Mega Constellations: Trends, Technologies and Vision

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Acknowledgements:
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SnT SIGCOM

THE GOVERNMENT
OF THE GRAND DUCHY OF LUXEMBOURG
Ministry of State

Department of Media, Telecommunications and Digital Policy

esa

European Commission

Fonds National de la Recherche Luxembourg

Track Record

- **14** years in operation
- **80+** Researchers
- **60+** R&D projects
- **60M€+** Funding
- **6** Industrial Partnerships

Research Areas

- 6G Communication Systems
- Non-Terrestrial Networks (SatCom-UAVs)
- Massive Antenna Arrays
- Quantum Communication Infrastructure

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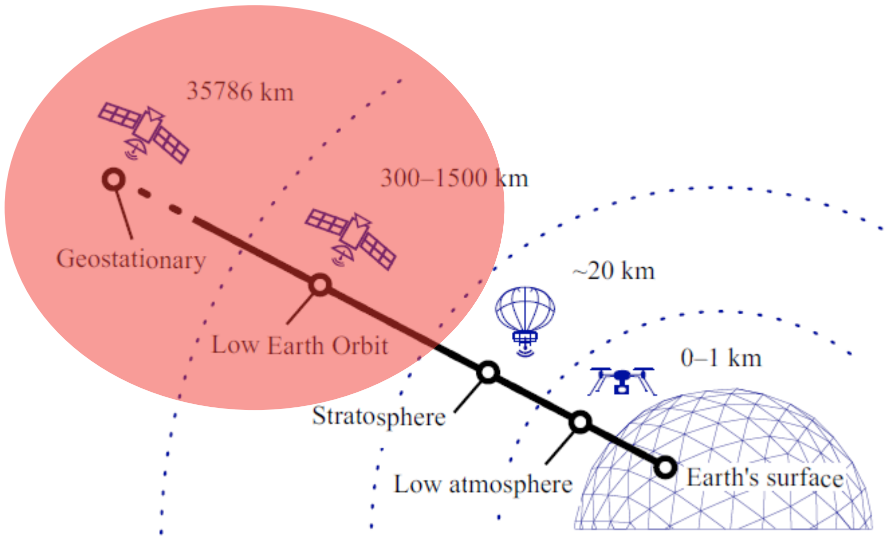
Outline

- **Introduction**
- **Established Services**
  - Broadband & Broadcast
  - Direct to Handheld
  - Satellite IoT
  - Data Offload & Backhauling
- **Emerging Services**
  - Planetary Communications
  - Quantum Communications
- **Historical Evolution, Challenges & Opportunities, Open Research Topics**

Setting the Scene: NTN and SatComs

Expectations

- Ubiquitous coverage / Digital Divide
- Maritime/aeronautical/Rural areas
- Wide area content delivery / data collection
- Direct smartphone/vehicle access



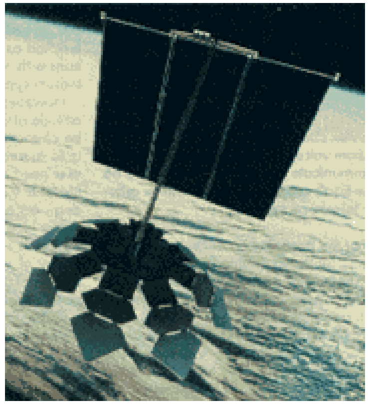
SatComs vs HAPS vs UAVs

- **System Coverage Area**
- **System OPEX & CAPEX**
- **Regulations / Sovereignty**

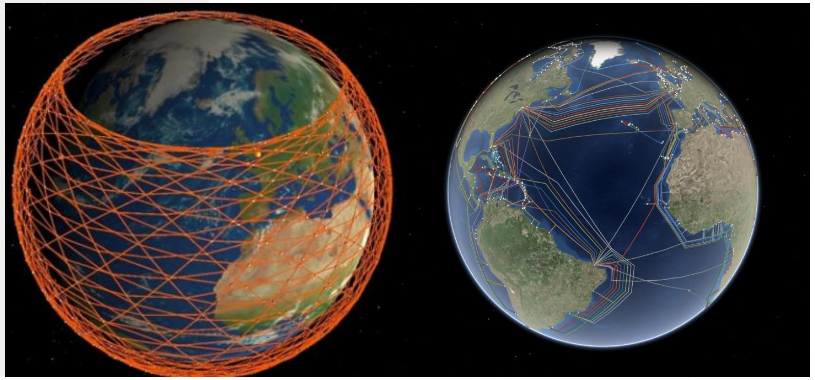
6G SatComs Renaissance

- **Economy**
  - Private/Venture Capital
  - Cheaper/Frequent launches
  - Economies of scale
  - 3GPP, Conveyor-belt production
- **Communication Technology**
  - New architectures
    - Large LEO constellations
    - Multi-layered satellite systems
  - Regeneration
    - Active elements in the sky
    - COTS in space

5 Myths

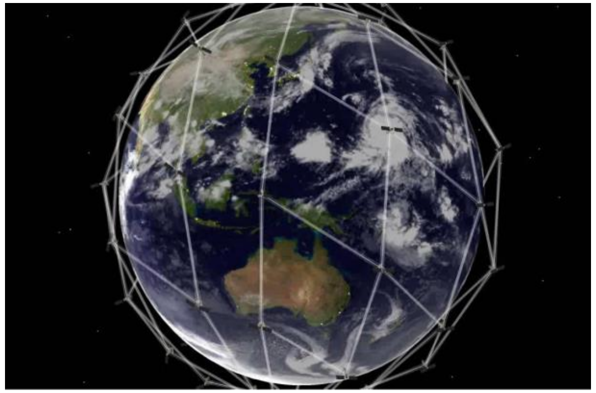


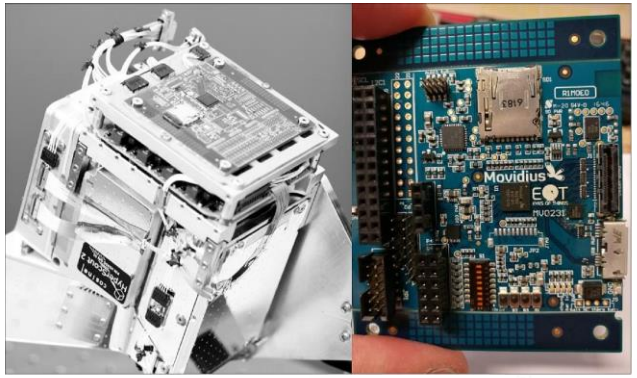
1. Satcom Data Services appeared recently
2. LEO constellations were launched in the 21st century
3. Smartphones get broadband through satellites
4. SatComs are strictly faster than optical fibers
5. SatComs only target internet access



5 Realities

1. Media consumption has become non-linear
2. Satcoms become progressively regenerative
3. Satellites are equipped with large active antennas
4. Intersatellite links have been in use for decades
5. AI Chipsets have flown in space





Broadband & Broadcast

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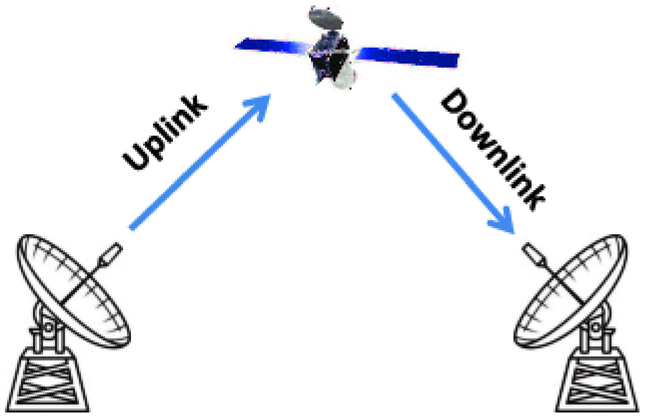
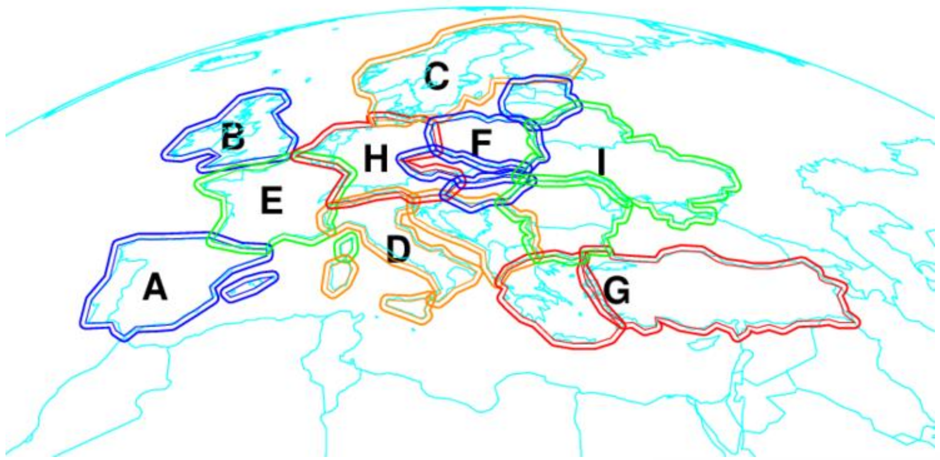
Historic Evolution

- **Direct to Home Broadcast**
  - Main revenue stream for decades

- **Ingredients:**
  - GEO Satellites
  - “Bent-pipe” architecture
  - Wide or linguistic beams
  - No return link
  - Linear TV service

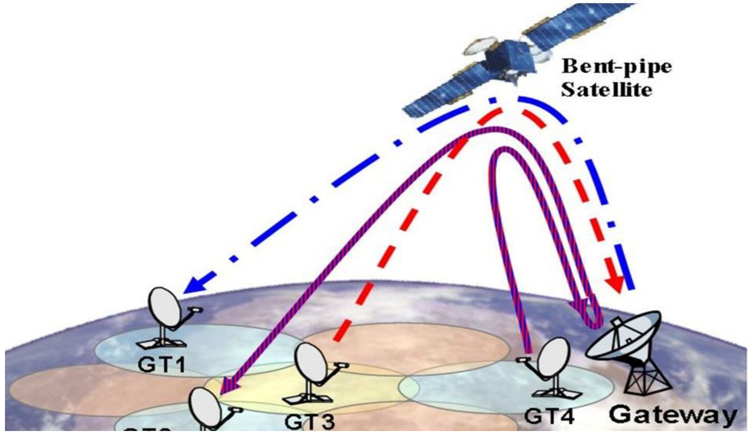
- **Wide coverage & Common linear content**
  - Optimal distribution platform

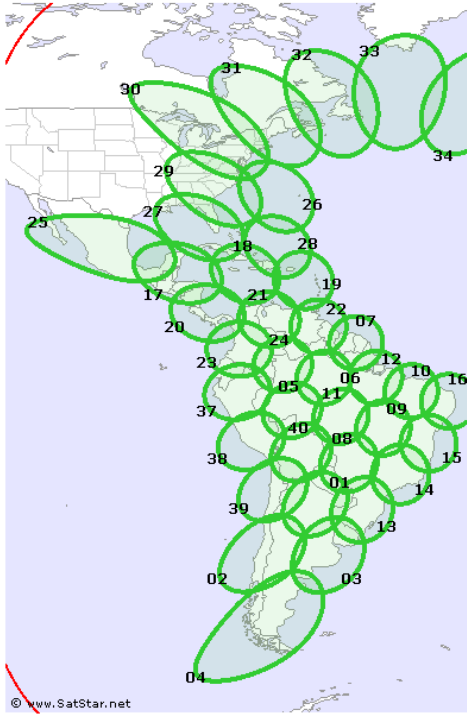




Broadband & Broadcast

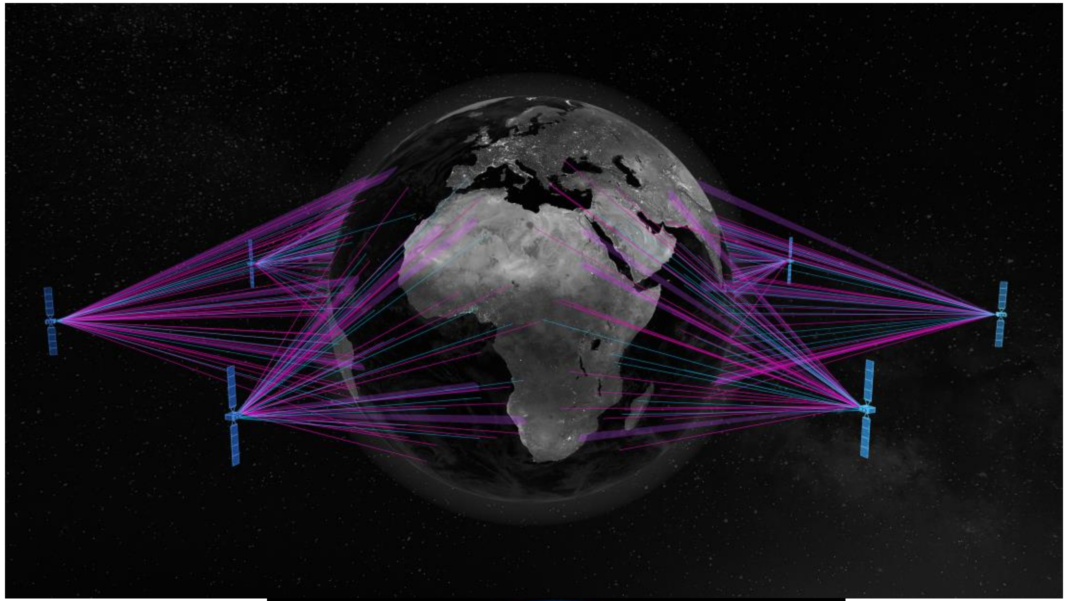
- **Internet Services**
  - OTT Streaming
- **Ingredients:**
  - GEO Satellites
  - Multibeam architecture
  - Return link
  - IP service
- Individual VSAT broadband links
- Why treat them together?
  - Digital Subscriber Line

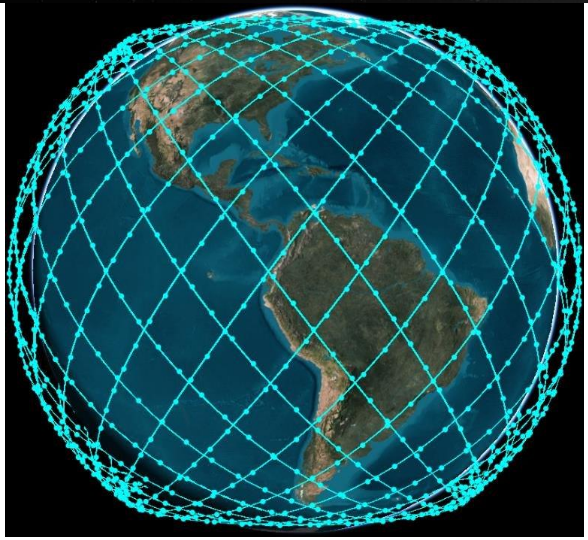




NGSO Constellations

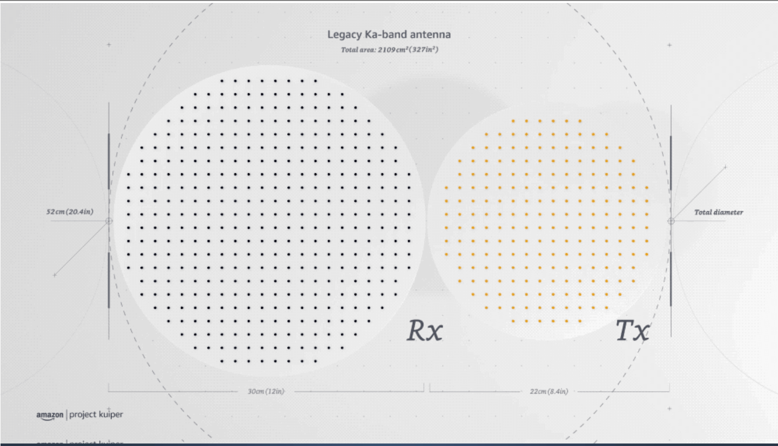
- MEO mPower
- LEO Starlink, OneWeb etc.
- **Multilayered:**
  - Eutelsat + OneWeb G/L
  - SES + Starlink G/M/L
- **Ingredients:**
  - Local coverage beams
    - 10x-100x Kms
  - Mobility & Tracking antennas
  - Broadband internet





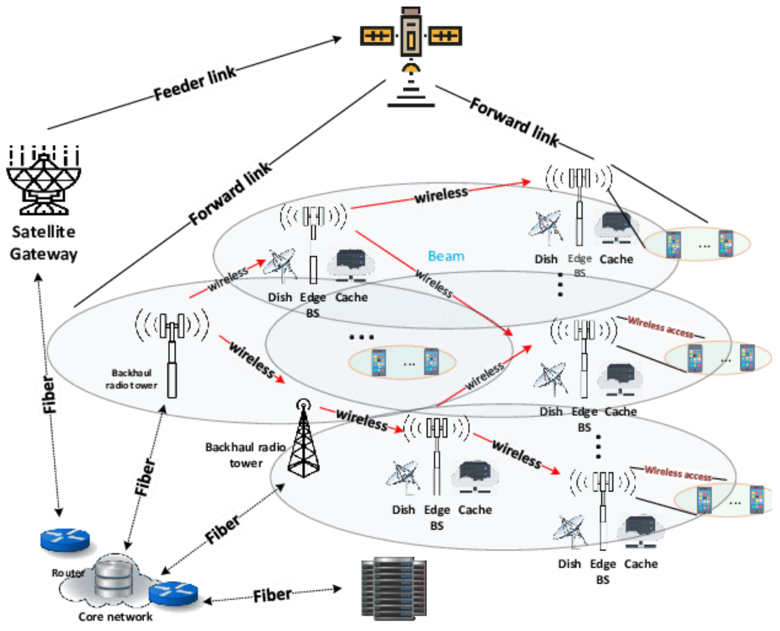
User Terminals

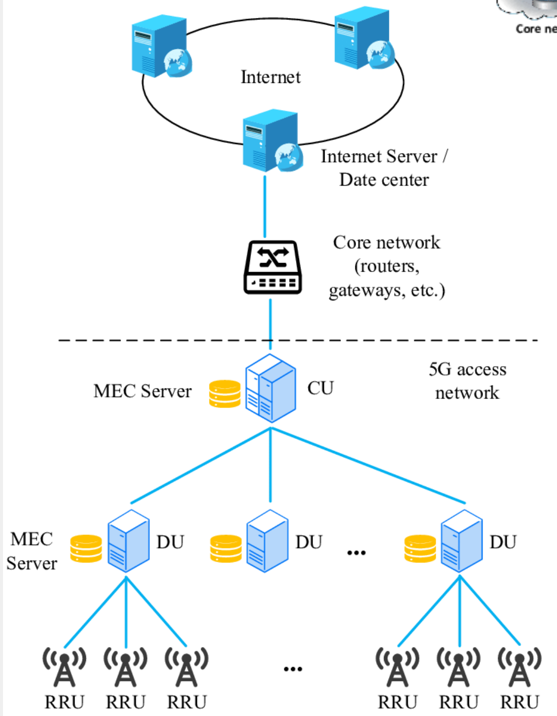
- SWaP (Size, Weight, and Power)
  - Residential, Aero, Maritime
  - Space to Space
- **Plug&Play**
  - Electromechanical beam steering
- **Multibeam connectivity**
  - Handovers
  - Multi-orbit
- **Terrestrial Integration**
  - Dual-use Terminals
  - Fixed Wireless Access



Is Broadcasting Dead?

