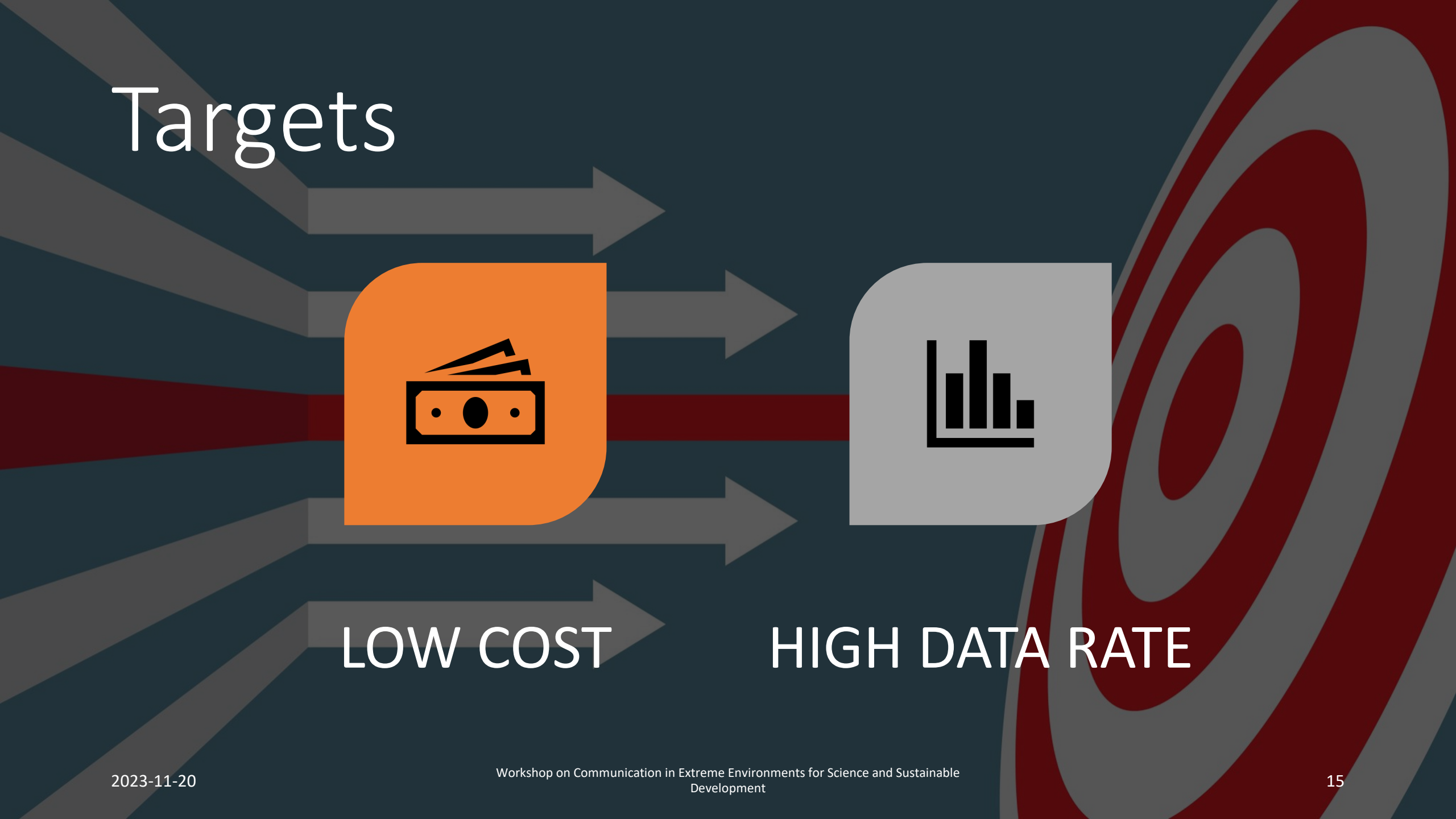
Captured on 2023-11-19

https://direct.starlink.com/



Data rates?

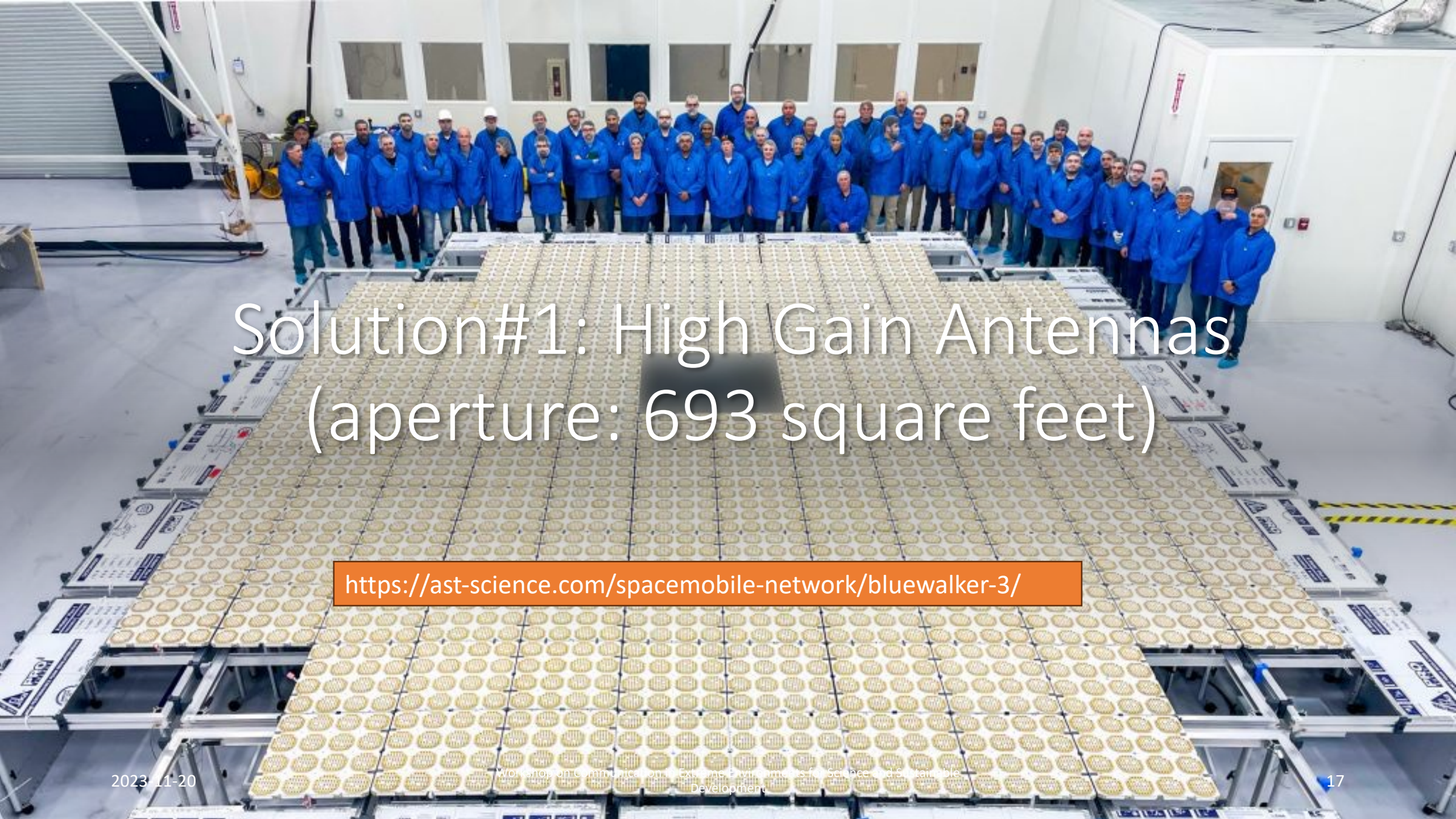
Targets



LOW COST

HIGH DATA RATE

How can we enable high rate direct to cell connectivity?



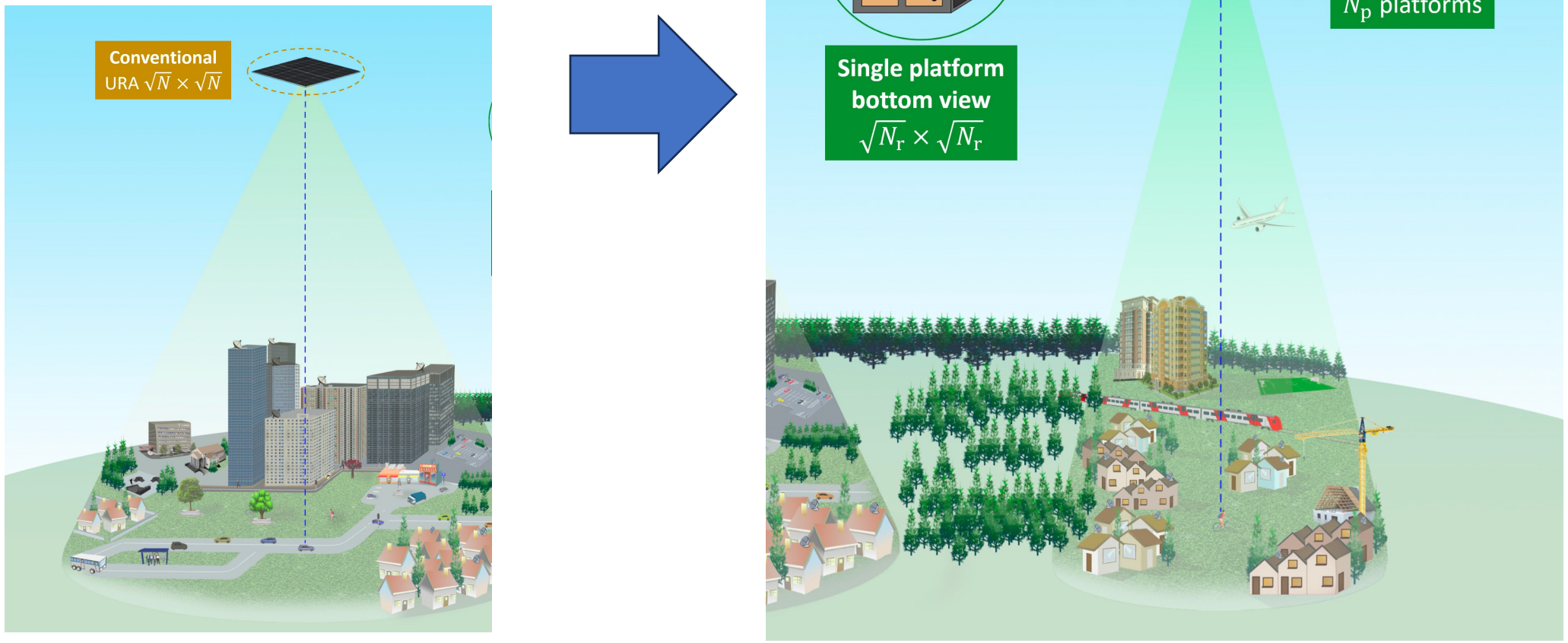
Solution#1: High Gain Antennas (aperture: 693 square feet)

https://ast-science.com/spacemobile-network/bluewalker-3/

Solution #2: Multiple Satellites

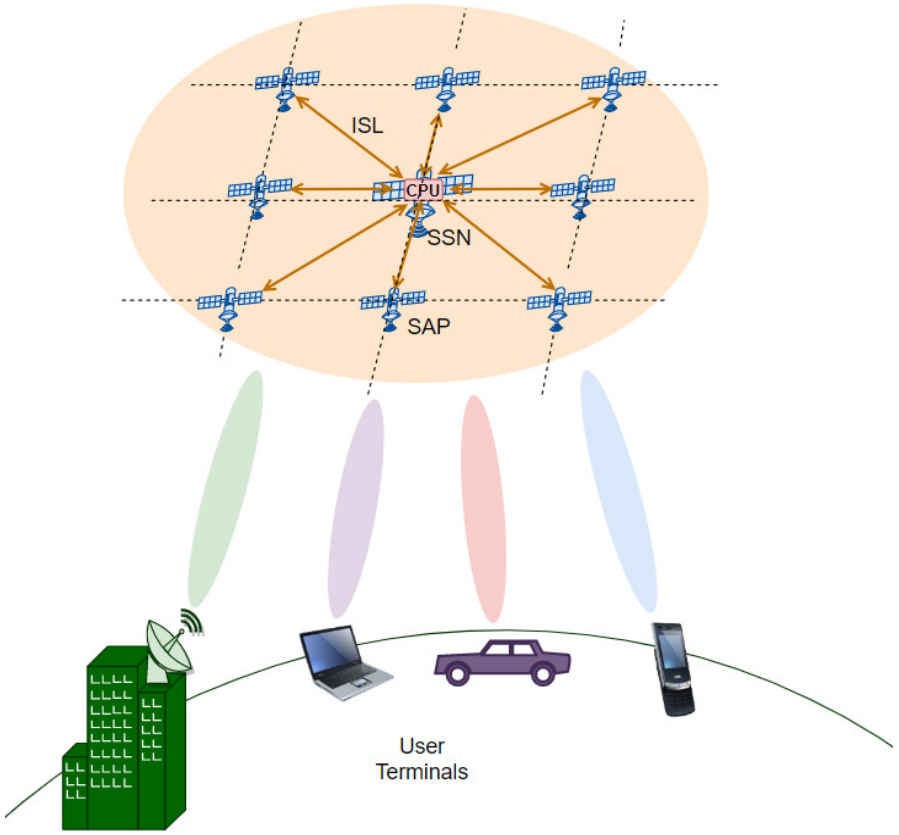
- Satellite Swarms
- Cell-free Massive MIMO

