Sustainable NTNs through AI, ISAC and RIS

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Acknowledgements:
SIGCOM RG Members

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THE GOVERNMENT OF THE GRAND DUCHY OF LUXEMBOURG
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esa

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ses

LABS

NOKIA Bell Labs

HUAWEI

ODYSSEUS SPACE

Track Record

- **15** years in operation
- **100+** Researchers
- **80+** R&D projects
- **70M€+** Funding
- **6** Industrial Partnerships

Research Areas

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

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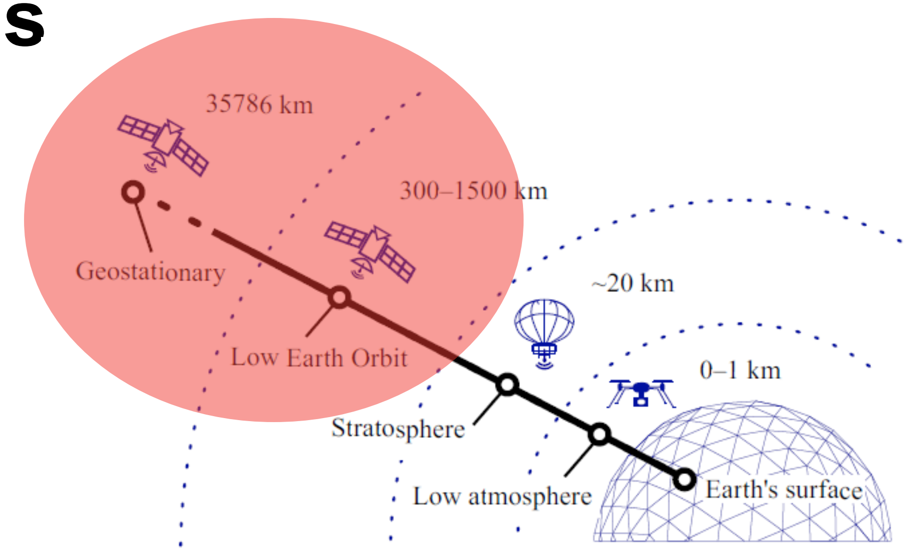
6G NTN Sustainability

Setting the Scene: NTN and SatComs



Expectations

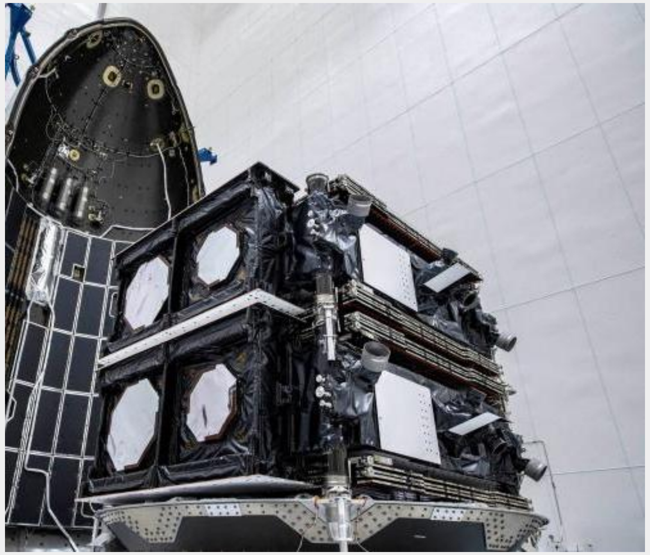
- Ubiquitous coverage / Digital Divide
- Maritime/aeronautical/Rural areas
- Wide area content delivery / data collection
- Direct smartphone/vehicle access

SatComs vs HAPS vs UAVs

Aspect	Satellites	HAPS	UAVs
Technology Readiness	Mature technology with high TRLs (up to TRL 9)	Emerging technology	Rapidly evolving, high TRLs for many applications
Regulation	Strict international and national regulations (e.g., ITAR, FCC)	Developing regulation, focus on airspace and environmental	Comprehensive regulations for commercial and recreational use
Business	Established market with major players	Growing interest, investments from aerospace companies	Diverse applications, defense, logistics

Satellite Evolution – Downhill battle

- First GEO 1960s
- 6 tons
- 15 years lifetime
- 35000 km



- First MEO 2010s
- 2 tons
- 12 years lifetime
- 8000 Km

- First megaLEO 2018
- ¼ ton
- 5 years lifetime
- 300-1500 Km

Terminal Evolution – Uphill battle

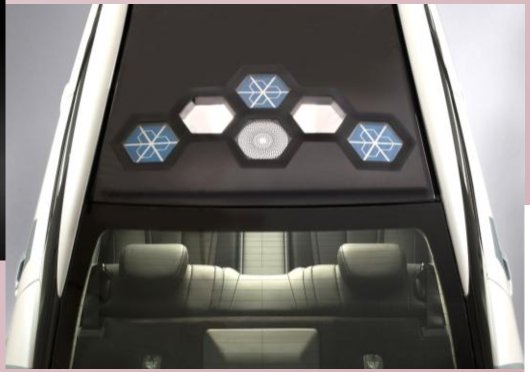
- Fixed GEO VSATs
- Parabolic reflectors
- Tens of Thousands

- Fixed LEO VSATs
- Flat panel
- Antenna array
- 5 Million

Direct-to-X

SWaP Challenge

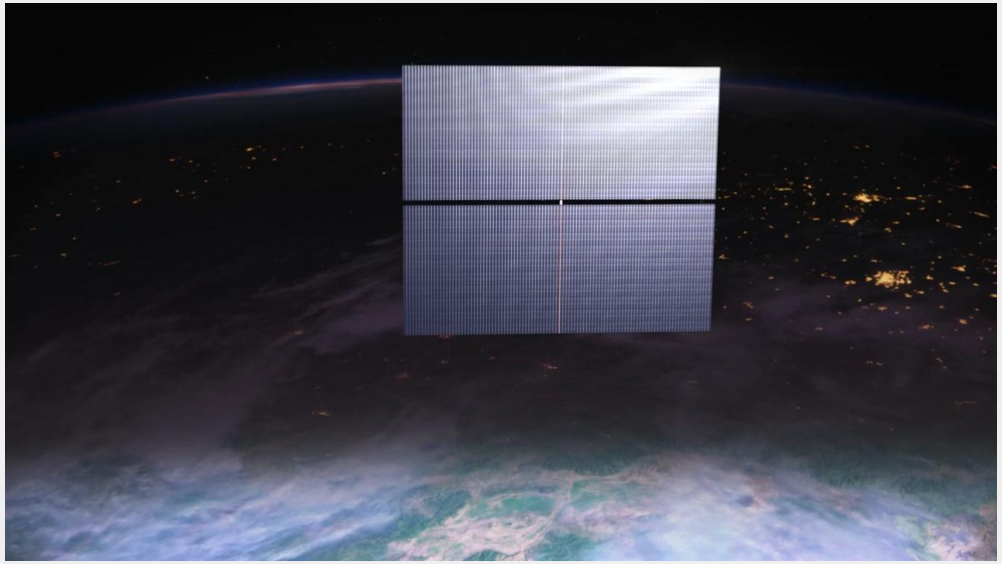
- Vehicular VSAT
- Rooftop
- Antenna array
- 1.5 Billion



- NTN Handheld, IoT sensor
- 3GPP Compliant
- 15 Billion

Sustainability

- **Resources:**
  - Fuel, Materials => Launch, Manufacturing
  - Spectrum => Heavily regulated
  - Orbits, Power
- **Comm performance:**
  - Higher payload mass, Denser Constellations
  - Higher Launch costs



- Starlink => High Density
- AST => High Payload Mass

Component	Single LEO Satellite	LEO Mega-Constellation
Space Segment	**High Share**	**Lower Share**
Launch	Moderate	**Dominant**
Ground Segment	Low	Moderate

