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at Northeastern University

Beyond Earth: Rethinking Wireless and Autonomy with AI

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On the news!

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iPhones Now Support Satellite Data Via T-Mobile's Cellular Starlink

September 18, 2025

If you have T-Satellite and a supported iPhone, you can access several Apple apps via satellite.

Manually reconnecting with Apple's satellite network. (Credit: PCMag/Michael Kan)

FOX 35 ORLANDO Live News Weather Good Day We Love Florida Contests More

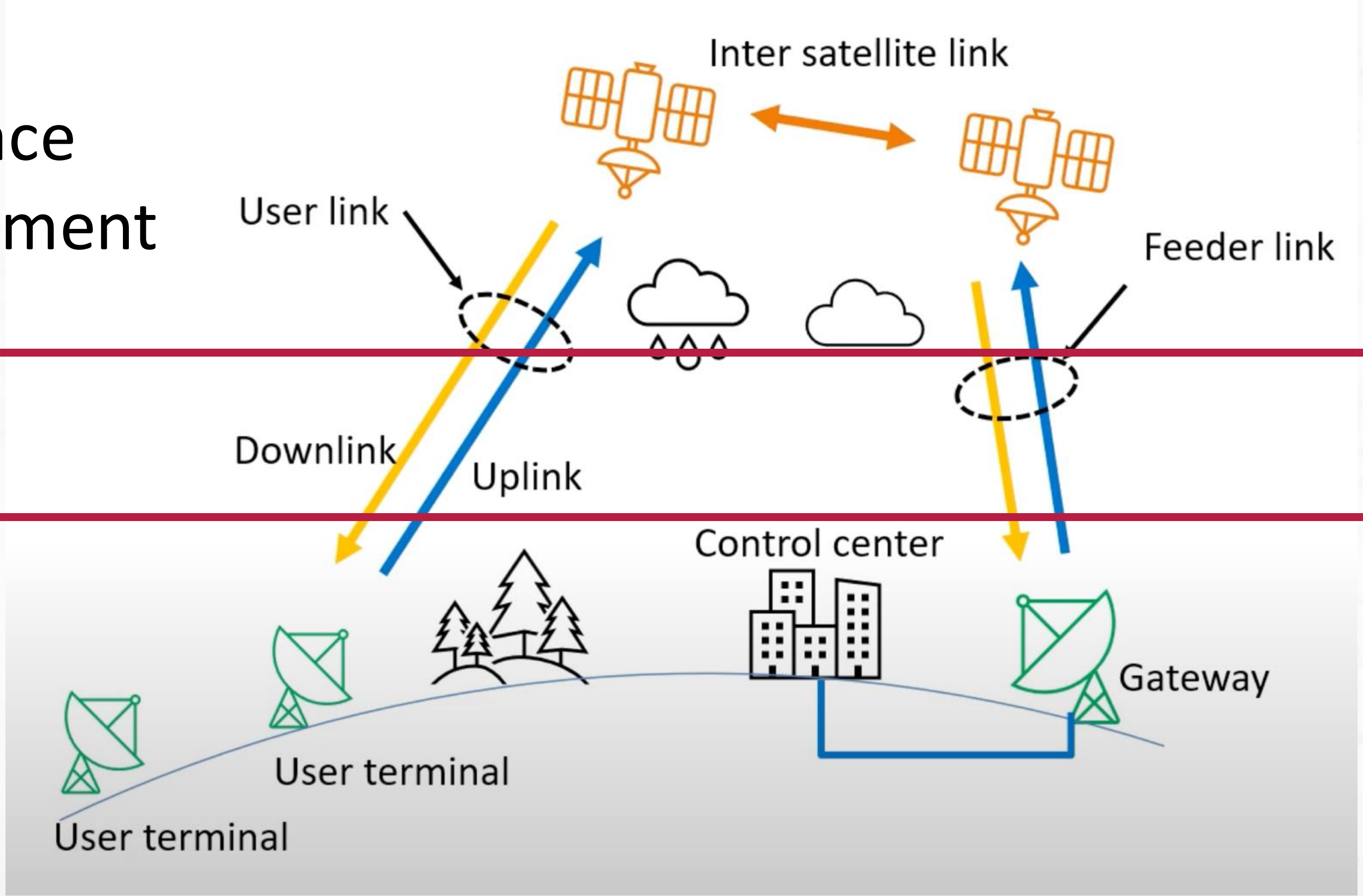
River Flood Warning is in effect, Lake County, Volusia County

ULA rocket launches 27 of Amazon's Project Kuiper internet satellites into space

By Annabelle Sikes | Published September 25, 2025 7:05am EDT | Air and Space | FOX 35 Orlando |

