Energy-Efficient Temporal Connectivity over LEO Satellites

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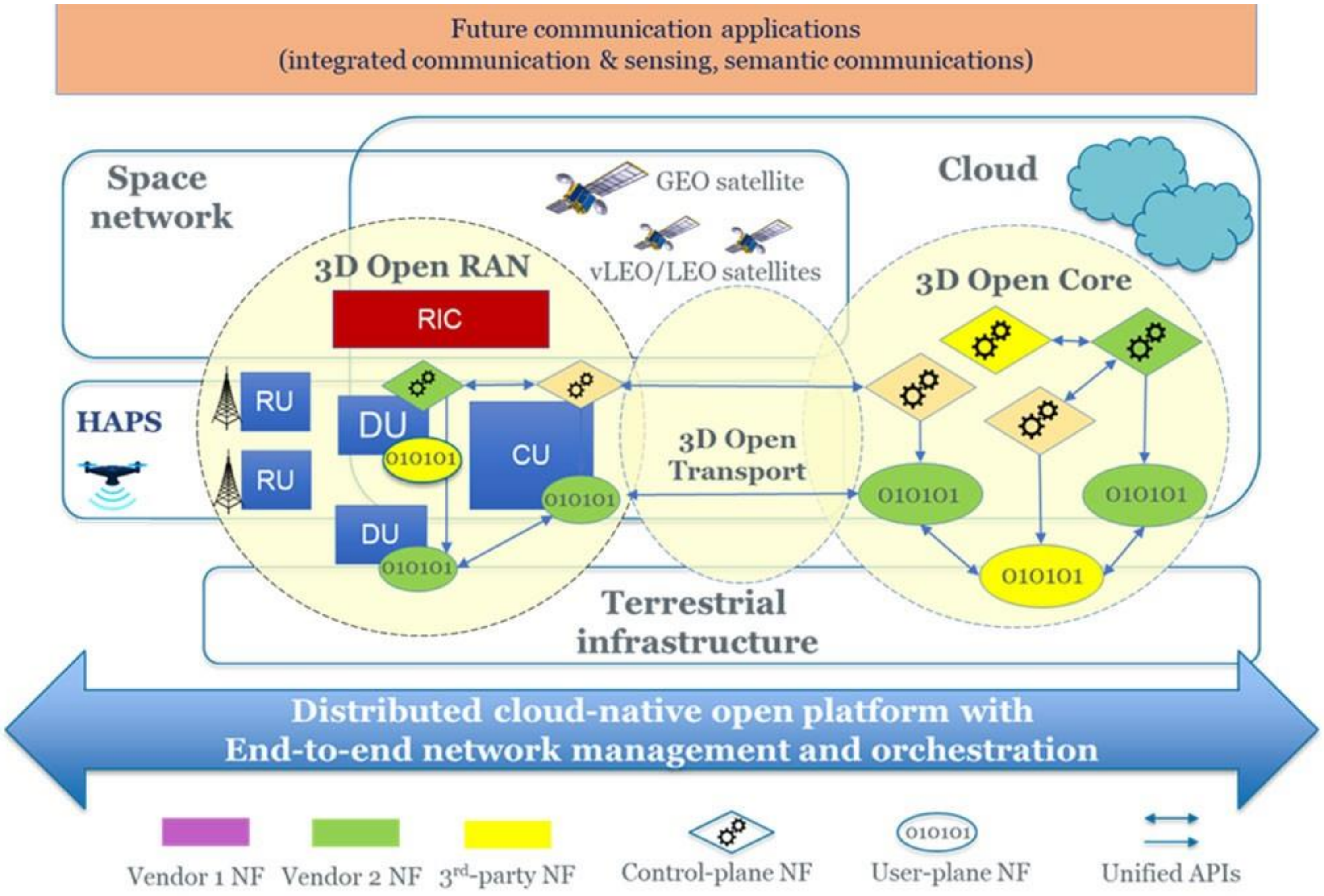
TUDOR