Satellite Swarms



D. Tuzi, E. Flores Aguilar, T. Delamotte, G. Karabulut-Kurt and A. Knopp, “Distributed Approach to Satellite Direct-to-Cell Connectivity in 6G Non-Terrestrial Networks,” accepted forpublication, IEEE Wireless (2023)

Cell-Free Massive MIMO (1/2)

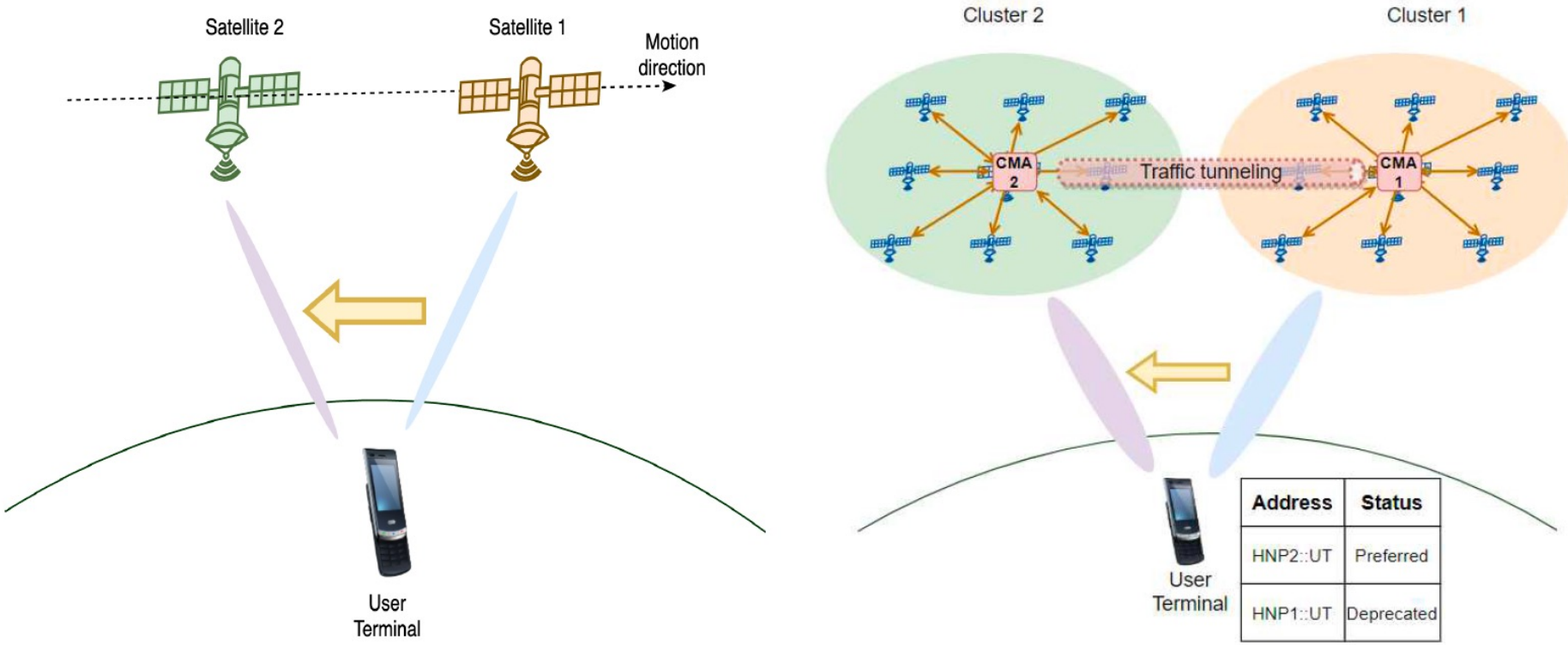


Design aspects:

- Duplexing technique,
- Pilot assignment,
- Beamforming,
- Handover management,
- …

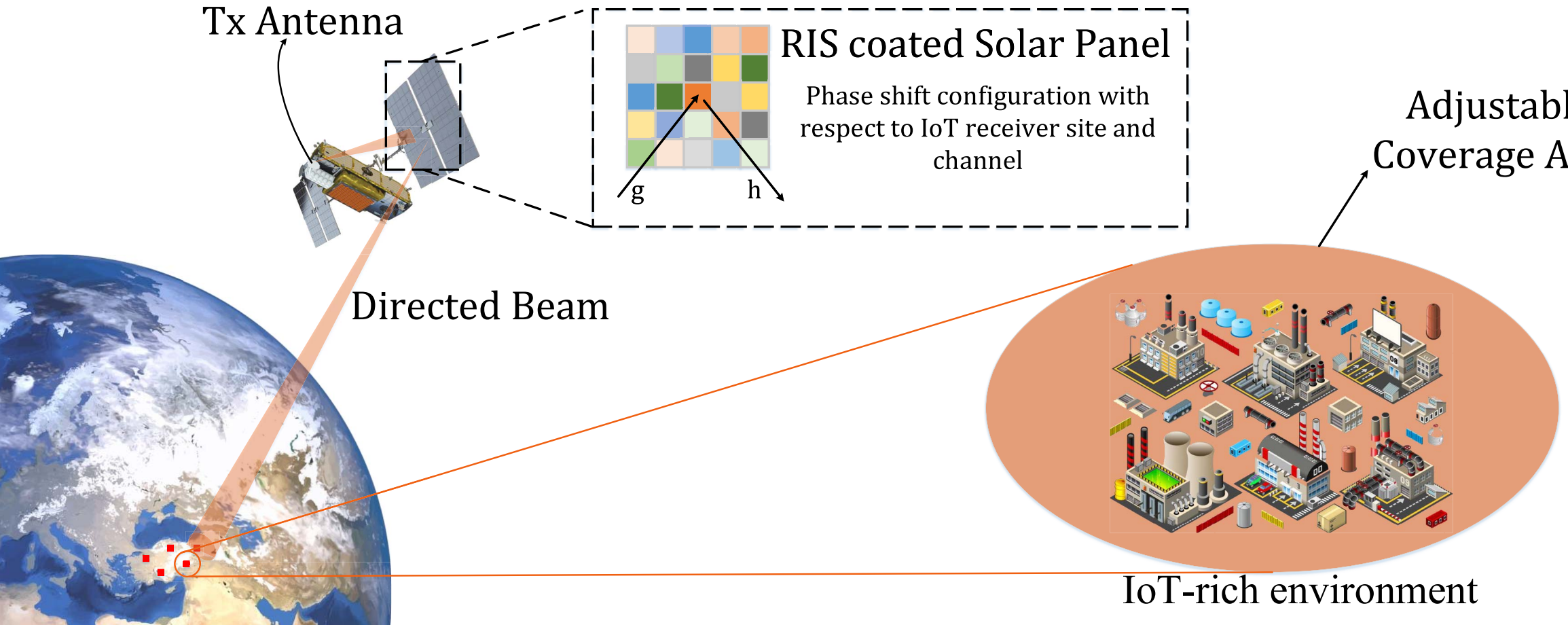
M. Abdelsadek, H. Yanikomeroglu, and G. Karabulut Kurt, “Future Ultra-Dense LEO Satellite Networks: A Cell-Free Massive MIMO Approach,” in IEEE International Conference on Communications (ICC) Workshop - SatMegaConst , Montreal (Virtual), Canada, 14-23 June, 2021.

Cell-Free Massive MIMO (2/2)



M. Abdelsadek, G. Karabulut Kurt, and H. Yanikomeroglu, “Distributed Massive MIMO for LEO Satellite Networks,” in IEEE Open Journal of the Communications Society, vol. 3, November 2022.

Solution #3: Reflective Intelligent Surfaces (RISs)



K. Tekbiyik, G. Karabulut Kurt, and H. Yanikomeroglu, "Energy-Efficient RIS-Assisted Satellites for IoT Networks," IEEE Internet of Things Journal, vol. 9, no. 16, August 2022.

Satellite Networks - Towards 6G

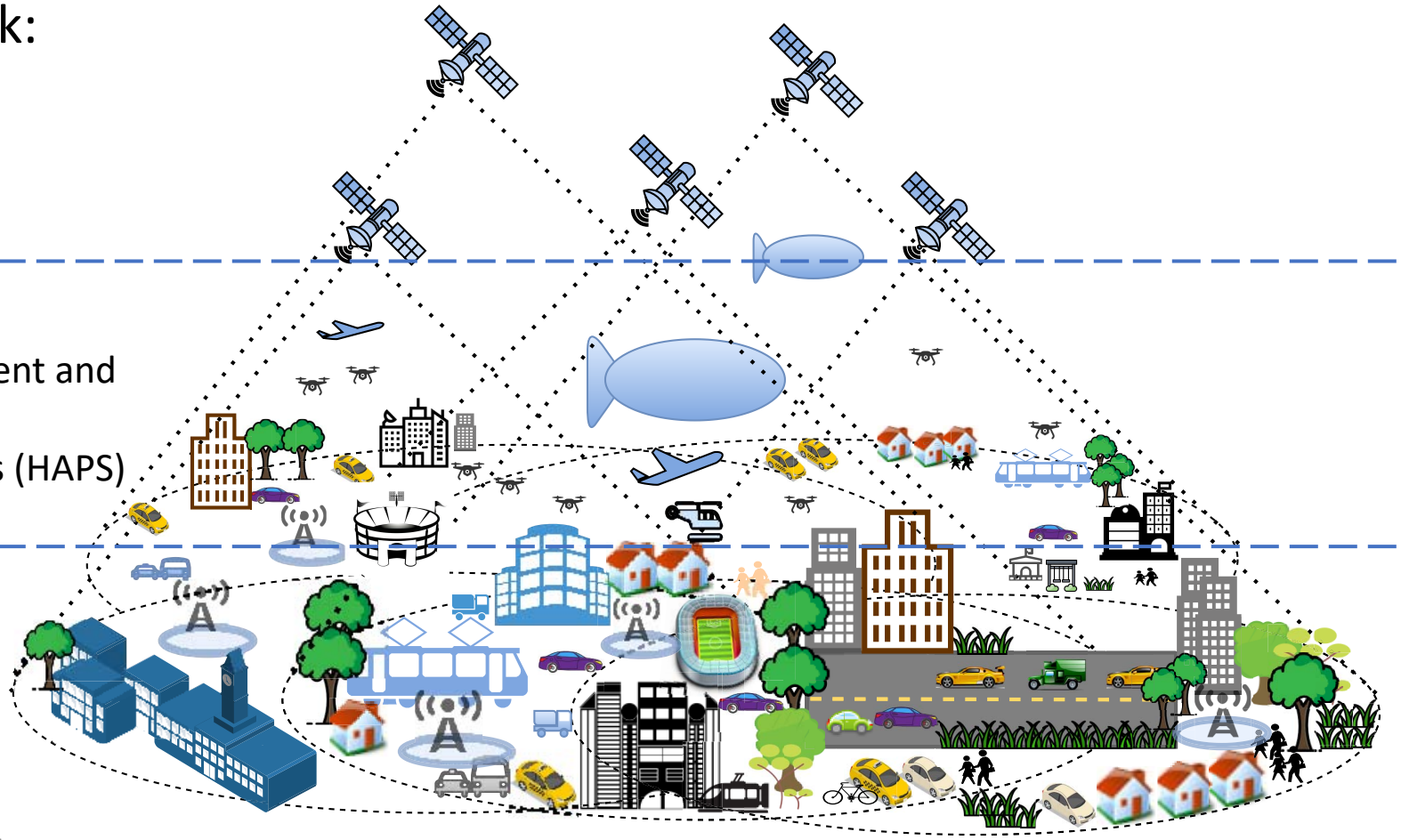
Integration of Terrestrial and Satellite Networks