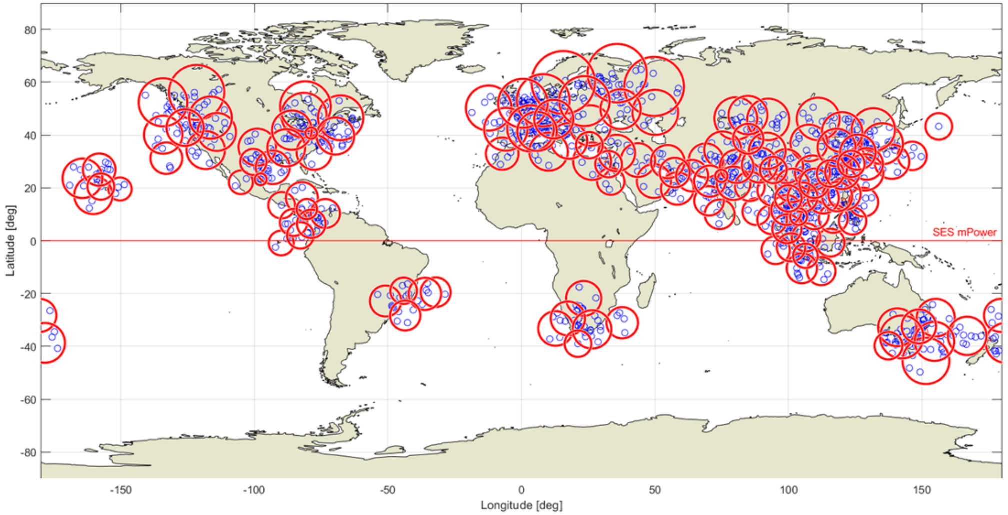
- Inefficient Content Distribution
- **Architectural Integration with 3GPP**
  - Interface to broadcasters
  - 5G Broadcast
- **Multi-layered Systems**
  - Adjustable broadcast region
- **Terrestrial Caching**
  - As close to the end-user
  - Telco cloud, CU, DU

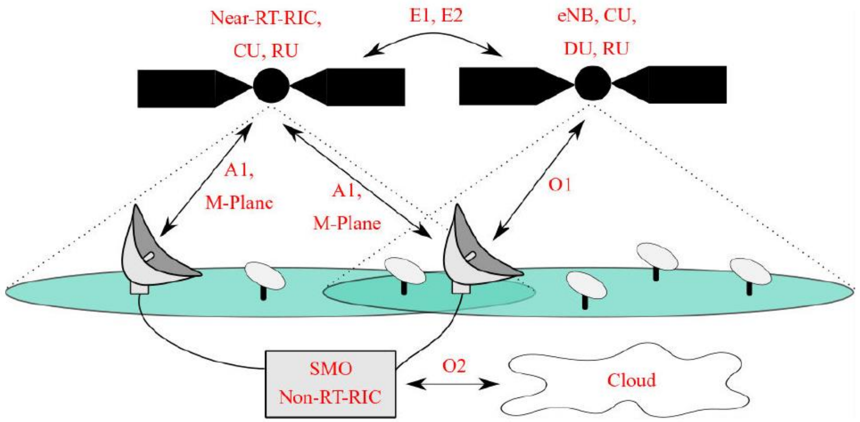




System Orchestration

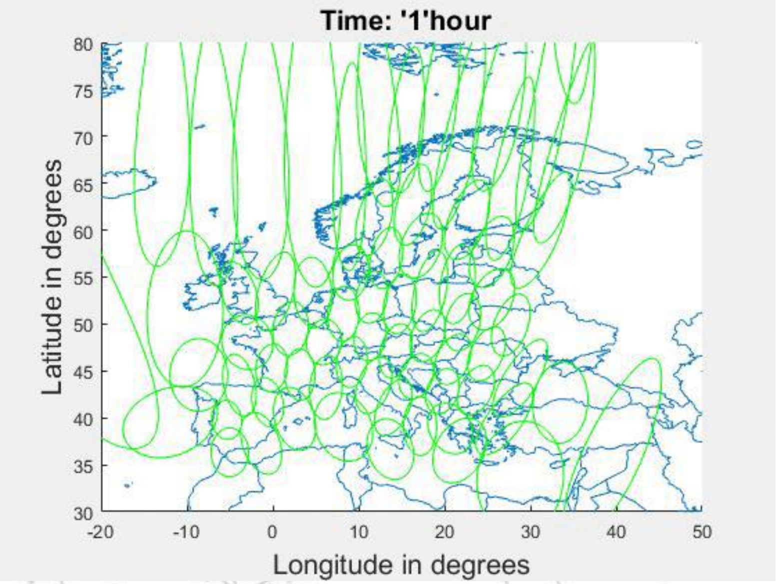
- **Complicated orchestration**
  - Quick handovers
  - Hotspots/Notspots
  - Multi-orbit, Multi-connectivity
  - Intersatellite links
- **Integration Layer + Functional Split**
  - Waveform, Carrier, Architecture
  - 5GNR vs Non-3GPP access
- **Open Challenges**
  - Open RAN philosophy
  - Distributed GW Network
  - Scalability



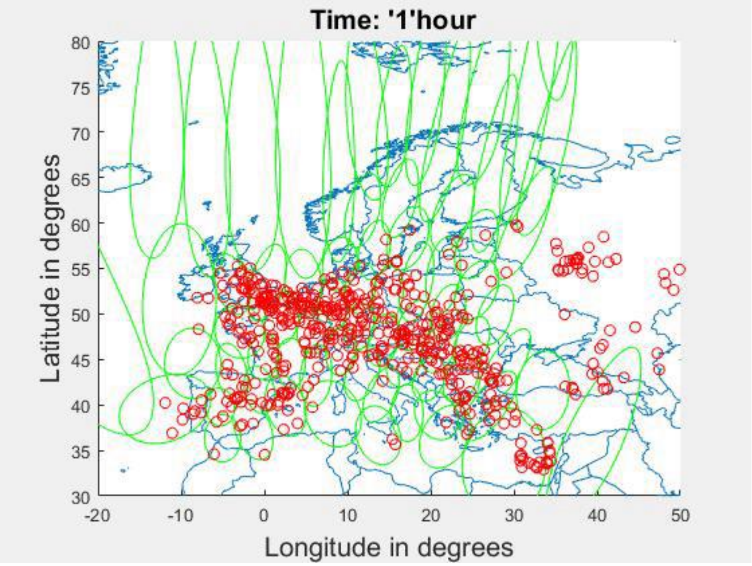


Example: Traffic-aware Beam Footprint Design

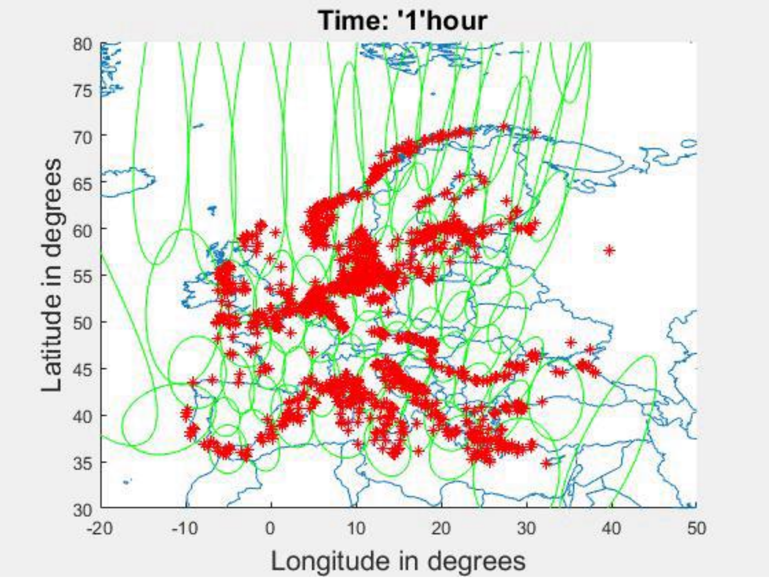
- Results : [Honnaiah21]



Adaptive beams at different time stamps of a day.



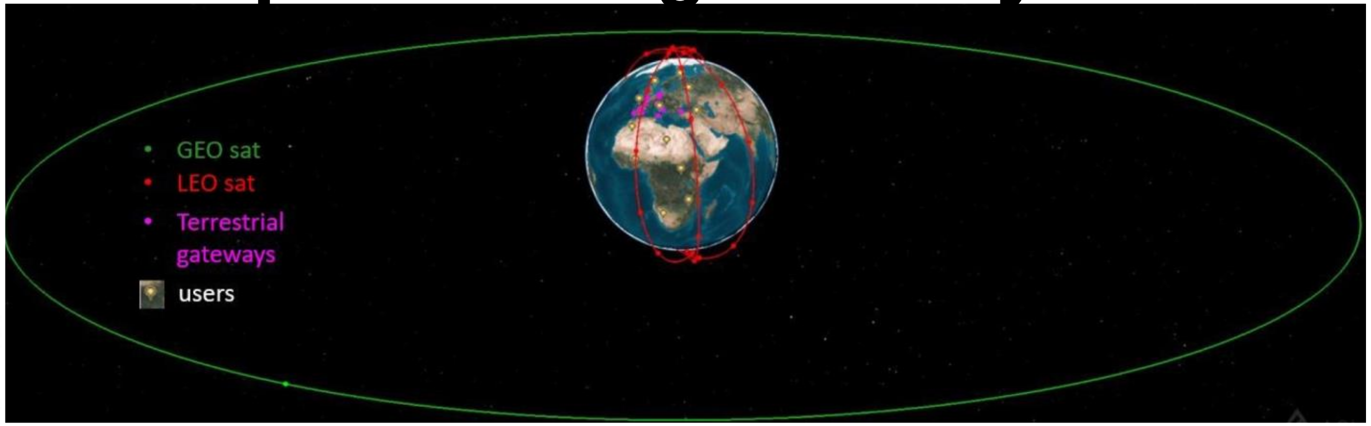
Adaptive beams with Flights/ aeronautical User locations at different time stamps of a day.

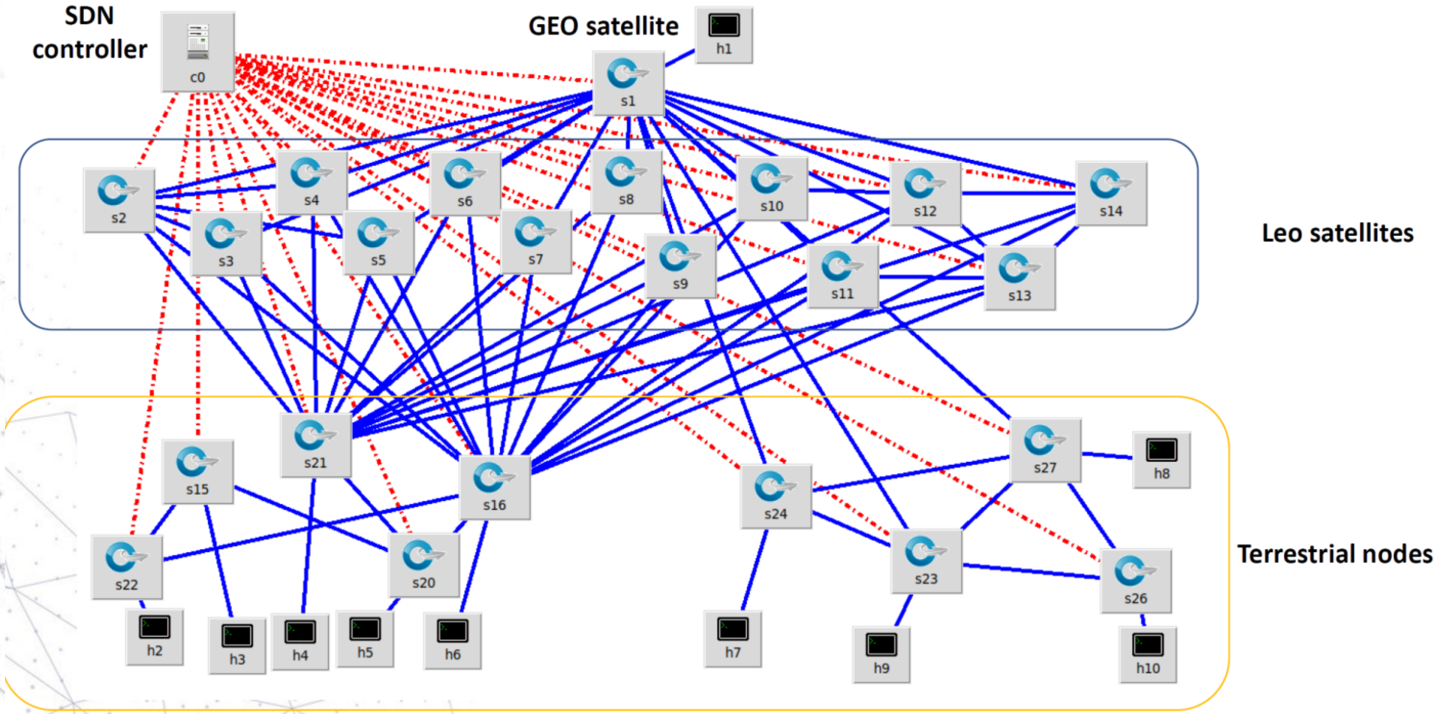


Adaptive beams with Ships/ Maritime User locations at different time stamps of a day.

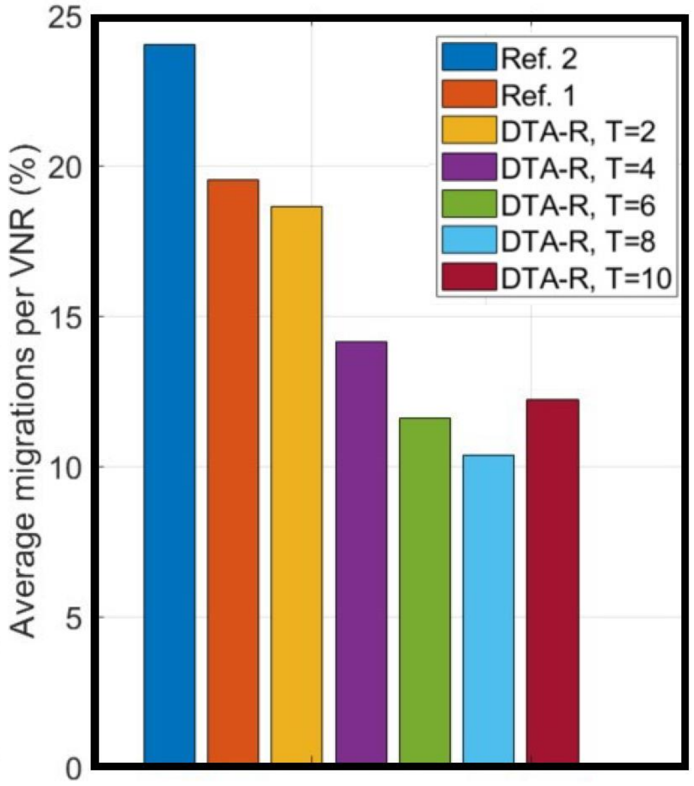
[Honnaiah2021] P. J. Honnaiah, N. Maturo, S. Chatzinotas, S. Kisseleff and J. Krause, "Demand-Based Adaptive Multi-Beam Pattern and Footprint Planning for High Throughput GEO Satellite Systems," in *IEEE Open Journal of the Communications Society*, vol. 2, pp. 1526-1540, 2021, doi: 10.1109/OJCOMS.2021.3093106.