SatComms: A general architecture

Space segment



Ground segment

SatComms: A general architecture

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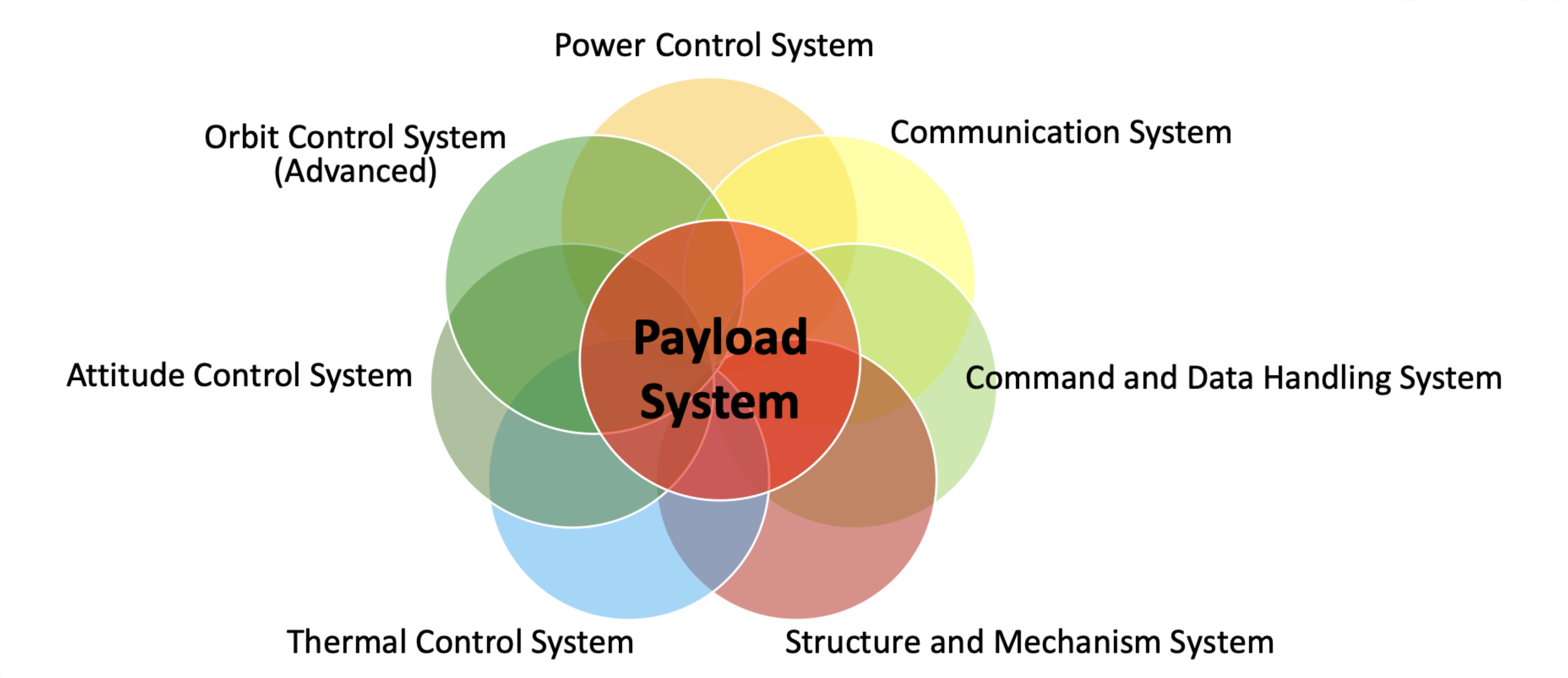
The satellite side



Megaconstellations…

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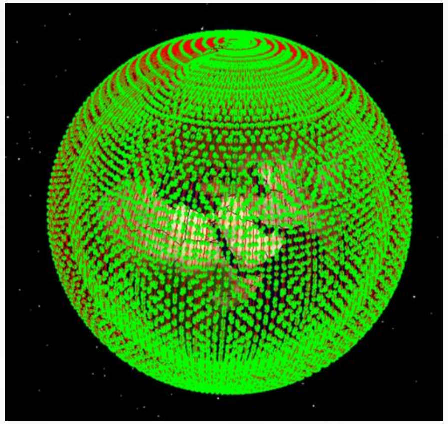

11,943 satellites *

Traditional Broadband Architecture

- Ku/Ka-band phased-array antennas
- Optical inter-satellite links
- Optimized for throughput

Centralized Control

- Ground Stations dependent

Fixed Computing Infrastructure

- Pre-configured routing software
- No ability to host third-party edge computing workloads.

* X. Yang, "Low Earth Orbit (LEO) Mega Constellations – Satellite and Terrestrial Integrated Communication Networks".

Limitations of current Constellations

Inefficient Spectrum Use

Up to **40% of available bandwidth wasted** due to fixed frequency allocations and lack of dynamic spectrum sharing of TN with NTN.

Pre-scheduled Operations

Orbital maneuvers and communication schedules must be planned days in advance, preventing quick responses to **weather events or emergencies.**

Limited Resilience

When hardware failures occur, satellites often require **manual intervention from ground control**, leading to **service outages lasting 4-6 hours**

Single purpose!

Too much satellites in constellations **interfere with other satellites observation and operations**!

The Motivation

The Space Economy Vision

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$1T+ Market by 2040

Manufacturing in Space

Ultra-pure fiber optics in microgravity environments. Impossible alloys and perfect semiconductors achievable only in zero-g conditions.

Automated Research

24/7 pharmaceutical experiments via robotic laboratories.
90% cost reduction in space experimentation cycles.

Lunar Presence

Permanent bases with direct Earth-Moon communication. Helium-3 mining operations for fusion energy production.