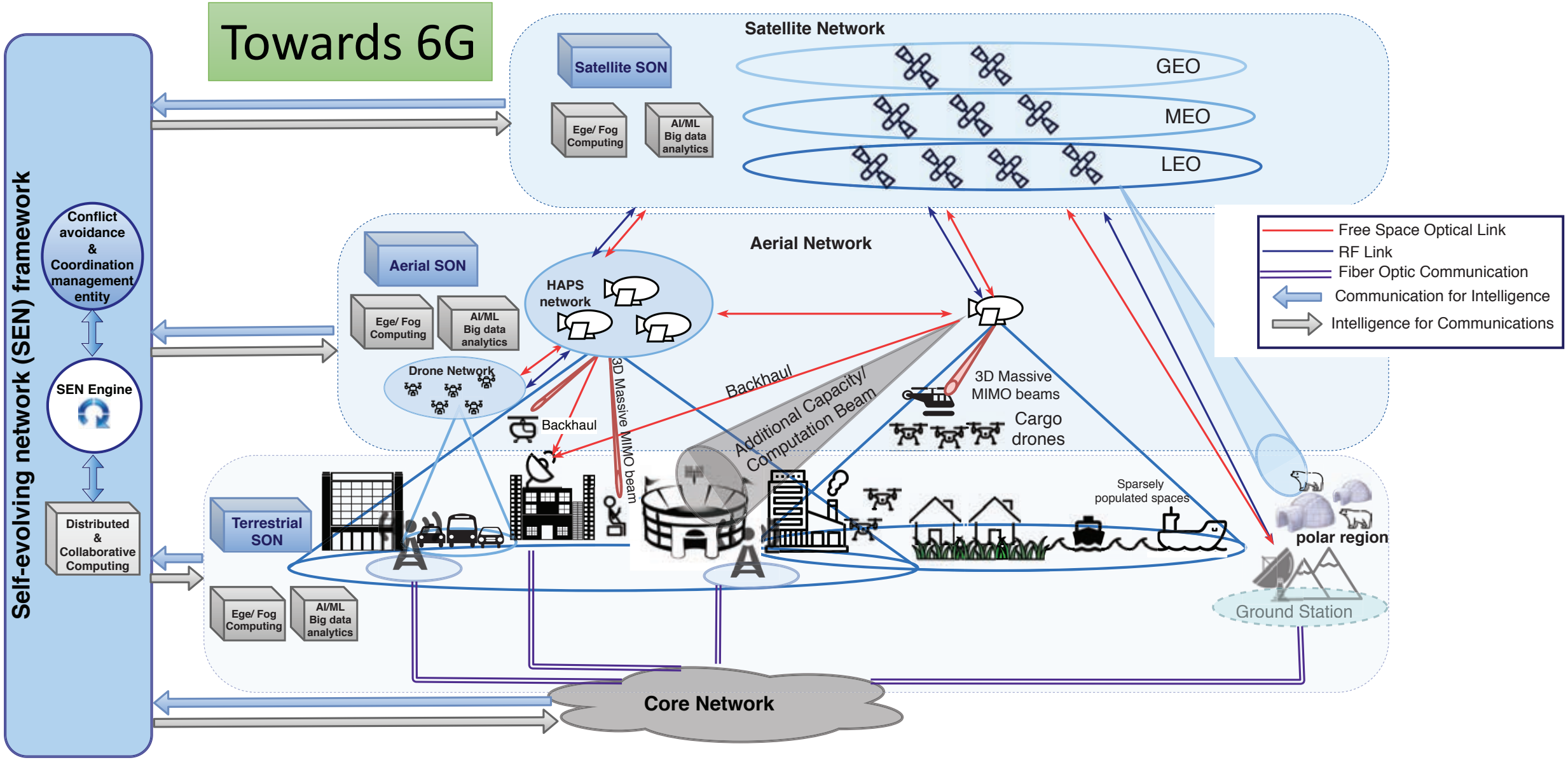
6G is envisioned as a vertical network:

3. Satellite Network :
   - VLEO/LEO/MEO/GEO

2. Aerial Network :
   - Drones (both as user equipement and base station)
   - High Altitude Platform Stations (HAPS)

1. Terrestrrial Network





T. Darwish, G. Karabulut Kurt, H. Yanikomeroglu, G. Senarath, and P. Zhu, "A Vision of Self-Evolving Network Management for Future Intelligent Vertical HetNet," in IEEE Wireless Communications, vol. 28, no. 4, Aug. 2021.

Release 16: Not so distant future

Platforms	Altitude range	Typical beam footprint size
Low-Earth Orbit (LEO) satellite	300 – 1500 km	100 – 1000 km
Medium-Earth Orbit (MEO) satellite	7000 – 25000 km	100 – 1000 km
Geostationary Earth Orbit (GEO) satellite	35 786 km	200 – 3500 km
UAS platform (including HAPS)	8 – 50 km (20 km for HAPS)	5 - 200 km
High Elliptical Orbit (HEO) satellite	400 – 50000 km	200 – 3500 km

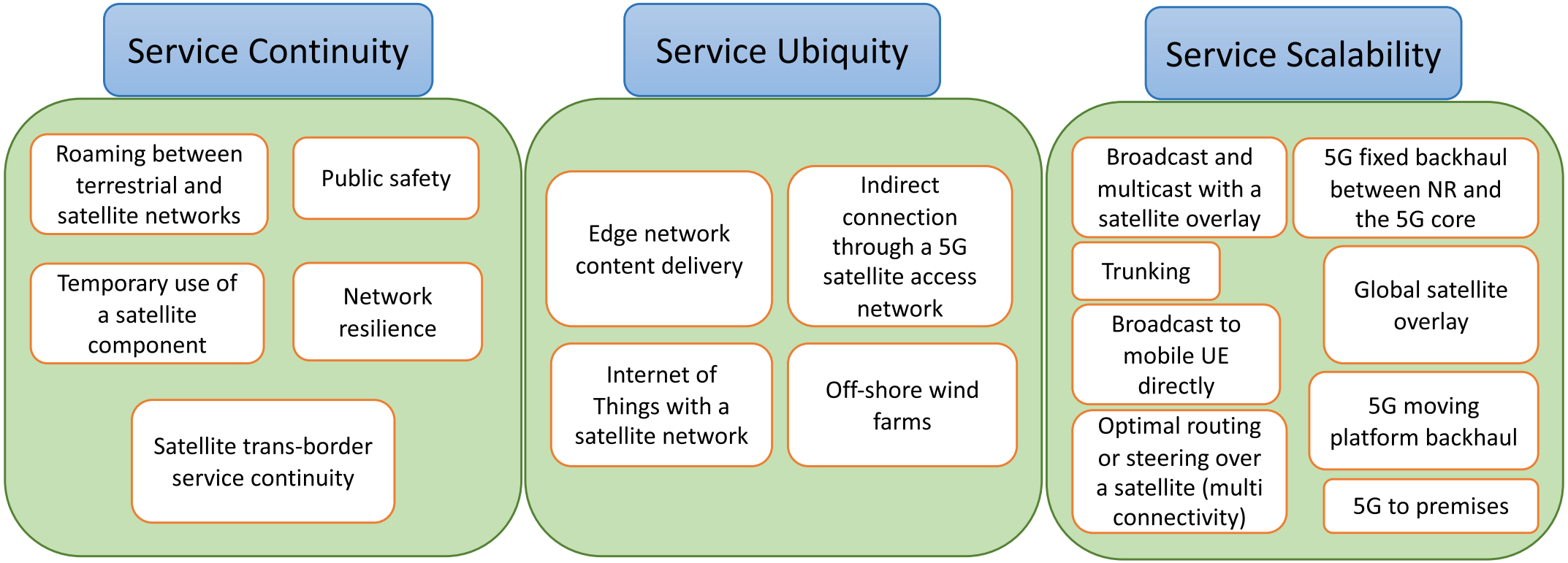
Table 4.1-1 Types of NTN platforms , 3GPP TR 38.821 V16.1.0 (2021-05)

3GPP Satellite Related Standardization Activities

Release	Item code	TSG	Title	Status
Release 15	TR 38.811	RAN	Study on NR to support NTN	Completed October 2020
Release 16	TR 22.822	SA	Study on using satellite access in 5G	Completed June 2018
Release 17	TR 23.737 First stage	SA	Study on architecture aspects for using satellite access in 5G	Started Release 16, June 2018 Last update Release 17, March 2021
	TR 23.737 Second stage	SA	Integration of satellite components in the 5G architecture	Started June 2020 Last update June 2021
	TR 28.808	SA	Study on management and orchestration aspects with integrated satellite components in a 5G network	Completed March 2021
	TR 38.821	RAN	Solutions for NR to support NTN	Started Release 16, June 2018 Last update Release 17, June 2021
Release 18	920035 (5GSATB)	SA	5G system with satellite backhaul	Completed June 2021
	920034 (SCVS)	SA	5G system with satellite access to support control and/or video surveillance	Started June 2021

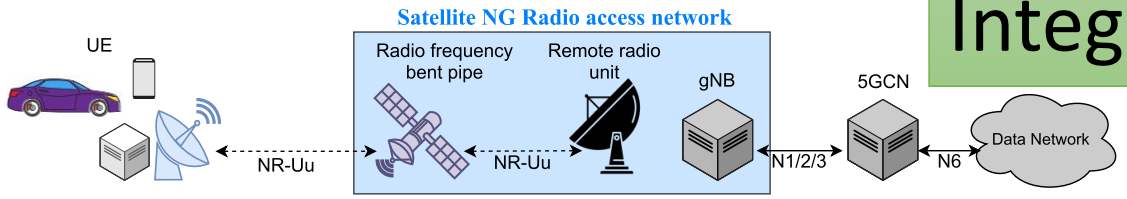
T. Darwish, G. Karabulut Kurt, H. Yanikomeroglu, M. Bellemare, and G. Lamontagne, “LEO Satellites in 5G and Beyond Networks: A Review from a Standardization Perspective,” in IEEE Access, vol. 10, March 2022.

Satellite Access Use-Cases for 5G & Beyond

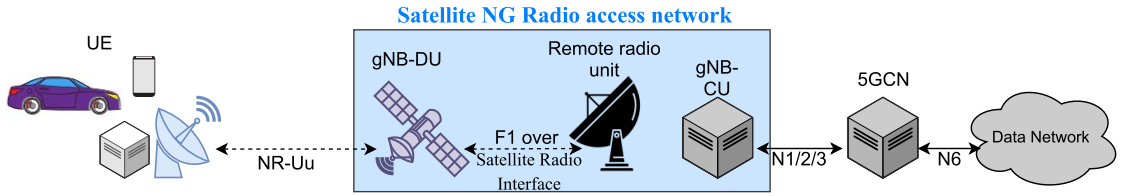


T. Darwish, G. Karabulut Kurt, H. Yanikomeroglu, M. Bellemare, and G. Lamontagne, "LEO Satellites in 5G and Beyond Networks: A Review from a Standardization Perspective," in IEEE Access, vol. 10, March 2022.

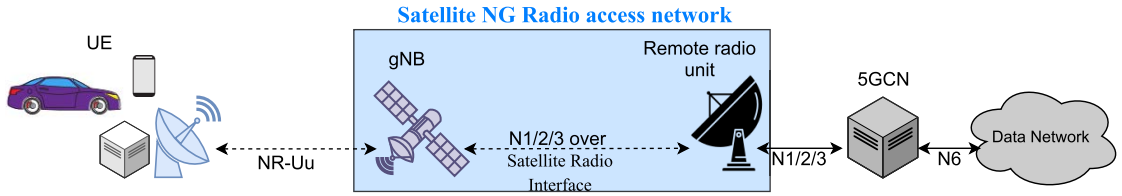
Terrestrial Network Integration



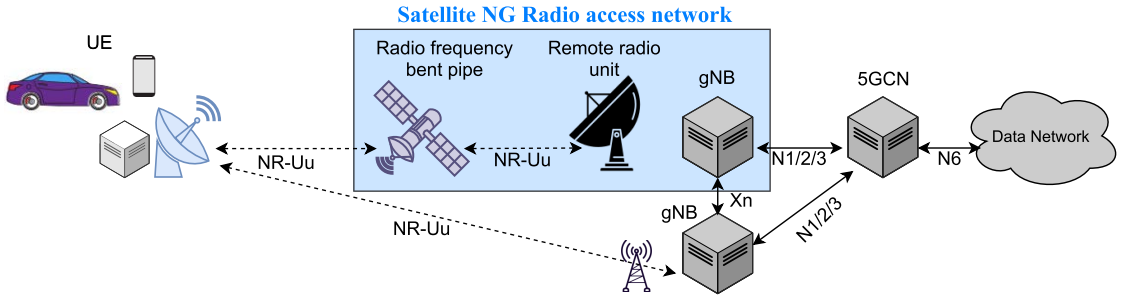
(a) NG-RAN architecture with transparent satellite