Example: Slicing over Dynamic Topologies



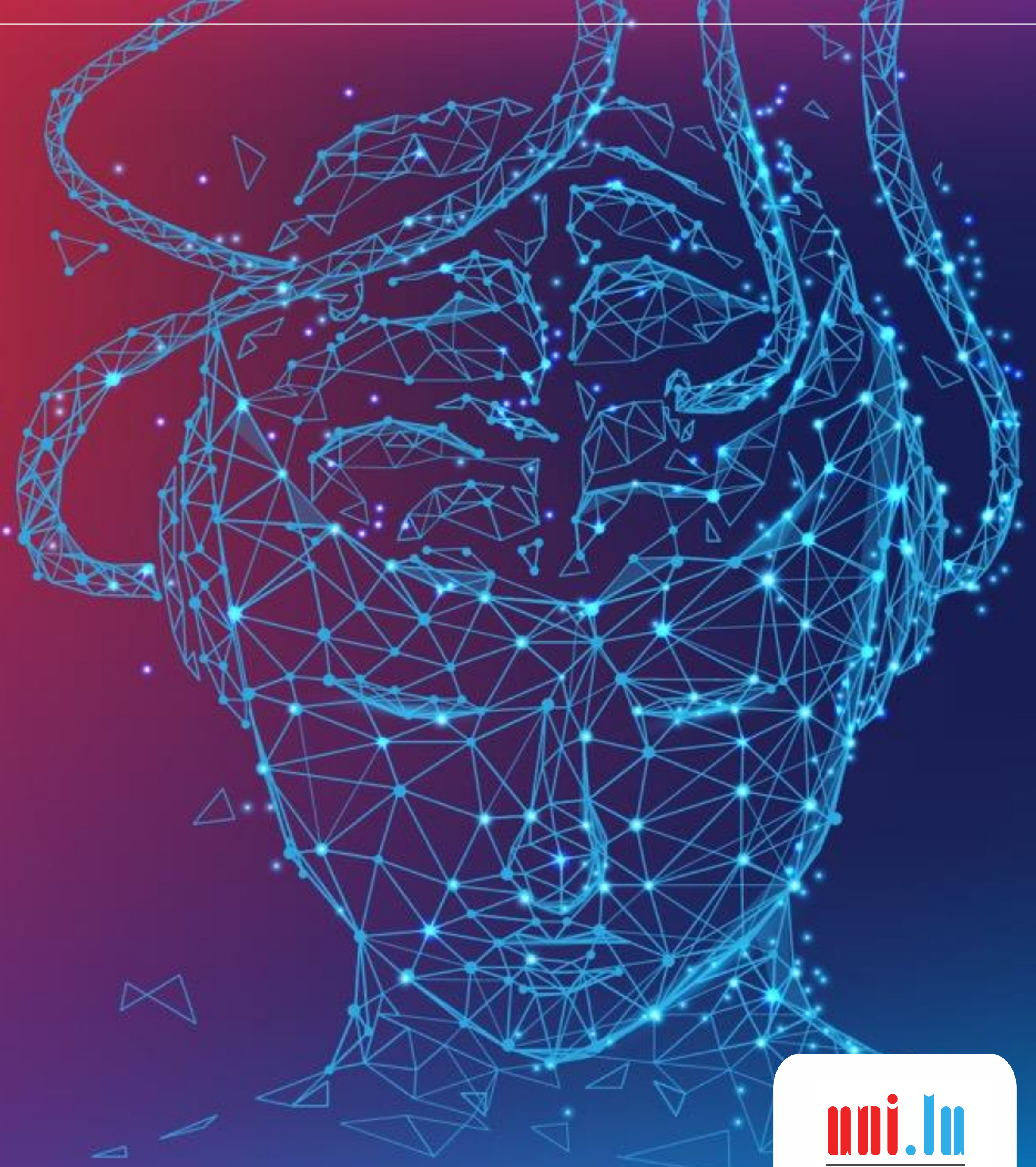


- Results : [Minardi23]



[Minardi23] Minardi et al., “Virtual Network Embedding for Dynamic NGSO Systems: Algorithmic Solution and SDN-Testbed Validation”, IEEE TNET, 2023.

Direct to Handheld



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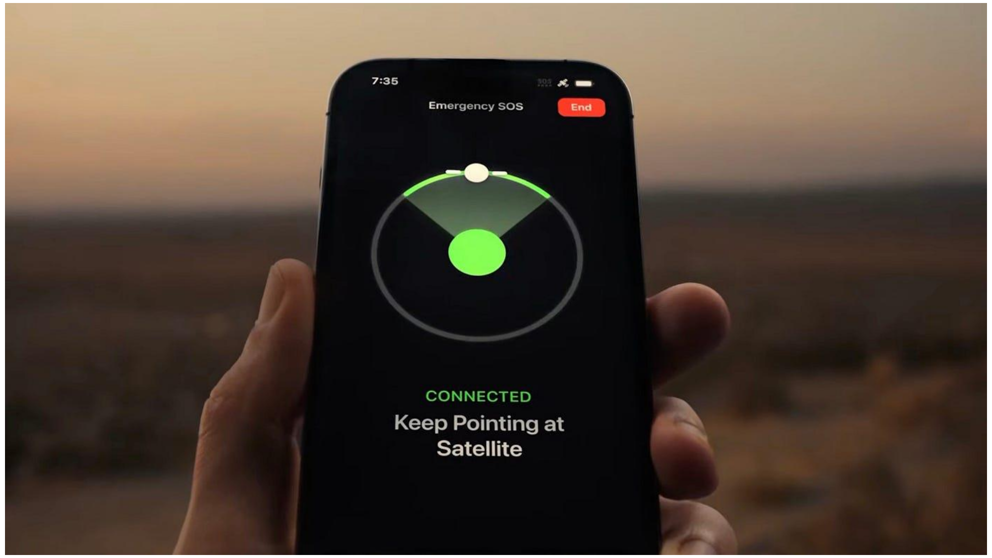
Historic Evolution

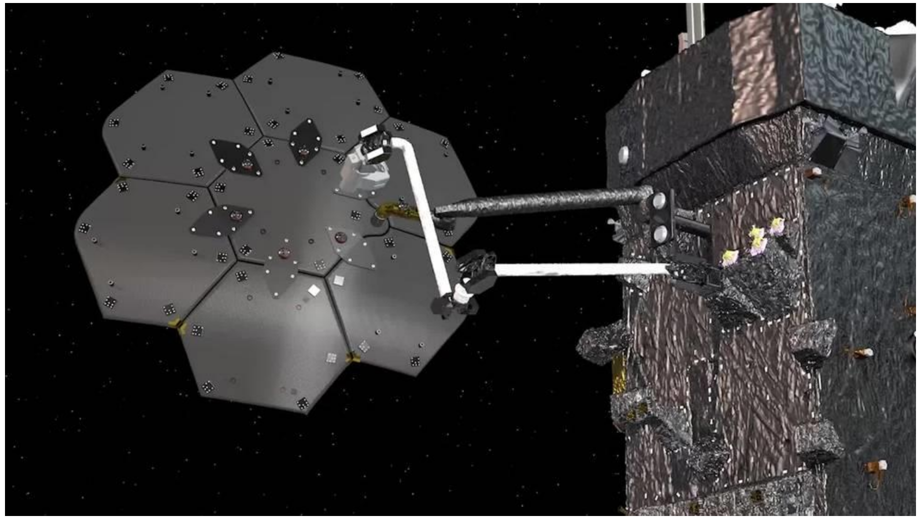
- **Handheld services**
  - Iridium, Globalstar, Thuraya
- **Opportunities:**
  - Smartphone market
  - 6G Ubiquitous coverage
  - Device feature – Emergency & Health
- **Challenges:**
  - Fixed smartphone SWAP
    - Link Budget
  - 3GPP Compliance
  - Scalability



Direct to Handheld

- **Key technologies:**
  - Large Antenna Arrays
    - Deployable => Electromechanics
    - In-orbit assembly => Robotics
    - Metamaterials => RIS, Holography
  - 5G Stack modifications
    - 5GNR over Satellite
      - ASMS, ICSSC Demos
    - AST Tests 2023: ~15 MBps

- **Risks:**
  - Business model uncertainty
  - Global coverage, standardization delays
  - Device-specific modes

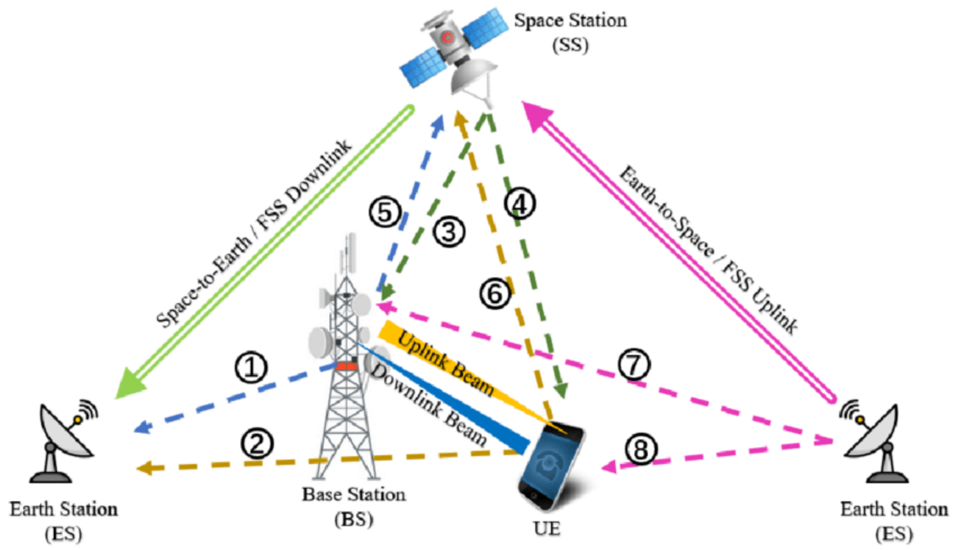


Open Topics

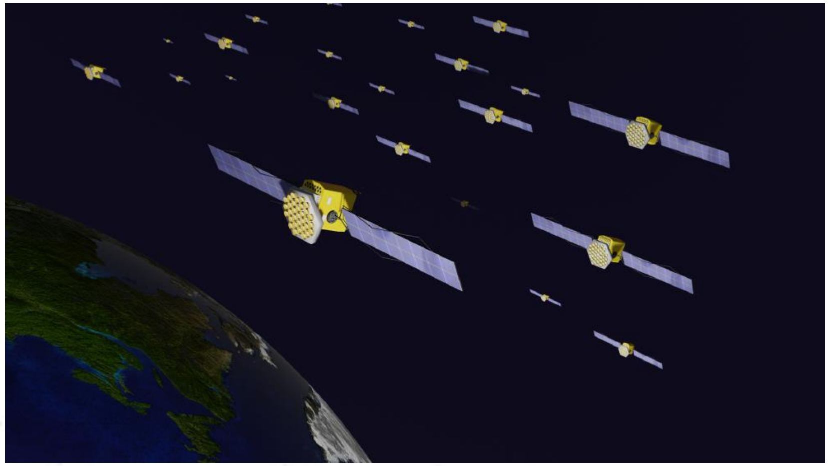
- **Spectrum**
  - Coexistence below 6Ghz- FCC

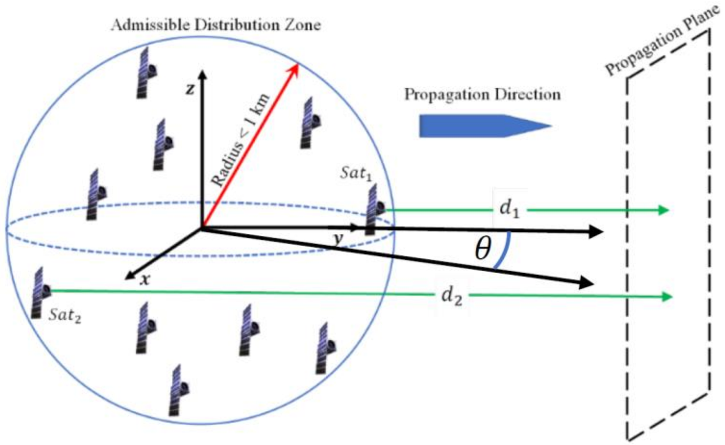
- **Service quality:**
  - Above 6GHz – mmWV
    - UT directivity => Beamforming
    - Coexistence with Satellite Services
  - Scalability
    - RRM & Handovers & Roaming
    - Integration with terrestrial systems

- **Architectures:**
  - Cohesive satellite swarms
  - Cell-free in space



Example: Cohesive Satellite Swarms





- Results : [Duncan23]

TABLE I: SIMULATION PARAMETERS

Parameter	Value
Pulse Bandwidth	50, 500 MHz
Pulse Shape	SRRC
Roll-off Factor	0.2
Oversampling Factor	4
Carrier Freq.	20 GHz
Position distribution	Gaussian
Position Std-Dev σ_p	500, 1000 m
Number of Nodes	8, 16, 256
Transmit Antenna	Omnidirectional
Number of repetitions for averaging	200
Number of SRRC samples	41
Number of re-sampling samples (Oversampling)	4
Re-sampling order	Cubic

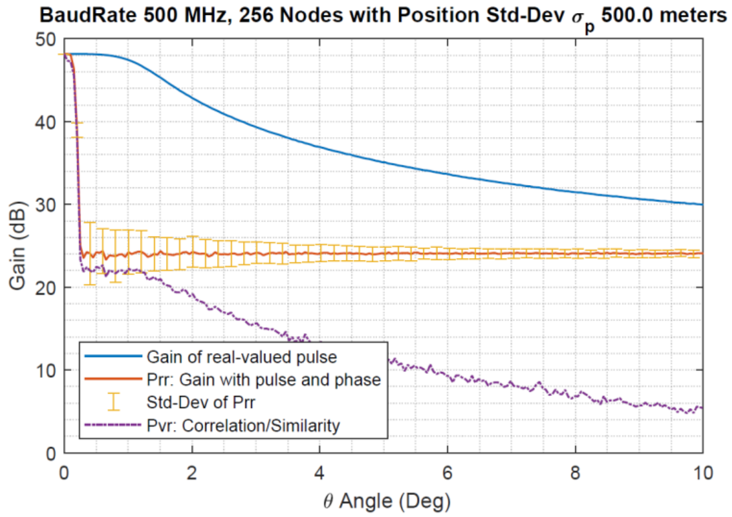


Fig. 8: Average expected Gains for multiple realizations of the array distribution. Baud Rate 500 MHz, **256 Nodes**, σ_p = 500 m. (200 realizations)

[Duncan23] Duncan et al., “Harnessing the Power of Swarm Satellite Networks With Wideband Distributed Beamforming”, PIMRC 2023.