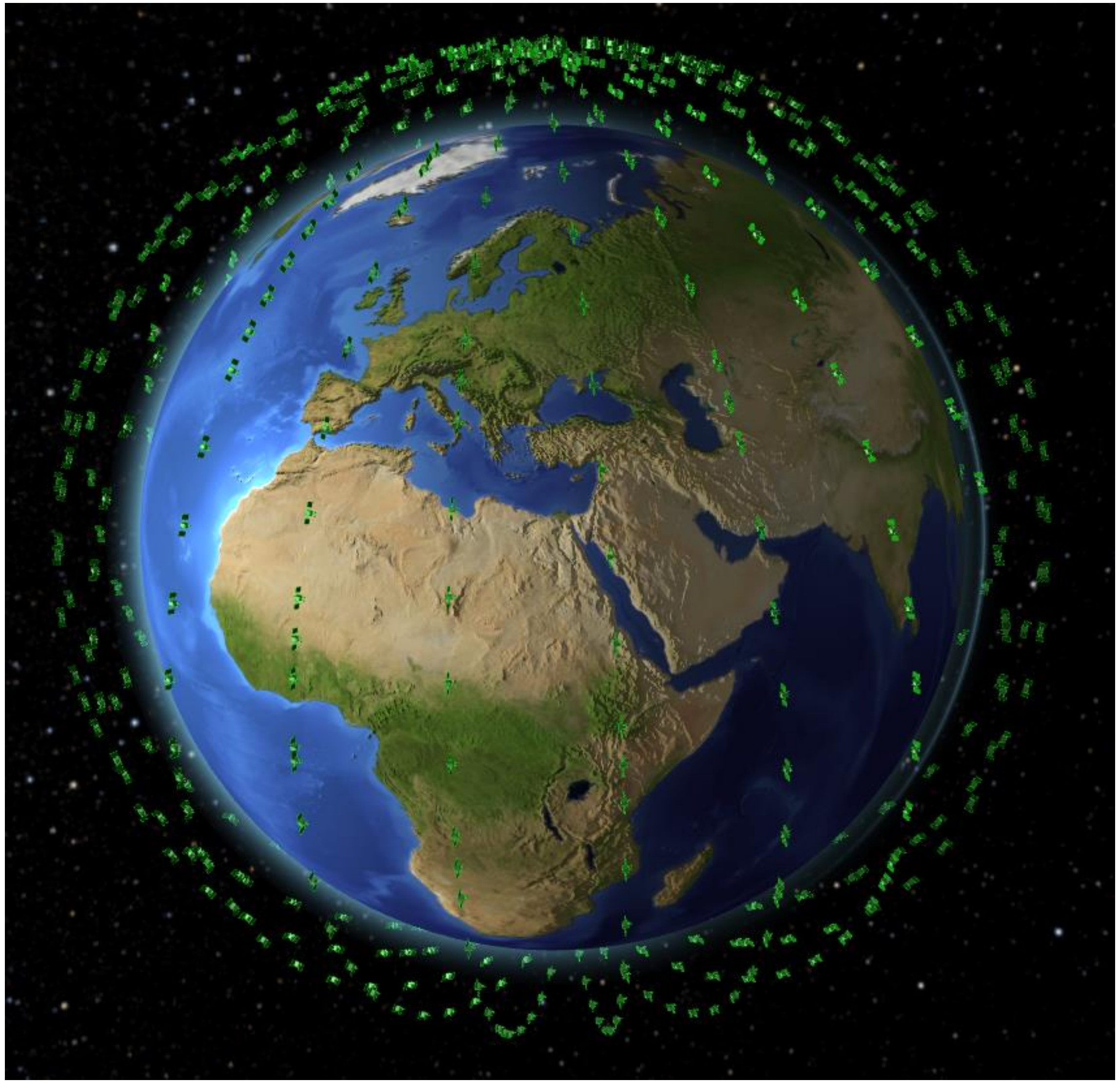

Future communication applications
(integrated communication & sensing, semantic communications)
Space network
GEO satellite
vLEO/LEO satellites
Cloud
3D Open RAN
RIC
RU
RU
DU
DU
CU
010101
HAPS
3D Open Transport
3D Open Core
Terrestrial infrastructure
Distributed cloud-native open platform with
End-to-end network management and orchestration
Vendor 1 NF
Vendor 2 NF
3rd-party NF
Control-plane NF
User-plane NF
Unified APIs

TUDOR Technical directions for LEO satellites

- Current Implementation
  - Fine-grained UPF disaggregation
  - Open service platform
  - Satellite cloud and application-network coordination
  - AI-based control-plane architecture
- In Progress
  - 6G control plane architecture spanning TN-NTN domains
  - <u>Energy Efficient LEO Networking (todays focus)</u>

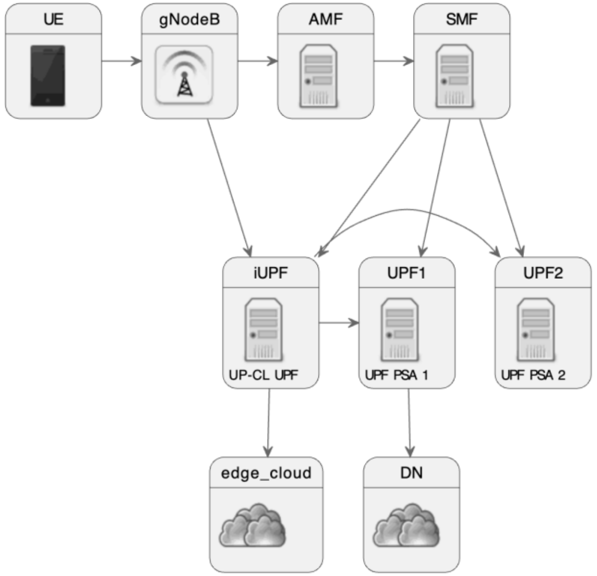
Satellite cloud and application-network coordination