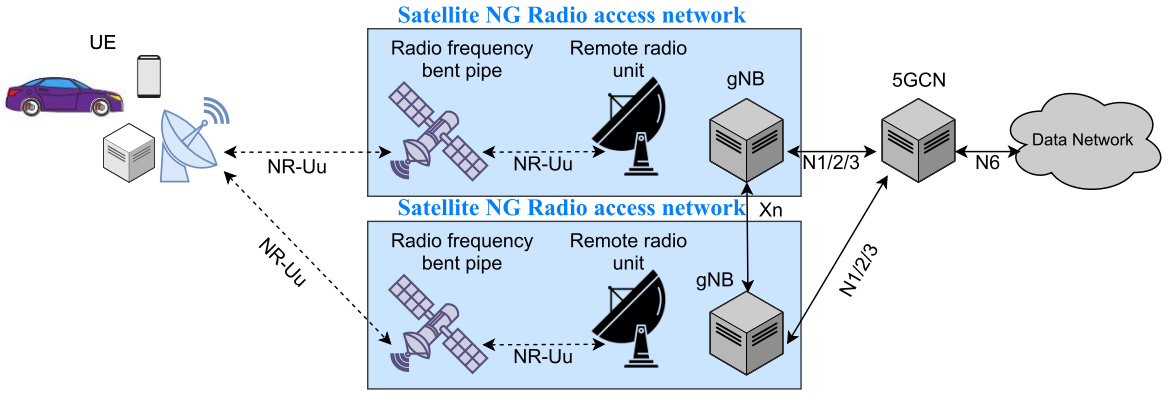
(b) NG-RAN with a regenerative satellite based on gNB-DU



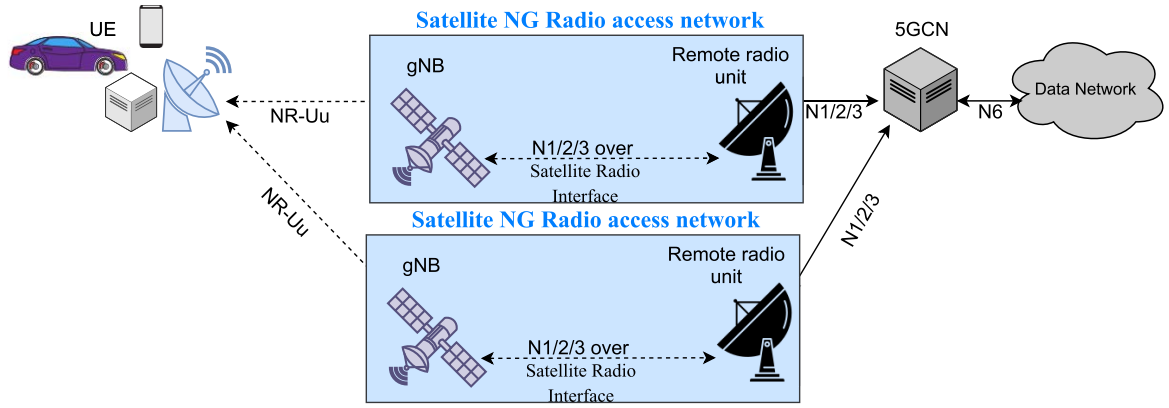
(c) NG-RAN with a regenerative satellite based on gNB processed payload



(d) Multi connectivity involving transparent satellite-based NG-RAN and cellular NG-RAN



(e) Multi connectivity between two transparent satellite-based NG-RAN



(f) Multi connectivity between two regenerative satellite-based NG-RAN (gNB on board)

Solutions for NR to Support NTN, 3GPP, document TR 38.821, 2021.

How can we enable high rate direct to cell connectivity?

High Altitude Platform Stations

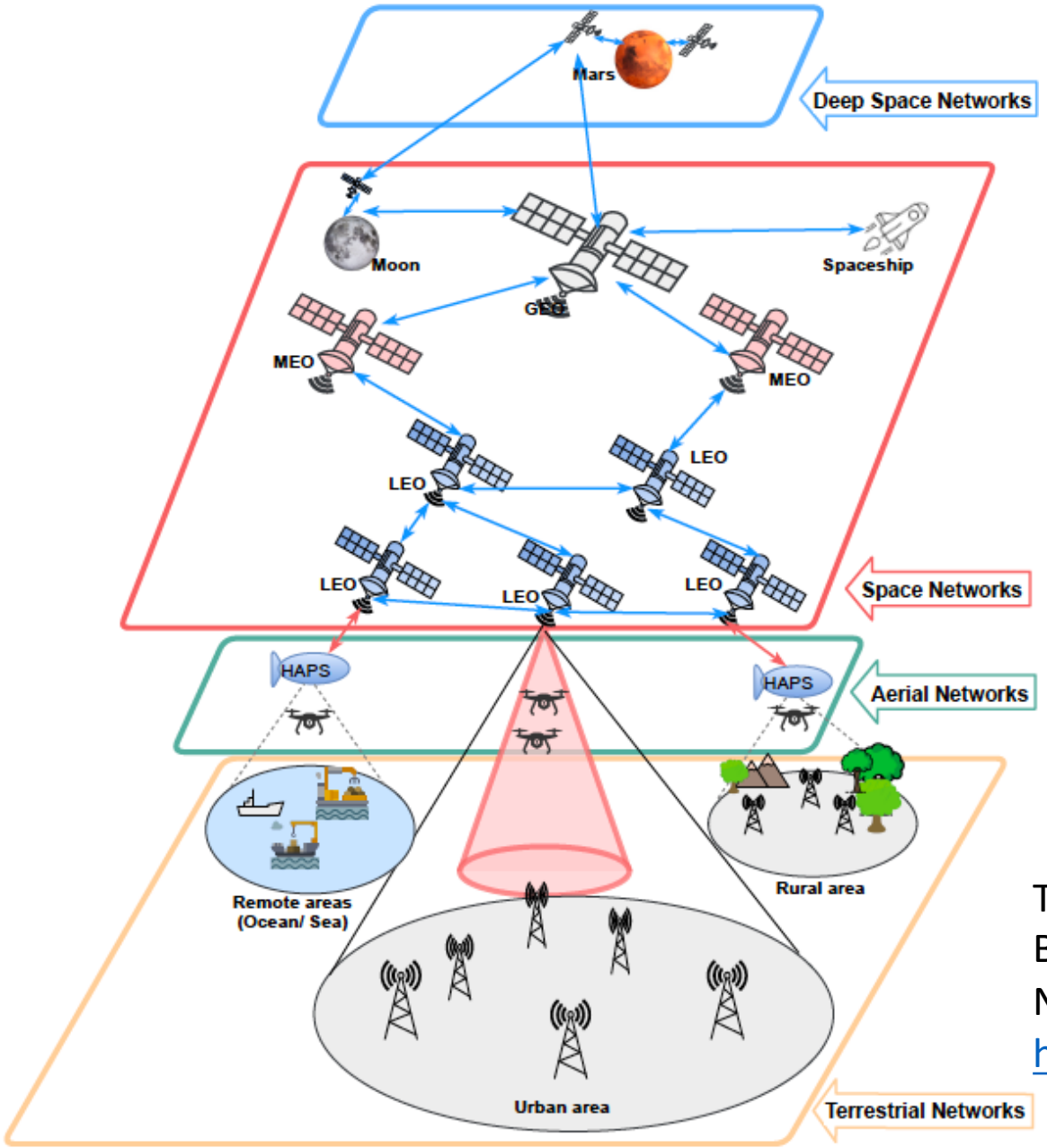
HAPS: A New (?) Network Element

- High altitude platform station (HAPS) systems operate in the stratosphere at an altitude of around 20 km
- A rather well established concept
- Triggered by industry ecosystems & technological innovations:
  - Autonomous avionics,
  - Array antennas,
  - Solar panel efficiency levels,
  - Battery energy densities

SHARP took its maiden flight on September 17, 1987 at Communications Research Centre http://www.friendsofcrc.ca/Projects/SHARP/sharp.html

https://www.itu.int/en/mediacentre/backgrounders/Pages/High-altitude-platform-systems.aspx

G. Karabulut Kurt, et. al., "A Vision and Framework for the HighAltitude Platform Station (HAPS) Networks of the Future," in IEEE CommunicationsSurveys and Tutorials, vol. 23, no. 2, Second Quarter, 2021



HAPS clusters serving as **Satellite Network Interface** will fuel the integration of terrestrial and satellite networks

T. Darwish, **G. Karabulut Kurt**, H. Yanikomeroglu, G. Lamontagne, M. Bellemare "Location Management in IP-based Future LEO Satellite Networks: A Review." *arXiv preprint arXiv:2101.08336* (2021). https://arxiv.org/abs/2101.08336

Possible solutions to overcome the connectivity challenges:

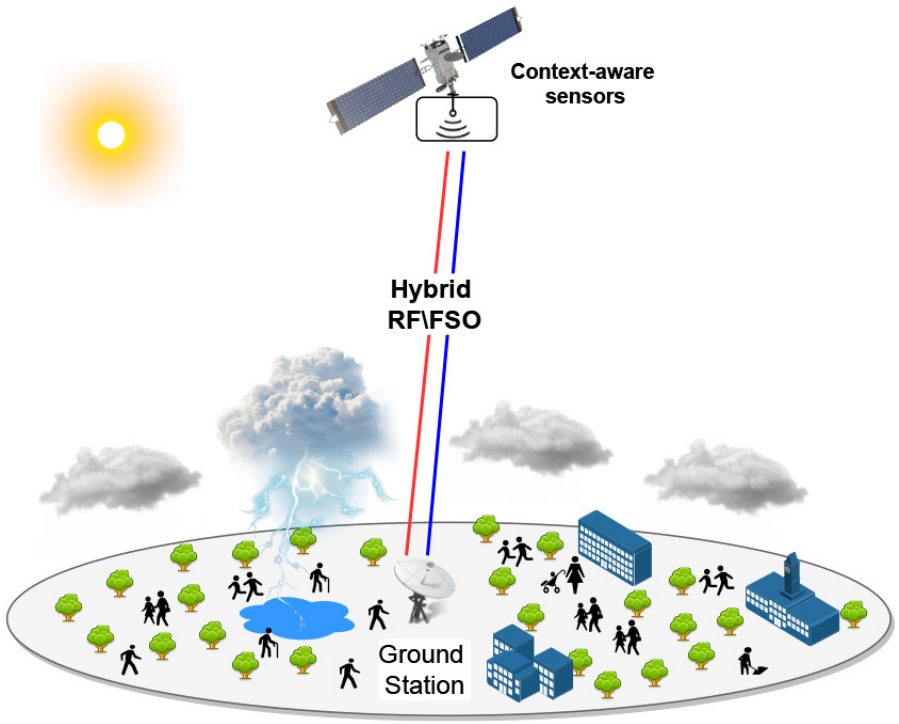
Use RF and FSO communications together to benefit from the complementary characteristics:

- Mixed RF-FSO
- Hybrid RF/FSO

Cooperative communications :

- Site diversity
- High-Altitude Platform Station (HAPS)
- HAPS Relay selection

Hybrid RF-FSO Links (1/2)



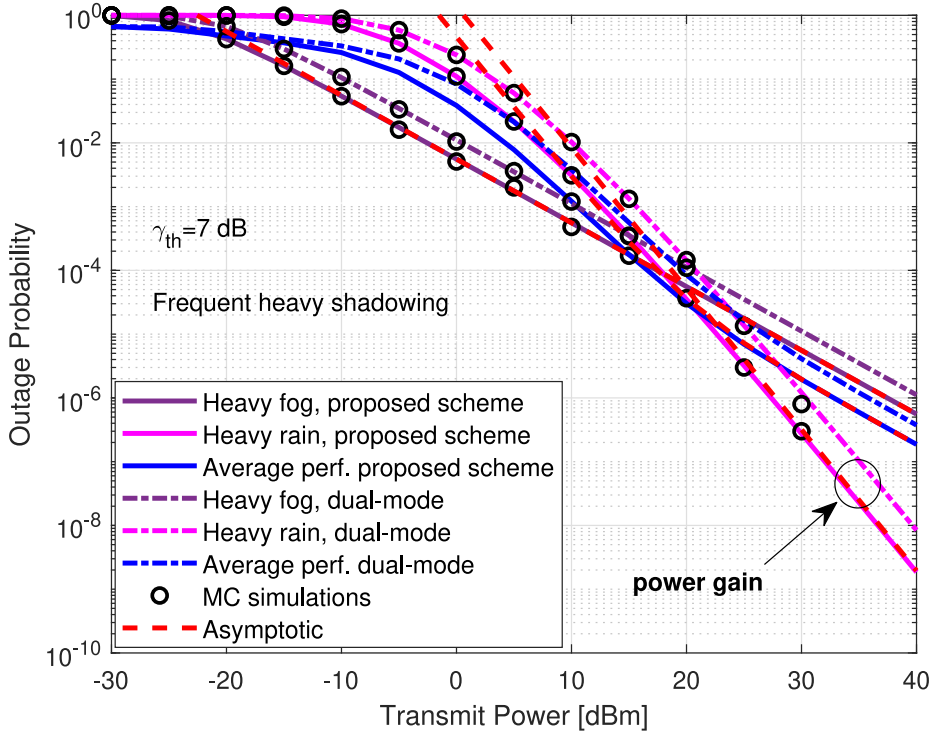
The satellite selects RF or FSO links depending on the weather conditions obtained from sensors and used for the context- awareness.