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Internet of Things

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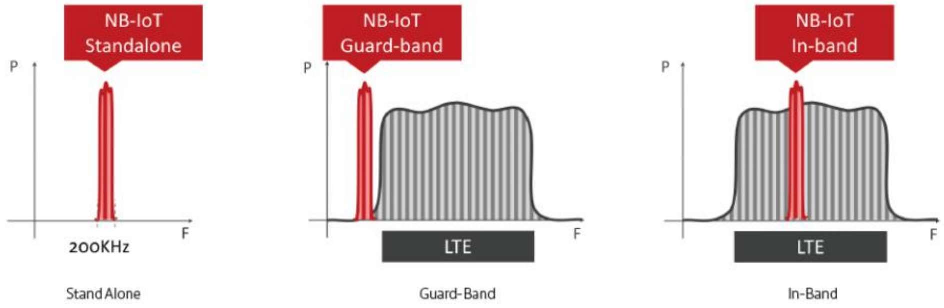
Internet of Things

- **ORBCOMM:**
  - ~ 30 LEO Satellites
  - Founded 1993
- **Opportunities:**
  - Cheaper access to space
  - Integrated ST access e.g. 3GPP
- **Plethora of ventures**
  - Lower rates
  - No need for constant coverage
  - Stand Alone or Integrated
    - Starlink + Swarm

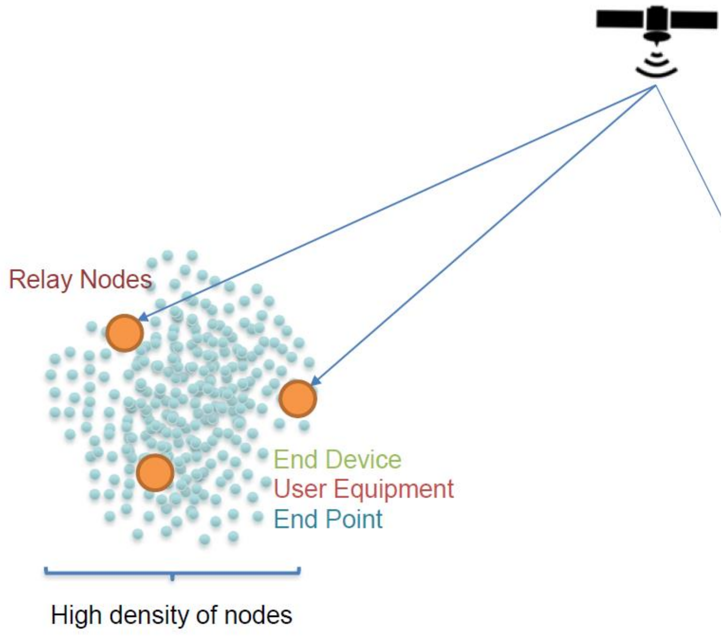


Satellite IoT

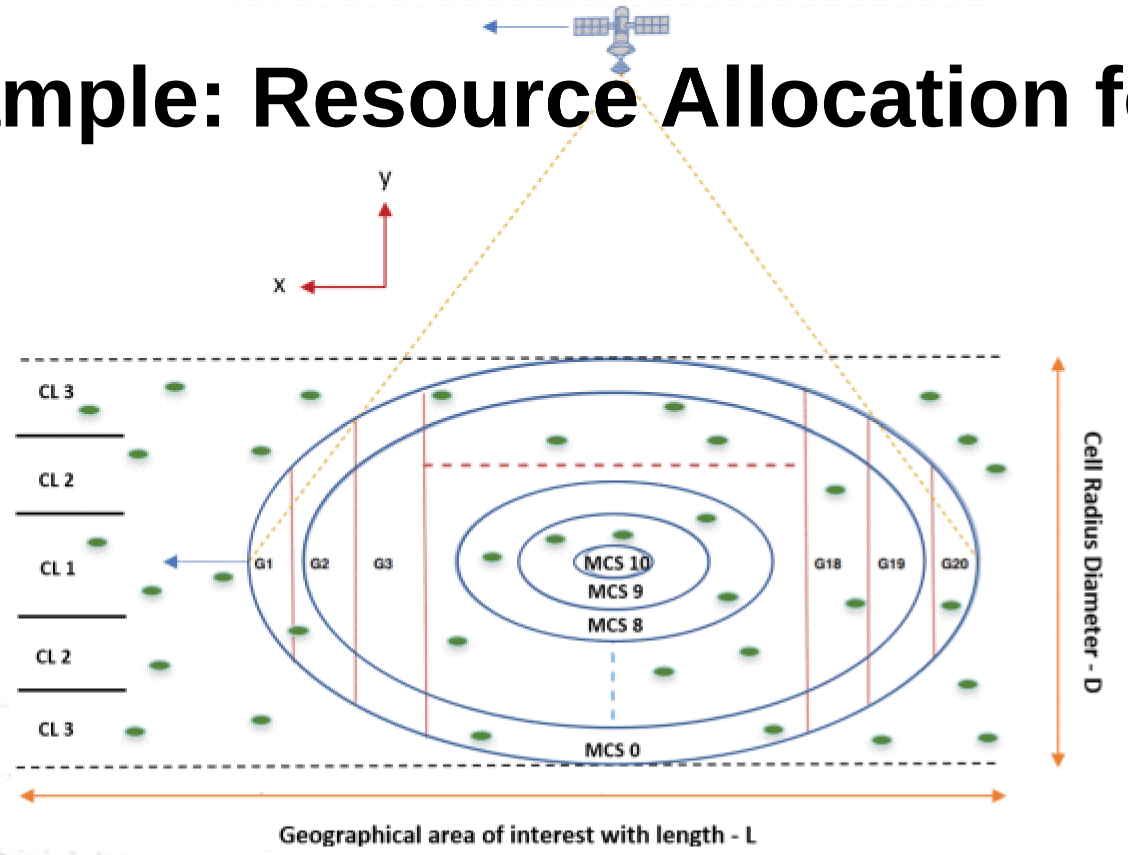
- **Multiple protocols/waveforms**
  - LoRa, NB-IoT, Legacy
  - Direct access vs Relaying/Fronthauling

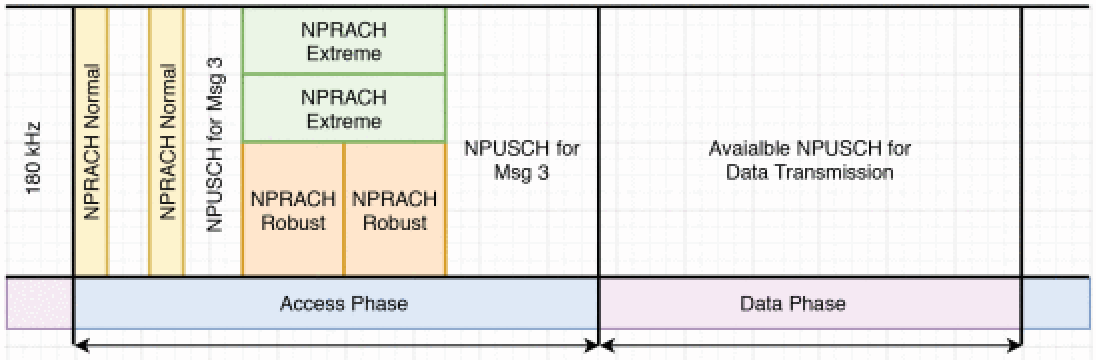
- **5GNR Integration**
  - Mobility – Doppler
  - Latency – Protocol timers

- **Low-power, low-form factor transceivers**
  - Closing the uplink
    - Transmit power
    - Antenna aperture
- **Orchestration**
  - Resource allocation / Scheduling

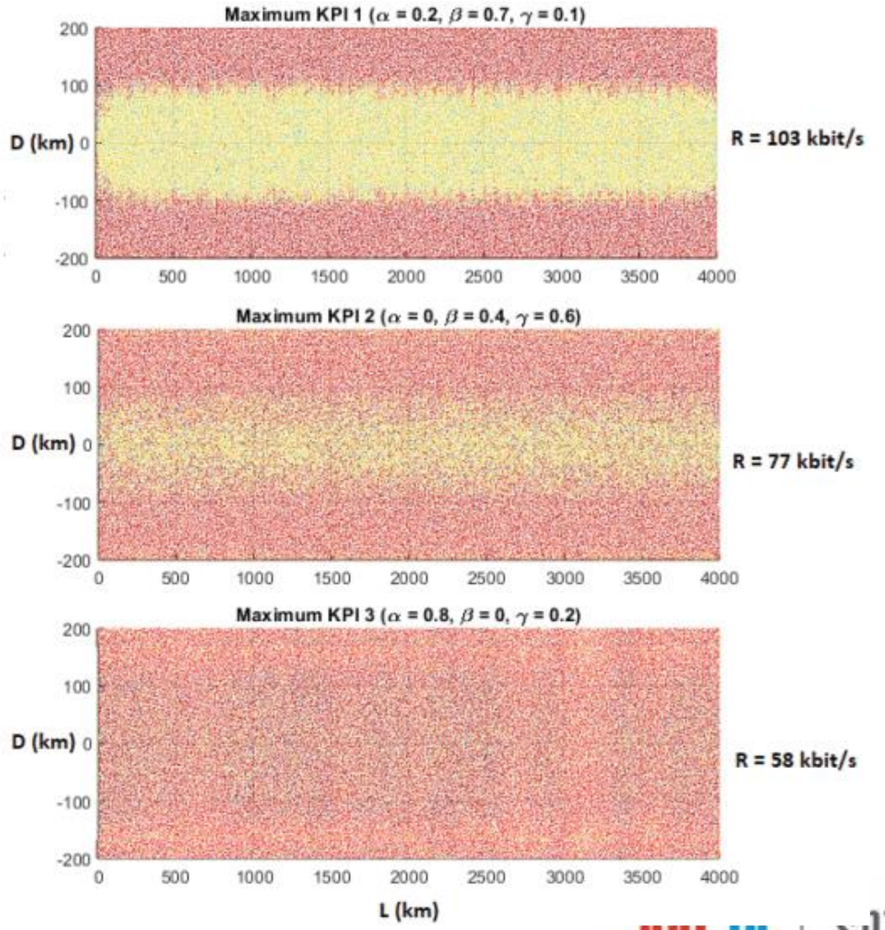


Example: Resource Allocation for Satellite IoT





- Results : [Kodheli22]



[Kodheli22] O. Kodheli, N. Maturo, S. Chatzinotas, S. Andrenacci and F. Zimmer, "NB-IoT via LEO Satellites: An Efficient Resource Allocation Strategy for Uplink Data Transmission," in IEEE Internet of Things Journal, vol. 9, no. 7, pp. 5094-5107, April 2022.

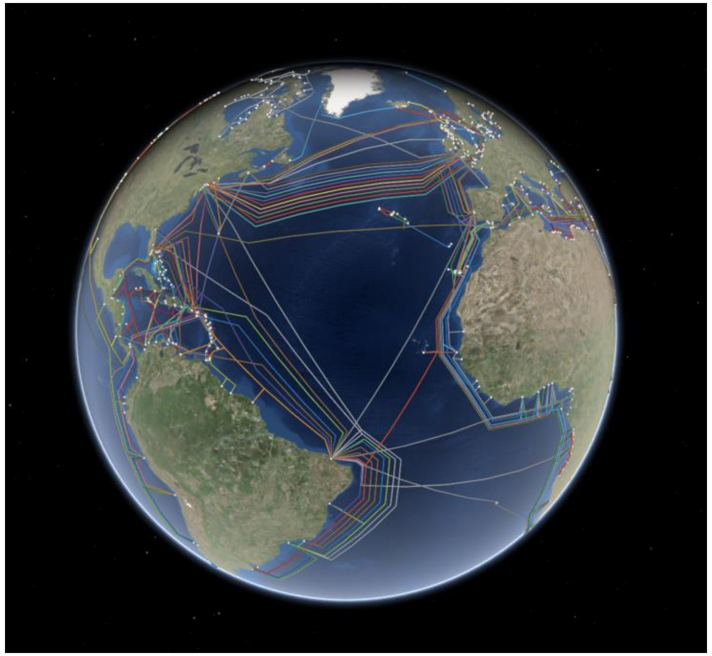
Data Offload & Backhauling

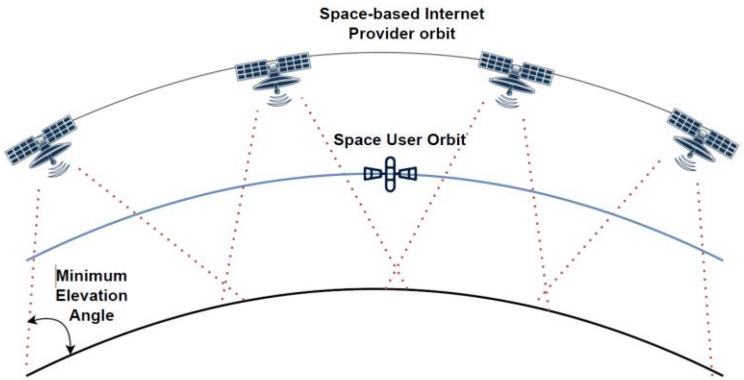
Historic Evolution

- **Legacy use cases:**
  - B2B
  - News gathering
  - Island connectivity

- **Margins under treat**
  - Terrestrial infrastructure
  - Underwater fiber optics

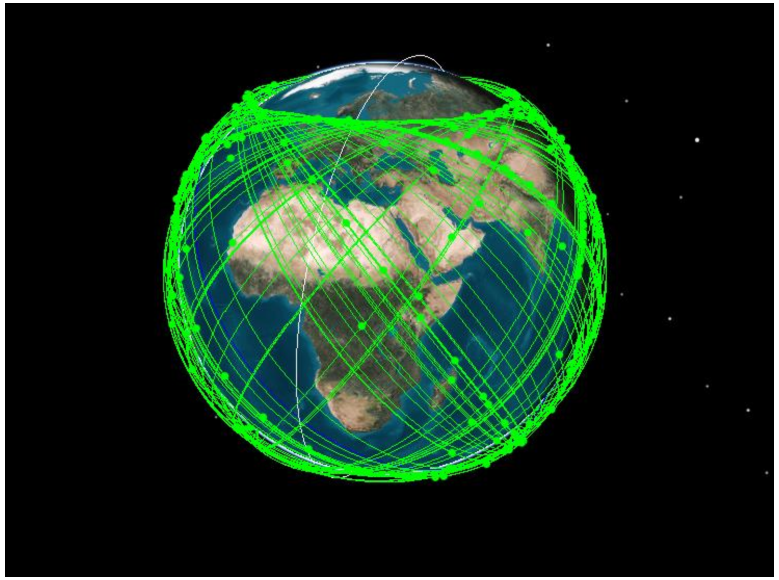
- <u>Serve Space rather than Ground…</u>

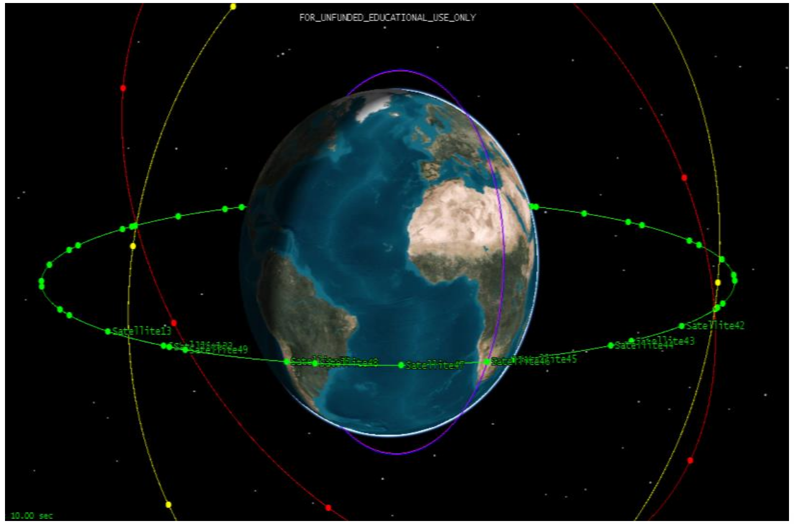




SAT-SPIN (Satellite Communications via Space-Based Internet Service)

- **Connecting space missions using space ISPs**
  - Apps: Earth Observation, Human Flight, IoT, IOD/IOV, Scientific
  - Services: Data Offload, TT&C
- **Space-based internet providers**
  - Starlink, O3b mPower and Oneweb
- **User Terminals**
  - Space mission at VLEO (300 Km altitude)
  - Biomas space mission – Sunsynchronuous orbit with 666 km altitude
  - Aqua space mission– Sunsynchronous orbit with 705 km altitude



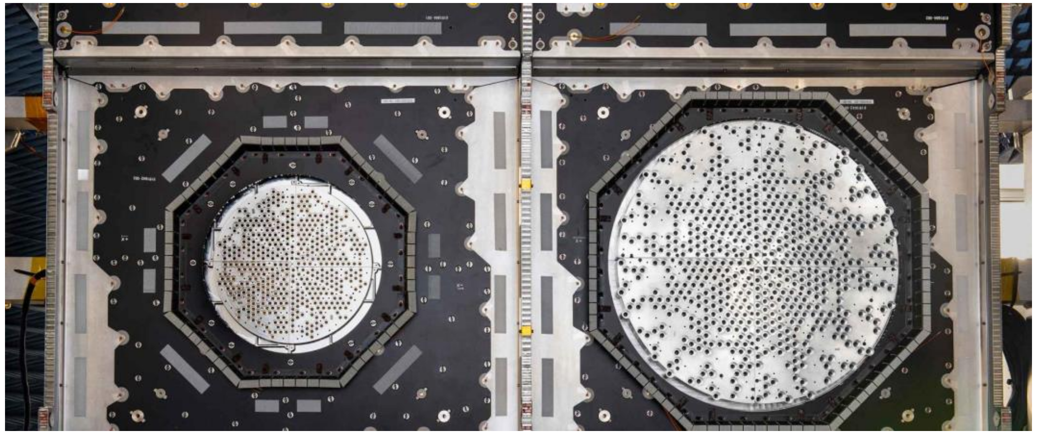


SAT-SPIN Challenges

- **2-way beamforming**
  - Fast relative mobility
  - High Doppler
  - High speed beam tracking
  - Power-mass limitations for antenna arrays on missions
  - Asymmetric UL-DL

- **Insights:**
  - MEOs offer better coverage than LEOs
  - UL is the most critical link
  - 10s of MBps are achievable

[Chougrani23] “Connecting Space Missions From NGSO Constellations: Feasibility Study”, arXiv:2309.16589



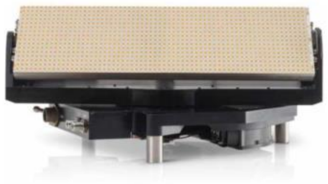


Figure 14 GetSat MilliSat LW
(dimensions: 52 cm diam., 23 cm height)

Figure 15 Kymeta u8
(dimensions: 89.5 cm x 89.5 cm x 12.3 cm)

Figure 16 GetSat Sling Blade
(dimensions: 73 cm x 10 cm x 84 cm)

Figure 17 Thinkom ThinWave
(dimensions: 91 cm diameter, 36 cm height)

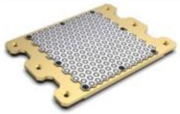


Figure 18 Cesium Nightingale I, antenna
(dimensions: 12 cm x 8.3cm x 7.3 cm)

Figure 19 Cesium Nightingale I, peripheral
(dimensions: 0.5 cm x 8.4 cm x 1.3 cm)