HAVEN-2 Space Station Credit: VAST Space

Beyond Earth: NTN in the 6G+ era

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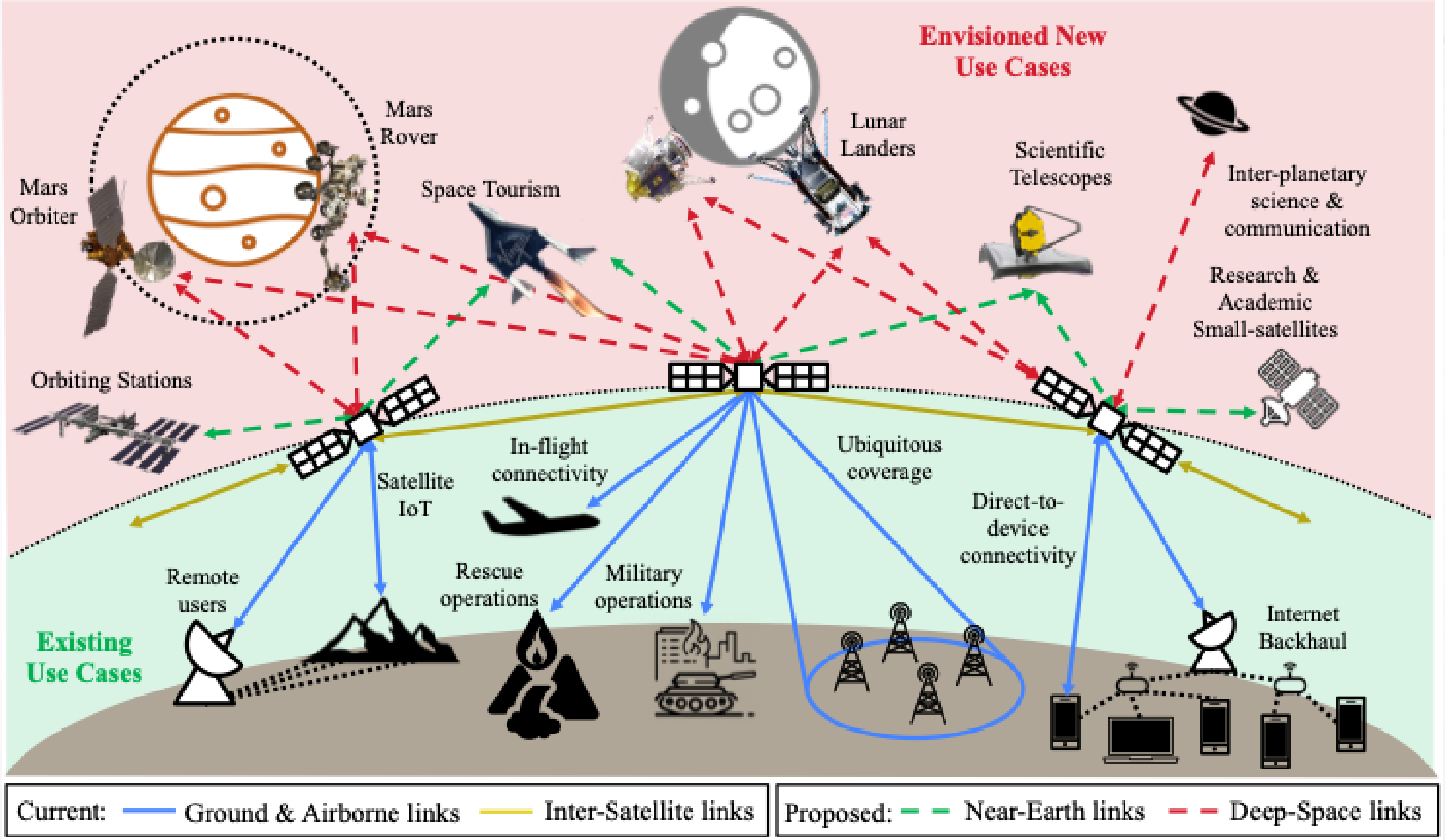
- Space-based Internet brings key advantages to the 6G era:
  - Ubiquitous, broadband connectivity to areas where wireless infrastructure does not exist or has been compromised
  - A "**back-haul in the Sky**" (**looking down**)
  - An intermediate hop for space networks (**looking up**)



Then…is only comms enough?

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1. The Infrastructure Challenge

01

Multi-Layer Integration

Communications + Sensing + Computing unified architecture

02

Intermediate Intelligence

Satellites as processing nodes, not just relay points

03

Bidirectional Capability

"Looking up" to deep space missions and coordination

04

Adaptive Systems

Energy-responsive computation and communication protocols

Then…is only comms enough?

2. The (Semi?) Autonomy Challenge

Communication delays demand intelligent independence

1. **Lunar Operations**
   1.3 seconds delay
2. **Mars Missions**
   8-24 minutes one-way delay
3. **Deep Space**
   Hours to days communication gaps

Decision-Making During Blackouts

Critical choices when Earth contact is impossible

Predictive Maintenance

Preventing failures before ground intervention possible

Adaptive Mission Planning

Real-time optimization based on changing conditions

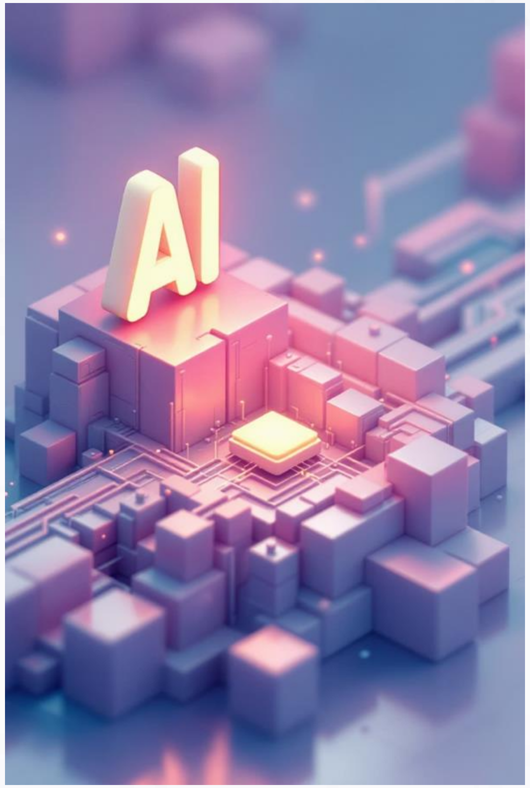
AI in Space: Hype vs Reality

The Hype

- "AI will revolutionize space exploration"
- "ChatGPT-powered autonomous satellites"
- Military FOMO driving blind investment