AI In Space

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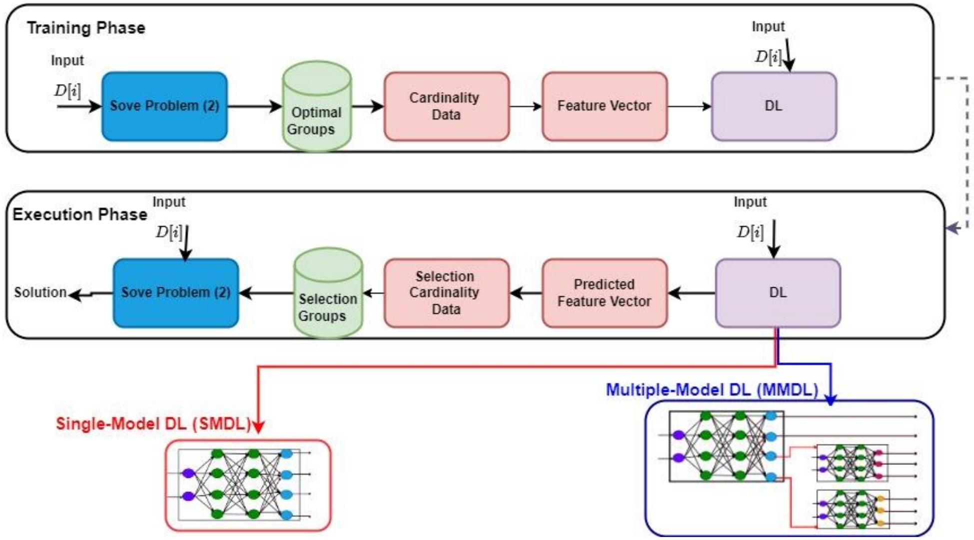
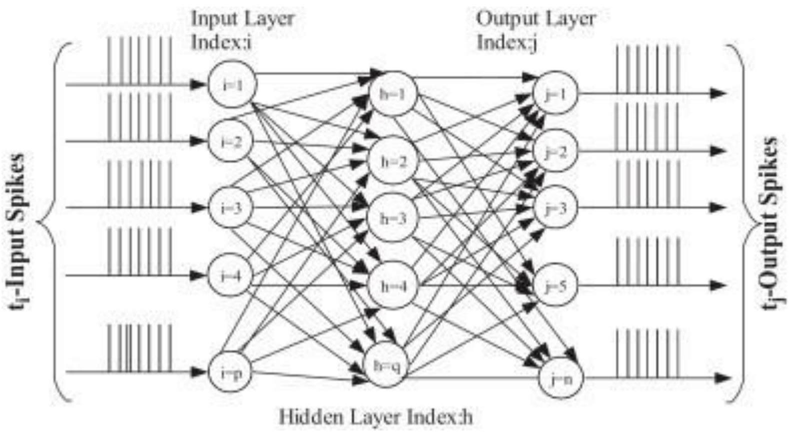
AI and Space: What For?

- **Acceleration**
  - Timely Near-optimal solutions
  - 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**
  - Near-optimal solutions with few Jouls
  - Function approximation trough pretraining
  - Neuromorphic computing
  - Onboard Processing in Satellite Communications Using AI Accelerators. Aerospace 2023, 10, 101.





G. Fontanesi et al., "Artificial Intelligence for Satellite Communication: A Survey," in IEEE Communications Surveys & Tutorials

On-board AI… are we there yet?

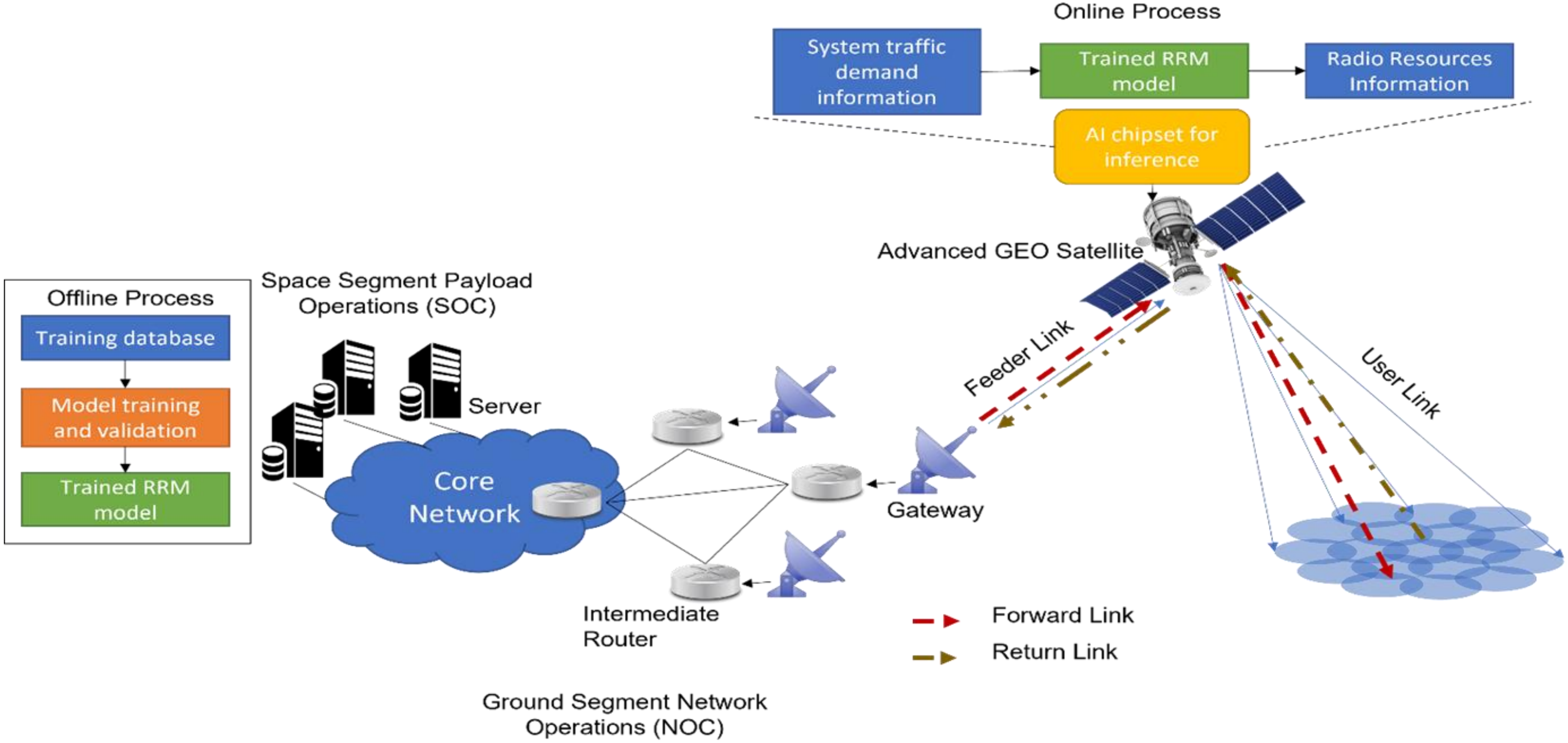
- **On-board AI applications, e.g.**
  - FEC for regenerative payloads
    - ✓ To reduce the complexity, and thus the power consumption of FEC decoding algorithms on-board satellites
  - Payload reconfiguration
    - ✓ To improve reaction time to unexpected events
  - Earth Observation applications
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