Planetary Communications

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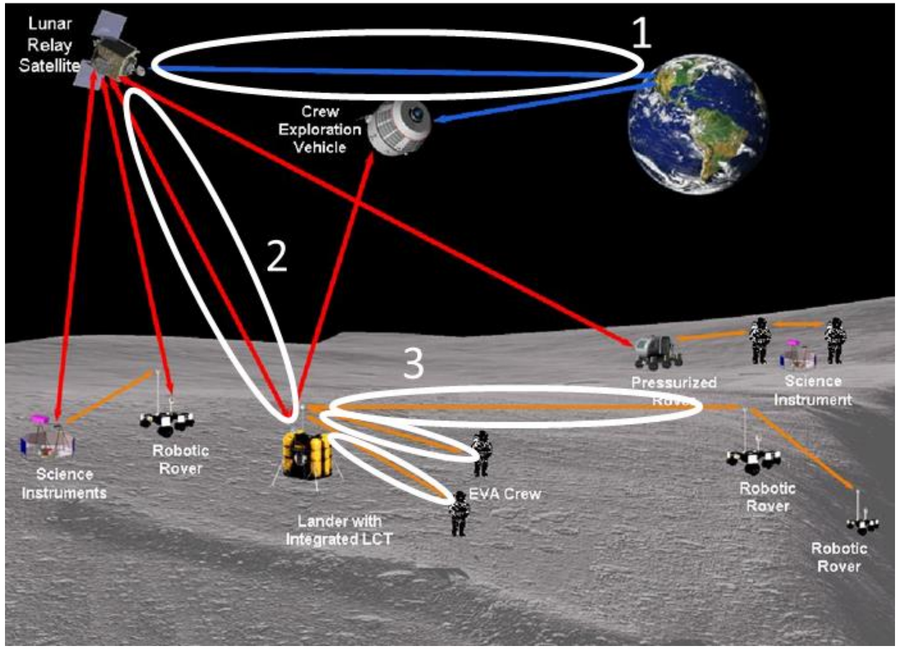
Space Communications beyond the Earth

- **6G SatComs will extend beyond the Earth**
  - Clear analogy with Earth-based networks, but
  - Space to Ground deployment

- **Extreme challenges**
  - Extreme radiation
  - Very large propagation delays
  - Limited power budget
  - Increased reliability for mission-critical comms

- **6G enablers for future extra-terrestrial comms**
  - Space Edge Computing
  - AI-accelerated Comms
  - Distributed processing
  - Ultra-reliable comms

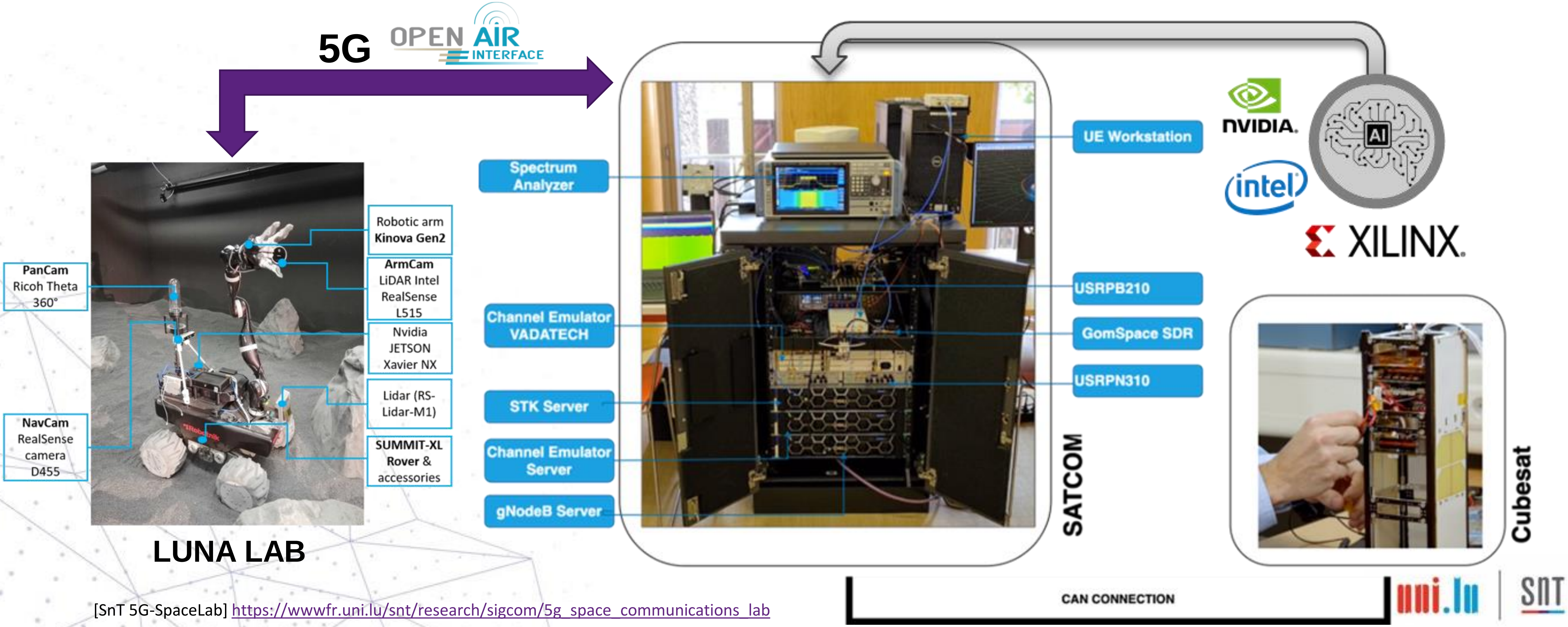


Common Extra-Terrestrial Links

1. Trunk / Inter-Planetary links
2. Orbit-to-Ground links
3. Space Proximity links

6GSPACE Lab (I)

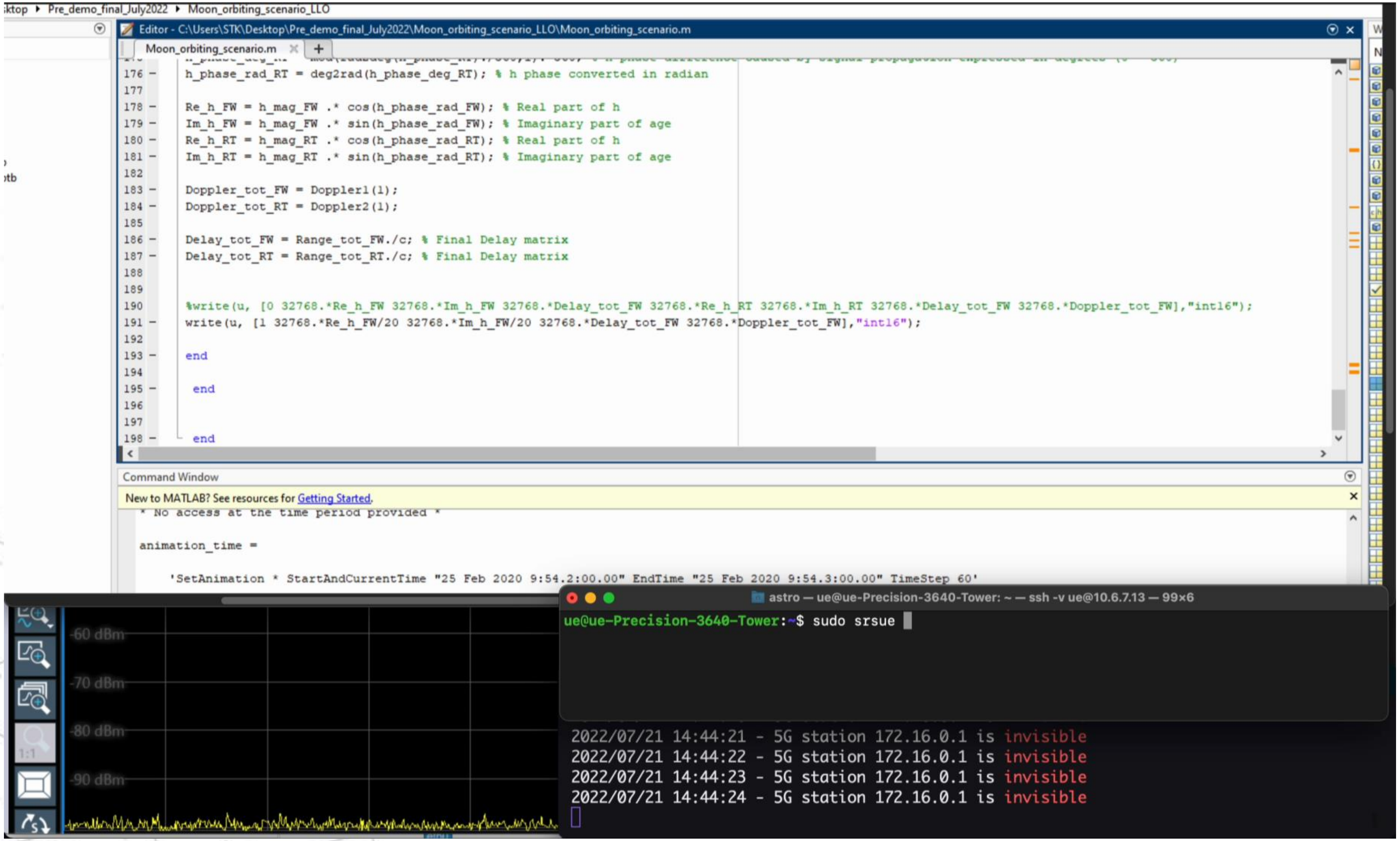
- **Interdisciplinary Joint Lab**
  - Communications, Robotics, CubeSats, Concurrent Design



[SnT 5G-SpaceLab] https://wwwfr.uni.lu/snt/research/sigcom/5g_space_communications_lab

5G Orbital Capabilities Emulation

5G LLO Mission



On-board AI… are we there yet?

- **On-board AI applications, e.g.**
  - FEC for regenerative payloads
    - ✓ To reduce the complexity, and thus the power consumption of FEC decoding algorithms on-board satellites
  - Payload reconfiguration
    - ✓ To improve reaction time to unexpected events
  - Earth Observation applications
    - ✓ To reduce the amount of data to be sent back to ground

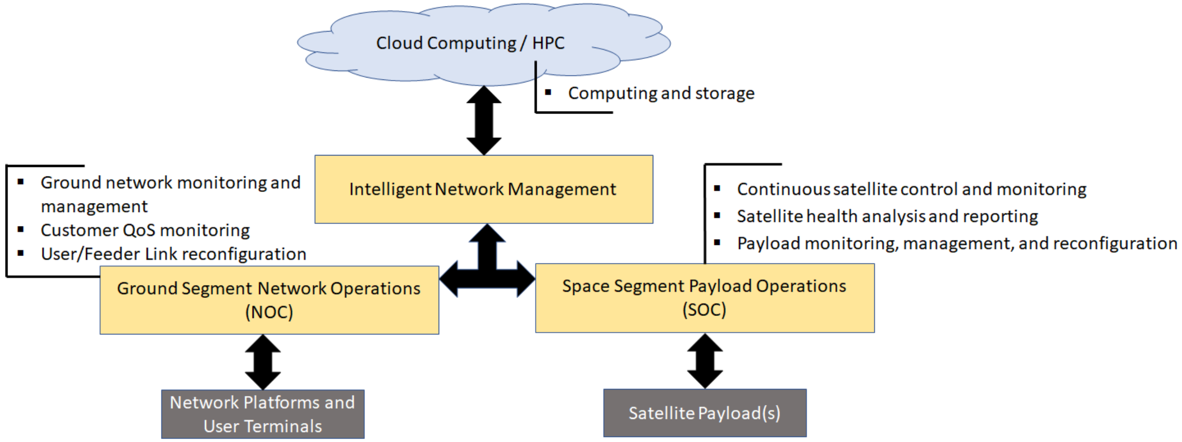
AI Chipset/Trade-Off KPIs	Computational Capacity	Memory	Power Consumption
Intel Movidius Myriad 2	1 TOPS	2 MB (DRAM 8 GB)	∼1 W
Intel Movidius Myriad X	4 TOPS	2.5 MB (DRAM 16 GB)	∼2 W
Nvidia Jetson TX2	1.33 TOPS	4 GB	7.5 W
Nvidia Jetson TX2i	1.26 TOPS	8 GB	10 W
Qualcomm Cloud AI 100 family	+70 TOPS	144 MB (DRAM 32 GB)	>15 W
AMD Instinct MI25	+12 TOPS	16 GB	>20 W
Lattice sensAI	<1 TOPS	<1 MB	<1 W
Xilinx Versal AI Core family	+43 TOPS	+4 GB	>20 W

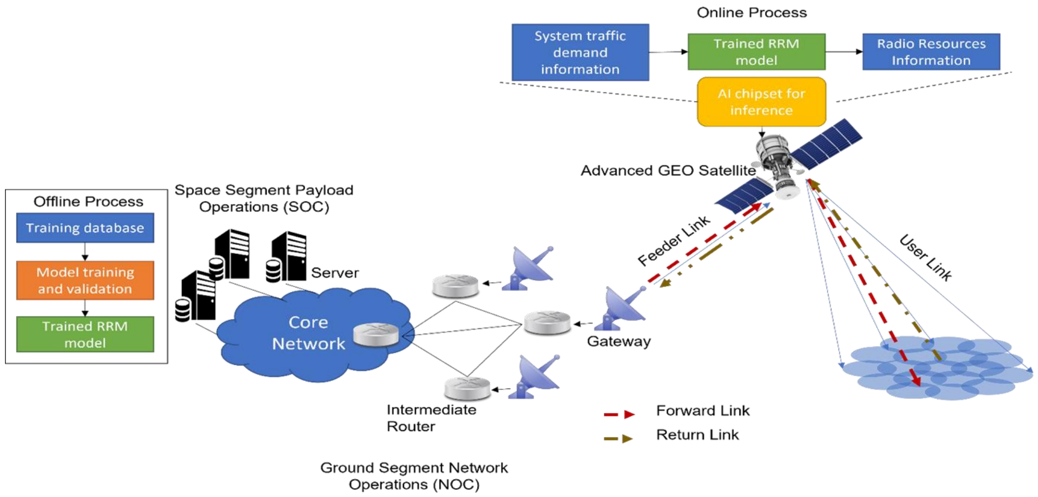
AI-Chip must be energy efficient and radiation tolerant, with memory and computational power adapted to the targeted application.

[Ortiz_MDPI] Ortiz-Gomez, F.G.; Lei, L.; Lagunas, E.; Martinez, R.; Tarchi, D.; Querol, J.; Salas-Natera, M.A.; Chatzinotas, S. Machine Learning for Radio Resource Management in Multibeam GEO Satellite Systems. *Electronics* **2022**, *11*, 992. https://doi.org/10.3390/electronics11070992

AI and Satellite Communications: Where?

- **FOR Space**
  - Congestion Prediction
  - Link Adaptation
  - Traffic classification
  - Channel prediction / estimation
  - Anomaly Detection in Telemetry Data
- **IN Space**
  - Interference Detection & Classification
  - Frequency plan optimization
  - Non-Linear Distortion
  - Antenna Array Configuration
  - Spectrum Management
  - Distributed network optimization

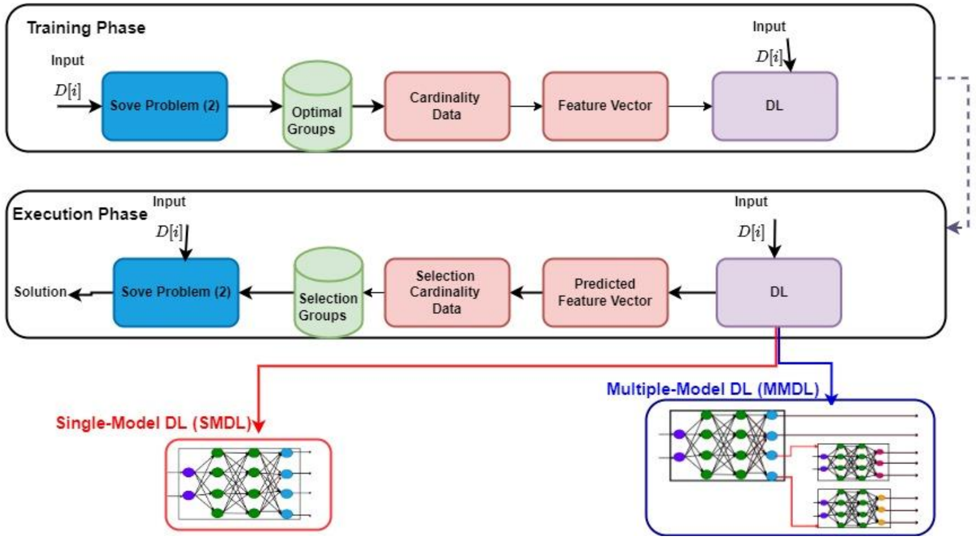


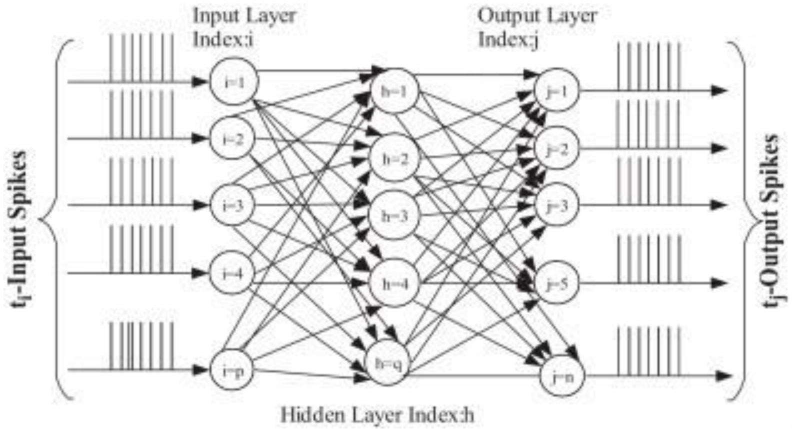


Fontanesi et al., “Artificial Intelligence for Satellite Communication and Non-Terrestrial Networks: A Survey”, Arxiv

AI and Satellite Communications: Why?

