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XXXVII Cycle

Innovative LEO Satellite Mega-Constellation Communication Systems

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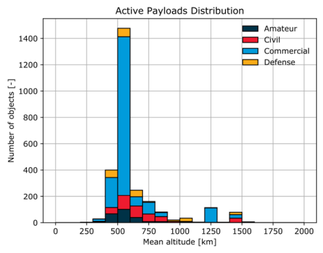
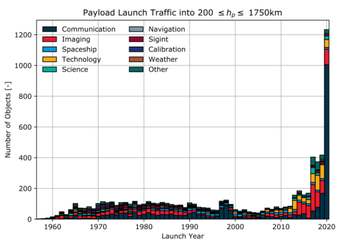
Research context and motivation

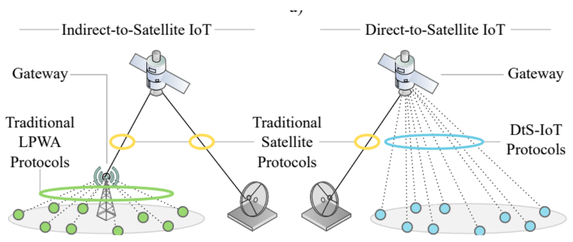
- Mega-constellations are the next step of space-based connectivity for terrestrial services, offering unrivalled coverage through hundreds-to-thousands of Low Earth Orbit (LEO) satellites for low-latency broadband and Internet-of-Things (IoT) applications.
- Meanwhile, thousands of satellites are being launched every year, all facing the same challenge: discontinuous and time-limited links with the ground - a major limitation for satellite-based data services. Ground Station Networks (GSN) and (optical) data relay systems (DRS) may not be enough to cope with demand.
- At the same time, the mega-constellation approach is very resource intensive, and cheaper alternatives are needed for delay-tolerant applications (i.e., IoT), especially where a pervasive terrestrial infrastructure is absent, temporarily out of service, or inadequate.

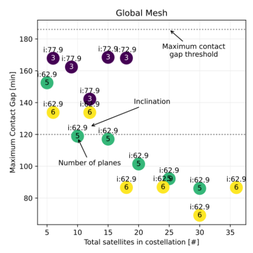


(a) Active Payload Distribution Over Mean Altitude



Source: ESA





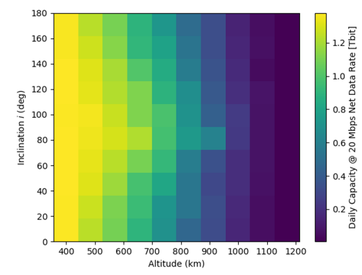
Addressed research questions/problems

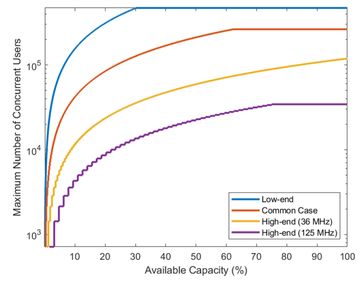
- ***To investigate the potential use of planned mega-constellations to serve spacecraft in LEO with broadband low-latency connectivity.***
  - What can space-based Internet services do for varying satellite applications and what are the minimum requirements for such connectivity?
  - Among the current projects, which constellations can provide such connectivity?
  - What type of connectivity performance can we expect and what a new space-based terminal will look like?
  - How does the designed concept compare with alternative solutions and what are the next development stages?
- ***Business case*** for the application of mega-constellations to space users: transform users into highly responsive nodes of a space-to-space network (high throughput, low latency, low cost).
- ***Disruptive***: satellites transformed into 24/7 available nodes of a high-performance network, enabling a myriad of ***innovative*** applications

- ***Are dense/mega constellations the only solution for global IoT connectivity?***
  - What can sparse constellations offer delay-tolerant IoT applications?
  - Would this be supported by standard NB-IoT / LoRaWAN applications?
  - How small can sparse constellations be?
  - What are the ideal constellations for such services?
- ***Sidetrack:***
  - How should radionavigation services be provided to Lunar users?
  - How should a jamming resilient satellite network, capable of detecting and mitigating jamming, be designed?

Novel contributions

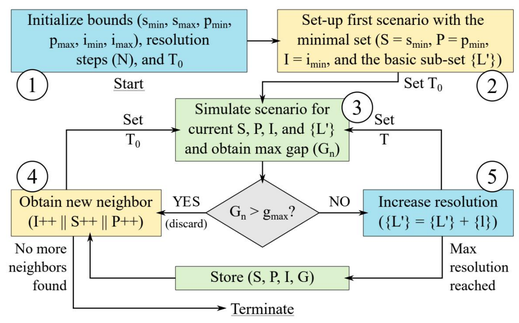
- Designed the LEO space terminal and demonstrated how mega-constellations can provide seamless connectivity to LEO spacecraft, creating a space-to-space network characterized by high throughput, low latency, and low cost. All the results show that the new approach can be potentially disruptive for the space ecosystem.
- Designed a sparse constellation for global IoT coverage requiring only 12.5%/22.5% of the satellites of dense constellations under LoRaWAN/NB-IoT delay constraints.
- Proposed a Frequency-Division Multiple Access Scheme for ESA's Lunar Radionavigation System (LNRS) so that users can access ranging and communication services.
- Patent request on Alternative Code Direct Sequence Spread Spectrum