The Reality

- LLM inference on datacenter GPUs: 100–500 W. Typical sat compute payload: 5–30 W (CubeSat) to ~100+ W (Starlink-class)."
- Current max reliability: 95-98% (space needs: >99.9%+)
- Model complexity vs harsh space constraints



Towards Programmable Space Edge in 6G

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NASA Goddard SPACE FLIGHT CENTER

Date: 07/23
Revision: v4

Current AI Technology in Space

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Domain	Applications
Remote Sensing	• Rapid Disaster Response (e.g., Wildfire Detection) • Data Triage including Image and Video Compression • Onboard Product Generation
Guidance, Navigation, and Control (GNC)	• Autonomous Rover Controls • Autonomous Hazard Detection and Landing • Horizon/Star Tracking • Terrain Classification
Mission Planning	• Intelligent Scheduling • Distributed System Missions
Communication	• Software Defined Radio • Cryptography

Table 1: Domains and applications that could significantly benefit from the use of onboard AI

1

Real-time AI Inference

Enabling in-orbit data analysis and decision-making capabilities to process information directly in space

2

Deep-space Autonomy

Supporting independent operations through sophisticated onboard computing systems

3

Mission-adaptive Operations

Implementing dynamic software-based reprogramming for optimized workload management

How do we start closing the gap?

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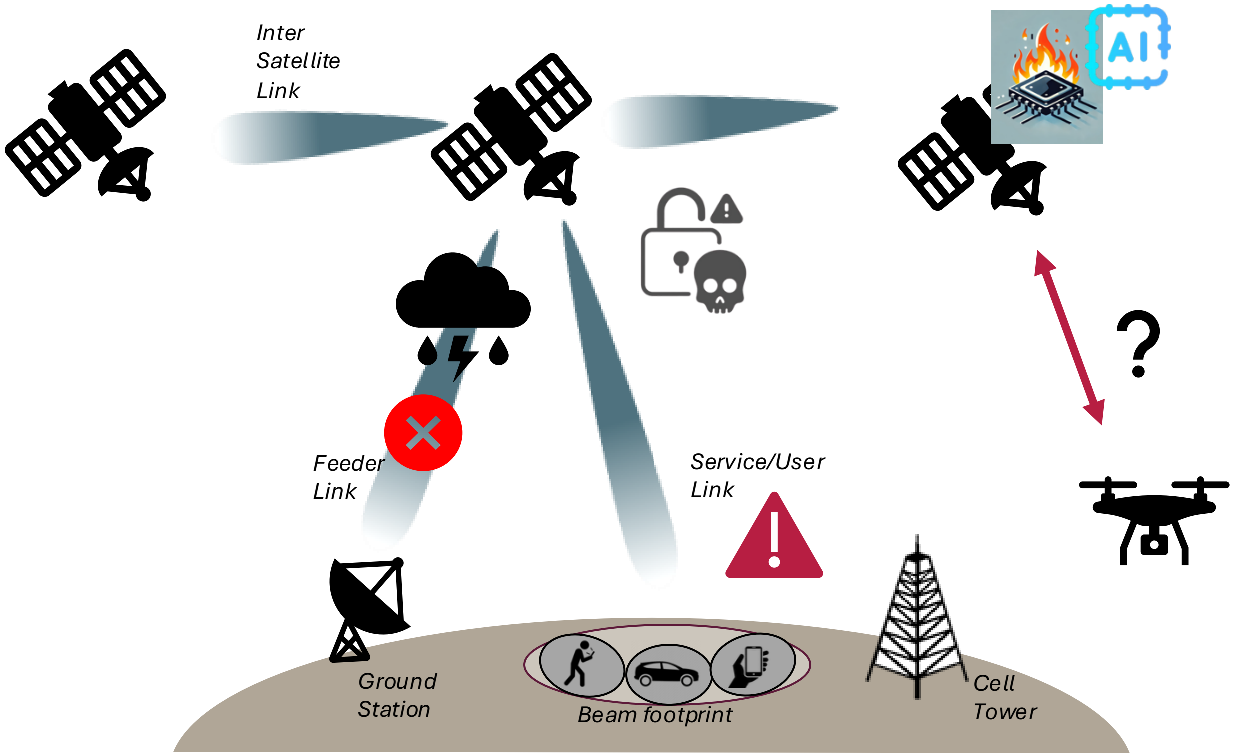


Challenges of NTN-TN integration

- Ground Dependent: Feeder Link Bottlenecks (Single PoF)
- No unified cross-orbit coordination+ control signaling delays
- Fast-changing topology & ISL availability
- Static spectrum → interference & underuse
- Security Risks and Expanded Attack Exposure
- Tight energy & compute budgets onboard for AI Model Lifecycle