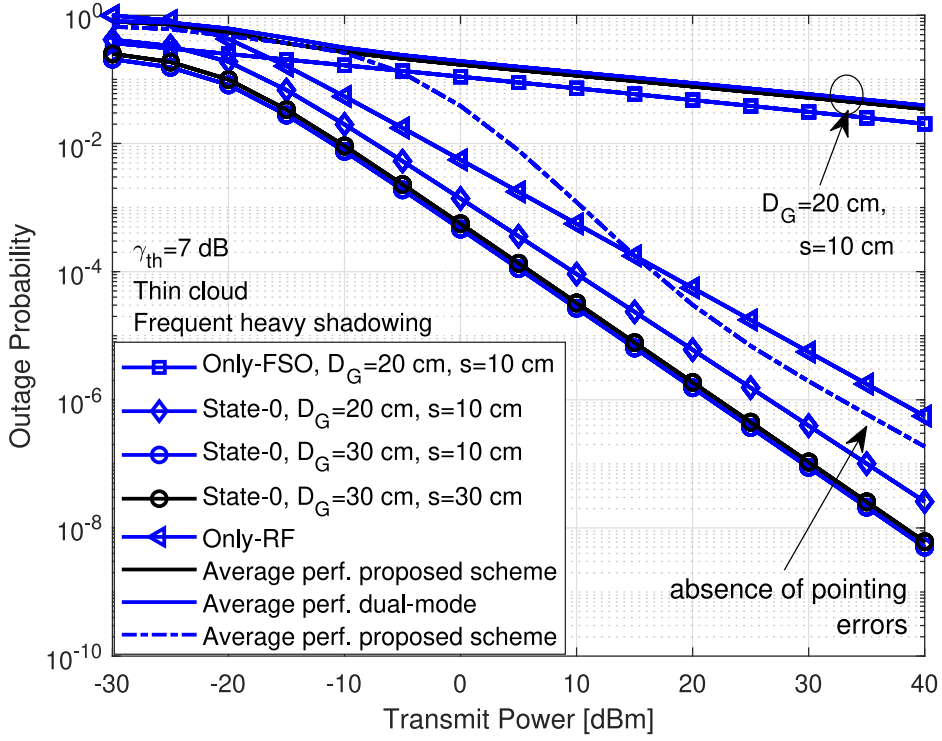
TABLE I
PROPOSED SCHEME

State (k)	Description	Observation	Transmission strategy
0	Thin Cloud	Both FSO and RF channels exhibit a higher performance	Dual (SC)
1	Rain	Only the FSO communication is favorable with full power	FSO
2	Fog	Only the RF channel is available with full power	RF

O. Ben Yahia, E. Erdogan, G. Karabulut Kurt, I. Altunbas, and H. Yanikomeroglu, "A Weather-Dependent Hybrid RF/FSO Satellite Communication for Improved Power Efficiency," in IEEE Communications Letters, vol. 11, no. 3, March 2022.

Hybrid RF-FSO Links (2/2)

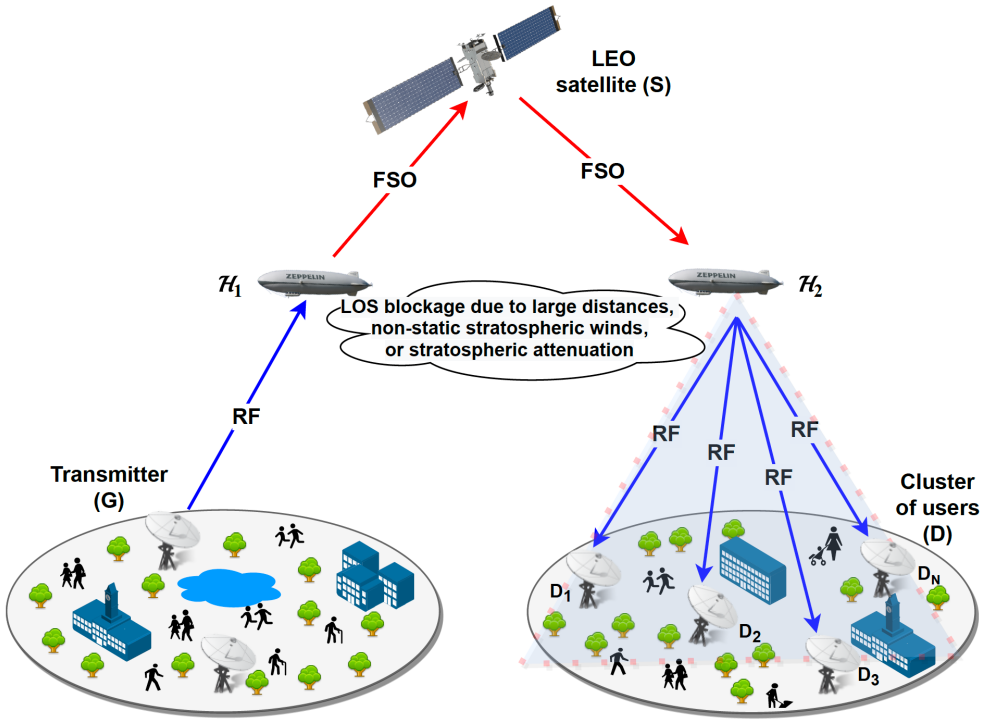




O. Ben Yahia, E. Erdogan, G. Karabulut Kurt, I. Altunbas, and H. Yanikomeroglu, "A Weather-Dependent Hybrid RF/FSO Satellite Communication for Improved Power Efficiency," in IEEE Communications Letters, vol. 11, no. 3, March 2022.

Cooperative Communications (1/2)

High-Altitude Platform Station (HAPS)

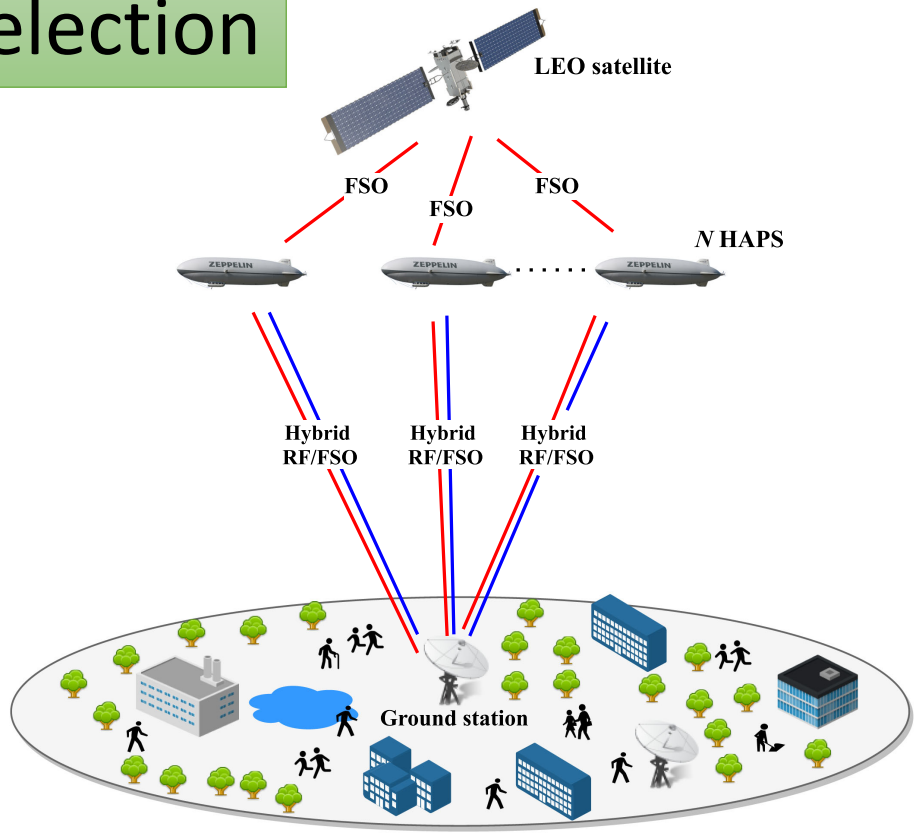


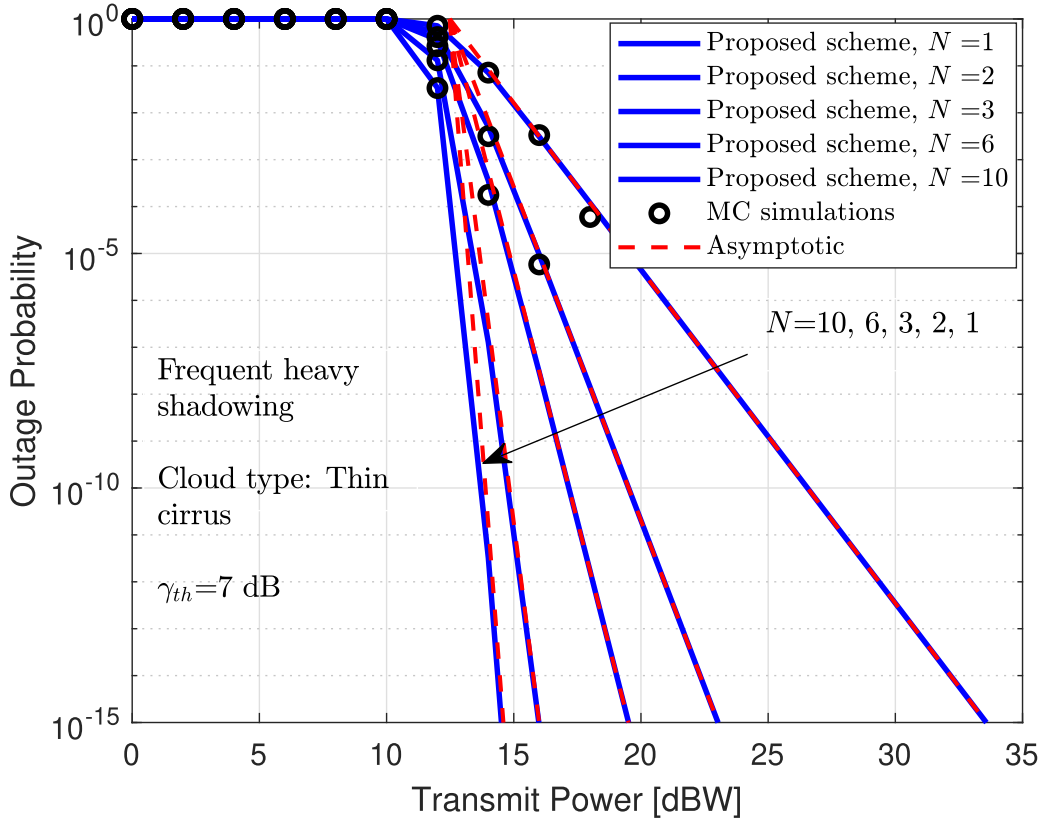
- Channel impairments:
  - The effect of beam wander-induced pointing error for the uplink,
  - The effect of aperture averaging technique and pointing error for the downlink
  - The effect of shadowing severity for RF communication.
- Performance metrics:
  - Outage probability (OP)
  - Bit error rate (BER)

O. Ben Yahia, E. Erdogan, G. Karabulut Kurt, "HAPS-assisted Hybrid RF-FSO Multicast Communications: Error and Outage Analysis," accepted for publication in IEEE Transactions on Aerospace and Electronic Systems, 2022.

