ML-Assisted Algorithms for 6G Non-Terrestrial Networks

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Acknowledgements:
SIGCOM RG Members

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Outline

- 5 Myths and 5 Realities
- Non-Terrestrial Architectural Aspects
- ML For Space
- ML In Space
- Open Challenges

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

- **13** years in operation
- **80+** Researchers
- **50+** R&D projects
- **40M€+** Funding
- **3** Industrial Partnerships

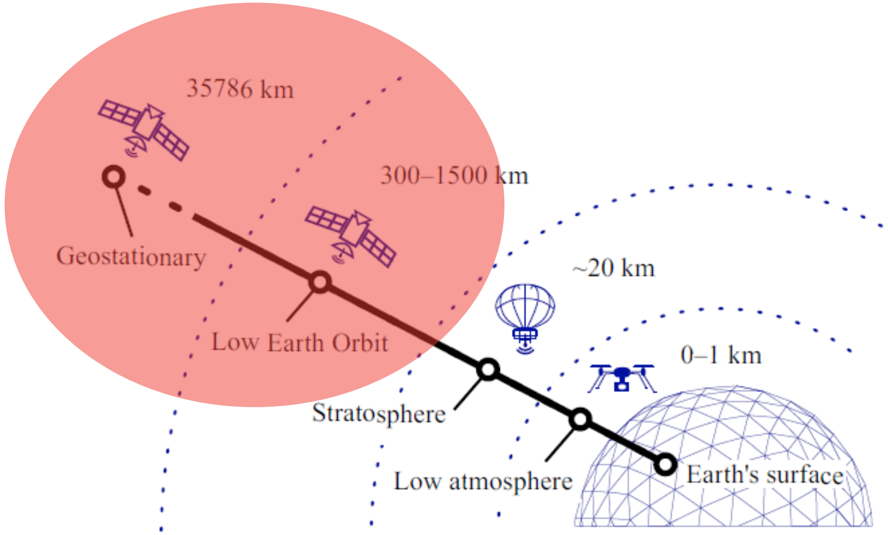
Research Areas

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

Setting the Scene: NTN and SatComs

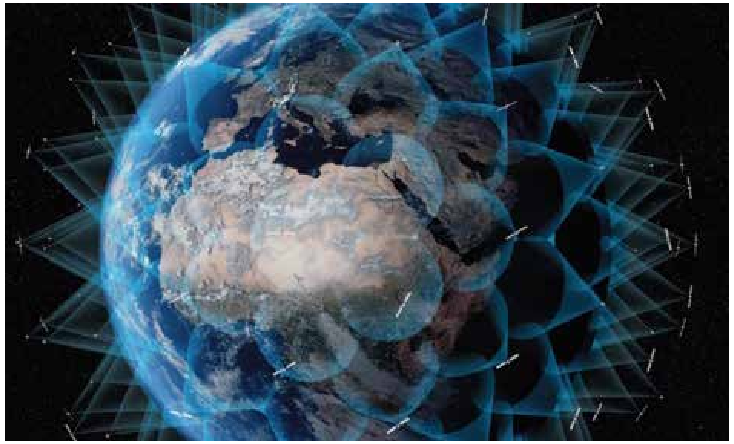
Expectations

- 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
- **Technology**
  - New services
    - Broadband, IoT, Non-linear TV
  - Regeneration
    - Active elements in the sky
    - COTS in space

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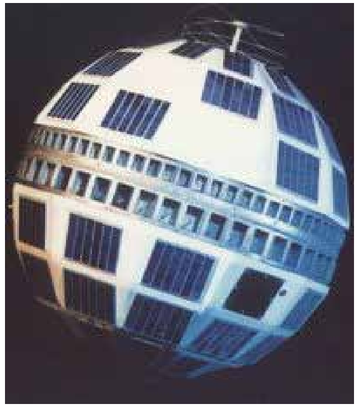
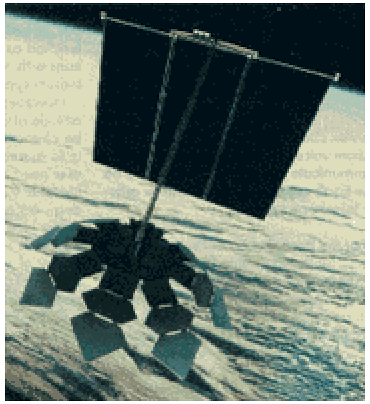
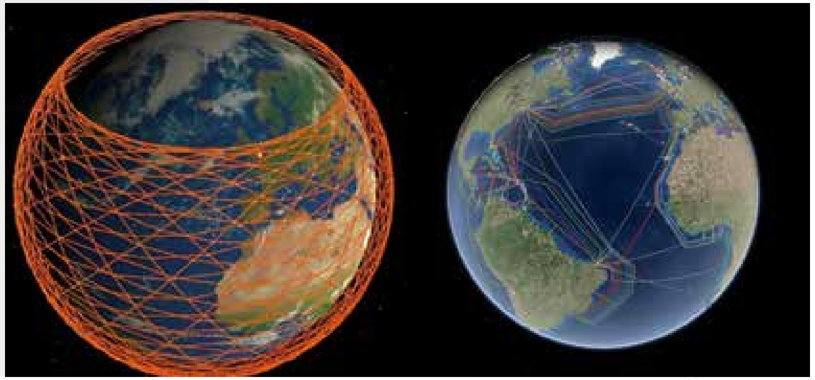
5 Myths



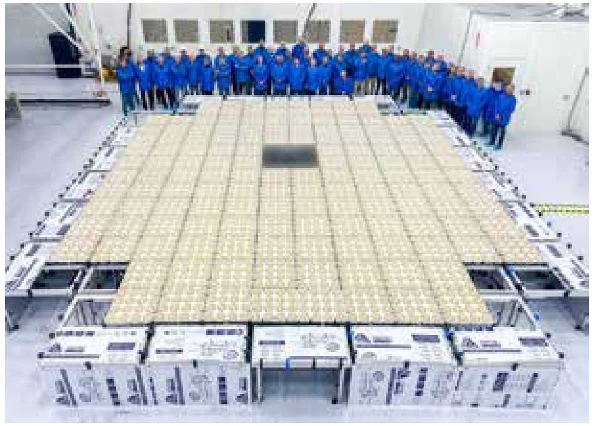


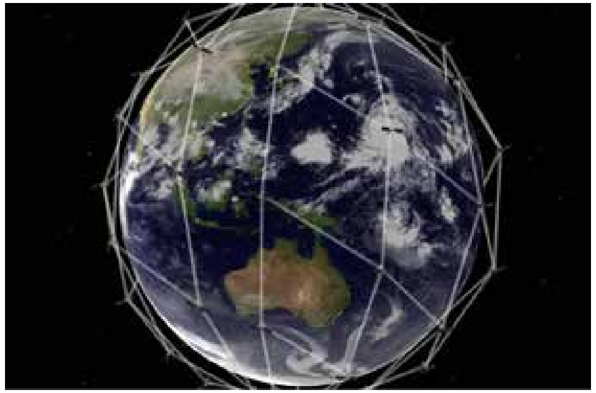
1. Satcom Data Services appeared recently
2. LEO constellations were launched in the 21st century
3. Smartphones can communicate through satellites
4. SatComs are strictly faster than optical fibers
5. SatComs only target internet access