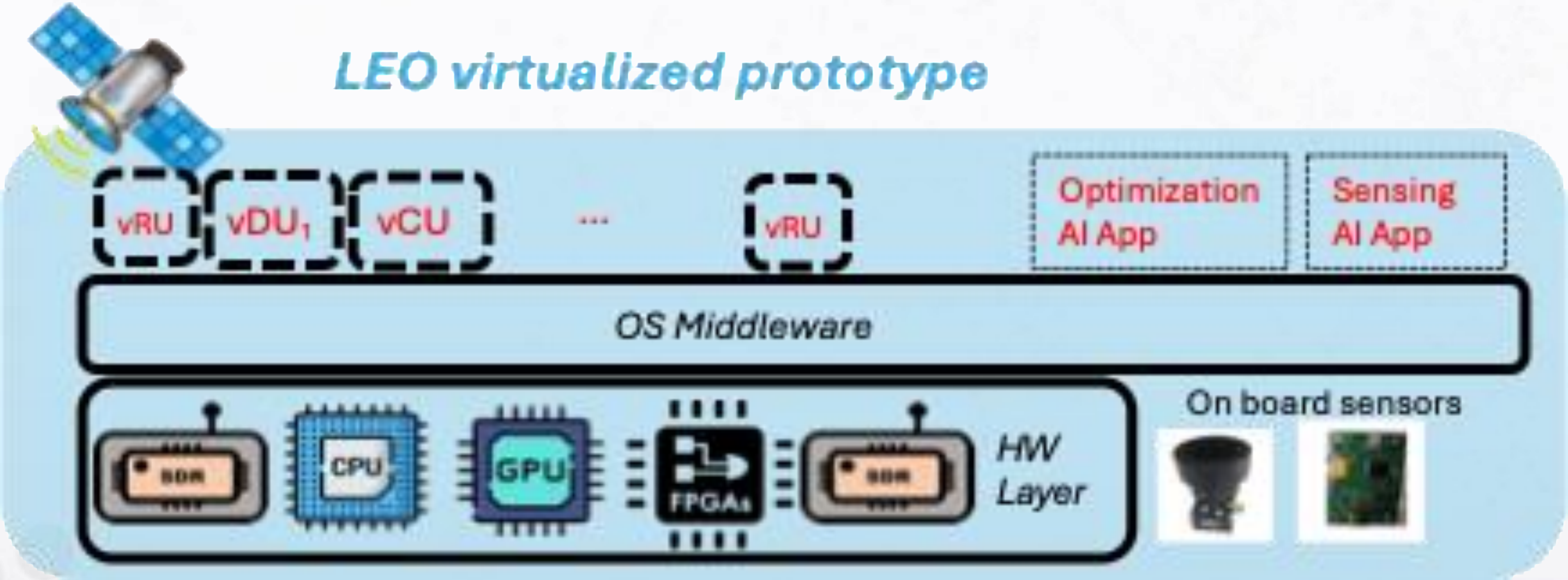
Eduardo Baena, Paolo Testolina, Michele Polese, Dimitrios Koutsonikolas, Josep Jornet, and Tommaso Melodia. "Space-O-RAN: Enabling Intelligent, Open, and Interoperable Non Terrestrial Networks in 6G." Accepted in IEEE Communications Magazine, June 2025.