Cooperative Communications (2/2)

HAPS Selection



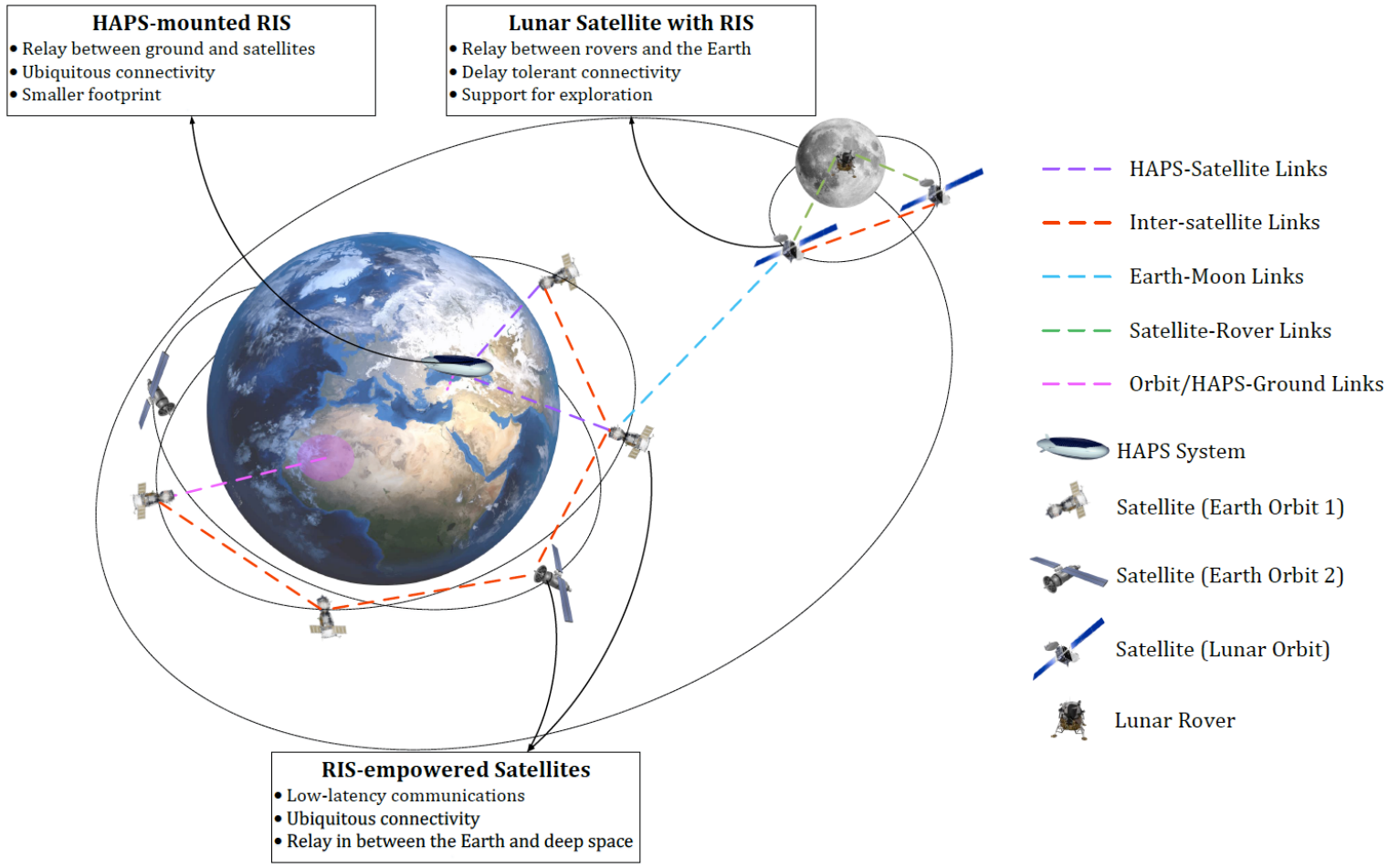


O. Ben Yahia, E. Erdogan, G. Karabulut Kurt, I. Altunbas, and H. Yanikomeroglu, "HAPS Selection for Hybrid RF/FSO Satellite Networks," IEEE Transactions on Aerospace and Electronic Systems, vol. 58, no. 4, August 2022.

How should the communication system design evolve?

Extension to Space Networks

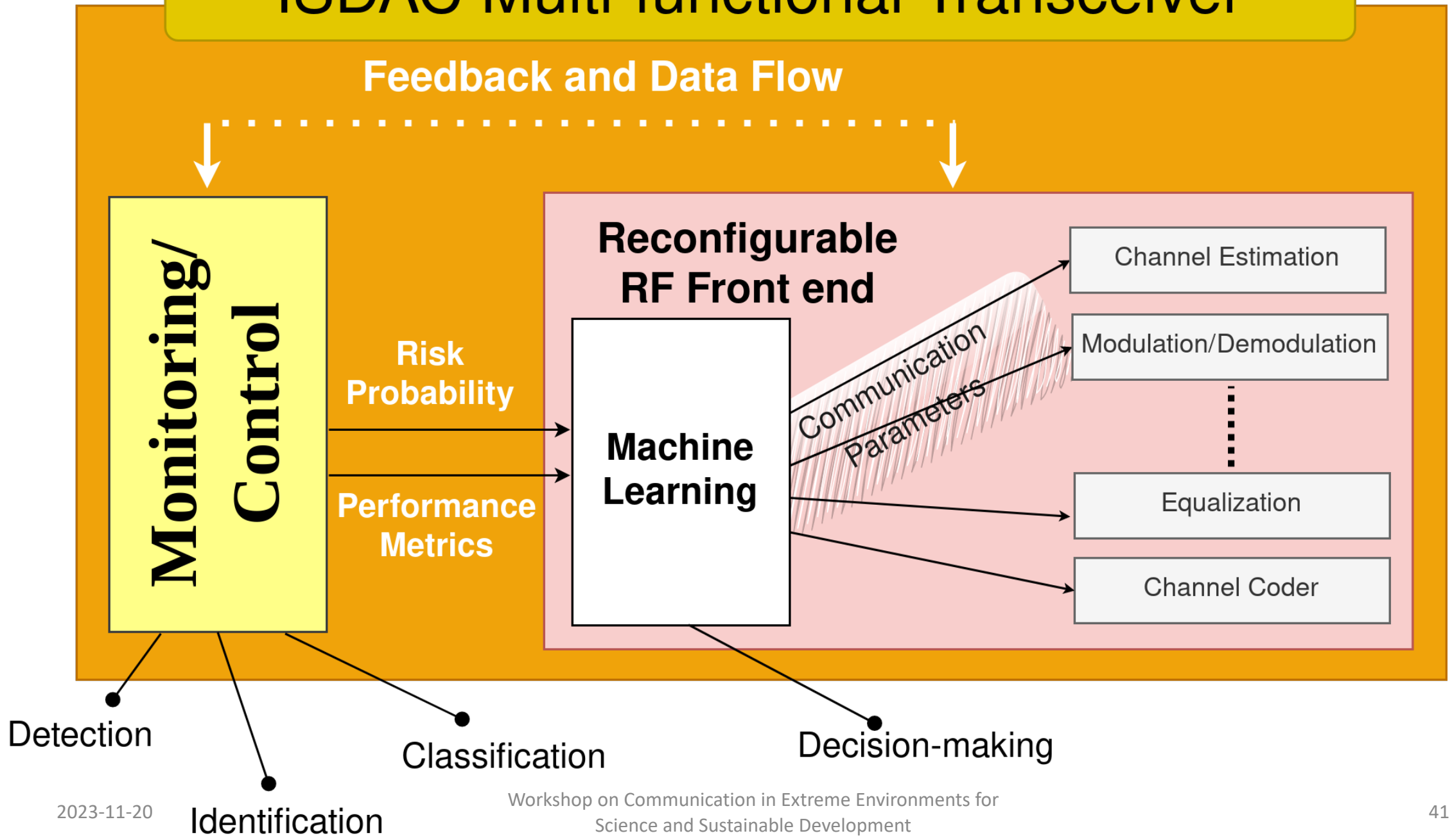
- Cooperation of terrestrial networks with non-terrestrial networks (NTNs)
- Mega-constellations of Low-Earth orbit (LEO) satellites
  - High-altitude platform station (HAPS) systems
  - UAV mounted drone-swarms



K. Tekbiyik, G. Karabulut Kurt, A.R. Ekti, and H. Yanikomeroglu, "Reconfigurable Intelligent Surfaces in Action for Non-Terrestrial Networks," in IEEE Vehicular Technology Magazine, vol. 17, no. 3, September 2022.

Sustainability	• For Earth • Beyond
Flexibility	• Multi-function • Multi-band
Autonomy	• Reliability • Security

ISDAC Multi-functional Transceiver



Multi-function Transceivers

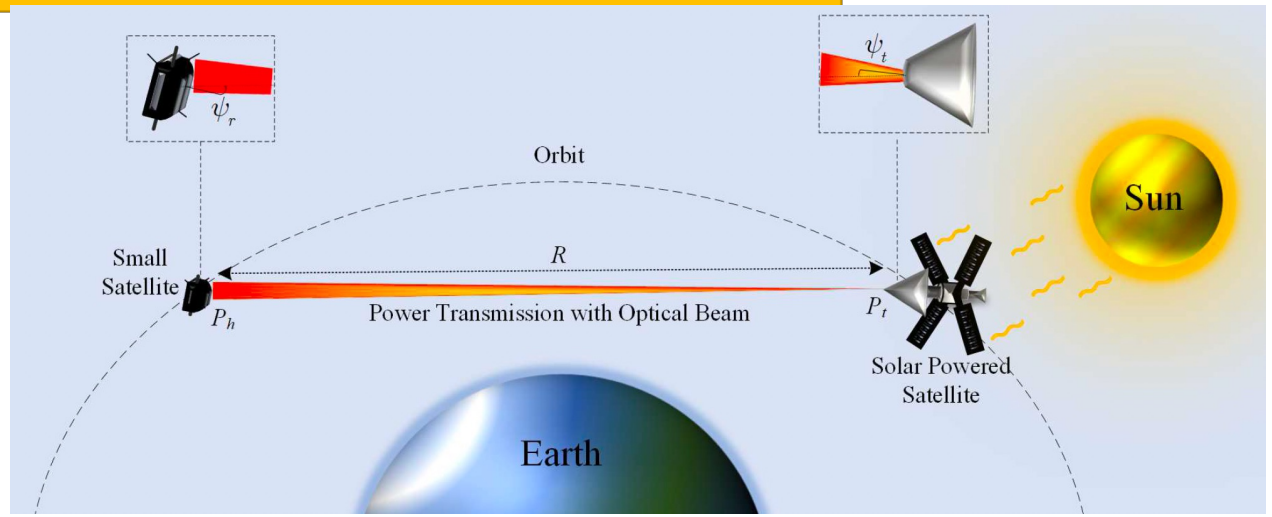
Simultaneous Information and Wireless Power Transfer (SWIPT)

Energy Harvesting

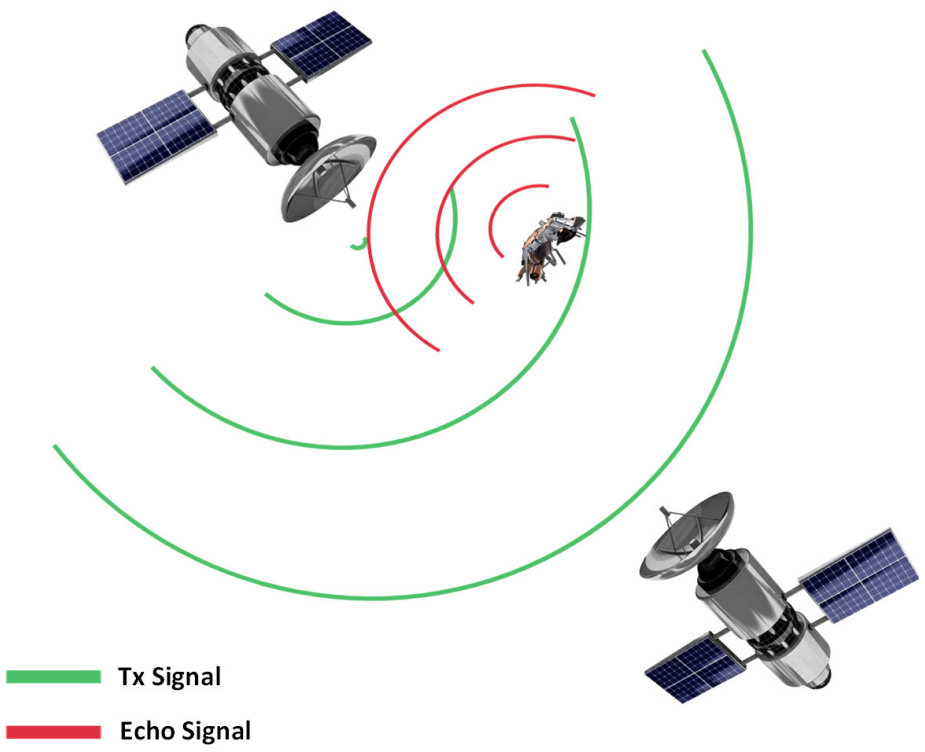
Joint Sensing and Communication (JCAS)

