Models and Methods for Near-Earth and Deep-Space Networks

That could fit the scope of SPACE RG

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Saarland University

- Models and Methods
  - Routing (Simulation, Optimization)
    - **DiscoRoute**: **orbital dynamics equations** in the path-finding loop [1,2].
  - Flow/Congestion control (Emulation)
    - **Stable route selection** and **congestion control adaptation** [3].
  - Battery-Aware Operations (Optimization)
    - Autonomous **battery-aware cross-link scheduling** [4].

Near-Earth

GOMSPACE

Flight-tested in GOMX-4 mission

- Funding
  - **ERC** PoC (LEOPowver), **ESA** ARTES (ConstellAI, ML4OISL), **EU** RISE (MISSION).

- [1] Gregory Stock, Juan A. Fraire, and Holger Hermanns. "**Distributed On-Demand Routing for LEO Mega-Constellations: A Starlink Case Study**". In: 11th ASMS/SPSC 2022, Graz, Austria, September 6-8, 2022. IEEE, 2022, pp. 1–8. DOI: 10.1109/ASMS/SPSC55670.2022.9914716. URL: https://doi.org/10.1109/ASMS/SPSC55670.2022.9914716.
- [2] Camilla Ottaviani, Alessandro Compagnoni, Juan A. Fraire, Giacomo Verardo, Gabriel Maiolini Capez, Daniel Gaetano Riviello, Gregory Stock, Carla Fabiana Chiasserini, and Roberto Garello. "**Advanced Routing Strategies for LEO and VLEO Constellations: Ensuring Polar Coverage**". In: 14th ASMS/SPSC 2025. In Press. IEEE, 2025.
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- [4] Gregory Stock, Juan A Fraire, Holger Hermanns, Eduardo Cruz, Alastair Isaacs, and Zhana Imbrosh. "**On the automation, optimization, and in-orbit validation of intelligent satellite constellation operations**". In: SSC21-V-05, 2021 AIAA/USU Conference on Small Satellites, Logan, Utah, USA (2022). URL: https://digitalcommons.usu.edu/smallsat/2021/all2021/168/.

Inria

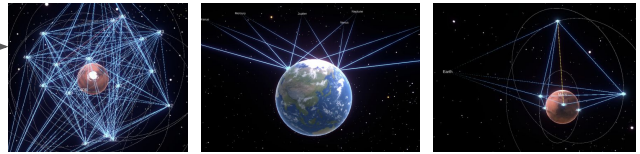
- Models and Methods
  - Links and Access (Simulation, Optimization)
    - **Protocols** for **Direct-to-Satellite IoT** [1] → *LoRa & 3GPP NB-IoT*
    - **Protocols** for **Direct-to-Cell** (D2C) access → *3GPP 5G/6G NTN*
    - **Constellation design** and **FSO operations**.
  - Routing (Optimization, Learning)
    - **CGR / SABR** (CCSDS): applicability, scalability, and reliability [2].
    - **Congestion mitigation** [3].
    - **Contact plan design** and **visualization** tools.

Near-Earth

Deep-Space

Interaction with 3GPP

With IPNSIG



- Funding
  - **ANR** PRCE (STEREO), **PEPR** 5G & FN (DONUTS).

- [1] Juan A. Fraire, Oana Iova, and Fabrice Valois. "**Space-Terrestrial Integrated Internet of Things: Challenges and Opportunities**". In: IEEE Communications Magazine. 60.12 (2022), pp. 64–70. URL: https://doi.org/10.1109/MCOM.008.2200215.
- [2] Pedro R D'Argenio, Juan Fraire, Arnd Hartmanns, and Fernando Raverta. "**Comparing Statistical, Analytical, and Learning-Based Routing Approaches for Delay-Tolerant Networks**". In: ACM Transactions on Modeling and Computer Simulation (2024). URL: https://doi.org/10.1145/3665927.
- [3] Yang, Lei, Juan A. Fraire, Kanglian Zhao, Ruhai Wang, Wenfeng Li, and Hong Yang. "**Optimizing deep-space DTN congestion control via deep reinforcement learning**." Computer Networks 255 (2024): 110865. URL: https://doi.org/10.1016/j.comnet.2024.110865.

D3TN

- Models and Methods
  - Protocol Stack (Implementation)
    - **µD3TN**: The first BPv7 transmission in space [1].
  - Protocol Architectures (Experimental)
    - **Recursive architectures** (RINA) → Drones simulating martian conditions.
    - **Ring Road Networks** (RRN) → ESA OPS-SAT laboratory [2].
    - **Cross-agency communications** → ESA/NASA IceCube network.
  - Space Cloud (Emulation)
    - Infrastructure supporting **compute payloads** across space assets.

Near-Earth & Deep-Space

- Funding
  - **ESA** (ColdSun, SSI-PPA), **SAB** (DarkSol), **BMBF** (RedMars) [3].

→ [1] Felix Walter, Marius Feldmann, Juan A Fraire, and Scott Burleigh. "**The Architectural Refinement of µD3TN: Toward a Software-Defined DTN Protocol Stack**". In: 2024 IEEE 10th International Conference on Space Mission Challenges for Information Technology (SMC-IT). IEEE. 2024, pp. 161–170. URL: https://doi.org/10.1109/SMC-IT61443.2024.00025.

→ [2] Marius Feldmann, Juan A. Fraire, Felix Walter, and Scott C. Burleigh. "**Ring Road Networks: Access for Anyone**". In: IEEE Communications Magazine 60.4 (2022), pp. 38–44. URL: https://doi.org/10.1109/MCOM.001.2100835.

→ [3] More information in:https://d3tn.com/.

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Juan’s Research on Free-Space Optics (FSO) Comms.

- Optimal FSO Terminal Placement [1]
  - **Goal**: Maximize contact time by optimally positioning gimbal-limited FSO terminals.
  - **Method**: Simulated annealing + genetic algorithms.
- Autonomous FSO Scheduling [2]
  - **Goal**: Maximize capacity in interplanetary and near-Earth laser networks.
  - **Method**: Exact optimization via MILP and algorithmic scheduling.
- FSO-Only LEO Networks via HAPS Relays [3, 4]
  - **Goal**: Evaluate LEO-to-HAPS FSO links to bypass weather with full optical constellations.
  - **Method**: Discrete-event simulations.
- Hybrid FSO/RF Inter-Satellite Links [5, 6]
  - **Goal**: Use RF side-channels (LPWAN) to assist ISL pointing.
  - **Method**: Prototyping, modeling, and simulative validation.

Universität des Saarlandes — Inria

Coop. Concordia University

Coop. Carleton University

Coop. i2cat

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- [2] Gerard, J., et al., “**Autonomous Max-Flow Interplanetary Laser Link Scheduling for Martian Exploration**,” in Proc. IEEE WiSEE, 2024.
- [3] Coeugnet, Benoit, et al. "**Routing in All-Optical LEO Constellations with High-Altitude Ground Stations**." 2024 IEEE MECOM. IEEE, 2024.
- [4] Madoery, Pablo G., et al. "**A Novel Non-Terrestrial Networks Architecture: All Optical LEO Constellations with High-Altitude Ground Stations**." 2024 IEEE ICC 2024..
- [5] Fernandez-Nino, Elena, et al. "**RF-assisted uncertainty cone reduction in free-space optical inter-satellite links**." IEEE Open Journal of the Communications Society (2024).
- [6] Fernandez-Nino, Elena, et al. "**A case study of an hybrid RF and optical inter-satellite link terminal to enhance optical pointing.**" 2024 EuCNC/6G Summit). IEEE, 2024.