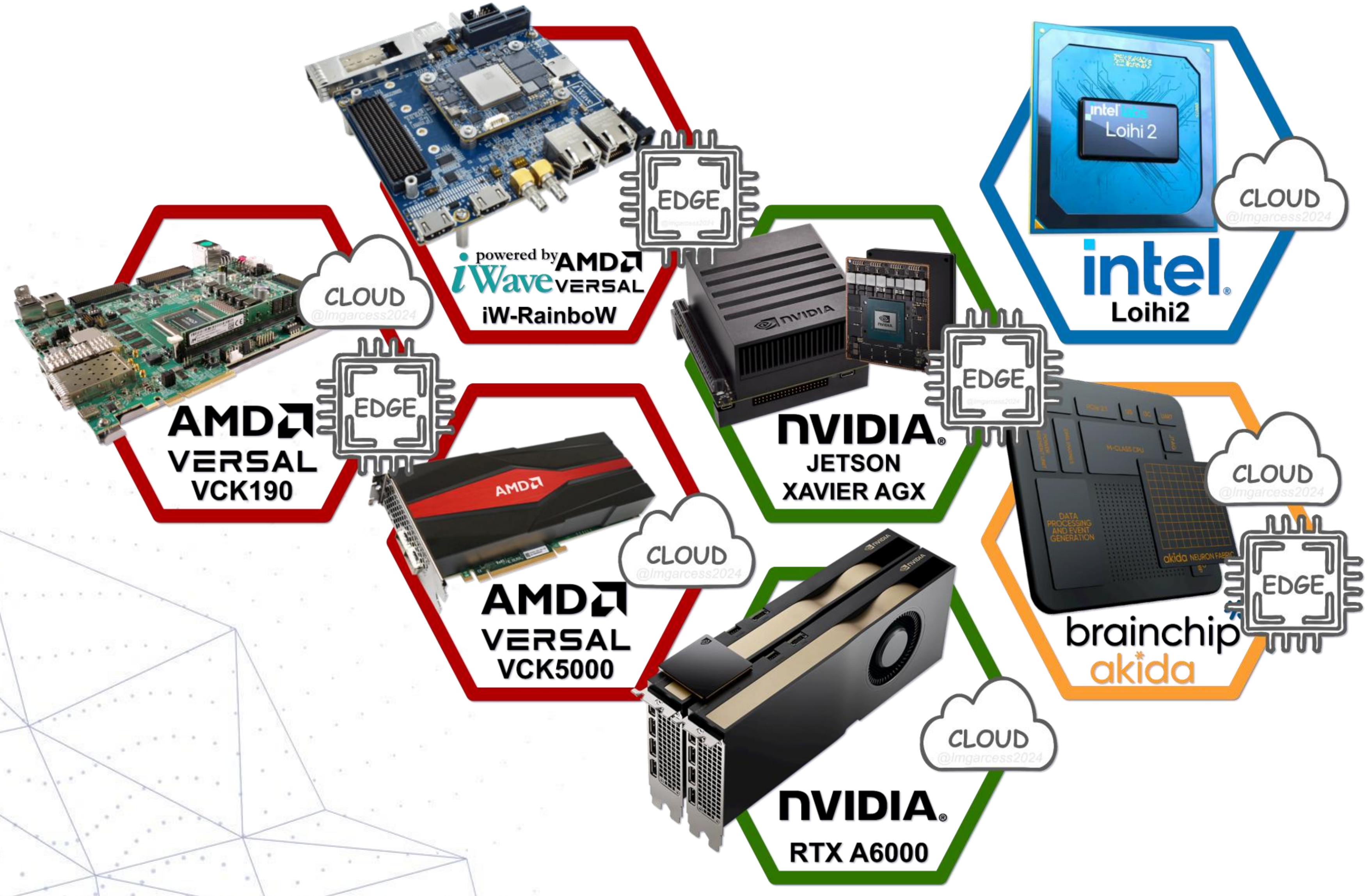
[Ortiz_MDPI] Ortiz-Gomez, F.G.; Lei, L.; LaguSatellitenas, E.; Martinez, R.; Tarchi, D.; Querol, J.; Salas-Natera, M.A.; Chatzinotas, S. Machine Learning for Radio Resource Management in Multibeam GEO Systems. *Electronics* **2022**, *11*, 992. https://doi.org/10.3390/electronics11070992

On-board AI: Principles & Architecture



- ML algorithm training is performed offline in ground segment
- The obtained model is uploaded to the on-board AI chipset

AI/ML Platforms at SIGCOM



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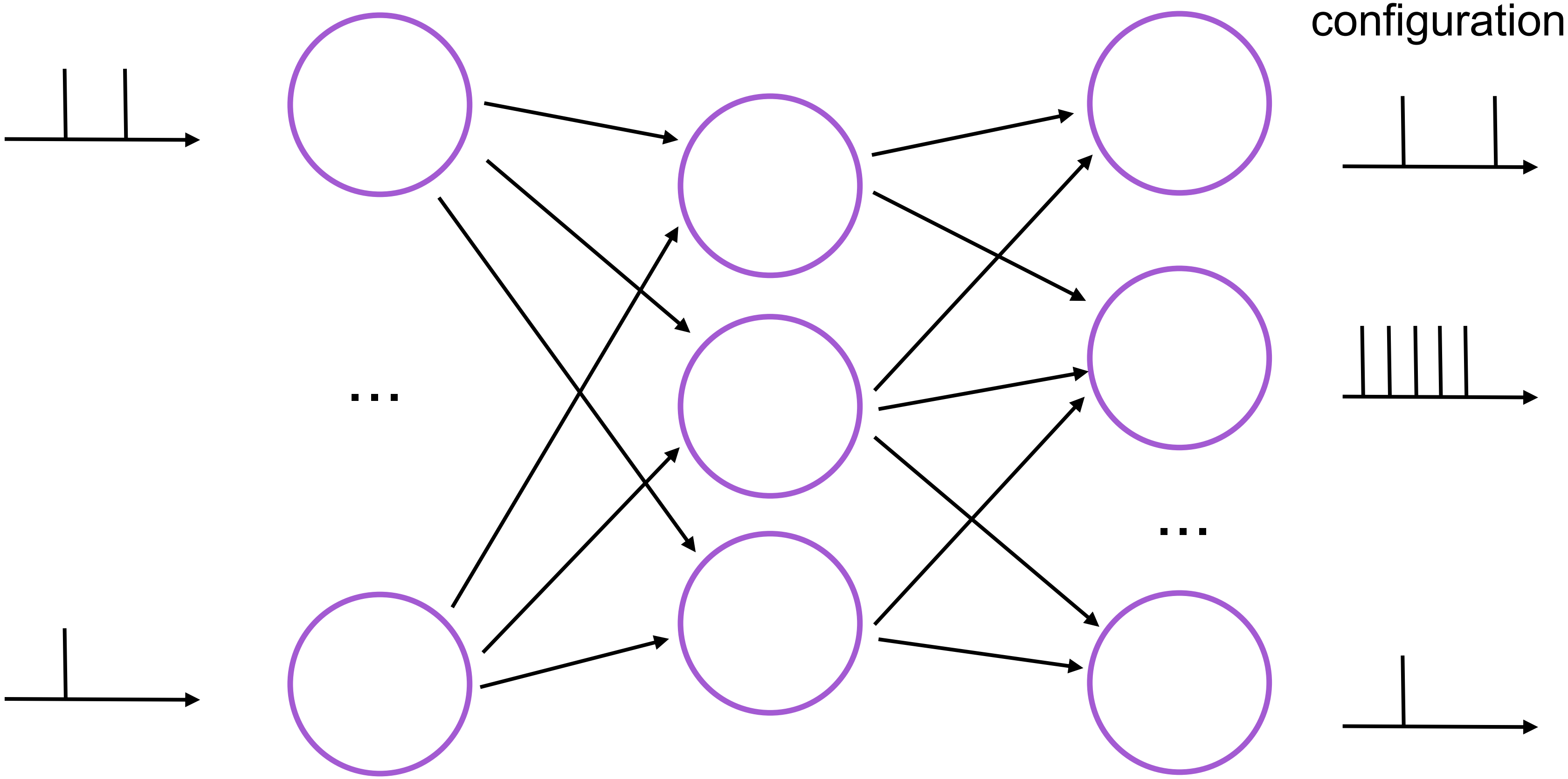
SNN model