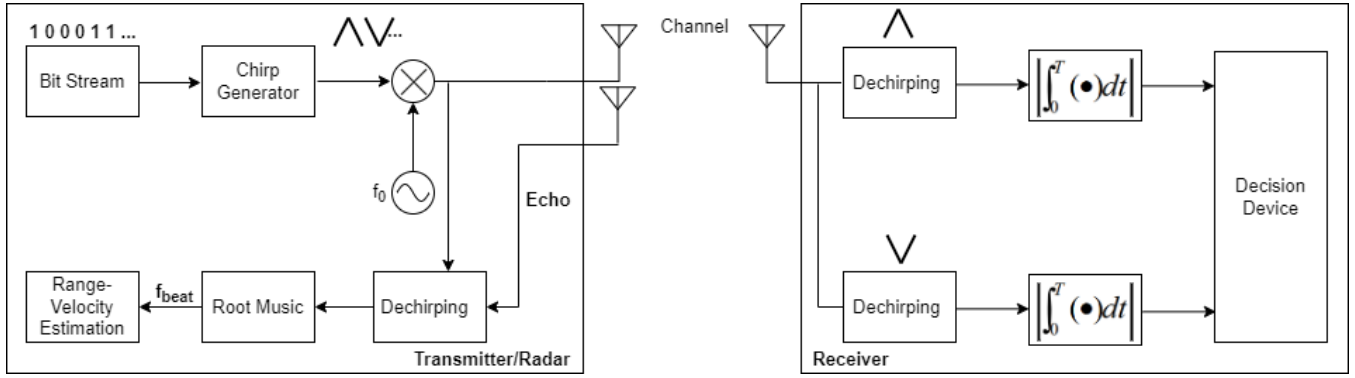
Wireless Power Transfer (WPT)

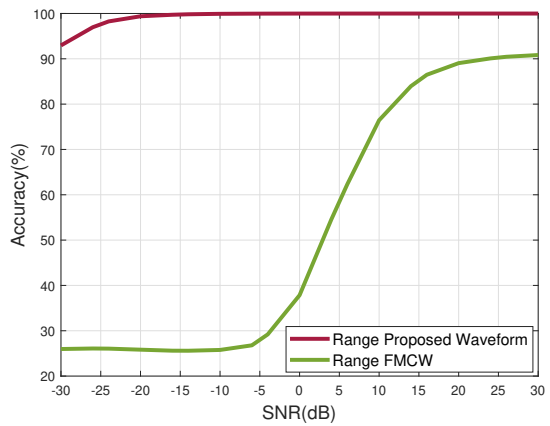
Space Debris Detection

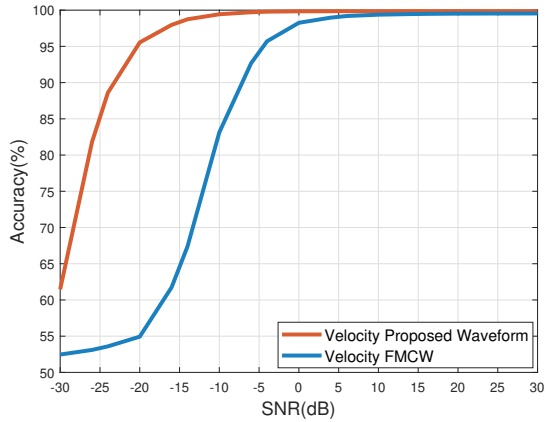


Joint Communication and Sensing





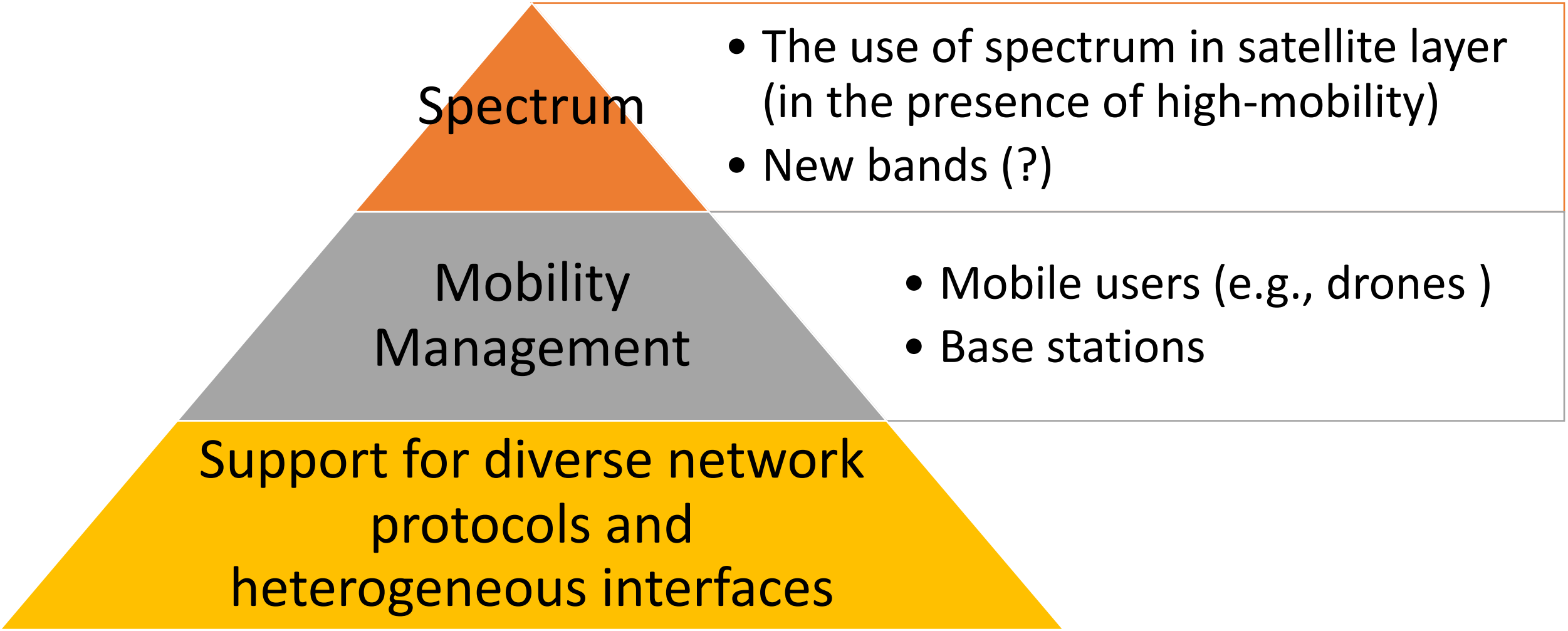




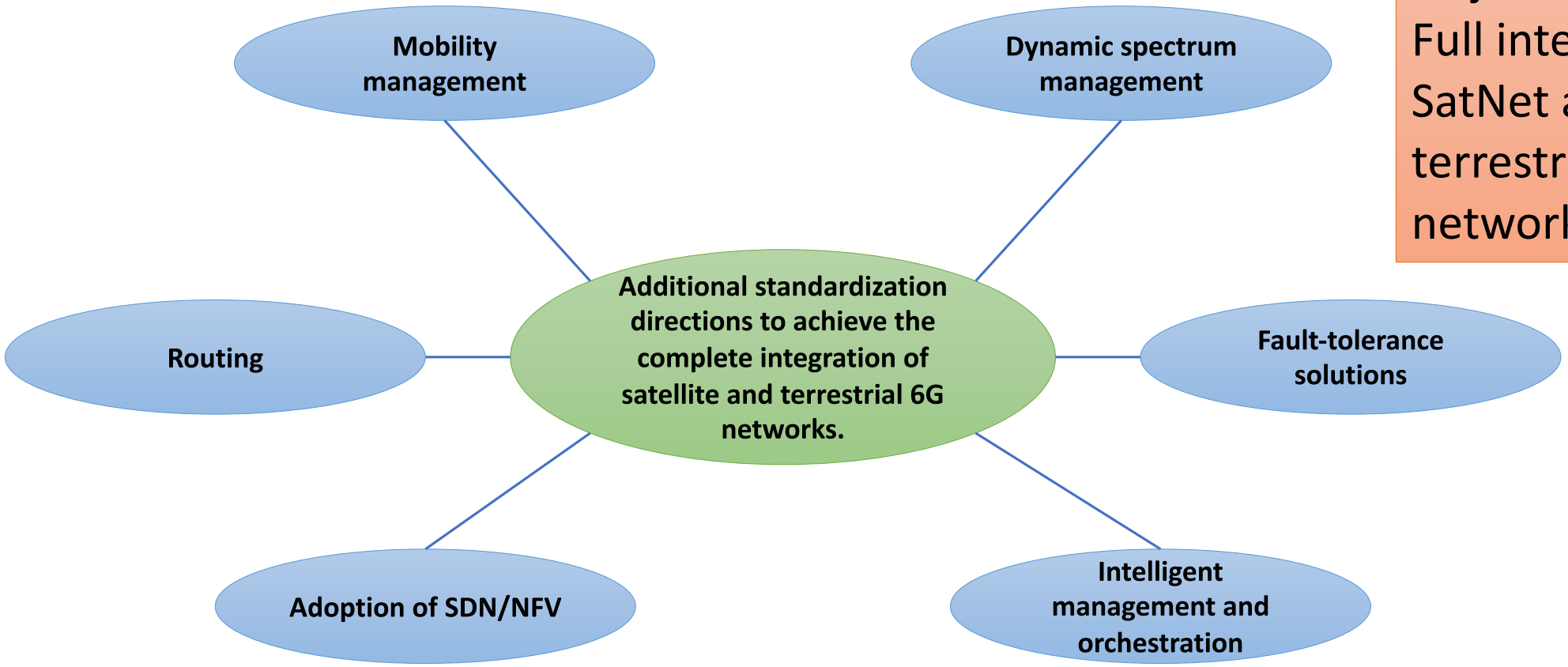
G. Sumen, G. Karabulut Kurt, and A. Gorcin, "A Novel LFM Waveform for Terahertz- Band Joint Radar and Communications over Inter-Satellite Links," in IEEE Global Communications Conference (GLOBECOM), Rio de Janeiro, Brazil, 4-8 December 2022.

Open research topics ?

Communication Aspects of NTN

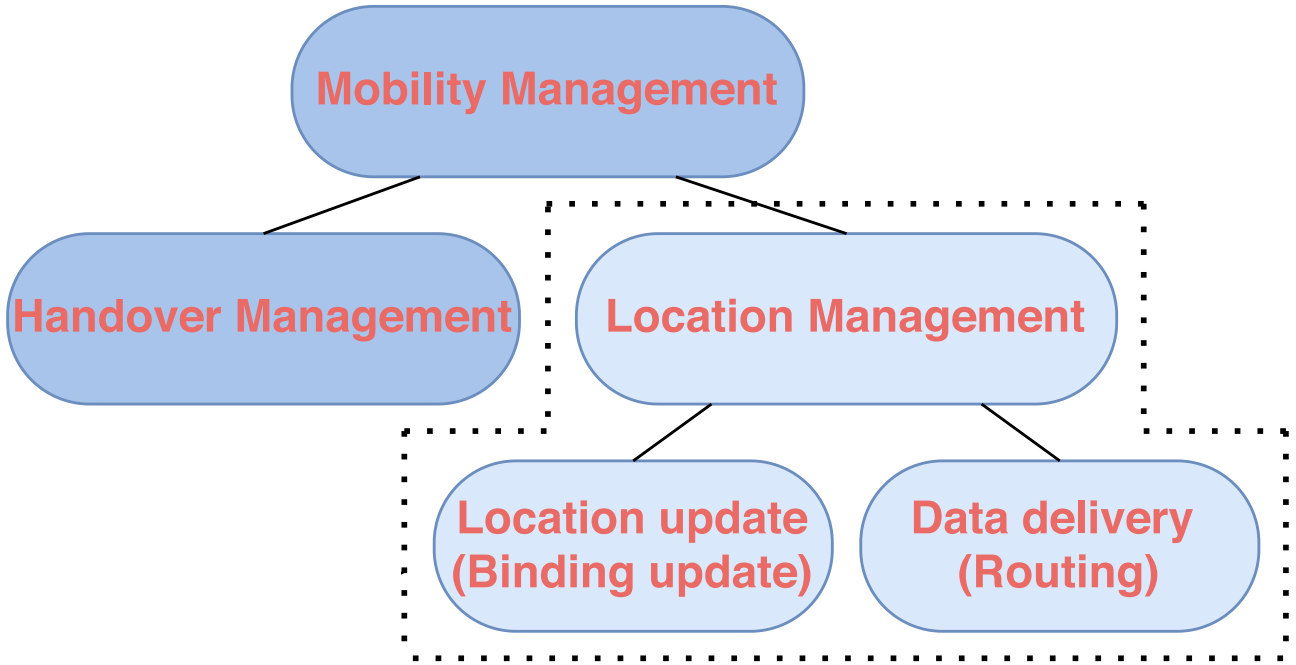


Standardization Directions



Objective:
Full integration of SatNet and terrestrial 6G networks.

Mobility Management



UNPRECEDENTED LOCATION MANAGEMENT SCENARIOS

- LEO Satellite–Based Mobile BSs Moving at High Speeds and Service Thousands of User Devices
- An LEO Satellite Can Be Connected to Two or More Networks Simultaneously

T. Darwish, G Karabulut Kurt, H Yanikomeroglu, G. Lamontagne, and M. Bellemare, “Location Management in Internet Protocol-based Future LEO Satellite Networks: A Review,” in IEEE Open Journal of the Communications Society, vol. 3, June 2022.