All you need is O-RAN

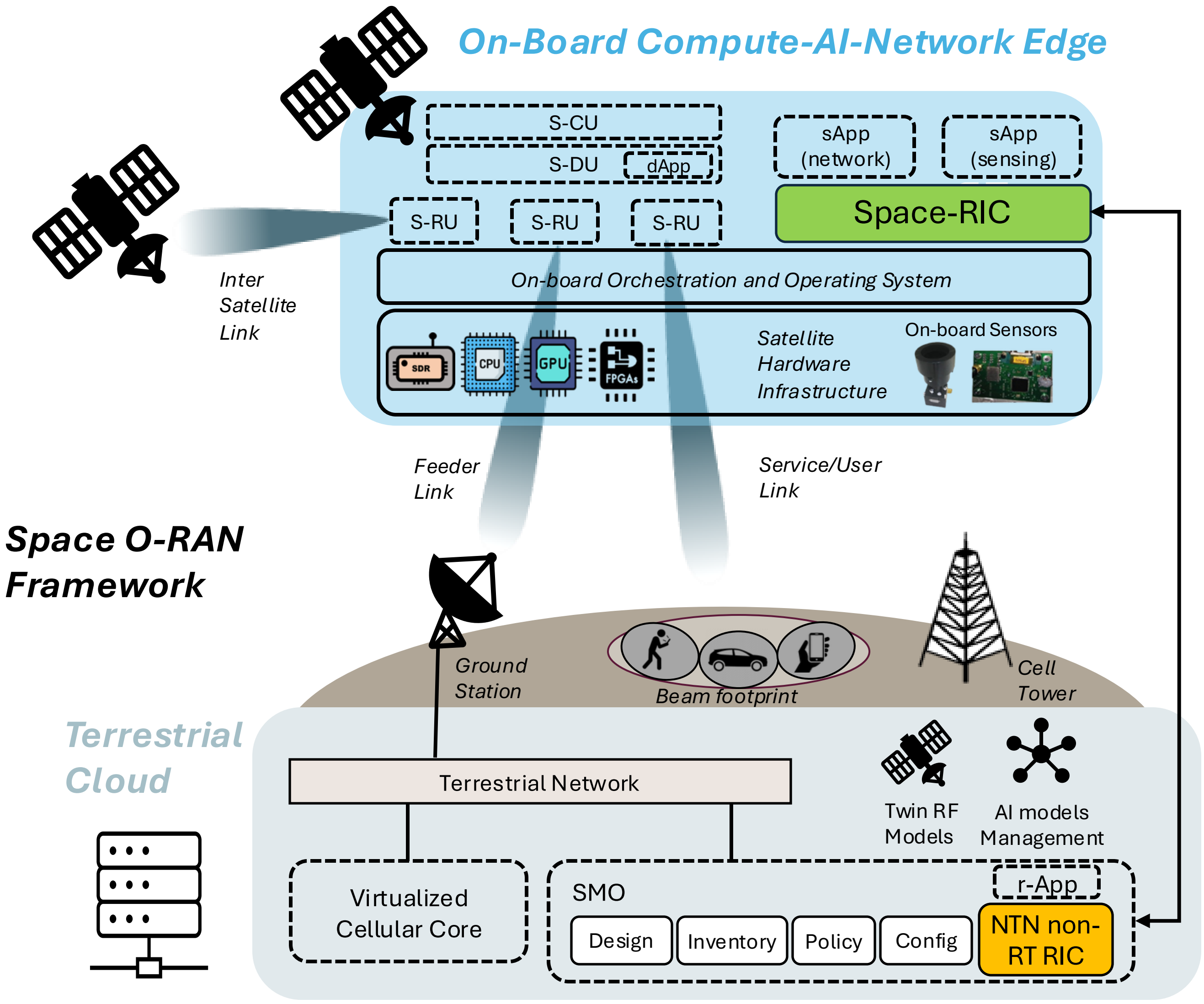
Industry
Partners

Towards Programmable Space Edge in 6G

- **Satellites as a Service (not just SatComms!)**
  - **Satellite full virtualization**
  - **Tailor-made computing architectures**



Space O-RAN control architecture



On-Board Edge

Ground-dependent: Space-RIC cluster-wide autonomy
High Control Latency: Multiscale s/dApp closed loop coordination
Dynamic ISL topology: Adaptive link-to-interface mapping
Power & compute limits
: AI-aware RAN + task offloading
Spectrum inefficiency: In-orbit coordination via sApps

Terrestrial Cloud

Resource Optimization: DT training + inference model updates.
Spectrum Policy planning via rApps and SMO
Links Security: Ephemeral key reauthentication. Quantum encryption. Federated Schemes.
Seamless Integration: O-RAN standard compatibility for global 5G/6G expansion

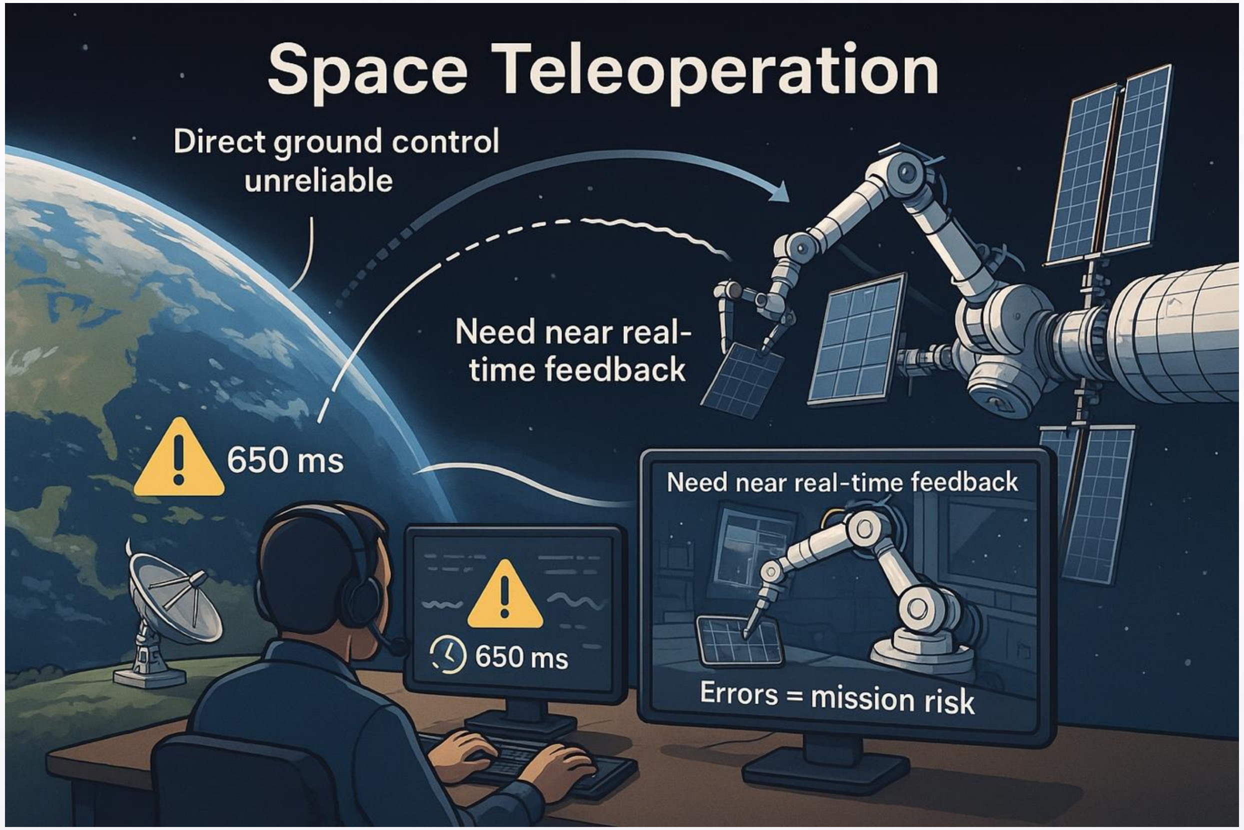
Enables New Use Cases

Ubiquitous AI-Driven Applications (sensing at the space edge)
Autonomous Disaster Response
On-demand coverage and rural networks
Satellite-to-Satellite services (private space stations operations)