Encoded CINR signals

SNN

Each output neuron corresponds to the index of a possible configuration

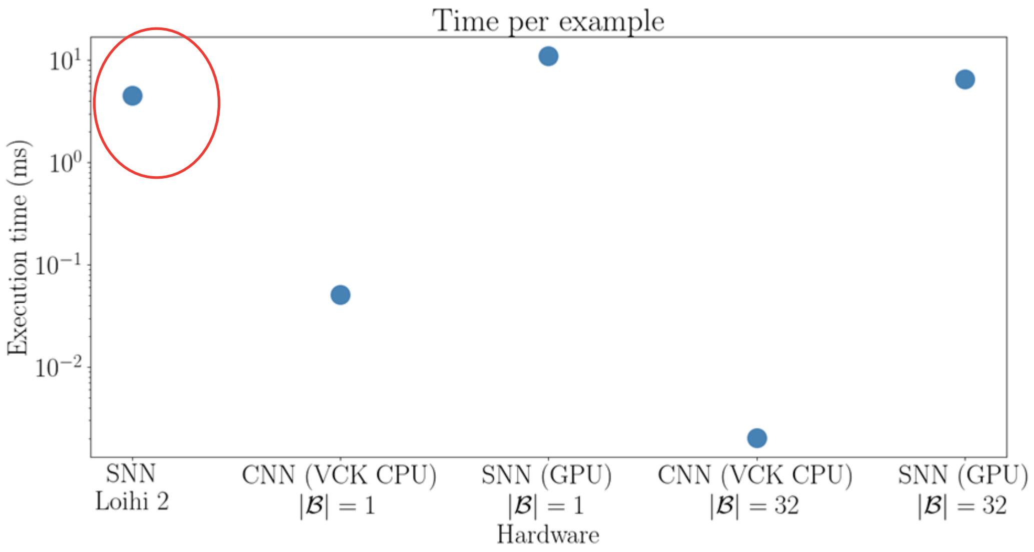


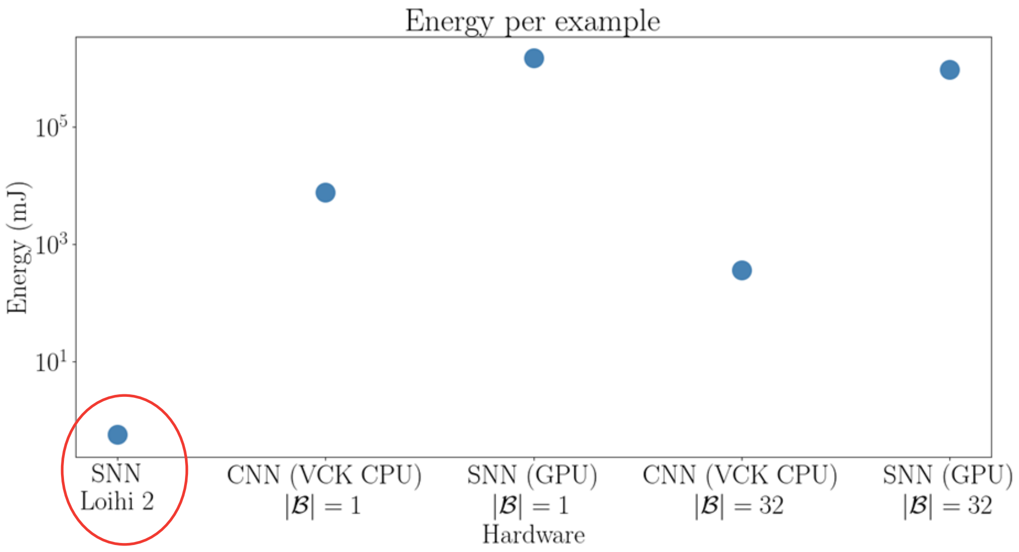
Payload Configuration 1

Payload Configuration 2

Payload Configuration N

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).

F. Ortiz *et al.*, "Energy-Efficient on-Board Radio Resource Management for Satellite Communications via Neuromorphic Computing," in *IEEE Transactions on Machine Learning in Communications and Networking*, vol. 2, pp. 169-189, 2024, doi: 10.1109/TMLCN.2024.3352569.

Communication, Sensing, Positioning on NTNs

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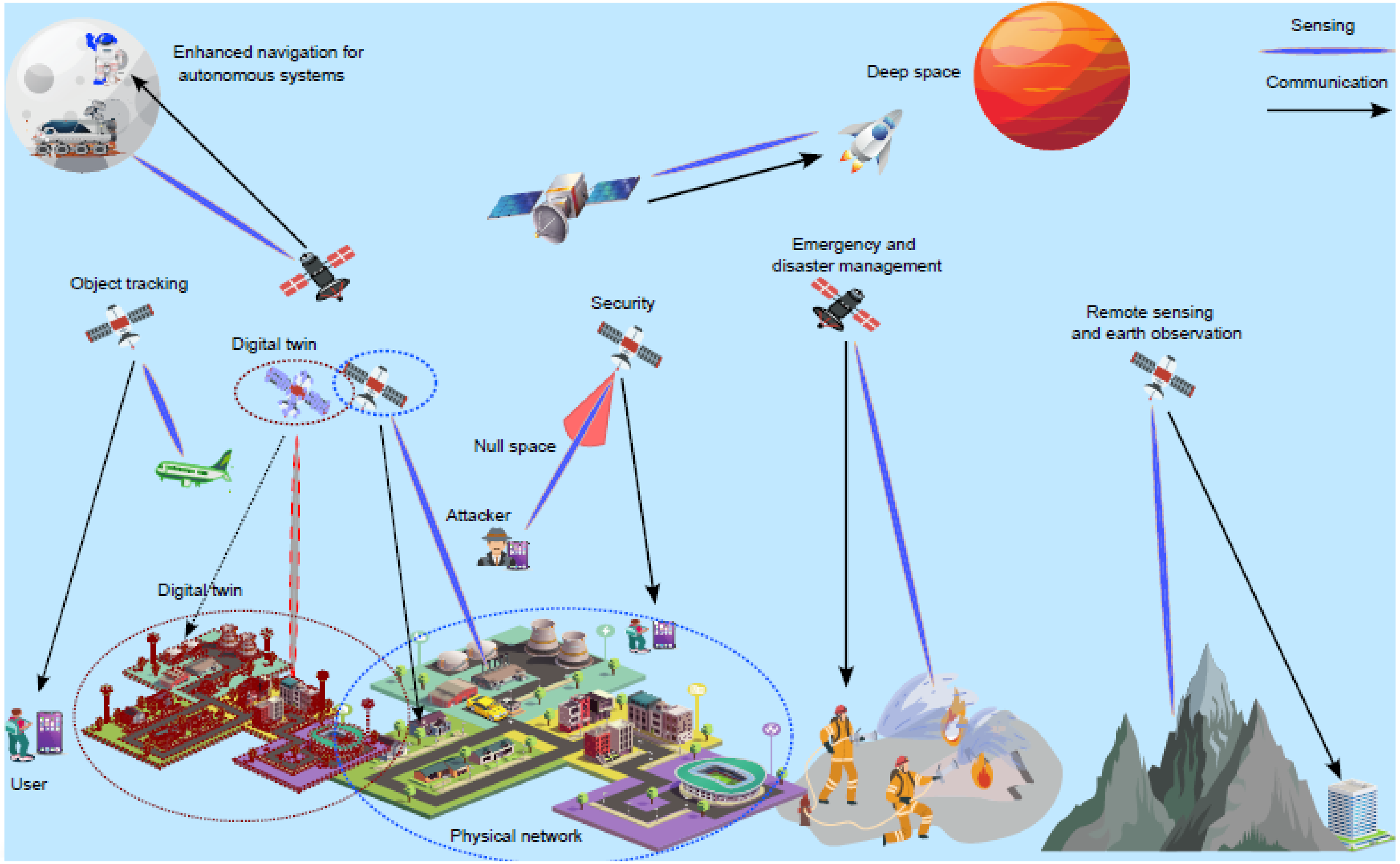
NTN Use Cases

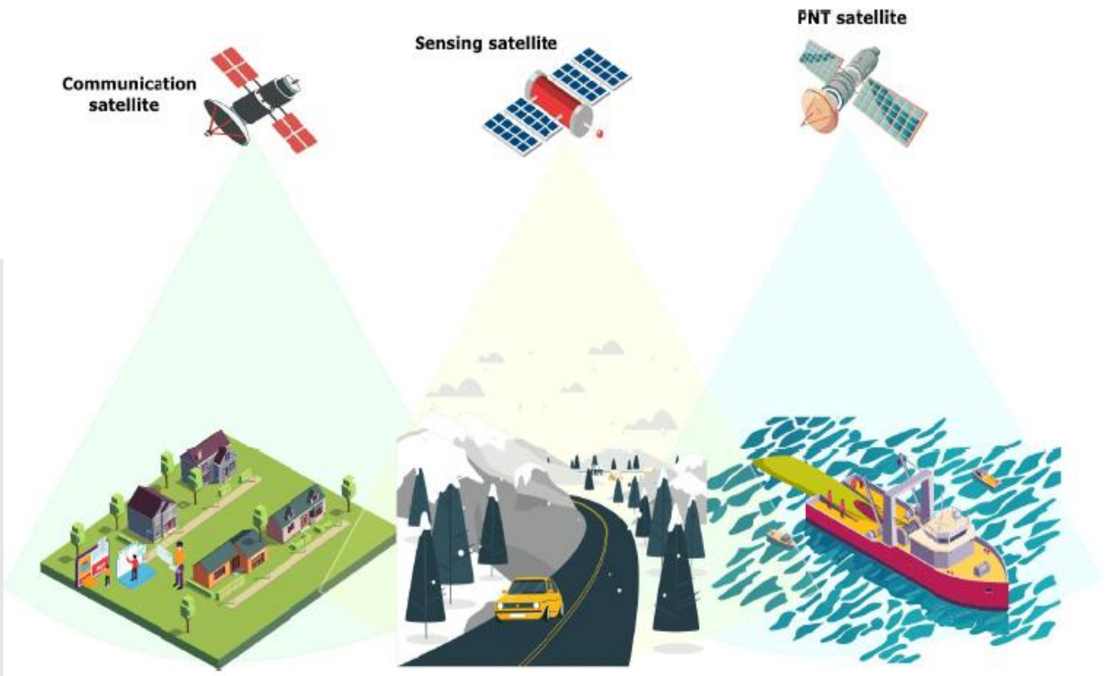
- **Why?**
  - Jointly use spectrum bands devoted to Earth Observation and SatComs
- **JCAS Applications**
  - Object tracking/verification
  - Security countermeasures for interference/jamming
- **LEO PNT**
  - Doppler effects
  - GNSS reliance