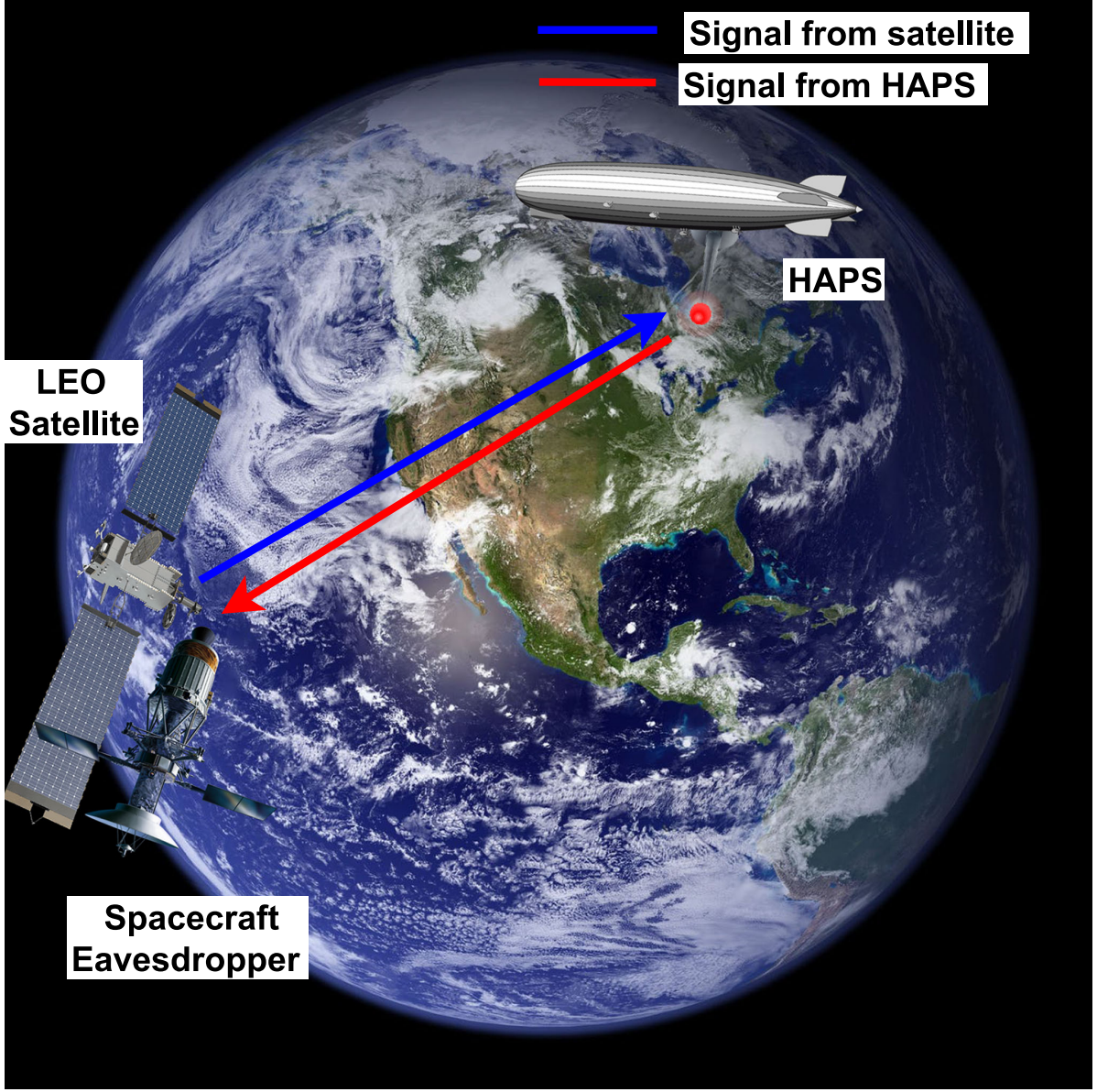
Intelligent Spectrum Management

- Dynamic and efficient spectrum management is important!
- The factors of unpredictable user mobility and satellite mobility make dynamic spectrum allocation more difficult

ITU-R: Managing the radio-frequency spectrum for the world
https://www.itu.int/en/mediacentre/backgrounders/Pages/itu-r-managing-the-radio-frequency-spectrum-for-the-world.aspx

Cross-Layer Design

- How to share the information among the layers ?
  - benefits by optimizing the different layers, but it requires the availability of the information of each layer.
  - It is challenging to design the interactions and sharing of the information among the different layers. This needs further investigation.
- Combined direct and indirect design
  - Combining the direct and indirect cross-layer design can be utilized to design an optimized system with high levels of adaptability and scalability.
  - However, this requires developing sophisticated models that consider the different parameters, status, and operating conditions.



Security ?

- Smart and Active eavesdropping
- Securing Massive MIMO
- Integration of AI/ML with security solutions

O. Ben Yahia, E. Erdogan, G. Karabulut Kurt, I. Altunbas, and H. Yanikomeroglu, “Optical Satellite Eavesdropping,” in IEEE Transactions on Vehicular Technology, vol. 71 no. 9, September 2022.

INTERNATIONAL TECHNICAL STANDARD FOR SPACE SYSTEM CYBERSECURITY - IEEE P3349 WORKING GROUP (WG)

Discover more!

> *an international technical effort to build a more (cyber)secure by design space sector*

Title: Standard for Space System Cybersecurity

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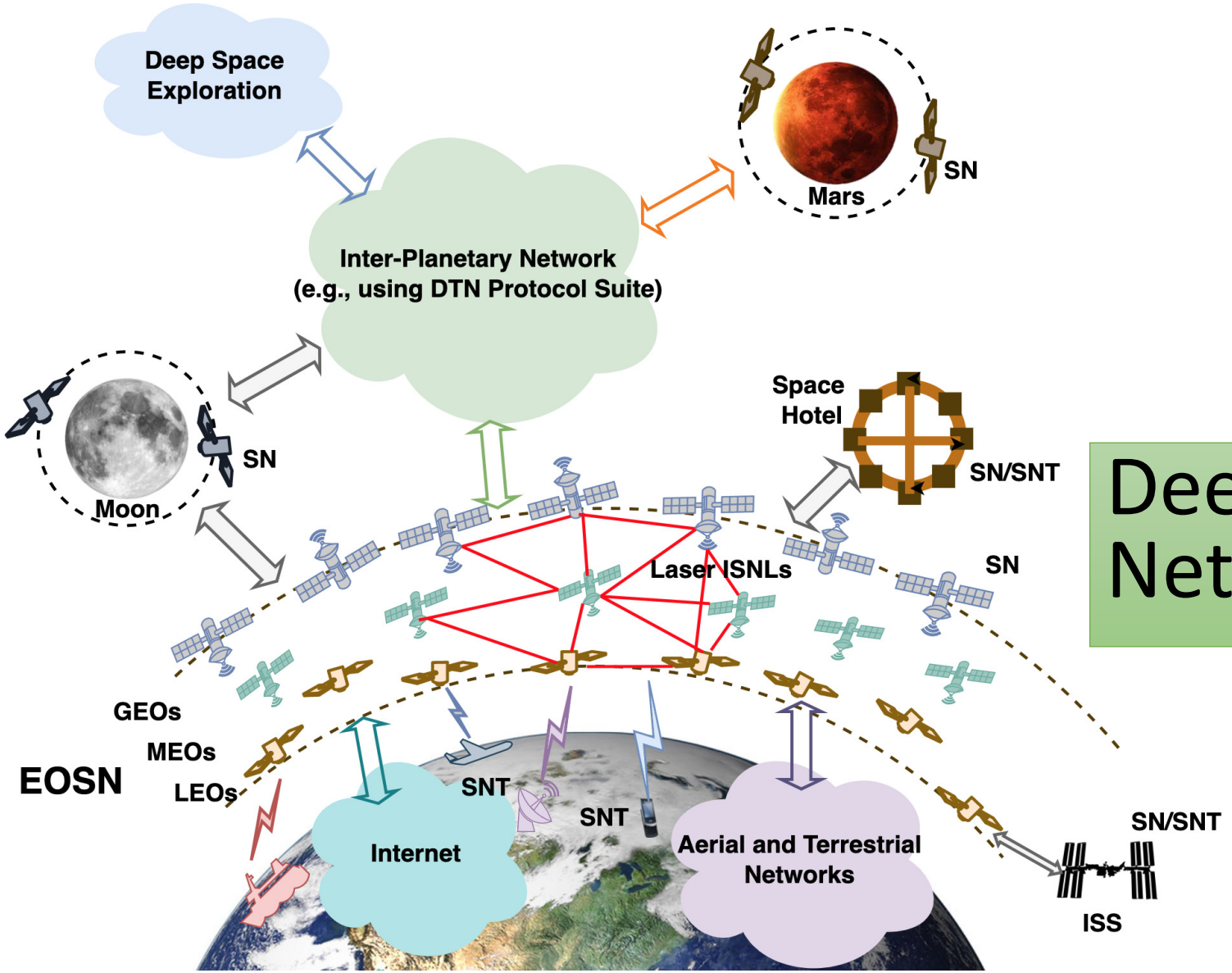
A quick overview & conclusion



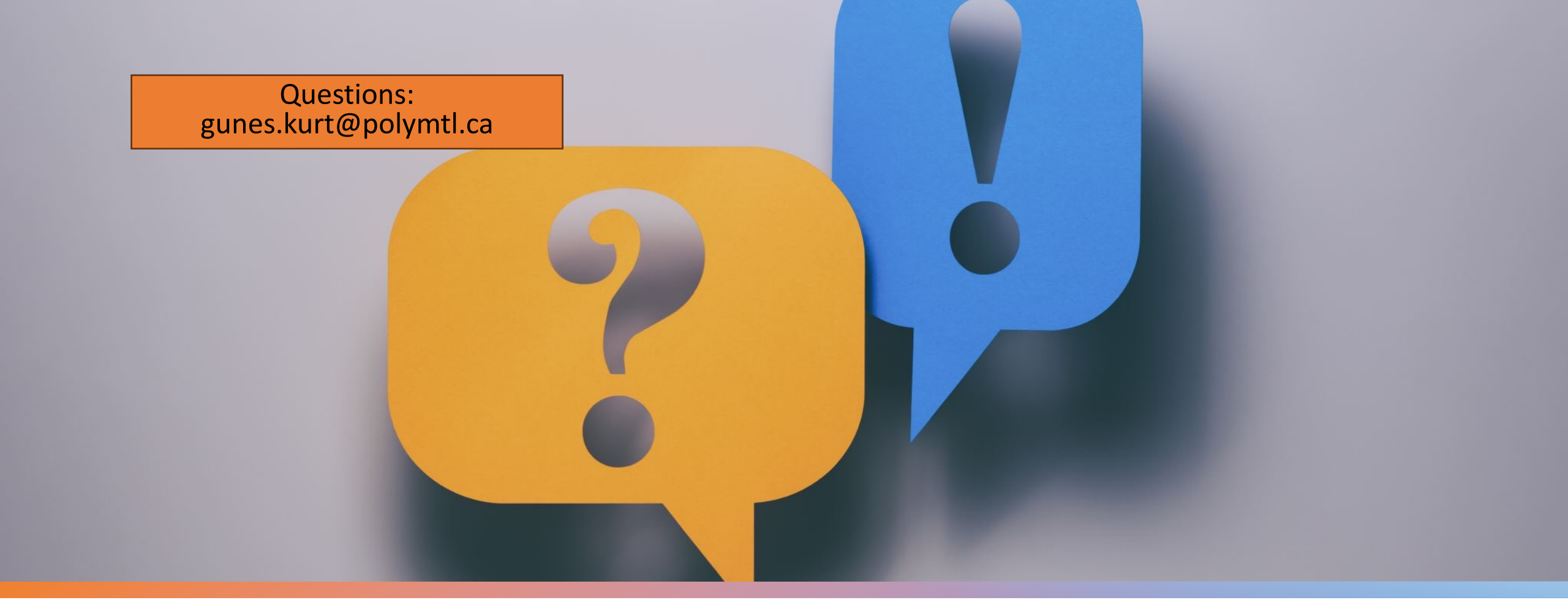
Deep-Vertical Networks

M. Y. Abdelsadek, A. U. Chaudhry, T. Darwish, E. Erdogan, G. Karabulut Kurt, P. G. Madoery, O. Ben Yahia, and H. Yanikomeroglu, "Future Space Networks: Toward the Next Giant Leap for Humankind," IEEE Transactions on Communications, vol. 71, no. 2, February 2023, (Invited Paper).

Conclusions

Target : Sustainable, reliable and secure NTNs

- Simple repetition of the terrestrial evolution in space will not be efficient
  - New designs should target:
    - Sustainability
    - Flexibility
    - Autonomy
    - and also security



Thank you for your attention

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