- **Acceleration**
  - <u>Timely Near-optimal solutions</u>
  - Learning-Assisted Optimization
  - “A Deep Learning Based Acceleration of Complex Satellite Resource Management Problem”, EUSIPCO2022.
  - Quantum Techniques
  - “Efficient Hamiltonian Reduction for Quantum Annealing on SatCom Beam Placement Problem”, ICC 2023.
- **Power Efficiency**
  - <u>Near-optimal solutions with few Jouls</u>
  - Function approximation trough pretraining
  - Neuromorphic computing
  - Onboard Processing in Satellite Communications Using AI Accelerators. Aerospace 2023, 10, 101.

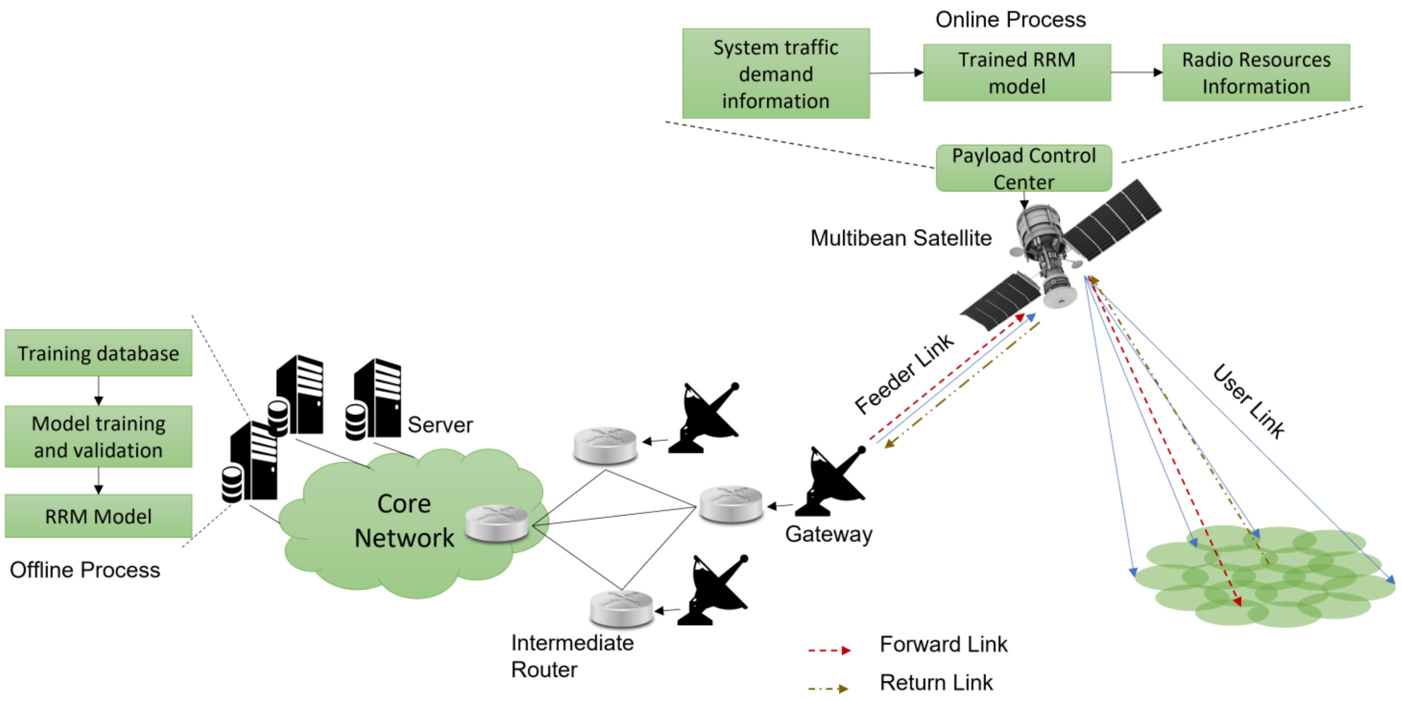




Fontanesi et al., “Artificial Intelligence for Satellite Communication and Non-Terrestrial Networks: A Survey”, Arxiv

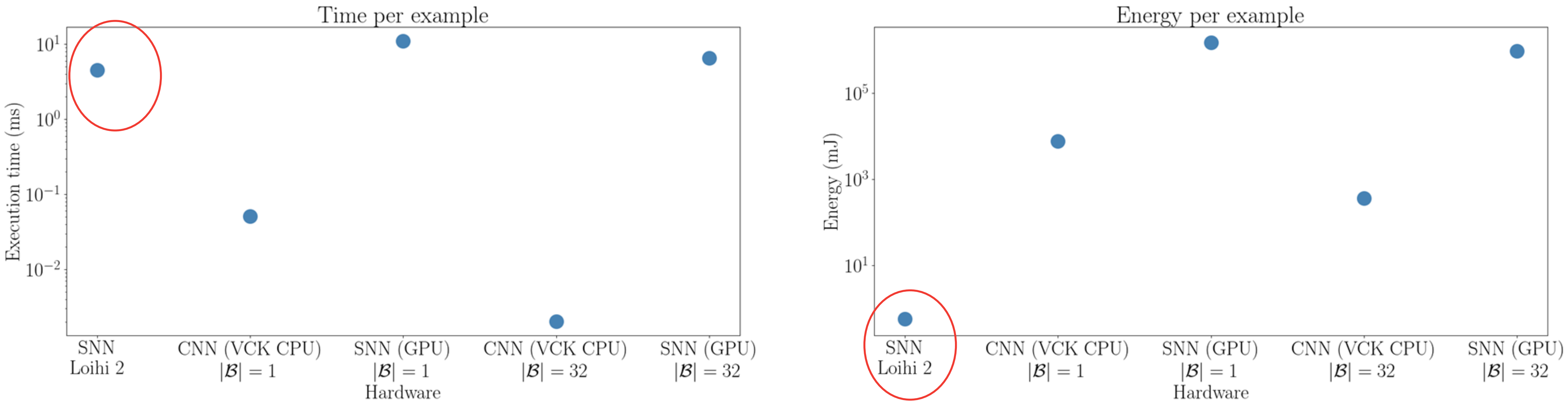
Neuromorphic Computing for Radio Resource Management

Candidate Scenario	Flexible Payload
System architecture	SDR payload
Air interface	Any air interface supporting multicarrier
AI-based technique(s)	Supervised Learning: Classification
Input / Output	Input: Traffic demand Output: configuration of the RF



A neuromorphic model based on a **spiking neural network (SNN)** and a non-neuromorphic model based on a **convolutional neural network (CNN)** were developed to compare the performance of both approaches.

Energy expenditure and runtime on Intel Loihi 2

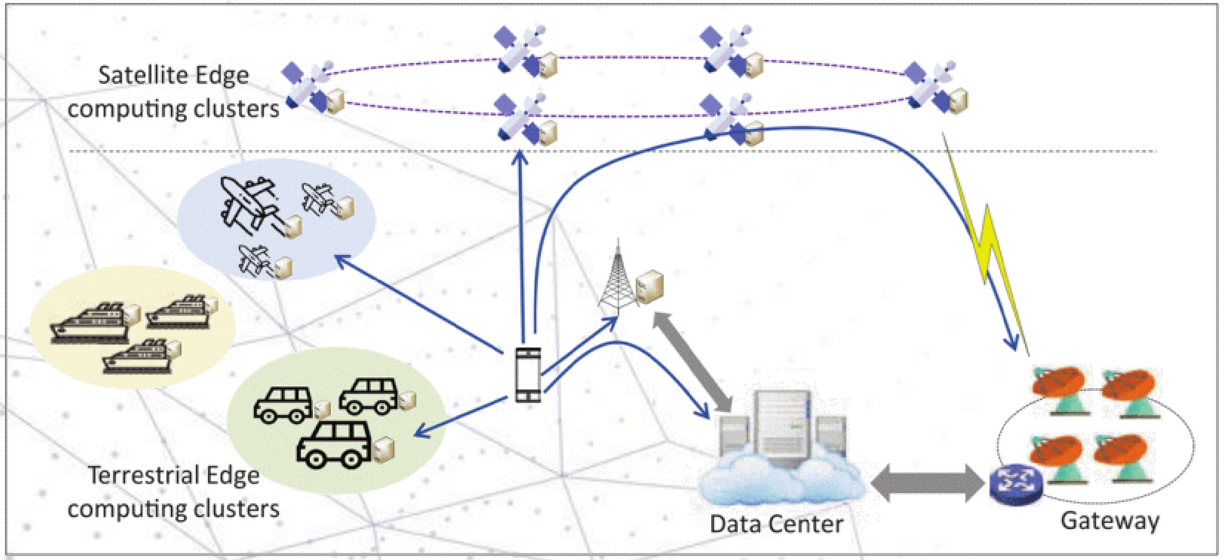


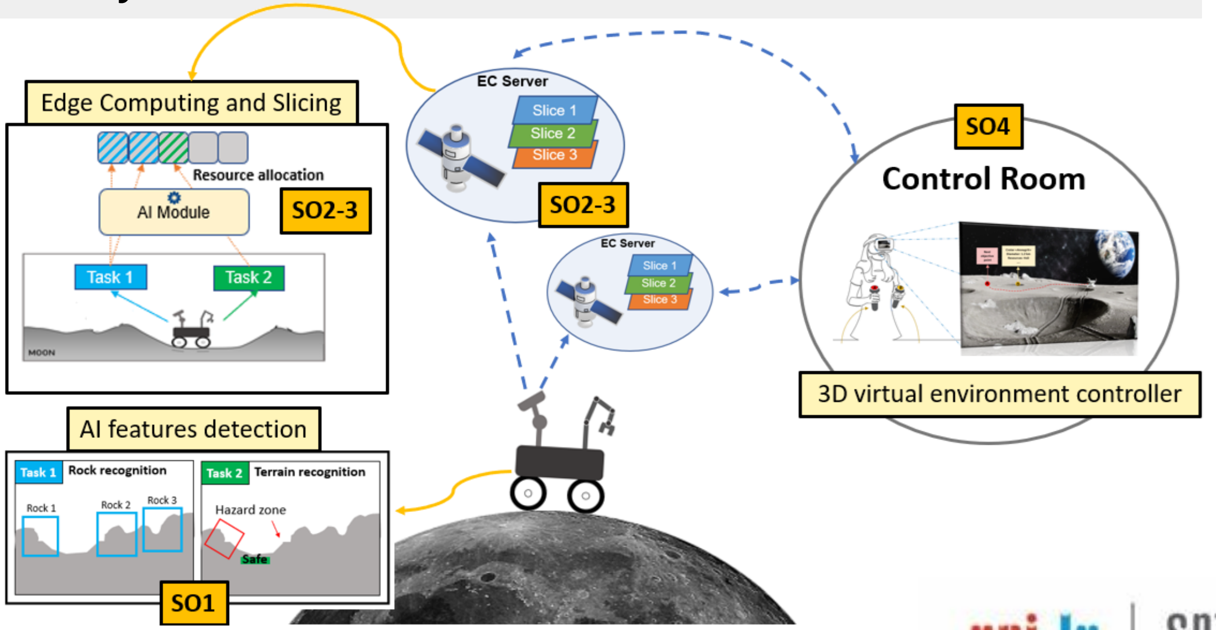
Comparison between execution of a Spiking Neural Network (SNN) on Loihi 2 and Convolutional Neural Network (CNN) on the CPU of the VCK 5000 (AI accelerator). Left: Average execution time per example. Right: Energy expenditure.

Ortiz et al. “Energy-Efficient On-Board Radio Resource Management for Satellite Communications via Neuromorphic Computing”, TMLCN, 2023, submitted.

Space-based Edge Computing

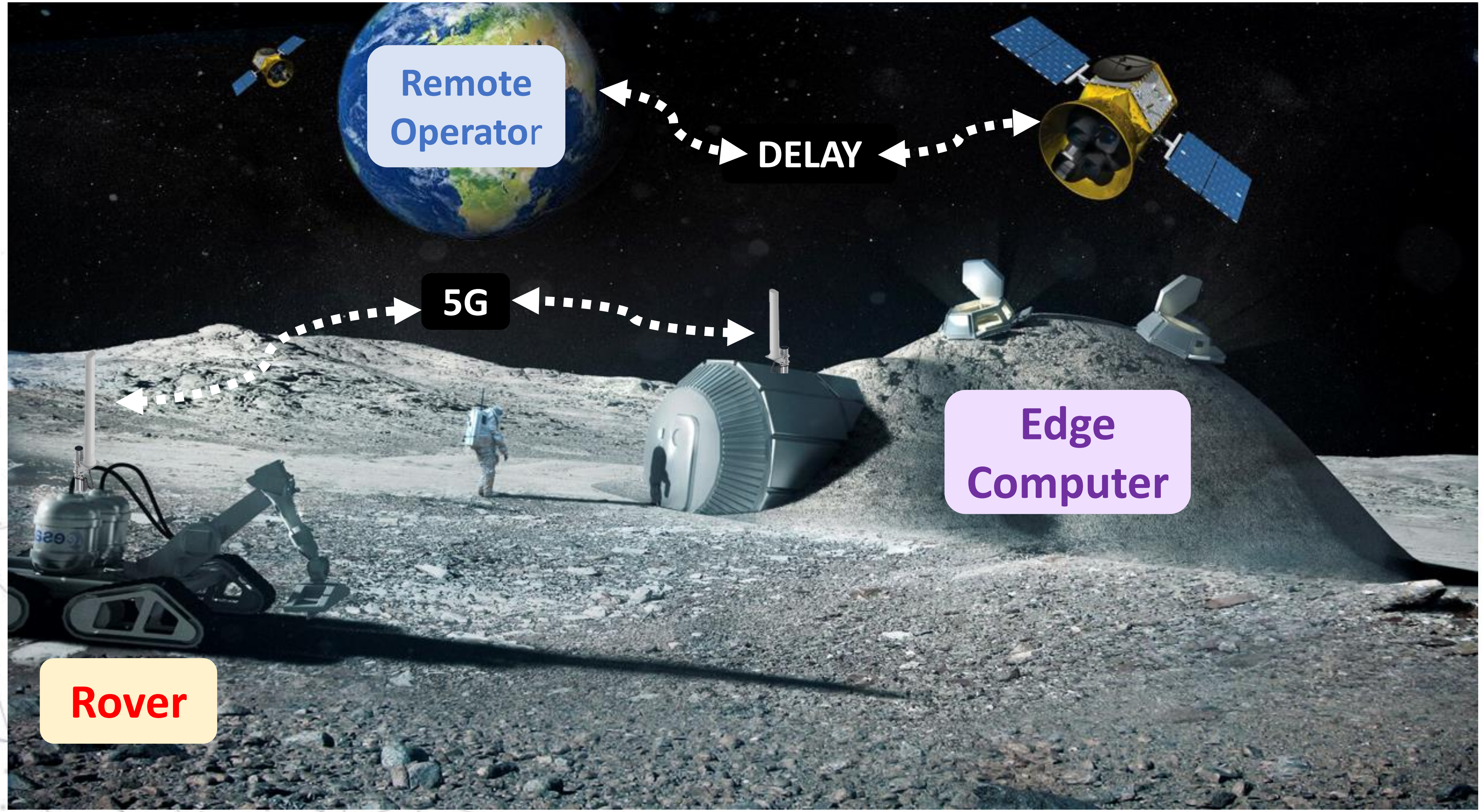
- **Edge Computing is a key-enabler of future space exploration**
  - Very large communication delays and low bitrates are bottlenecks for:
    - Teleoperation and telecommand
    - Image processing and feature recognition
    - Resource allocation and network management
  - Data must be (pre-)processed at the edge
  - AI-chipsets as enabler for low-complexity / low-power processing
  - Federated learning and reconfigurability used for dynamic network