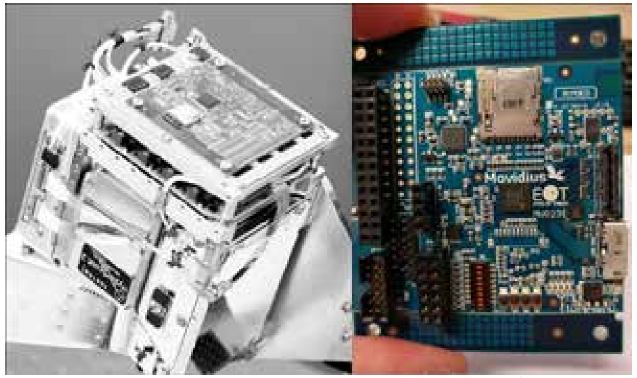


5 Realities

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



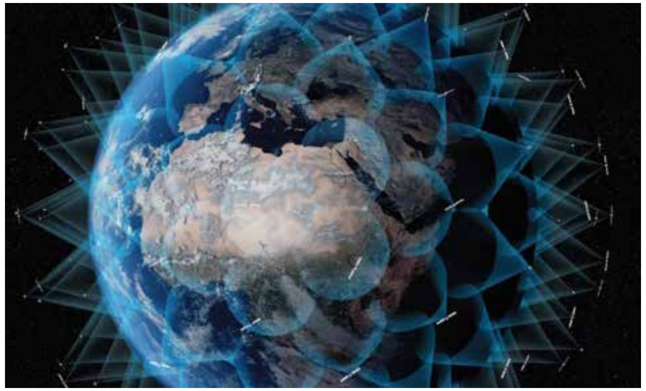




Non-Terrestrial Architectural Aspects

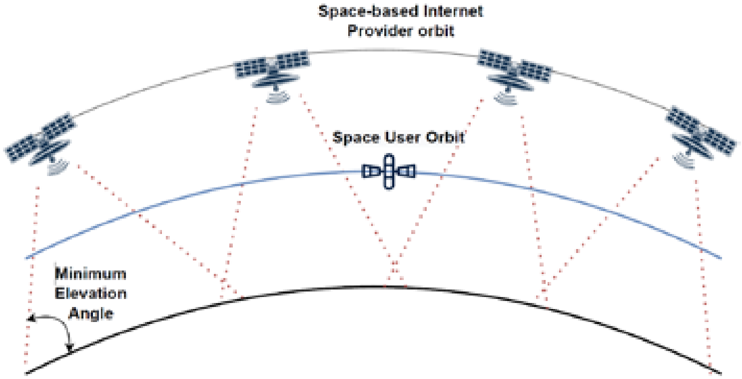
Non-Terrestrial Architectural Aspects

- Multi-layered Networks
- Open architectures (RAN) for Space
- Integrated Satellite-Terrestrial Networks
- Satellite IoT
- Space Edge Processing



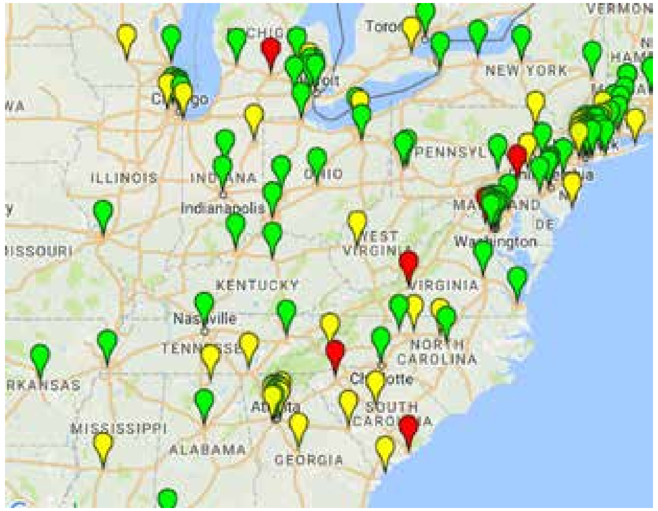
Multi-layered Networks

- **4-layered Infrastructure:** GEO-MEO-LEO-GW
- **Users:**
  - Ground Users (Broadband, Handheld, IoT)
  - **Space Users (EO, IoT)**
- **GW Network:**
  - Shared GWs (e.g. Amazon GS) vs Satellite Uplink
  - Coverage vs Distance trade-off
- **Inter-satellite Links:**
  - EDRS (LEO-GEO), Iridium/Starlink (LEO-LEO)
  - RF (Ka) vs FSO



Integrated Satellite-Terrestrial Networks

- **Real-world Examples**
  - Sirius XM
  - European Aviation Network
  - Apple+Globastar, T-Mobile+Starlink
- **SFN vs MFN**
  - Architecture vs RAN integration
  - Converged Core / Non-3GPP access
  - 5GNR over Satellite – ASMS, ICSSC Demos
- **Coherent reception in SFN**
  - Sync challenges, Channel Modelling, Interference



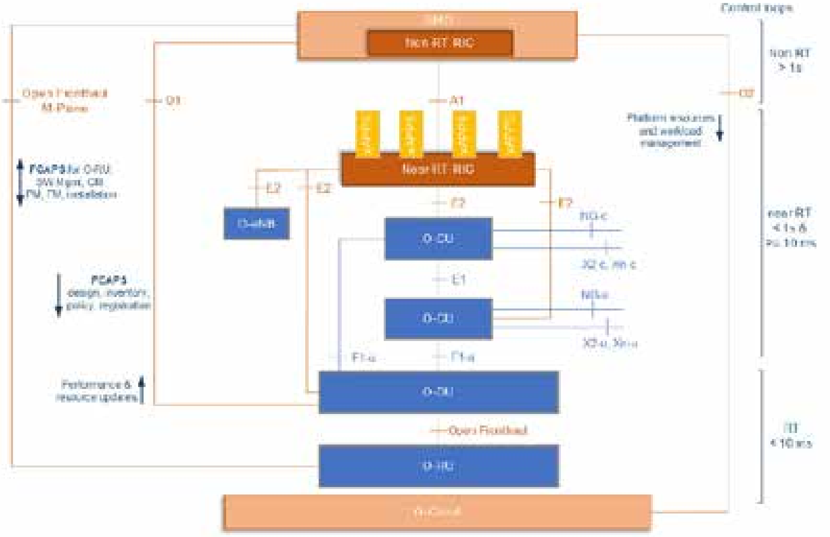
- 5G-LEO: OpenAirInterface extension for 5G satellite links, ESA.
- 5G-GOA: 5G-Enabled Ground Segment Technologies Over-The-Air Demonstrator, ESA.

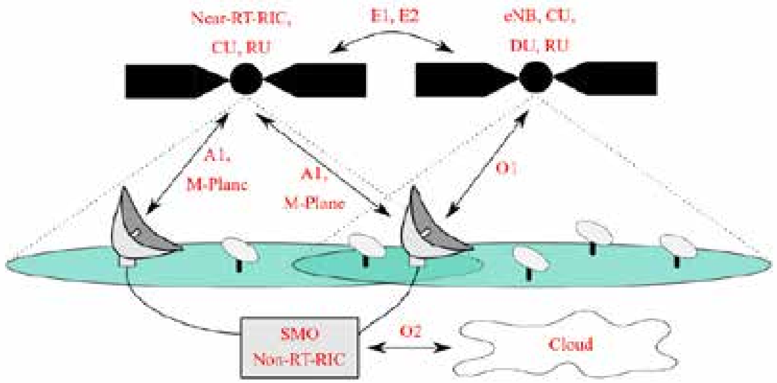
Open architectures (RAN) for Space

- **Limited Interoperability**
  - Standard compliance (e.g. DVB) not given

- **3GPP and Open RAN**
  - Onboard Regeneration ó Disaggregation
  - Standardization Compliance ó Open Interfaces

- **Limited on board resources**
  - Progressively move Us in the sky
    - RU => DU => CU
- **Interfaces over the SatCom wireless channel**
  - Ground-Earth
  - Inter-satellite
- **Interfaces to Satellite Control Centre**



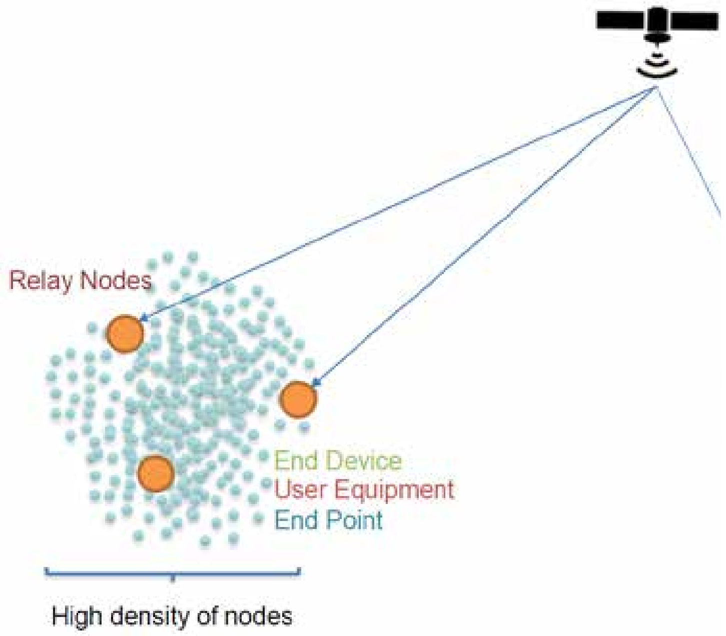


Satellite IoT

- **Plethora of ventures**
  - Data collection, software updates
  - Lower rates / No need for constant coverage