Sheemar et al., “Joint Communications and Sensing for 6G Satellite Networks: Use Cases and Challenges”, https://arxiv.org/abs/2501.05243
Sheemar et al.,“Joint Communications, Sensing, and Positioning in 6G Multi-Functional Satellite Systems: Survey and Open Challenges”, https://arxiv.org/abs/2509.25937

Motivation

- Satellite systems verticals: communications, sensing, and Positioning, Navigation, and Timing (PNT).
- Typically designed, built, and launched independently, with its own dedicated hardware, signal processing chains, and allocated frequency bands.



Disadvantages:

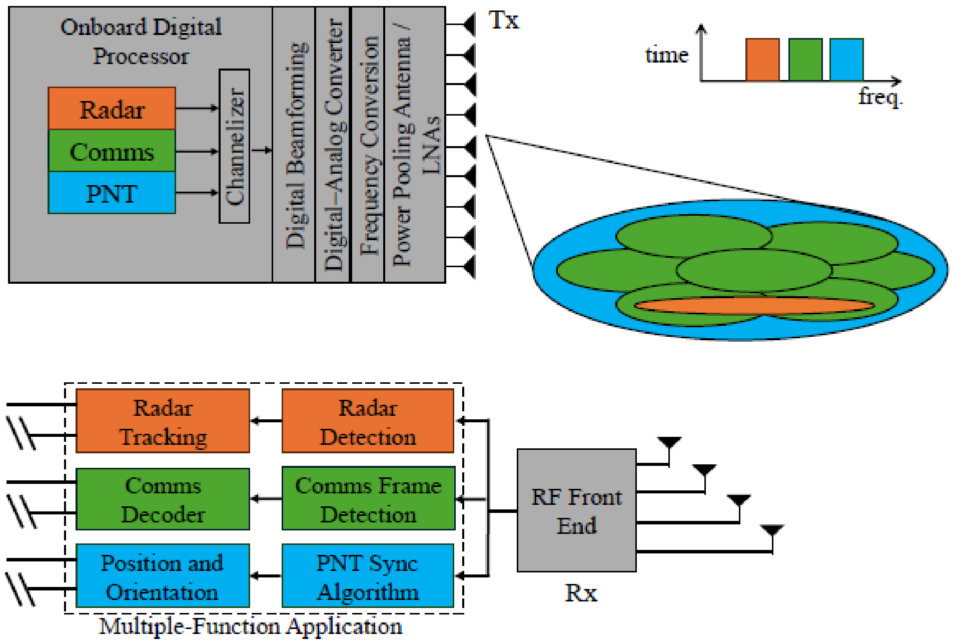
1. **Inefficiency of Separate Systems:** The use of separate, dedicated hardware for communications, sensing, and PNT, leading to redundant components and inefficient design.
2. **Increased Mass and Volume:** The significant mass of multiple standalone payloads directly elevates launch costs and operational complexity.
3. **Higher Power Consumption:** Operating multiple, distinct systems requires more energy, placing a greater demand on the satellite's power subsystem and reducing overall efficiency.
4. **Underutilized Resources:** Using adjacent or separate frequency bands for each independent function leads to poor spectral efficiency and wasted resources.

Cooperative Payloads

- We classify the multi-functional payloads based on the level of integration. At the lowest-level of complexity, we have Cooperative Payloads, in which the integration is only achieved at the *hardware level*.

Key Features:

- **Foundational Hardware Sharing:** Represents the base level of integration, where communications, sensing, and PNT systems share a common hardware platform (e.g., antennas, processors) but retain their own distinct, traditional signals.
- **Preservation of Legacy Waveforms:** Unlike more advanced integration levels, this approach does not require new signal designs; subsystems maintain their proven waveforms (e.g., OFDM, FMCW) operating in the same or adjacent frequency bands.
- **Significant SWaP-C Reduction:** By consolidating multiple payloads into a single platform, it delivers substantial improvements in Size, Weight, Power, and Cost compared to traditional, separate systems.



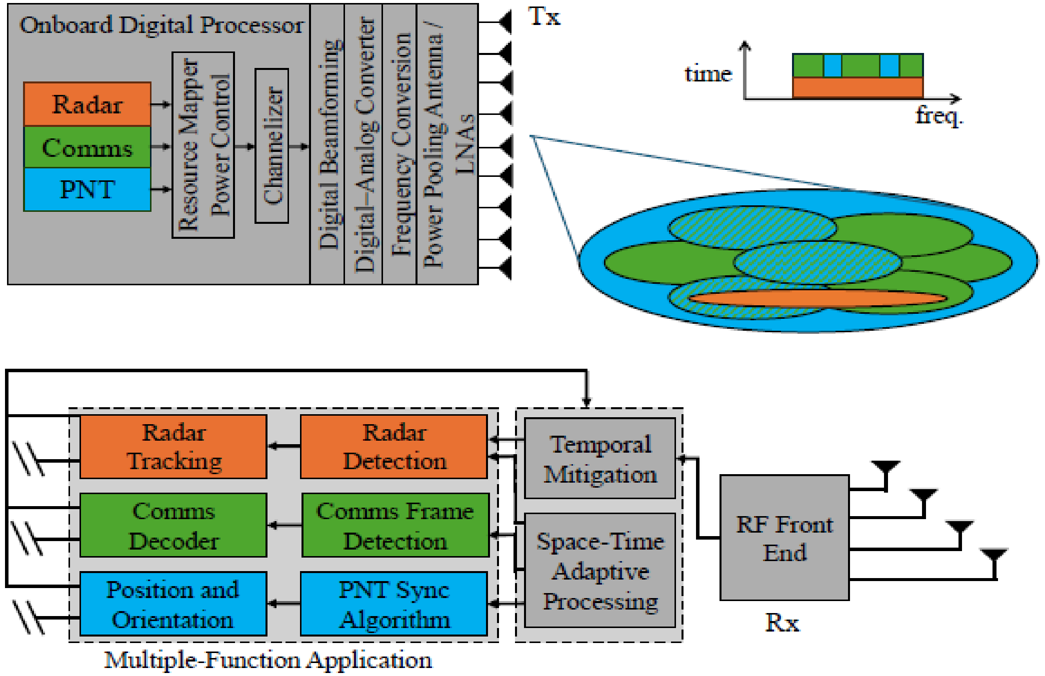
[1] C.K. Sheemar, J. Querol, W.U. Khan, P. Thiruvasagam, S. Solanki, I. Edjekouane, C. Garcia, and S. Chatzinotas, “Joint Communications, Sensing, and Positioning in 6G Multi-Functional Satellite Systems: Survey and Open Challenges”, under review in IEEE Communications Surveys & Tutorials [Online Available] *arXiv preprint arXiv:2509.25937*.

Integrated Payloads

- At the mid-level of complexity, we have Integrated Payloads, in which the integration is achieved at the *hardware and frequency band level.*

Key Features:

- **Unified Frequency and Hardware:** This level integrates communications, sensing, and PNT onto a single hardware platform that also operates within a shared frequency band, moving beyond mere hardware consolidation.
- **Domain-Based Multiplexing:** Interference is managed by multiplexing the distinct signals in domains other than frequency, such as time (TDM), space (beamforming), or code (CDM), enabling their coordinated, simultaneous coexistence.
- **Maximized Spectral Efficiency:** By fully reusing the same spectral band for all three functionalities, this approach achieves a significant leap in spectral efficiency and enhanced hardware utilization compared to cooperative systems.