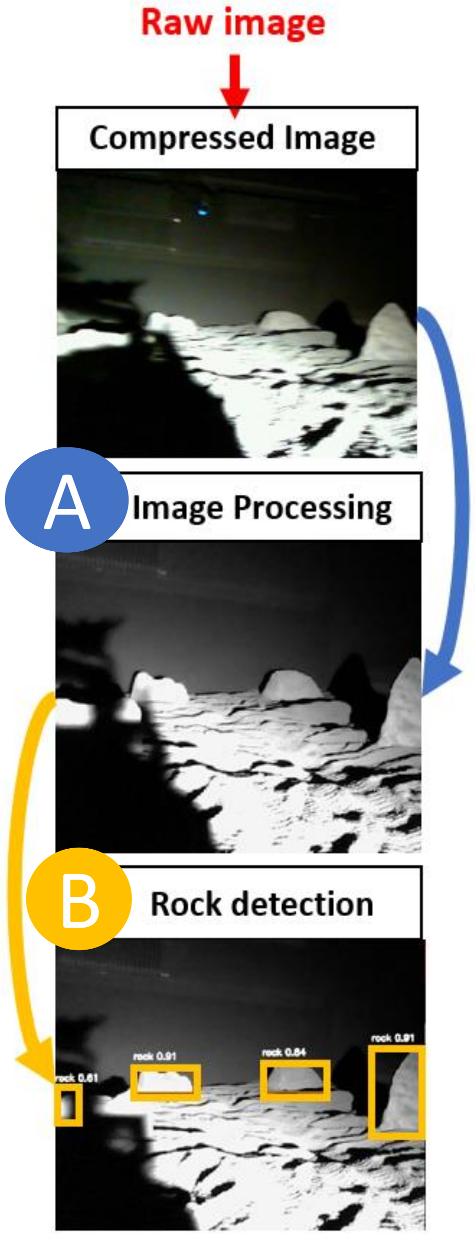




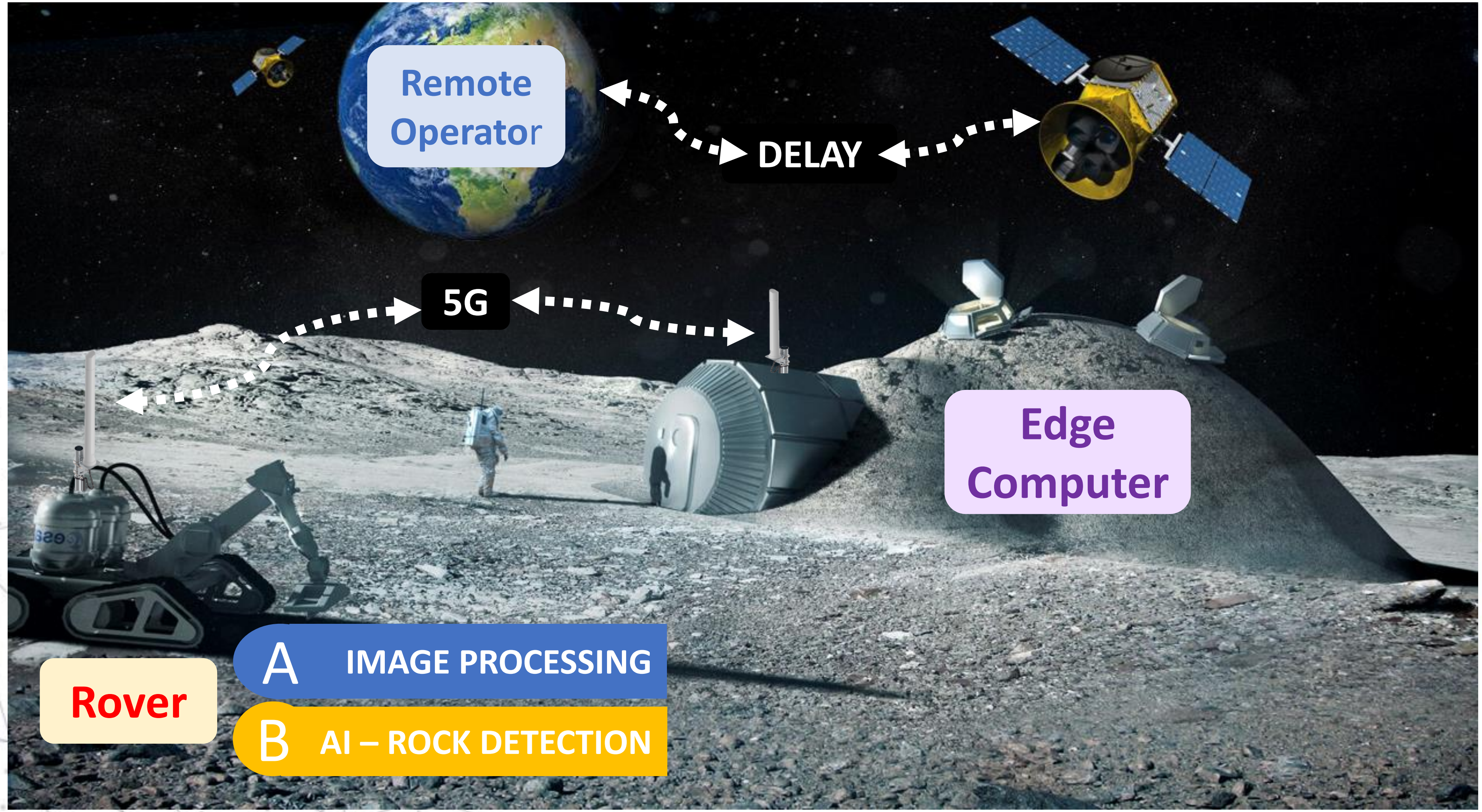
[Khodeli2022] O. Kodheli et al., '5G Space Communications Lab: Reaching New Heights," in 6th IEEE International Workshop on Wireless Communications and Networking in Extreme Environments (IEEE WCNEE 2022), Marina Del Rey, LA, California, USA, June 2022

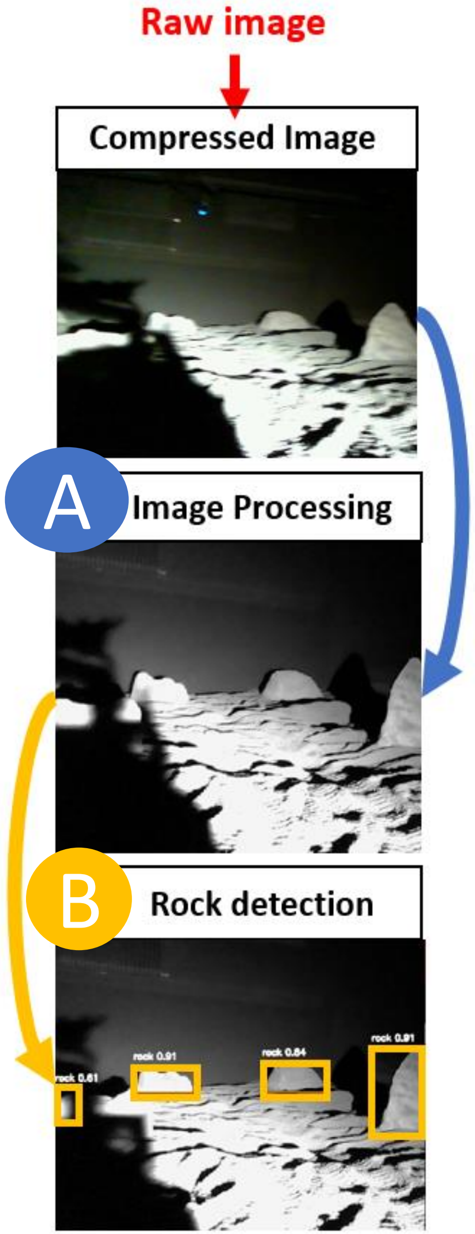
Space-based Edge Computing





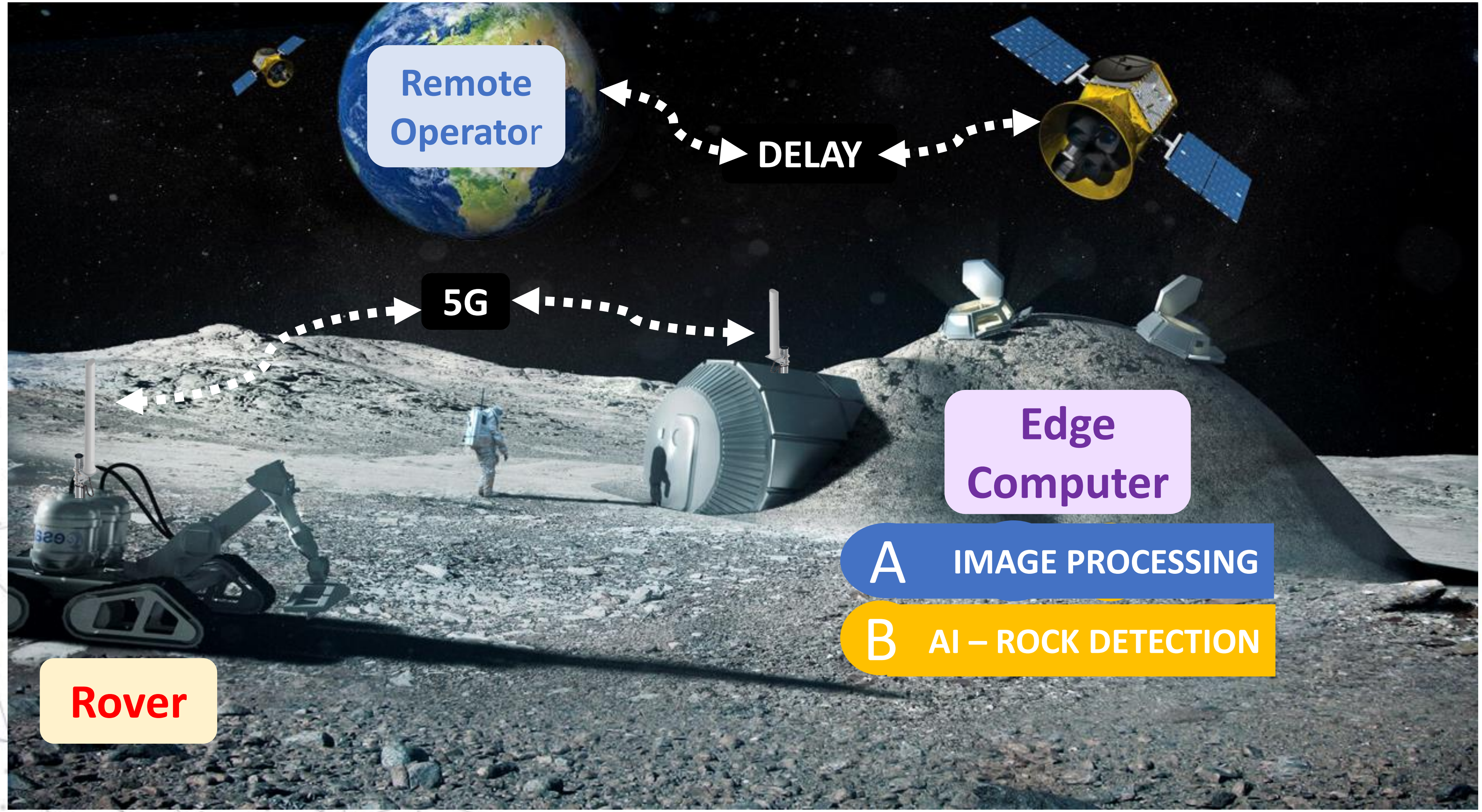
Space-based Edge Computing

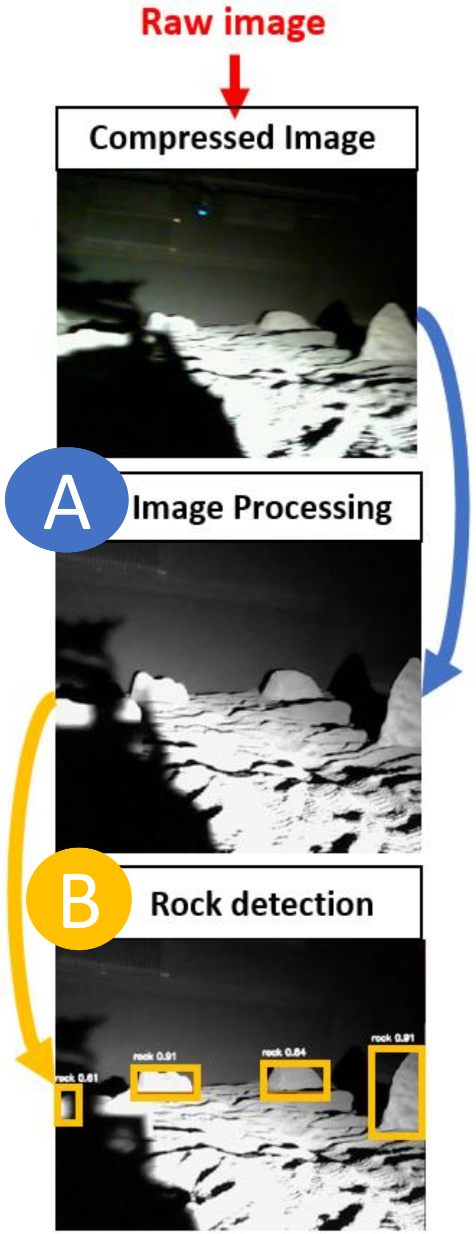




SCENARIO 1 (OBC)

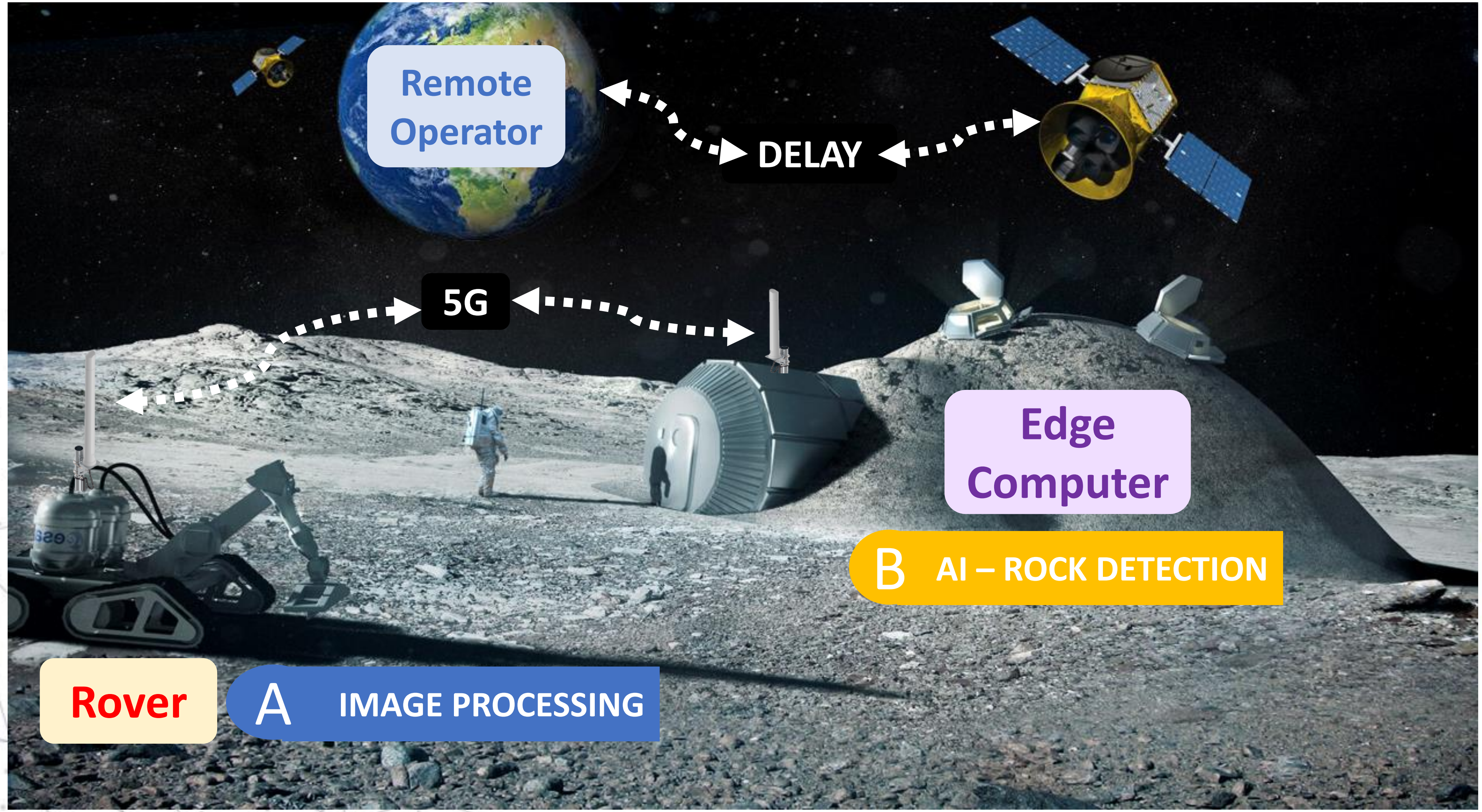
Space-based Edge Computing

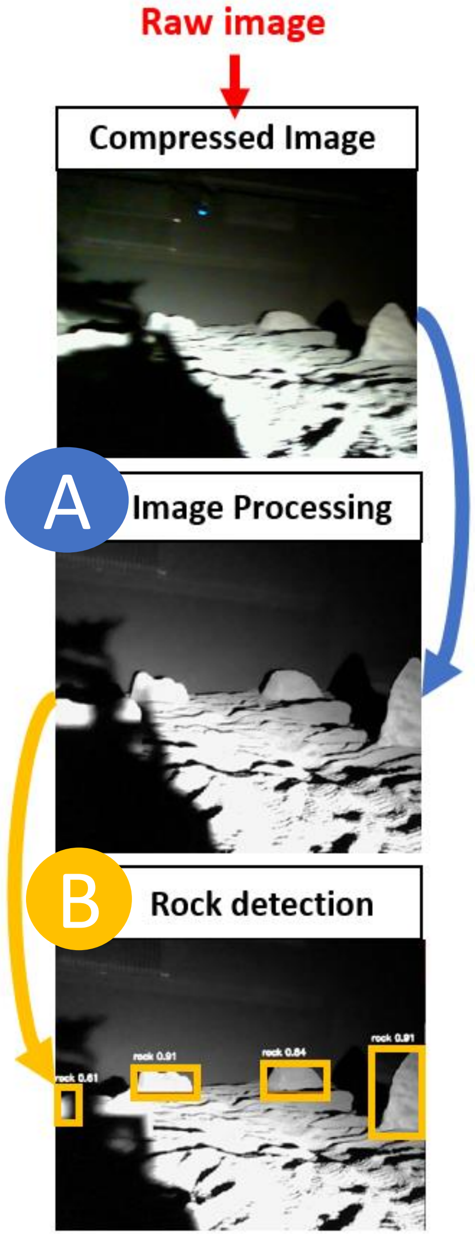




SCENARIO 2 (EC)