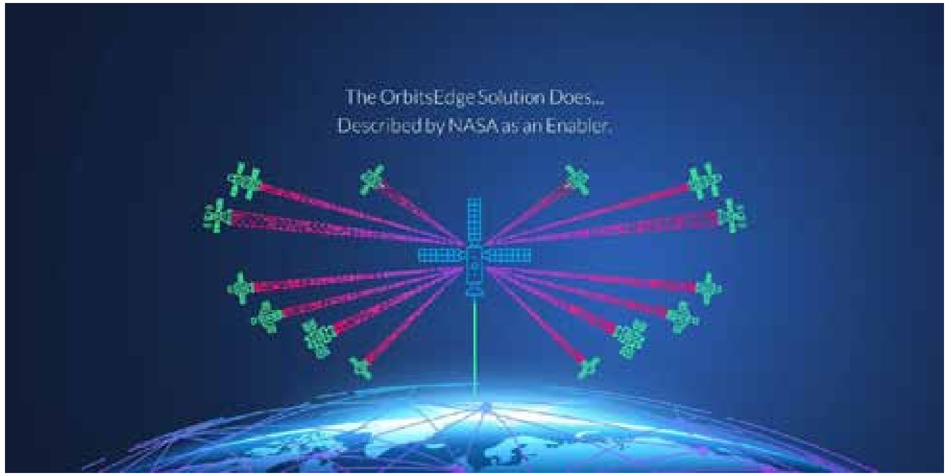
- **Multiple protocols/waveforms**
  - LoRa, NB-IoT, Legacy
  - Direct access vs Relaying/Fronthauling

- **Low-power, low-form factor transceivers**
  - Closing the uplink
    - Transmit power
    - Antenna aperture
  - Mobility – Doppler
  - Latency – Protocol timers
  - Resource allocation / Scheduling



Space Edge Processing

- **Why?**
  - OPEX Carbon Footprint
  - Data downlink reduction
  - Space exploration
  - Federated/SW-defined payloads
- **Why NOT?**
  - CAPEX Carbon Footprint
  - Space hardening
- **Applications**
  - IoT, Earth Observation
  - Self-organized SatCom Constellations
  - In-orbit Manufacturing/Servicing



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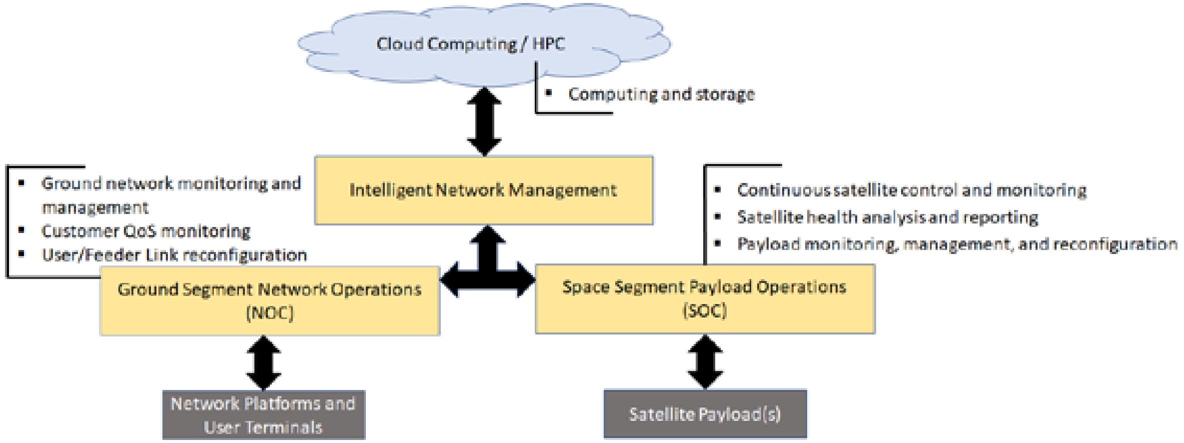
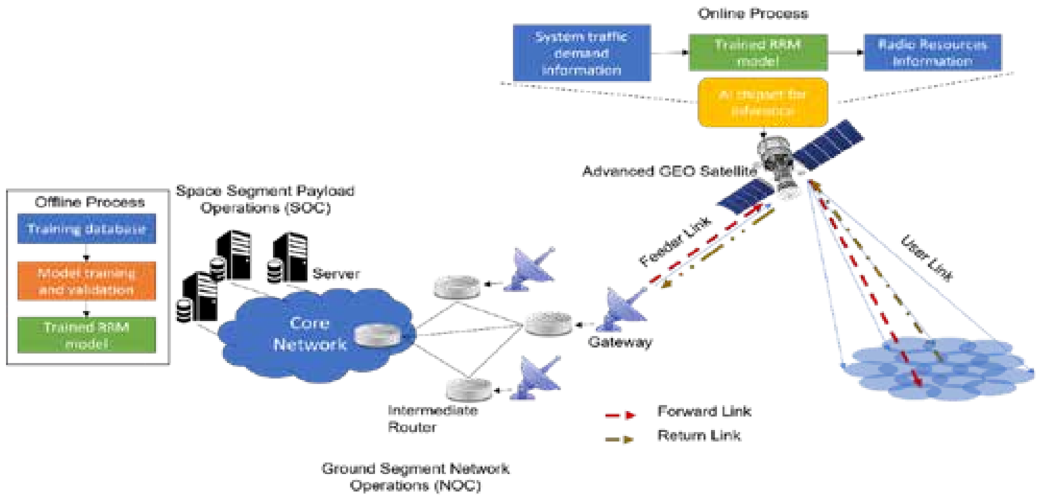
AI and Satellite Communications

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





AI For Space

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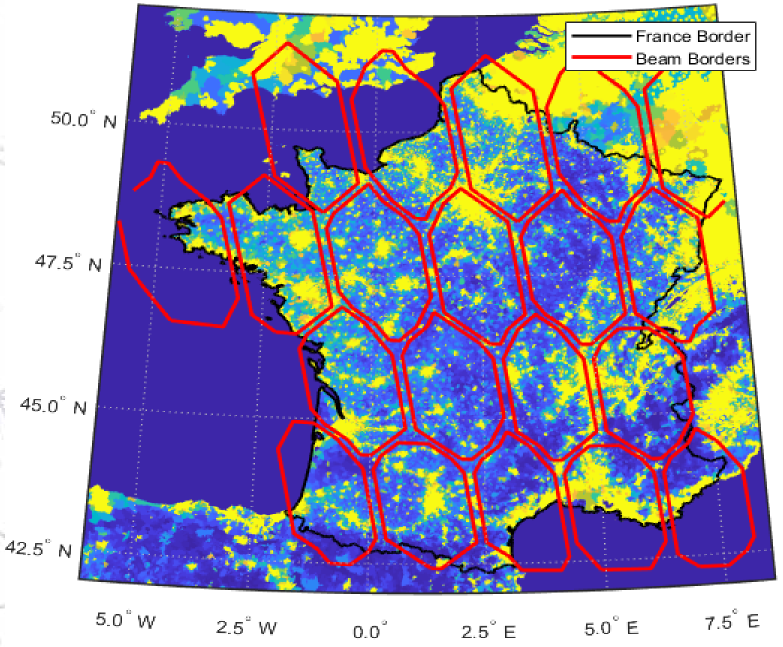
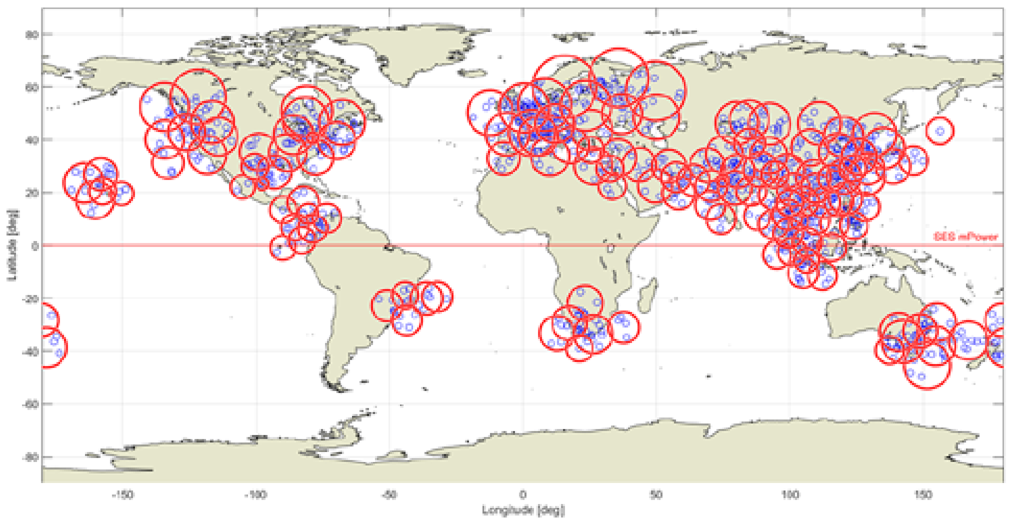
Motivation (1)

- **Reconfiguration capabilities through SW-Defined Satellites**
  - Next generation of satellite communications (either GSO or NGSO) are built with the capability to dynamically reconfigure system parameters (power, bandwidth, beamforming).