Use Case: Space Facilities Teleoperation

Problem: Earth Teleoperation in LEO requires URLLC

- ✓ Direct ground control is unreliable due to orbital movement & intermittent ground station visibility.
- ✓ High-precision robotic operations in microgravity (e.g., maintenance, assembly) require near real-time feedback
- ✓ Fluctuations in network latency can cause errors in critical space station operations.



Use Case: Space Facilities Teleoperation

Step 1: Low-Latency AI Inference (dApps at Space Facility Level)

- Predicts network-induced delay
- Adjusts robotic arm movement dynamically
- Ensures smooth, precise teleoperation despite connectivity variations

Step 2: Intelligent Network Adaptation (xApps for Network Optimization)

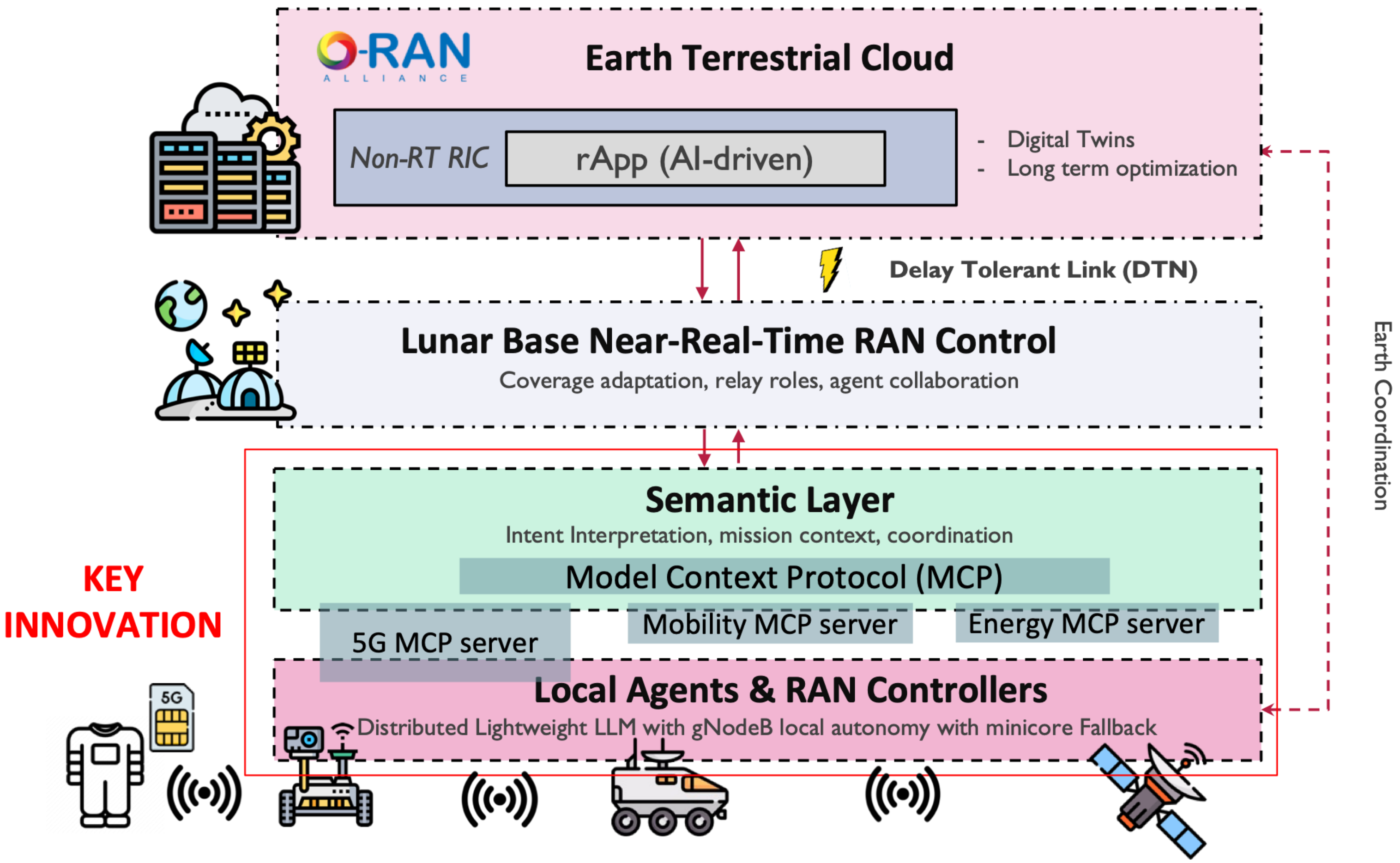
- AI **optimizes downlink & inter-satellite links** for **low packet loss** and **stable connections**.
- **Dynamic modulation & coding schemes (MCS)** adjust for variable conditions.
- **Critical commands (e.g., emergency shutdowns)** get priority network resources