Space-based Edge Computing

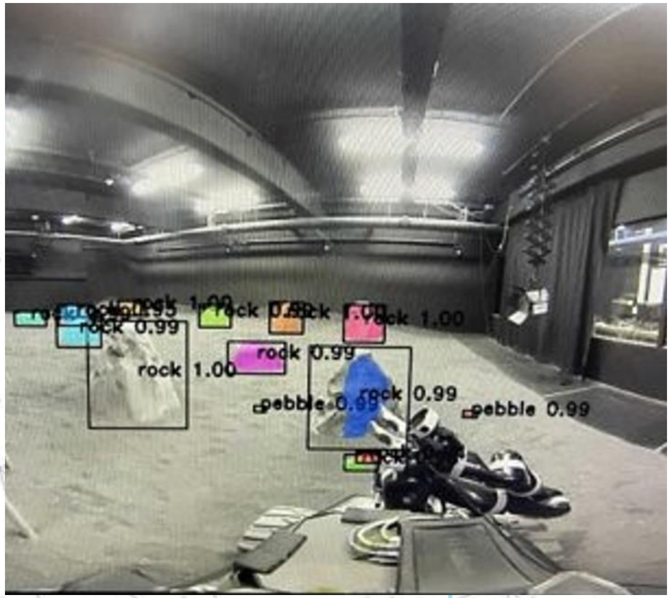




SCENARIO 3 (DC)

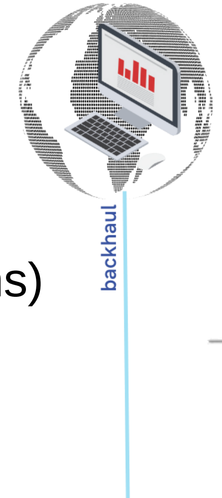
Space-based Edge Computing

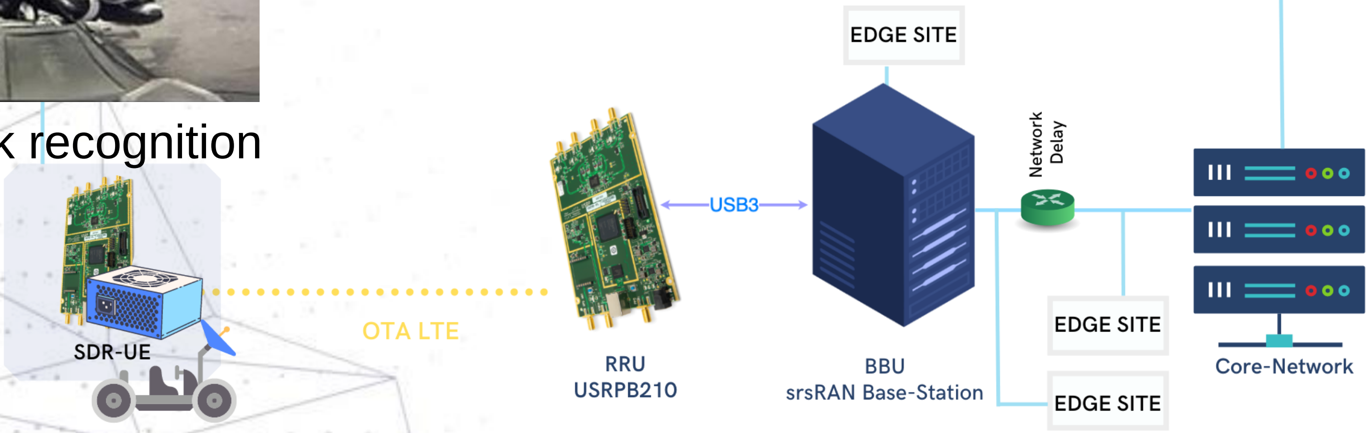
- **AI-based Edge Computing Lab Example**
  - Lunar rover teleoperation

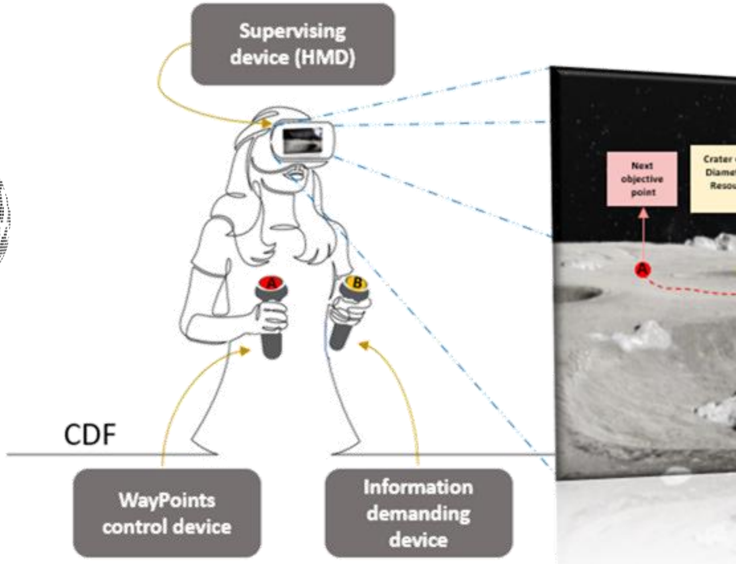


Application: Rock recognition

Edge Computer Conf.:
1. Rover (0 ms)
2. gNB / Base-Station (< 1 ms)
3. Lunar Core Network (2–20 ms)
4. Lunar Orbiter / Gateway (30–300 ms)

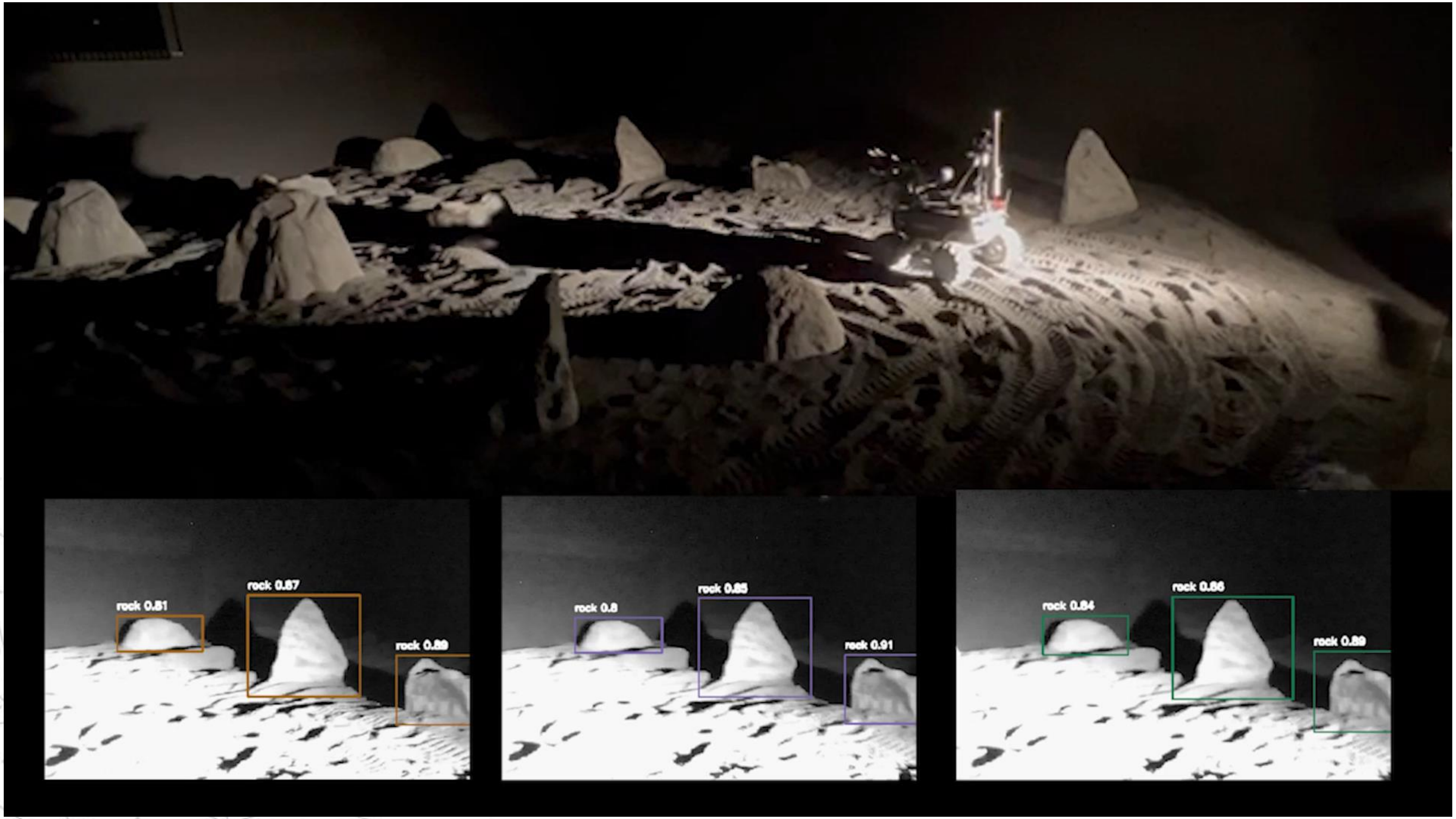






KPIs:
1. Rover autonomy
2. Overall E2E delay
3. AI Performance

Space-based Edge Computing Demo



CASE 1. NVIDIA Jetson

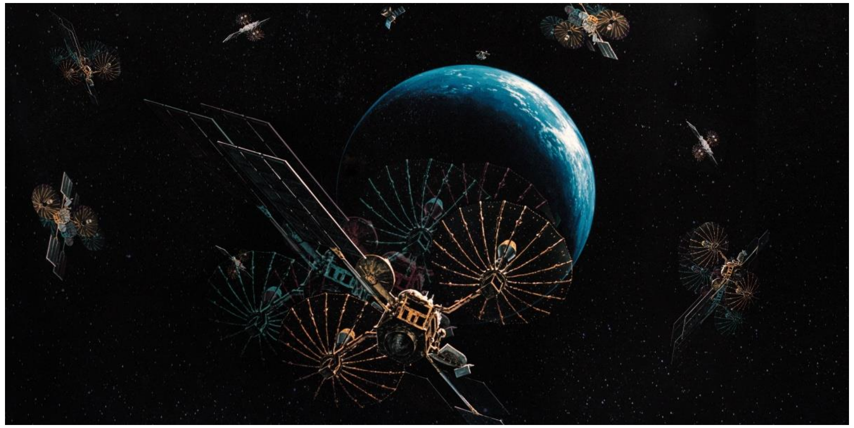
CASE 2. EC

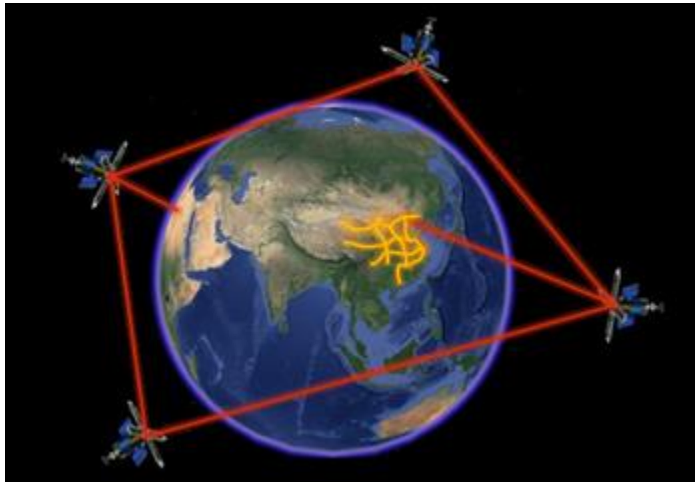
CASE 3. NVIDIA Jetson & EC

Quantum SatComs

- **Quantum Key Distribution**
  - Interconnect regional QCIs
  - P2P Ground connections through Satellite
  - Satellite as Trusted Node
  - Decoherence through atmosphere
  - Intra-Domain and Hybrid network orchestration

- **Quantum Space Internet**
  - Space Quantum Computer through Free Space Optics
  - Energy efficiency: bits modulated on single photons
  - Efficient cryogenics through passive cooling
  - Zero-carbon power generation
  - Interstellar communications: Quantum state decoherence
  - Superdense coding / Quantum teleportation over hybrid FSO





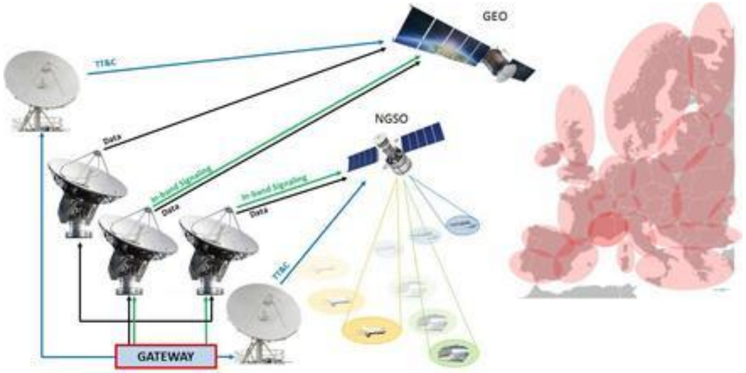
Open Challenges

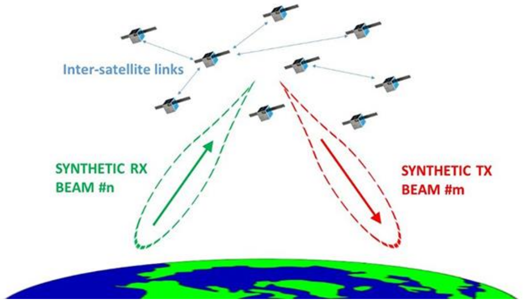
Open Challenges

Short-term

- **Compact multi-beam antennas for SatComs**
  - Both terminal (multi-orbit) and satellite-side
  - Reflectarrays, Optics
- **Low-power full-stack regeneration**
  - Full Base Stations in space
  - AI Chipsets in space
- **Distributed Satellite Systems**
  - Self-organized Swarms
  - Ultra-large Antenna arrays
  - Coherent communications
- **Space QCI**
  - From Space QKD to Space Quantum Internet
- **Lunar/Martian Comm Infrastructure**
  - Space to Ground buildup

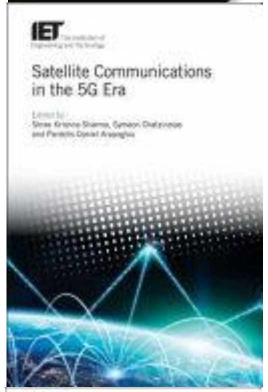
Long-term





Selected Publications

- Fontanesi et al., “Artificial Intelligence for Satellite Communication and Non-Terrestrial Networks: A Survey”, Arxiv
- Al-Hraishawi H. et al., “Characterizing and Utilizing the Interplay between Quantum Technologies and Non-Terrestrial Networks”, Arxiv
- Al-Hraishawi H. et al, “A Survey on Non-Geostationary Satellite Systems: The Communication Perspective”, IEEE COMST, 2023.
- L. M. Marrero et al., "Architectures and Synchronization Techniques for Distributed Satellite Systems: A Survey," IEEE Access, 2022
- Geraci G. et al, “What Will the Future of UAV Cellular Communications Be? A Flight from 5G to 6G”, IEEE COMST, 2022.
- Azari M. et al. “Evolution of Non-Terrestrial Networks From 5G to 6G: A Survey”, IEEE COMST, 2022.
- Kodheli O. et al, “Satellite Communications in the New Space Era: A Survey and Future Challenges”, COMST, vol. 23, no. 1, Q1 2021.
- Lagunas E. et al, “Non-Geostationary Satellite Communications Systems”, IET, 2022.
- Sharma S.K. et al, Chatzinotas S., Arapoglou P.D., “Satellite Communications in the 5G Era”, IET, ISBN: 978-1785614279, 2018.



Selected Projects

- Neuro-Sat: The Application of Neuromorphic Processors to Satcom Applications, ESA.
- ARMMONY: Ground-Based Distributed Beamforming Harmonization For The Integration Of Satellite And Terrestrial Networks, FNR.
- SmartSpace: Leveraging AI to Empower the Next Generation of Satellite Communications, FNR.
- PROSPECT: High data rate, adaptive, internetworked proximity communications for Space project, ESA.
- 5G-LEO: OpenAirInterface extension for 5G satellite links, ESA.
- SAT-SPIN: Satellite Communications via Space-Based Internet Service Providers. ESA.
- SPAICE: Satellite Signal Processing Techniques using a Commercial Off-the-shelf AI Chipset, ESA.
- EGERTON: Efficient Digital Beamforming Techniques for On-board Digital Processors, ESA.
- 5G-GOA: 5G-Enabled Ground Segment Technologies Over-The-Air Demonstrator, ESA.
- MEGALEO: Self-Organized Lower Earth Orbit Mega-Constellations, FNR.
- 5G-SpaceLab: 5G Space Communications Lab, UniLu.

THE GOVERNMENT OF THE GRAND DUCHY OF LUXEMBOURG
Ministry of State
Department of Media, Telecommunications and Digital Policy

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