Quickly and flexibly assign radio resources according to:
a) Mission characteristics
b) Current geographical distribution of traffic





Motivation (2)

- **Optimization problems encountered in Satellite Communications**
  - Typical problems consider a huge search space due to:
    - hundreds / thousands of beams
    - wide bandwidth and granularity
  - Two types of solutions:
    - **Optimization-based solution**

      \+ Accurate solution

      \- complex procedures

      \- computationally intensive
    - **Heuristic-based solution (widely adopted)**

      \+ less complex procedure

      \+ not computationally intensive

      \- Low accuracy

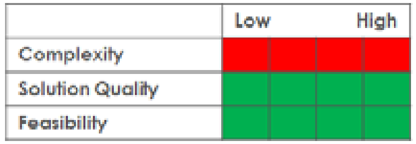
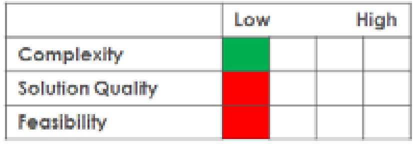
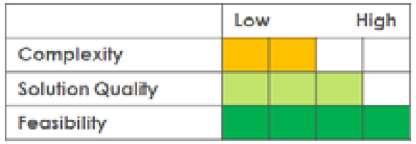
      \- Needs a lot of testing to fine-tune the heuristic decisions

Can we aim at something accurate and fast?

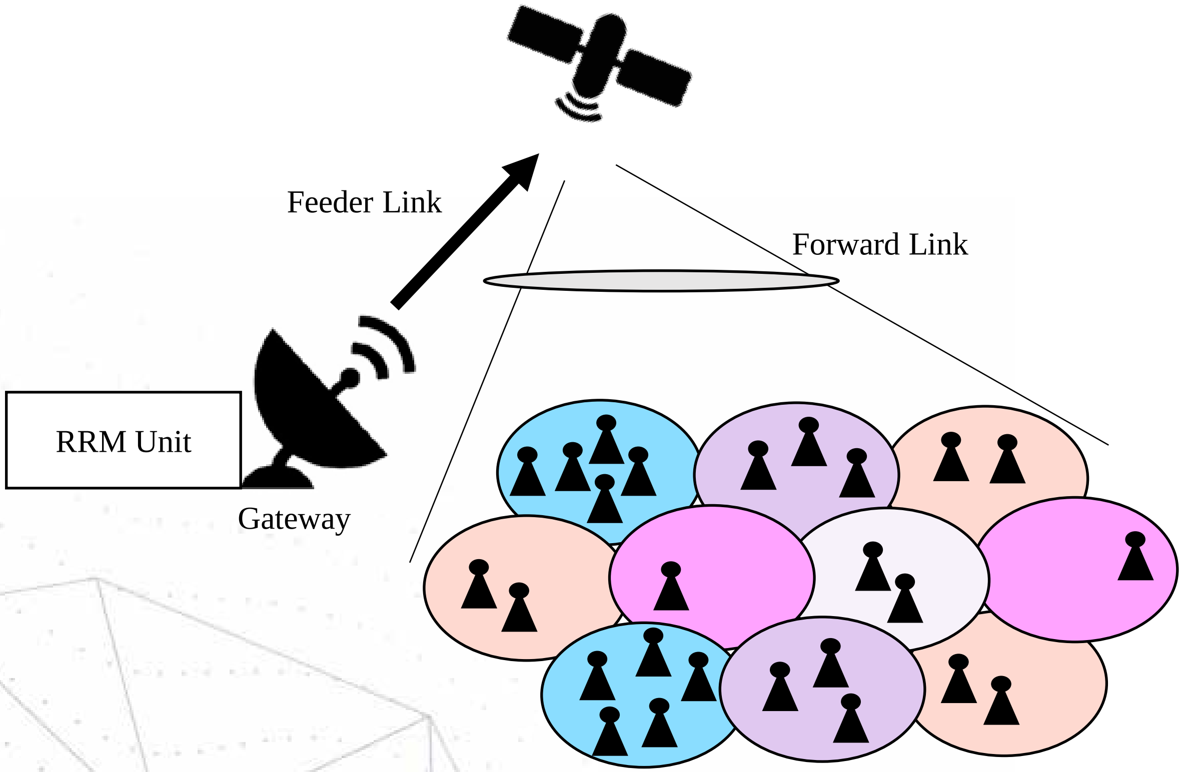
Deep Learning Based Acceleration

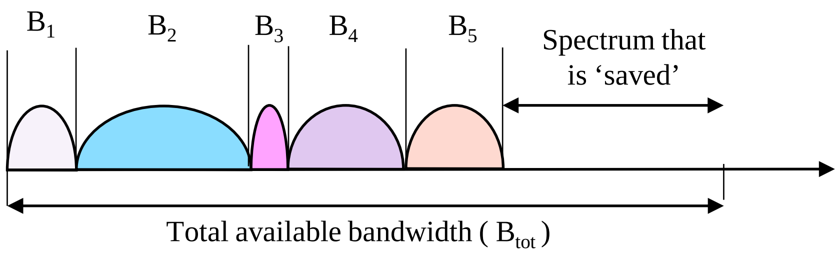
- Once an optimization problem is proved to be hard, e.g., NP-hard, it is difficult to expect that a heuristic solution can meanwhile achieve satisfactory performance and with very low complexity to support real-time optimization.

A **trade-off** between the algorithm's **computational complexity** and the **solution quality** needs to be considered

Conventional Optimization (Non-ML)	Offline end-to-end learning (supervised learning)	Resource optimization assisted by off-line learning (new)
Solving difficult optimization problems to a satisfactory performance would require a long span of computing time. 	Estimation errors in machine-learning output may disrupt the solution feasibility and lead to suboptimal performance. 	1) The well-trained machine/deep learning model is executed prior to the optimization process. 2) The optimization process uses the deep-learning based prediction to either confine its search space or cut off non-optimal combinations. 

Example 1: Bandwidth allocation





More demand = More Bandwidth

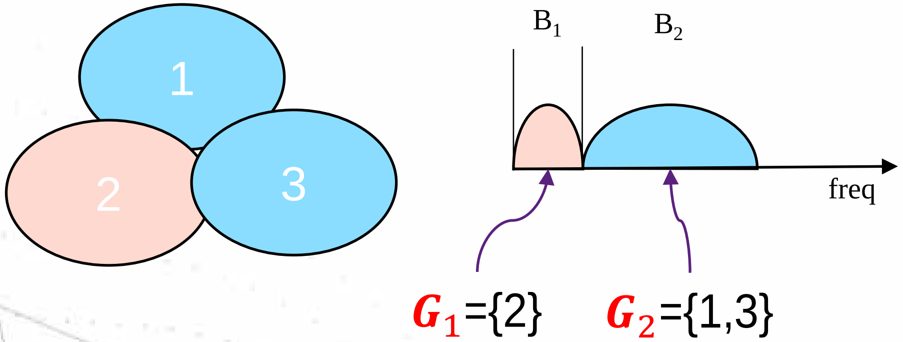
<u>Design Goal</u>: Minimize spectrum usage while minimizing unmet demand.

[**Abdu_2022**] T.S. Abdu, S. Kisseleff, L. Lei, E. Lagunas, J. Grotz, S. Chatzinotas, "A Deep Learning Based Acceleration of Complex Satellite Resource Management Problem", European Signal Processing Conference (EUSIPCO), Serbia, Sept. 2022.