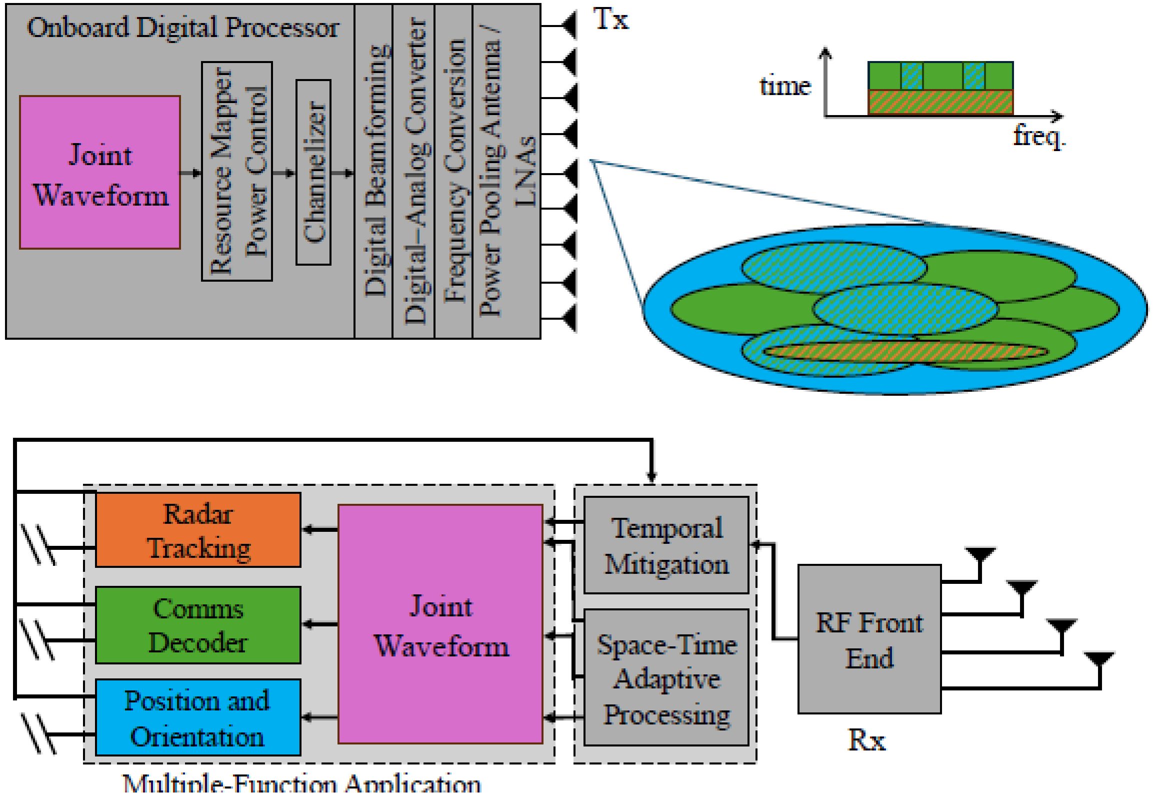
[1] C.K. Sheemar, J. Querol, W.U. Khan, P. Thiruvasagam, S. Solanki, I. Edjekouane, C. Garcia, and S. Chatzinotas, “Joint Communications, Sensing, and Positioning in 6G Multi-Functional Satellite Systems: Survey and Open Challenges”, under review in IEEE Communications Surveys & Tutorials [Online Available] *arXiv preprint arXiv:2509.25937*.

Joint Payloads

- At the highest-level of complexity, we have Joint Payloads, in which the integration is achieved at the *hardware, frequency band and signal level.*

Key Features:

- **Unified Signal Paradigm:** This highest level of integration uses a single, unified waveform designed from the ground up to simultaneously perform communications, sensing, and PNT, eliminating the concept of separate signals for each function.
- **Ultimate Resource Efficiency:** This approach achieves the highest possible spectral and hardware efficiency by eliminating the overhead of coordination and multiplexing required in lower integration levels
- **Inherent Functional Synergy:** The integrated design allows the functions to mutually enhance each other; for example, sensing can inform communications with real-time channel data, and communications signals can be used for positioning.



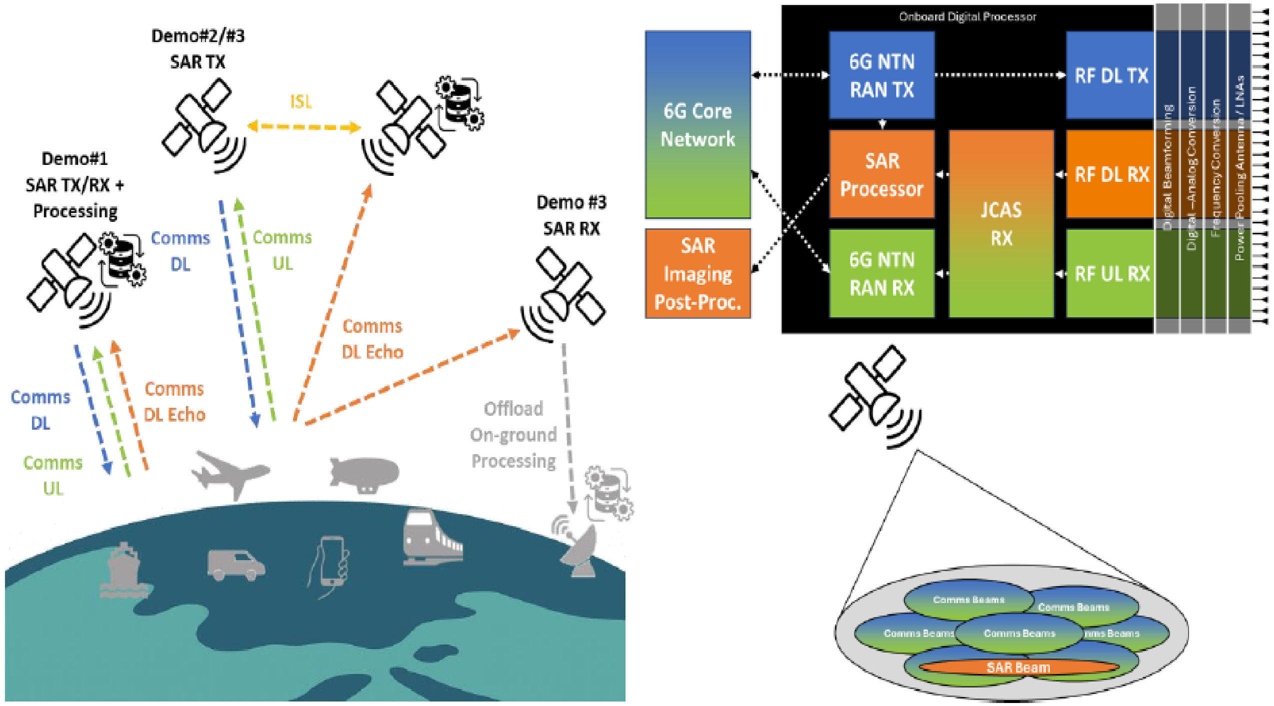
[1] C.K. Sheemar, J. Querol, W.U. Khan, P. Thiruvasagam, S. Solanki, I. Edjekouane, C. Garcia, and S. Chatzinotas, "Joint Communications, Sensing, and Positioning in 6G Multi-Functional Satellite Systems: Survey and Open Challenges", under review in IEEE Communications Surveys & Tutorials [Online Available] *arXiv preprint arXiv:2509.25937*.

Demonstrators and High-Level Architecture

We aim to present three demonstrators for JCAS:

- Monostatic with On-Board Processing.
- Bistatic with On-Board Processing.
- Bistatic with Processing on the Ground.