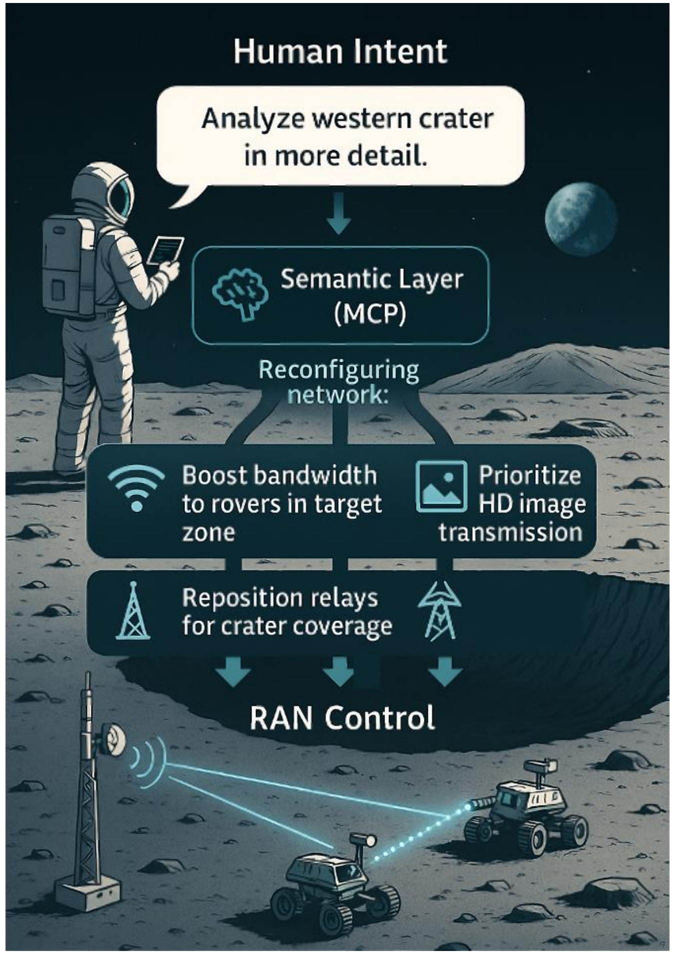
Step 3: Predictive Traffic Scheduling & AI Model Updates (rApps for Long-Term Network Planning)

- **AI learns from past teleoperation sessions** to improve future robotic responsiveness.
- **Predicts orbital connectivity gaps** and pre-schedules handovers across ground stations & ISL networks

Next: Agentic Semantic Control for Lunar Networks

Architecture Overview





From ARA to Orbit

Bridging Earth-to-space development challenges

~2k

Coverage Area

km^2 satellite-like footprint

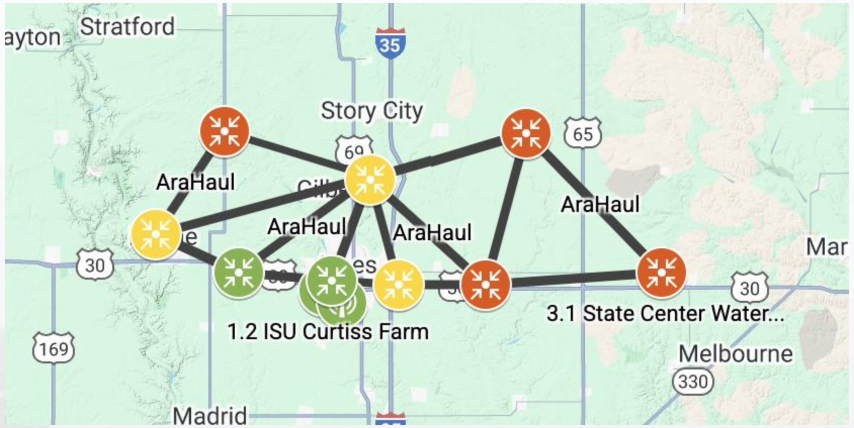
3

Backhaul Types

Microwave, mmWave, FSO integration

Real-World Validation Platform

- Agricultural traffic patterns mirroring space constraints
- **Weather** integration tests atmospheric effects
- Open access for global research collaboration
- Seamless transition from terrestrial to space deployment



Research Questions

- Can AI agents coordinate across 60 km^2 without central control?
- How do federated learning algorithms perform under space-like communication constraints?

Resilient Communications:

- What handover strategies emerge when FSO links fail during weather events?
- Can predictive models anticipate optimal communication paths before link degradation?

Space-Analog Validation:

- Do Earth-based atmospheric effects adequately simulate space communication challenges?
- How do energy-constrained algorithms scale from terrestrial to orbital power budgets?

Cross-Layer Intelligence:

- What network topologies emerge from multi-objective optimization (latency, energy, reliability)?

Towards an AI-Managed Internet in Space

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- O-RAN provides the **modular and standardized architecture** needed for **NTN-TN integration**.
- **AI-driven virtualization** enables satellites to become adaptive, reconfigurable computing nodes
- The **fusion of sensing, communication, and AI inference** in space will unlock new capabilities for planetary exploration, deep-space missions, and autonomous space networks.

Takeaway: Space networks must evolve from *fixed-function systems to self-adaptive, resilient, AI-managed infrastructures.*

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Let's build the space internet together

Lets stay in touch!

Space-O-RAN preprint

SCAN ME

Agentic Semantic Wireless preprint

SCAN ME