Example 1: Bandwidth allocation

Notation Example: N = 3 beams

The beams that share the same bandwidth are classified in a group G_m, and the group G_m operates in B_m



$$\underset{B_m, P_m}{\text{minimize}} \sum_{i=1}^{N} max\left(1 - \frac{C[i]}{D[i]}, 0\right) + \sum_{G_m \in \boldsymbol{G}} \frac{B_m}{B_{total}}$$

Subject to

$T1: \sum_{G_m \in \boldsymbol{G}} B_m \leq B_{total}$

$T2: B_m \geq 0, \forall_m$

$T3: \sum_{G_m \in \boldsymbol{G}} |G_m| P_m \leq P_{total}$

$T4: P_m \geq 0, \forall_m$

Fro N = 3 beams, we have $M = 2^3 - 1 = 7$ groups

G_1={2} → B_1

G_2={1,3} → B_2

G_3={1} → B_3=0

G_4={3} → B_4=0

G_5={1,2} → B_5=0

G_6={2,3} → B_6=0

G_7={1,2,3} → B_7=0

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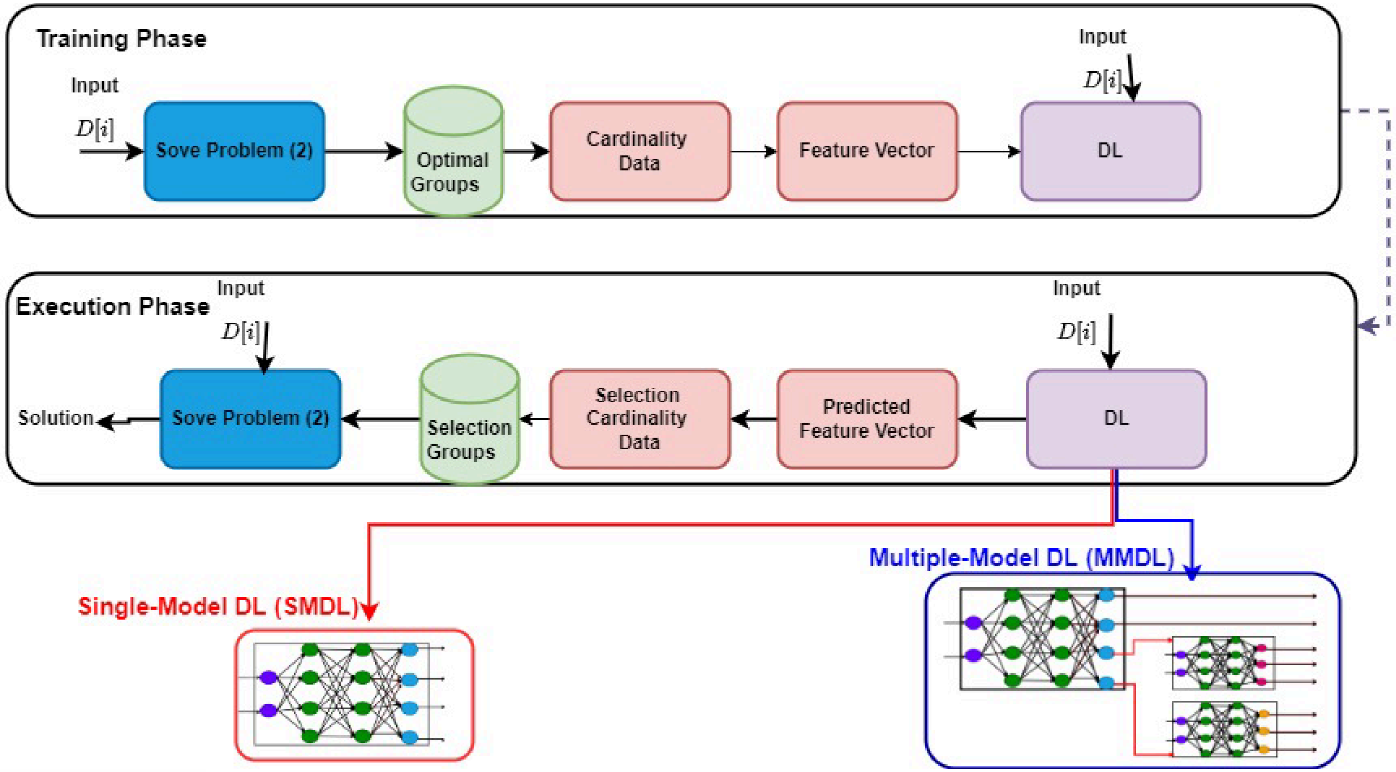
Example 1: Bandwidth allocation

- The problem can be manipulated to reach a linear programming formulation, which can be solved optimally by **Simplex Algorithm (SA)**
- However, the input optimization parameter $\{B_1, B_2, \dots, B_m, \dots, B_M\}$ increases exponentially ($M = 2^N - 1$) as the number of beams increases.
- Consequently, the complexity of solving (2) for relatively big number of beams becomes extremely complex.

- DL ACCELERATION APPROACH: How to reduce size of groups?
  - Learning the cardinality of the most 'popular' groups.
  - Create reduce set of groups as input for optimization problem.



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Example 1: Bandwidth allocation

- N= 20, N = 21, and N = 22 beams to evaluate the proposed DL approach
- Single virtual user located at the center of each beams aggregating all beam demand.

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Pure Optimization: SA
Proposed DL-acceleration: SA+SMDL, SA+MMDL

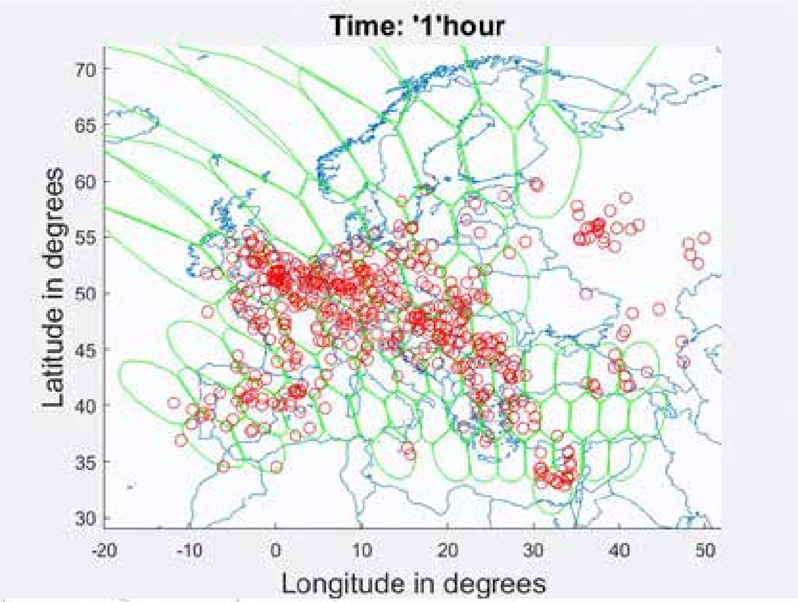
Beams	SA	SA+SMDL	SA+MMDL
20	34.1118 s	24.7525 s	10.8427 s
21	87.0577 s	44.2976 s	21.3881 s
22	165.949 s	123.3419 s	56.4812 s

SA+MMDL reduce the computation of the original problem by 25,67% and 65,96%, respectively

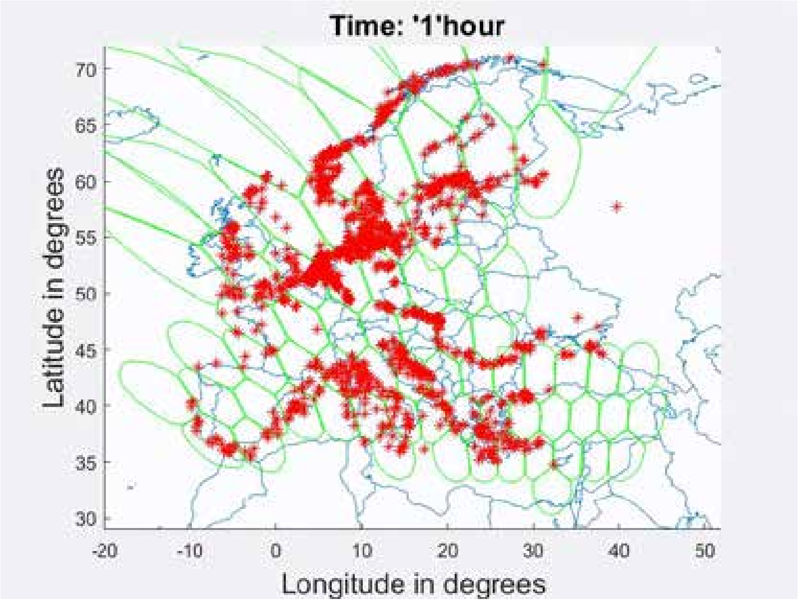
[**Abdu_2022**] T.S. Abdu, S. Kisseleff, L. Lei, E. Lagunas, J. Grotz, S. Chatzinotas, "A Deep Learning Based Acceleration of Complex Satellite Resource Management Problem", European Signal Processing Conference (EUSIPCO), Serbia, Sept. 2022.