Adopted methodologies

- Designed a numerical coverage simulator that propagates user and satellite trajectories, computing link accesses and statistics while evaluating relevant policies, user and satellite models, channel models and physical layer parameters. Monte Carlo approach: user satellites uniformly distributed across main payload planes, plus satellites close to constellation orbital planes. Constellations described as per FCC/ITU filings.
- Extended gradient-descent methodology to derive quasi-optimal orbital parameters for regional and global sparse IoT constellations for NB-IoT and LoRa, exploiting ad-hoc heuristics to converge towards the minimal satellite fleet that satisfies coverage constraints.



Future work

- On the Use of Mega-Constellations in Space:
  - Design & Prototype Antenna
  - Apply Adaptive Code and Modulation
  - Explore the use of side-lobes for communication with nearby space users (i.e., Space IoT/TT&C applications)
  - Expand the Concept to MEO constellations and user terminals
  - Explore how user and satellite behaviour impact system performance
  - Explore network-layer aspects
- Sparse Satellite Constellation Design & Direct-to-Satellite NB-IoT
  - Explore Channel Access Challenges
  - Model User & Constellation Traffic
- Multiple Access Sequences For Satellite Constellations Without Centralised Management
- Jamming Detection and Mitigation for Satellite Networks (Jeans) – Techniques for Intelligent Jamming Detection and Mitigation of Satellite IoT Gateways

Submitted and published works

- R. Garello, F. Dovis, G. Taricco, A. Nardin, G. Maiolini Capez (2022). ***Patent on Alternative Code Direct Sequence Spread Spectrum*** (submitted)
- G. Maiolini Capez, M. A.. Caceres, C. P. Bridges, S. Frey, R. Armellin, R. Garello, P. Bargellini. ***Characterisation of Mega-Constellation Links for LEO Missions with Applications to EO and ISS Use Cases*** (2022) In: IEEE Transactions on Aerospace and Electronic Systems (to be submitted Oct 2022)
- G. Maiolini Capez, M. A.. Caceres, C. P. Bridges, S. Frey, R. Armellin, R. Garello, P. Bargellini (2022). ***On the Use of Mega Constellation Services in Space***. In: Nature Communications (passed first editorial assessment, under peer review)
- G. Maiolini Capez, S. Henn, J. A. Fraire, R. Garello (2022***). Sparse Satellite Constellation Design for Global and Regional Direct-to-Satellite IoT Services***. In: IEEE Transactions on Aerospace and Electronic Systems
- L. M. Gagliardini, G. Maiolini Capez,, A. Cornacchia, R. Tuninato, A. Arcieri, F. Stesina, S. Corpino. ***An Academic Ground Station as a Service (GSaaS) Devoted to CubeSats***. Conference: ESA TT&C 2022 (11/2022)
- B. Ripani, A. Modenini, R. Garello, G. Maiolini Capez, G. Montorsi (2021) ***On the use of Pseudo-Noise Ranging with high-rate spectrally-efficient modulations***. Conference: SpaceOps 2021 (05/2021)
- G. Maiolini Capez, L. Buinhas, M. A. Caceres, S. Setty (2021) ***Distributed Space Traffic Management Solutions with Emerging New Space Industry***. Conference: SpaceOps 2021 (05/2021)

List of attended classes

- CNIT School on Optical SDM Transmission (13/12/2021. 10 hours)
- ESA Academy – Space Debris Training Course (16/05/2022, 44 hours)
- 01QTEIU - Data mining concepts and algorithms (03/02/2022, 4 CFU)
- 01RGBRV - Optimization methods for engineering problems (07/06/2022, 6 CFU)
- 01SFVRV - Metamaterials: Theory and multiphysics applications (01/04/2022, 4 CFU)
- 01QRPRV - Satellite Navigation signal exploitation for atmospheric and environmental monitoring (30/06/2022, 3 CFU)
- 01SHMRV - Entrepreneurial Finance (18/01/2022, 1 CFU)
- 01UNVRV - Navigating the hiring process: CV, tests, interview (18/01/2022, 1 CFU)
- 01UNYRV - Personal branding (13/01/2022, 1 CFU)
- 02RHORP - The new Internet Society: entering the black-box of digital innovations (16/1/2022, 1 CFU)

External activities:

- Didactic and research activities @ Escola Politécnica da Universidade de São Paulo (06/06/2022-19/06/2022)
- SatNEx School 2021: Reinventing Satellite Communication Networks beyond the Digital Era (23/11/2022-25/11/2021)
- SatNEx School 2022: High Throughput Satellites Systems Design from Theory to Practice (04/09/2022-05/09/2022)
- 11th Advanced Satellite Multimedia Conference, 17th Signal Processing for Space Communications (06/09/2022-08/09/2022)

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