Note that the selected demonstrations convers all types of satellites and future missions. For example, Monostatic covers "**High-Performance**" satellites, Bistatic (On-Board) covers "**Constellations & Distributed Systems**", Bistatic (Ground) covers **"Small & Cost-Driven Satellites"**



(a) (b)

(a) 3 proposed JCAS SAR Demonstrators (b) J-CROSS Testbed high-level functional block diagram

Intelligent Antennas for NTN

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Satellite Antennas

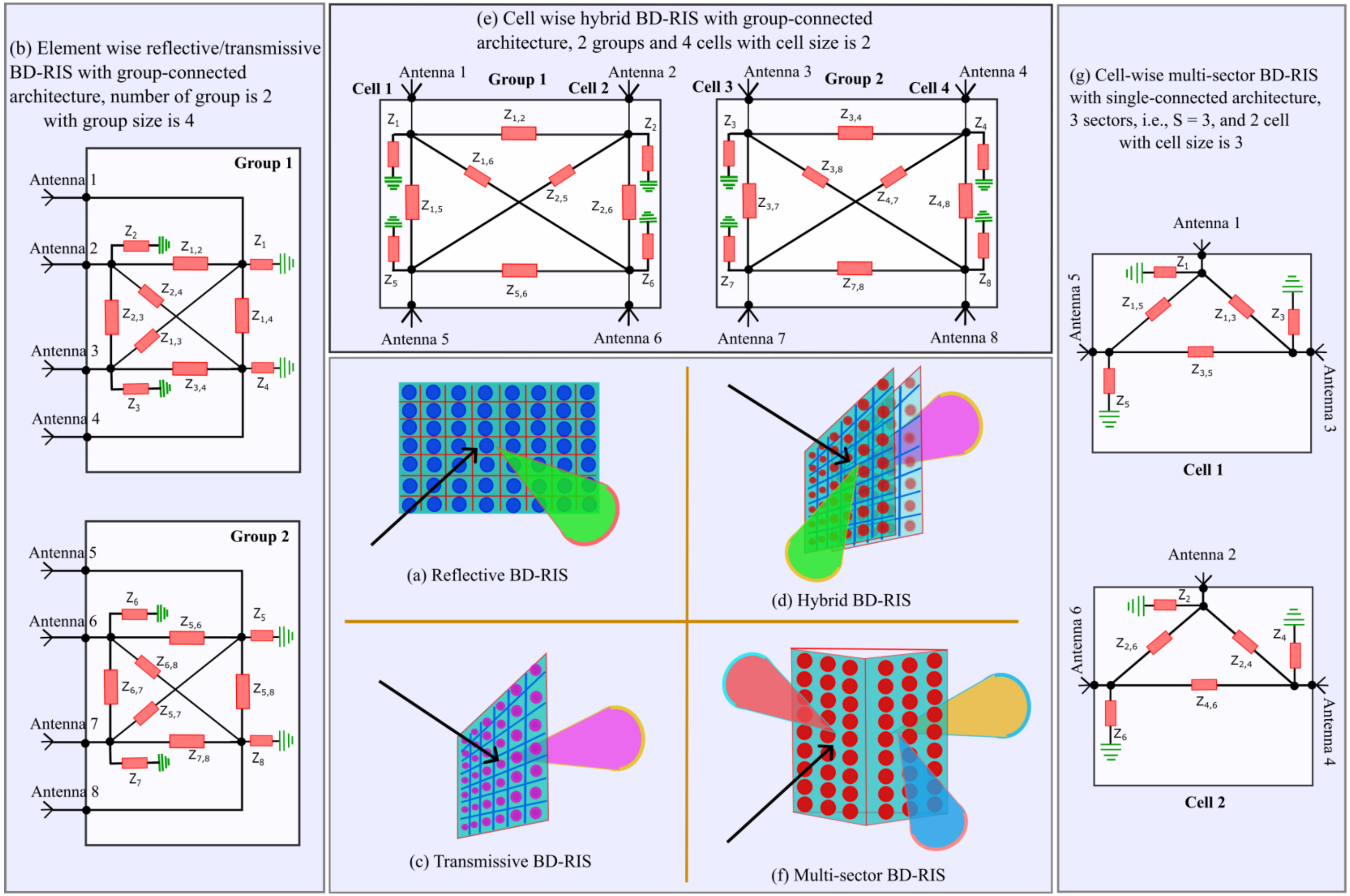
- **Regeneration by default**
  - Remove noise amplification
- **Link budget is key**
  - Antenna gain-directivity is needed
- **Satellite Large Antenna Arrays**
  - Deployable => Electromechanics
  - In-orbit assembly => Robotics
  - Cohesive satellite swarms => Synchronization
  - Metamaterials => RIS, Holography, SIM

Beyond Diagonal RIS

BD-RIS →
- Single-connected
- Fully connected
- Group-connected

TABLE II: Comparison of D-RIS and BD-RIS technologies.

Comparison	D-RIS	BD-RIS
Manipulation of RF wave	Phase shift	Phase and amplitude
Adaptability	Low	High
BF	Limited	Advanced
Power consumption	Low	Moderate
Hardware design	Low complex	High complex
System performance	Low	High
Coverage area	Half-Space	Full space
Interference Management	Medium	High
Spectral Efficiency	Medium	High
Capacity Improvement	Medium	High
Hardware Cost	Low	High
Energy efficiency	High	Low
Computational Complexity	Low	High



Khan Wali Ullah, Ahmed M, Sheemar CK, Di Renzo M, Bruno Clerckx, Lagunas E, Mahmood A, Shah ST, Dobre OA, Querol J, Chatzinotas S., Zhu Han "Survey on beyond diagonal RIS enabled 6G wireless networks: Fundamentals, recent advances, and challenges". arXiv preprint arXiv:2503.08423. **2025** Mar 11.

Ahmed Manzoor and **Khan Wali Ullah**, et al., "A Survey on STAR-RIS: Use Cases, Recent Advances, and Future Research Challenges," in IEEE Internet of Things Journal, vol. 10, no. 16, pp. 14689-14711, 15 Aug.15, **2023**.

Intelligent Surfaces for NTNs

- **RIS as signal relays**
  - Weak link budget. Ideal reflection coefficients are required
  - Large propagation delays. Coordination among satellite and RIS is challenging
  - Propagation geometry. Flying elements can act as obstructions
- **RIS as satellite antennas**
  - Promising if SWaP is reduced

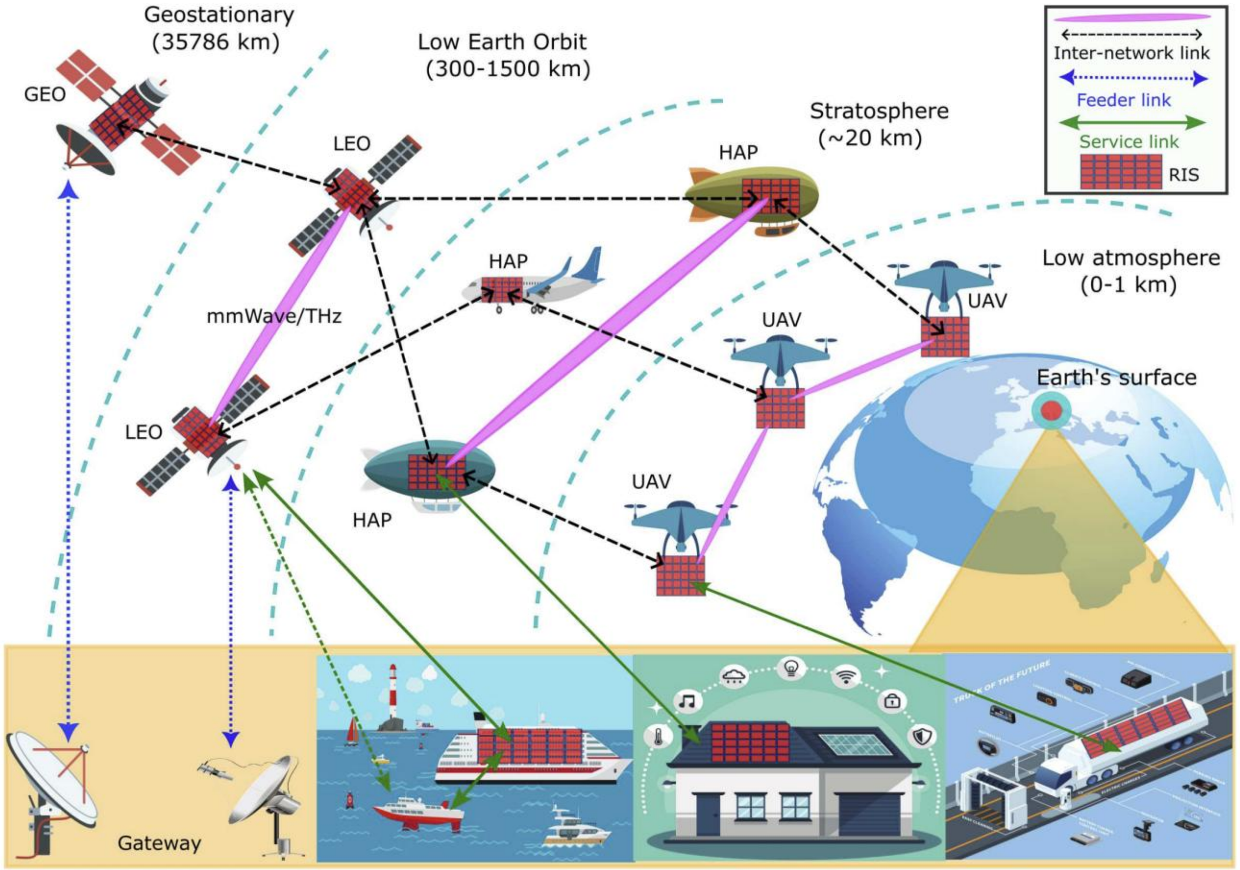


Fig. 1: RIS-integrated multilayered NTNs.