Example 2: Planning beam footprint (1)

- Regular beams are planned in hexagonal grid layout for coverage enhancement
- Users are mobile, non-uniformly distributed, and have spatiotemporally varying traffic demand.
- Under-use the offered throughput (beam capacity is unused) or overload the beam (beam demand is unmet)[Honnaiah2021].



Aeronautical User locations at different time stamps of a day.



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.

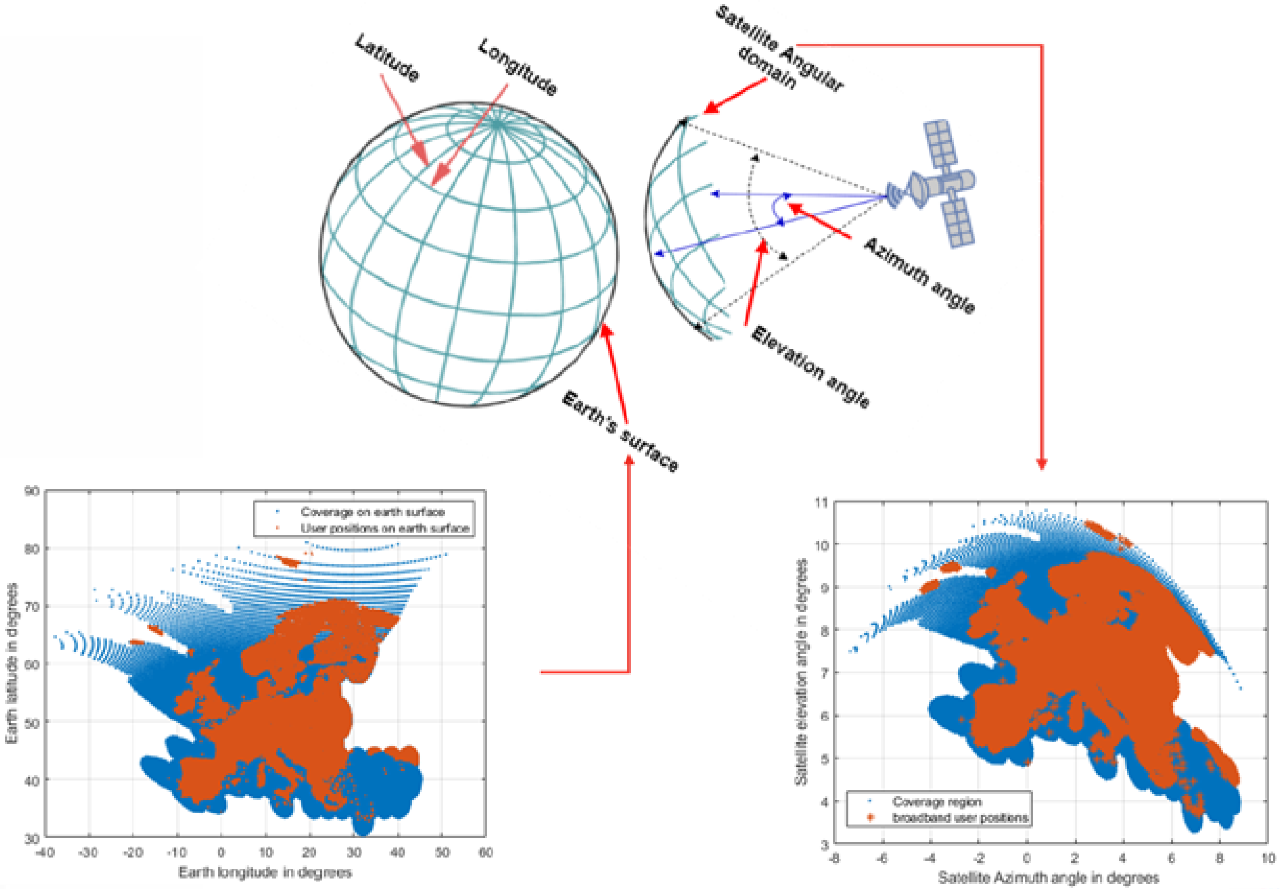
Example 2: Planning beam footprint (2)

- Dynamic demand-based beam pattern design and footprint planning was proposed in [Honnaiah2021] as a 4 step procedure.

Step 1: Domain transformation

$$X_{U,E} = R_e * cos(Lat_U) * cos(Lon_U) \quad (8a)$$
$$Y_{U,E} = R_e * cos(Lat_U) * sin(Lon_U) \quad (8b)$$
$$Z_{U,E} = R_e * sin(Lat_U) \quad (8c)$$

$$azimuth_U = \tan^{-1} \frac{Y_{U,S}}{X_{U,S}} \quad (8g)$$
$$elevation_U = \tan^{-1} \frac{Z_{U,S}}{\sqrt{(X_{U,S})^2 + (Y_{U,S})^2}} \quad (8h)$$



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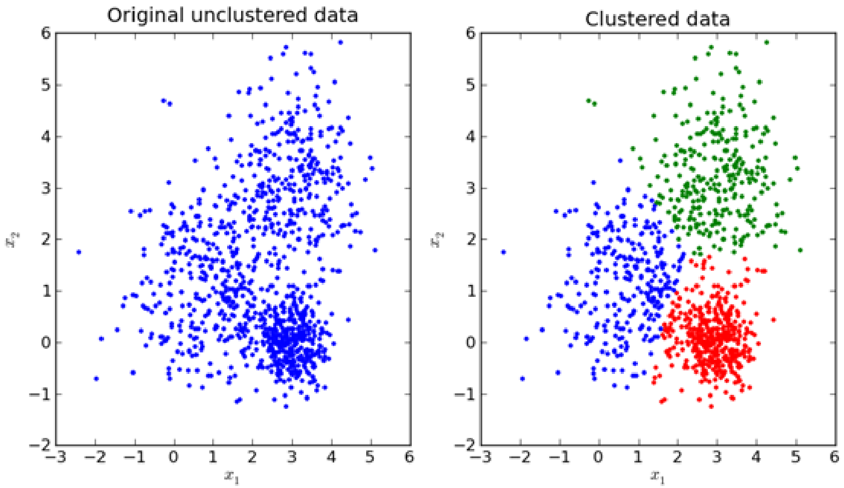
Example 2: Planning beam footprint (3)

- Dynamic demand-based beam pattern design and footprint planning was proposed in [Honnaiah2021] as a 4 step procedure.

Step 2: Weighted k-means Clustering (demand based) of distributed users



$$WED_{(\mathbf{x}_n, \mathbf{c}_{\mathcal{T}^k})} = ((\mathbf{x}_n - \mathbf{c}_{\mathcal{T}^k})(\mathbf{x}_n - \mathbf{c}_{\mathcal{T}^k})')\left(\frac{\sum_{n\in S_k}(d_n)}{\sum_{n=1}^{N}(d_n)}\right) \tag{9a}$$

$$\mathbf{c}_{\mathcal{T}^k} = \frac{1}{\sum_{n\in S_k} d_n}\sum_{n\in S_k} d_n \mathbf{x}_n \tag{9b}$$

Algorithm 1 Loyd's Iteration Partition Clustering Algorithm

procedure CLUSTERING($K, X, d, D_{K\times N}, C_s, DM, M$) ▷
K= Total number of beams,
$X = \{u_1, u_2 ... u_N\}$ = Broadband user set,
$d = \{d_1, d_2 ... d_N\}$ = User demand in Mbps,
$C_s = \{\mathbf{c}_{\mathcal{T}^1}, \mathbf{c}_{\mathcal{T}^2} ... \mathbf{c}_{\mathcal{T}^k}\}$ = Initial seeds for cluster centres,
DM = Distance Metric,
$\Re_{K\times N}$ = distance matrix,
M = Maximum number of iterations

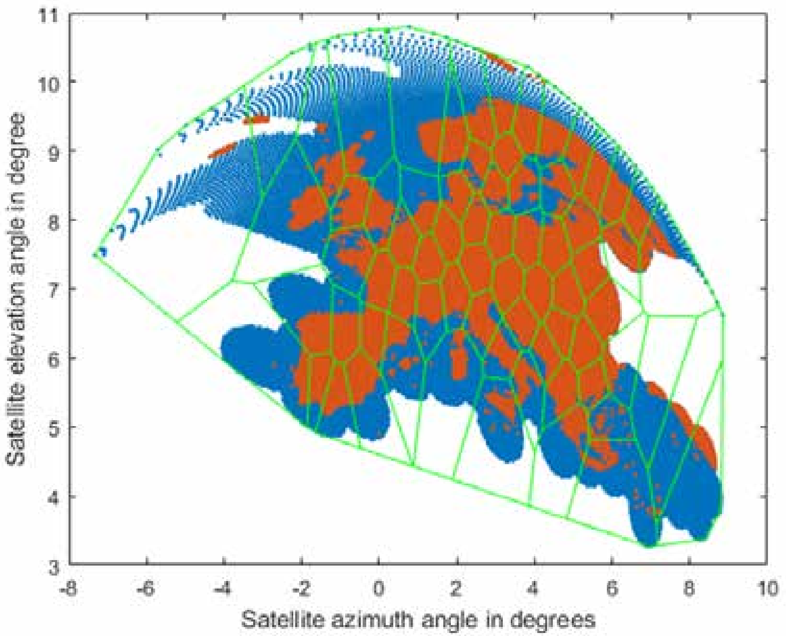
[Step 1] Choose cluster centres $\{\mathbf{c}_{\mathcal{T}^1}, \mathbf{c}_{\mathcal{T}^2} ... \mathbf{c}_{\mathcal{T}^k}\}$ defined by C_s selected as per $k-means++$ Algorithm.
while (Cluster assignments do not change) OR (M is not reached) **do**
[Step 2] Compute distance $\Re_{K\times N}$ between each of $\{\mathbf{c}_{\mathcal{T}^1}, \mathbf{c}_{\mathcal{T}^2} ... \mathbf{c}_{\mathcal{T}^k}\}$ and all of $\{u_1, u_2 ... u_N\}$ using DM shown in (9a).
[Step 3] Assign $\{u_1, u_2 ... u_N\}$ users to K clusters $\{\mathcal{T}^1, \mathcal{T}^2 ... \mathcal{T}^K\}$ based on the minimum distance between the users and cluster centre using $\Re_{K\times N}$.
[Step 4] Compute new cluster centres $\{c_1, c_2 ... c_K\}$ by using (9b).
end while
end procedure

[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 2: Planning beam footprint (4)

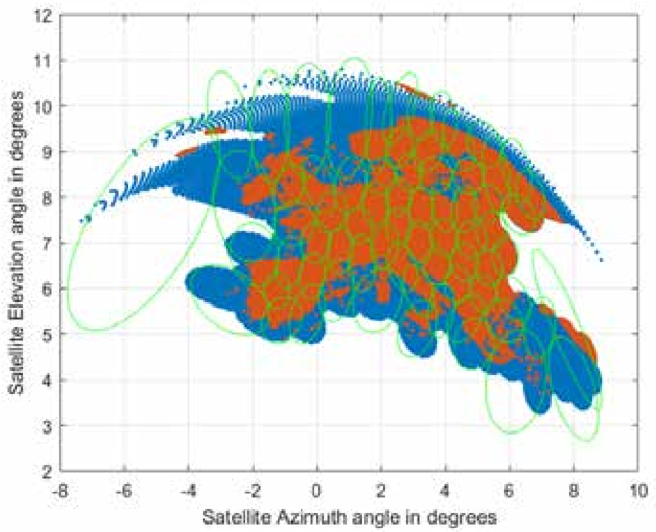
- Dynamic demand-based beam pattern design and footprint planning was proposed in [Honnaiah2021] as a 4 step procedure.

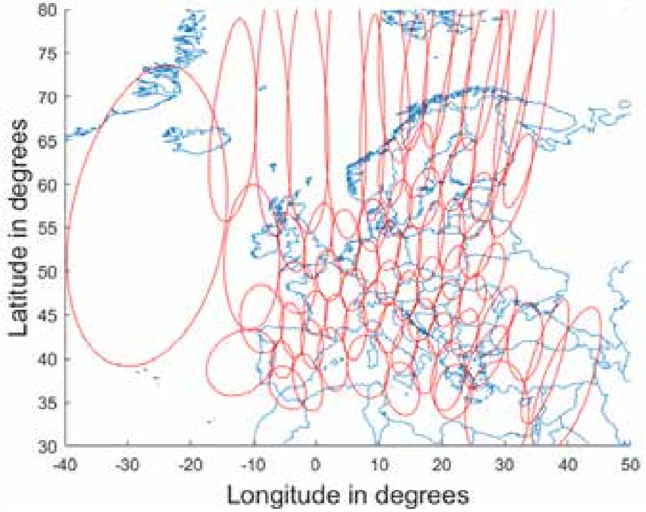
Step 3 : Voronoi Tessellation



Beam boundaries (shown using green convex polygons) defined by Voronoi Tessellations in satellite angular domain. Sampled coverage area is shown in blue and the user positions are shown in red

Step 4 : Elliptic approximation





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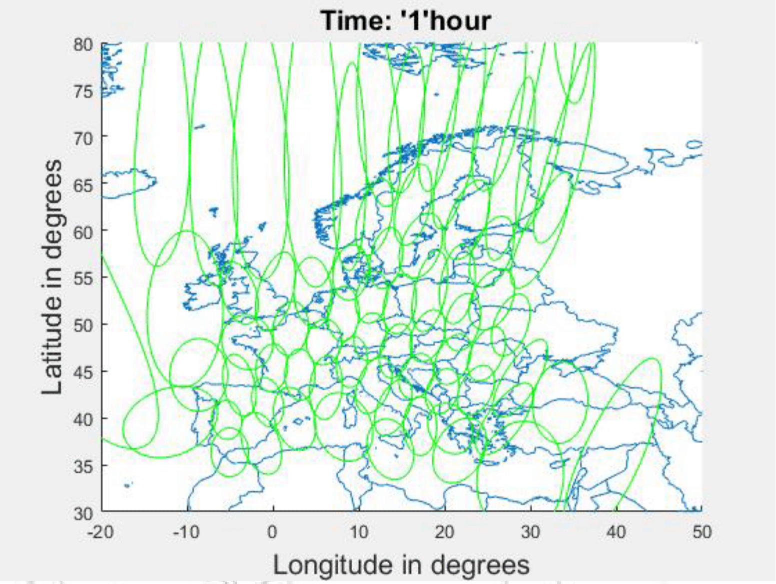
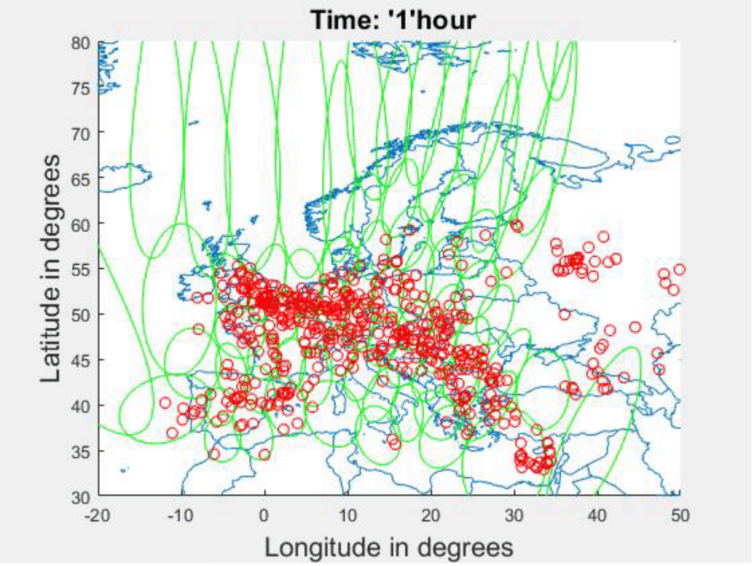
Example 2: Planning beam footprint (5)