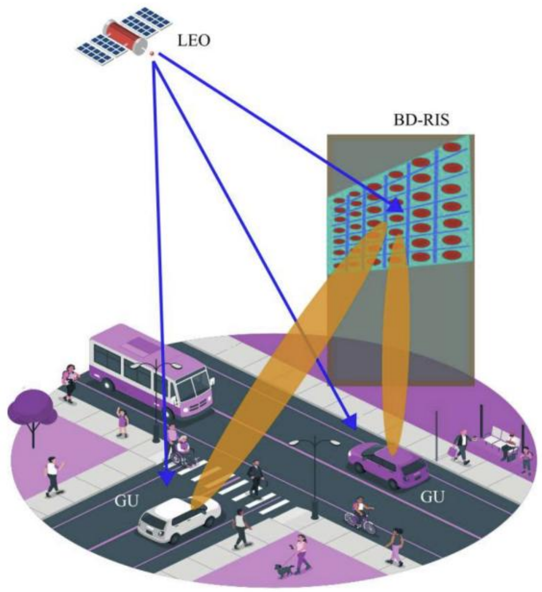


Fig. 3: BD-RIS enabled LEO communication.

W. U. Khan, A. Mahmood, C. K. Sheemar, E. Lagunas, S. Chatzinotas and B. Ottersten, "Reconfigurable Intelligent Surfaces for 6G Non-Terrestrial Networks: Assisting Connectivity from the Sky," in IEEE Internet of Things Magazine, vol. 7, no. 1, pp. 34-39, January 2024.
W. U. Khan, A. Mahmood, M. A. Jamshed, E. Lagunas, M. Ahmed and S. Chatzinotas, "Beyond Diagonal RIS for 6G Non-Terrestrial Networks: Potentials and Challenges," in IEEE Network, vol. 39, no. 1, pp. 80-89, Jan. 2025.

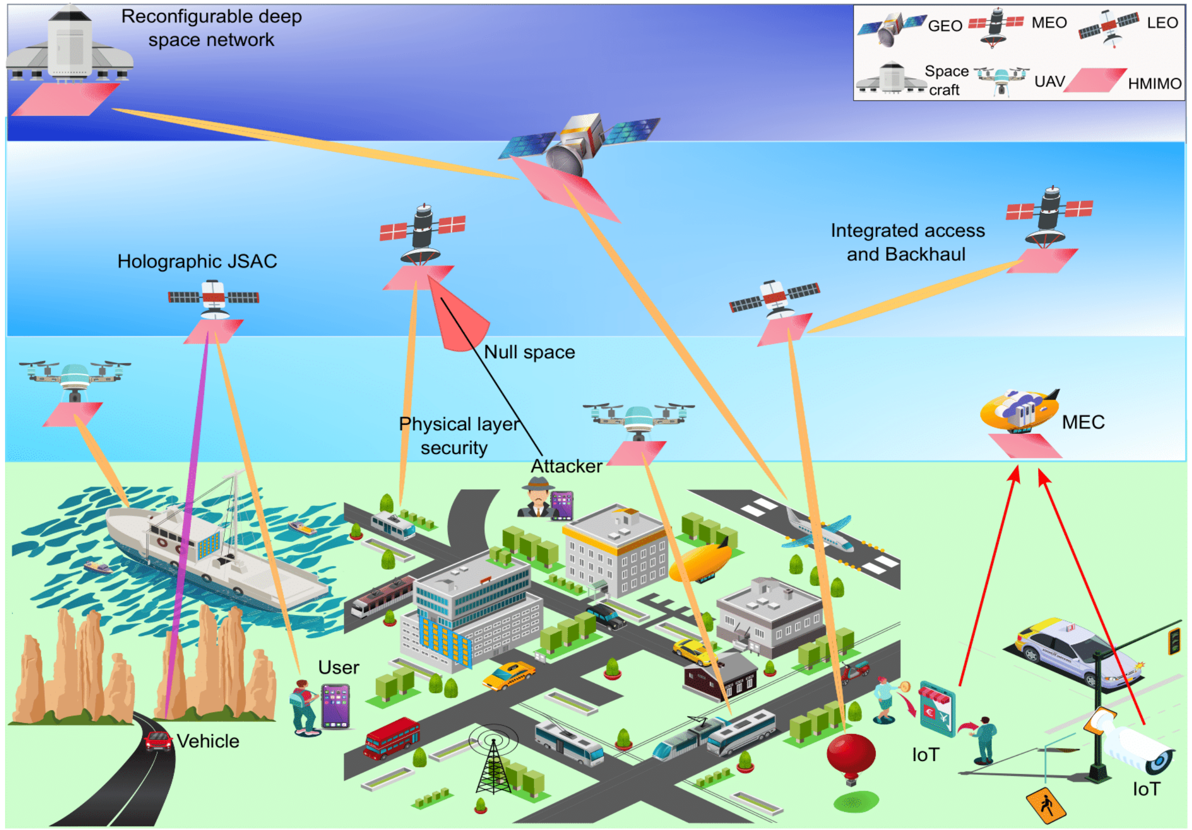
Holographic Communications for NTNs

Motivation for Holographic RHS in NTNs

•Traditional NTN antennas are bulky, power-hungry, and expensive, limiting scalability.

•Holographic RHS arrays offer compact, lightweight, and low-power alternatives.

•HMIMO provides fine-grained beam control and real-time reconfigurability, essential dynamic channels, Doppler shifts, and interference-limited operation.



Challenges:

- Closed-loop vs Open-loop approaches
- Prototypes and practical models for power consumption
- Size/weight comparisons to conventional antenna arrays

G. Iacovelli, C.K. Sheemar, W.U. Khan, A. Mahmood, G.C. Alexandropoulos, J. Querol, and S. Chatzinotas, “Holographic MIMO for next generation non-terrestrial networks: Motivation, opportunities, and challenges”, minor review IEEE Vehicular Technology Magazine, [Online Available[*arXiv preprint arXiv:2411.10014*.

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Wrap Up

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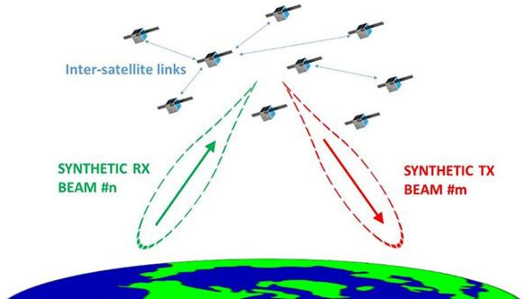
Open Challenges & Roadmap

Short-term

- **Power-efficient Compact multi-beam antennas**
  - Metamaterials
- **Low-power Onboard Processing**
  - AI Chipsets in space
- **Distributed Satellite Systems**
  - Ultra-large Antenna arrays
- **Multi-Functional Satellite Systems**
  - Joint Comm/Sensing/Positioning

Long-term



Selected Publications

- Sheemar et al.,"Joint Communications, Sensing, and Positioning in 6G Multi-Functional Satellite Systems: Survey and Open Challenges", ArXiv
- Ntontin et al., "A Vision, Survey, and Roadmap Towards Space Communications in the 6G and Beyond Era", PROC, 2025.
- Fontanesi et al., "Artificial Intelligence for Satellite Communication and Non-Terrestrial Networks: A Survey", COMST, 2025
- Al-Hraishawi H. et al., "Characterizing and Utilizing the Interplay between Quantum Technologies and Non-Terrestrial Networks", COMST, 2024
- 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.

Selected Projects

- ETHER: sElf-evolving terrestrial/non-Terrestrial Hybrid nEtwoRks, Horizon SNS
- 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.
- MEGALEO: Self-Organized Lower Earth Orbit Mega-Constellations, FNR.
- 6GSpaceLab: 6G Space Lab, UniLu.

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