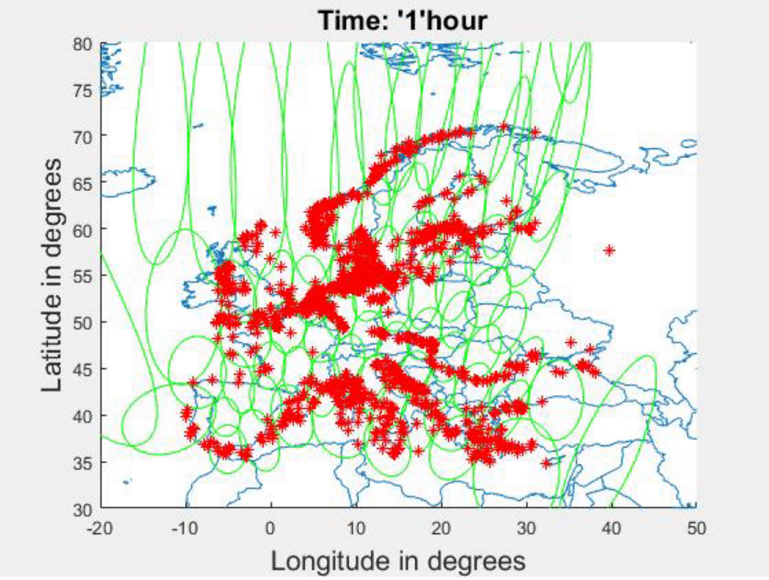
- Results : Adaptive beams from [Honnaiah2021]



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.

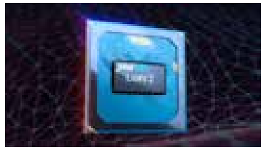
AI In Space

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

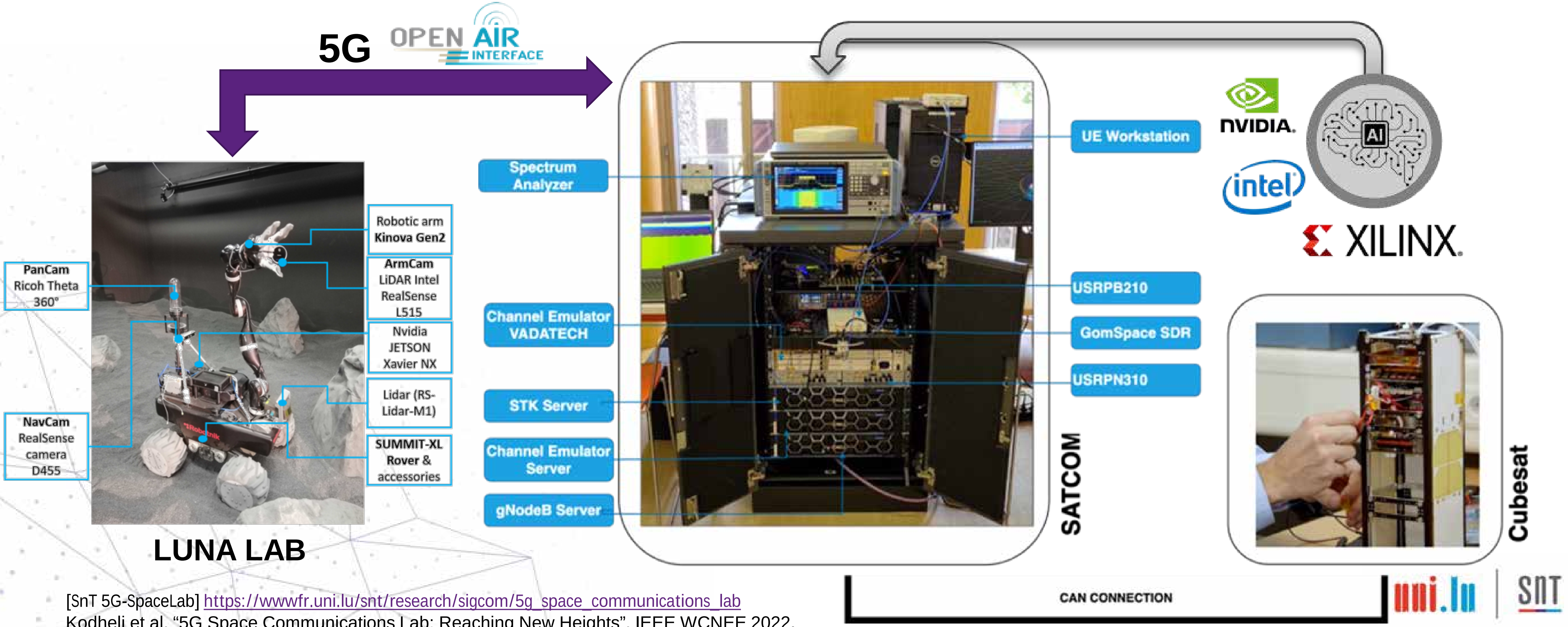
AI-Chip must be energy efficient and radiation tolerant, with memory and computational power adapted to the targeted application.



[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

6GSPACE Lab & Emulation

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



[SnT 5G-SpaceLab] https://wwwfr.uni.lu/snt/research/sigcom/5g_space_communications_lab
Kodheli et al, "5G Space Communications Lab: Reaching New Heights", IEEE WCNEE 2022.

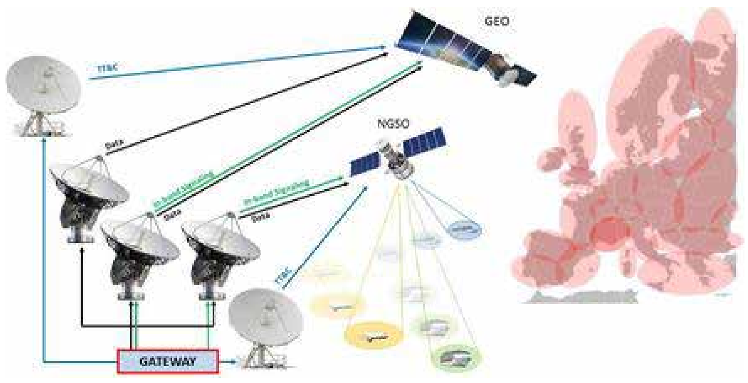
Open Challenges

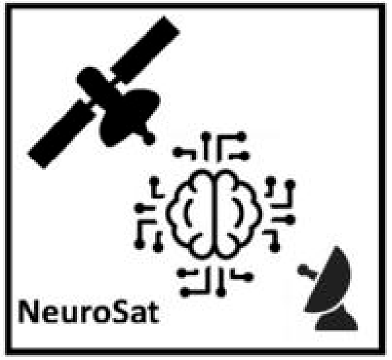
Open Challenges

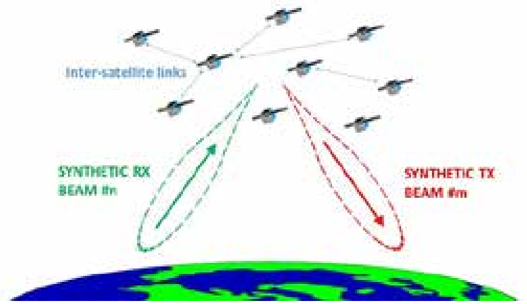
Short-term

- **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

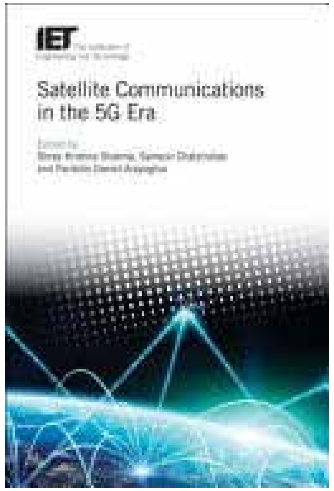






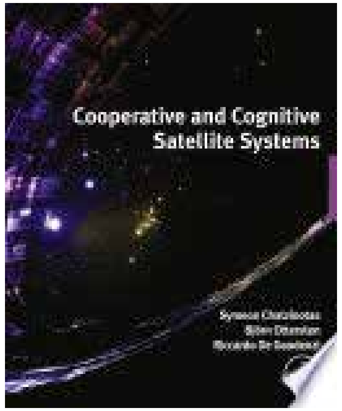
Selected Publications

- Al-Hraishawi H. et al, “A Survey on Non-Geostationary Satellite Systems: The Communication Perspective”, https://arxiv.org/abs/2107.05312
- Martinez L. et al, “Architectures and Synchronization Techniques for Distributed Satellite Systems: A Survey”, https://arxiv.org/abs/2203.08698
- 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.



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