- Assume application servers are hosted on LEO constellation for low-latency
- The satellite hosting the server is in orbit and will eventually move to the other side of the planet
- Migrate state between server instances to keep latency within tolerable bounds
- Design new software architecture to simplify state migration
- Design optimal strategy, to trade off:
    - Keep latency low
    - Reduce state migration frequency

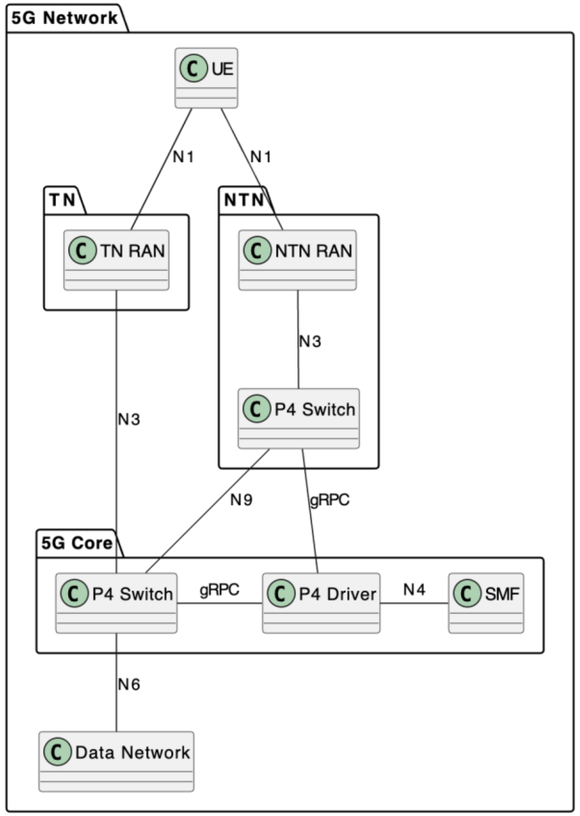


Fine-grained UPF disaggregation

- Existing UPF architecture may experience control plane congestion for NTN
    - Handovers occur every few minutes
    - UE session must migrate to new i-UPF
- Simplify i-UPF design to reduce requirements
    - Minimise reconfiguration of GTP tunnels
- Pre-install state on every UPF during UE registration
    - Upon handover, only the anchor UPF needs to update state



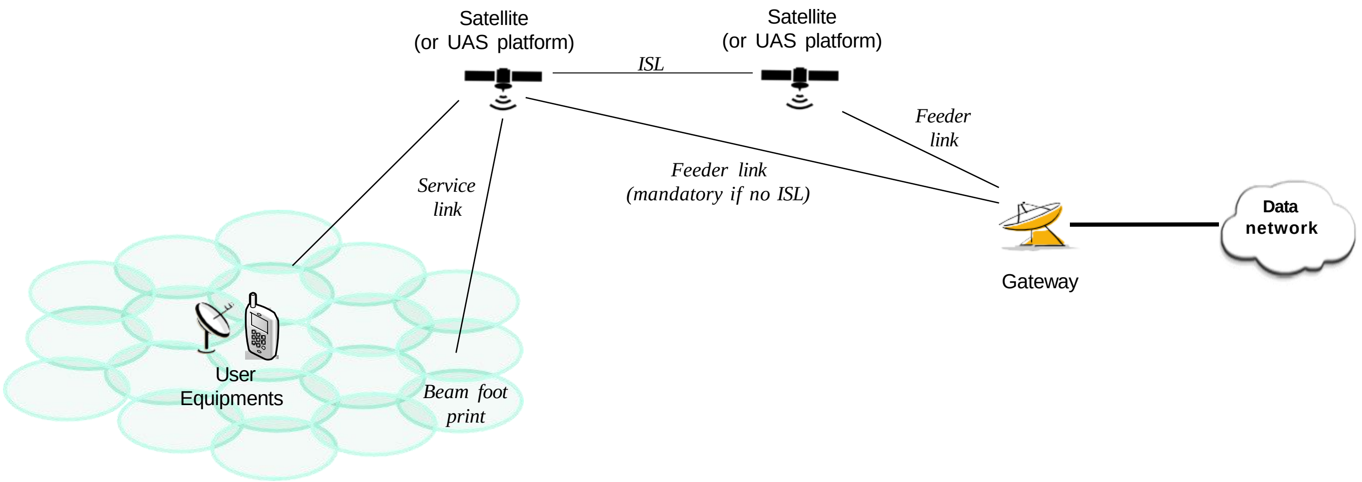
Current i-UPF architecture

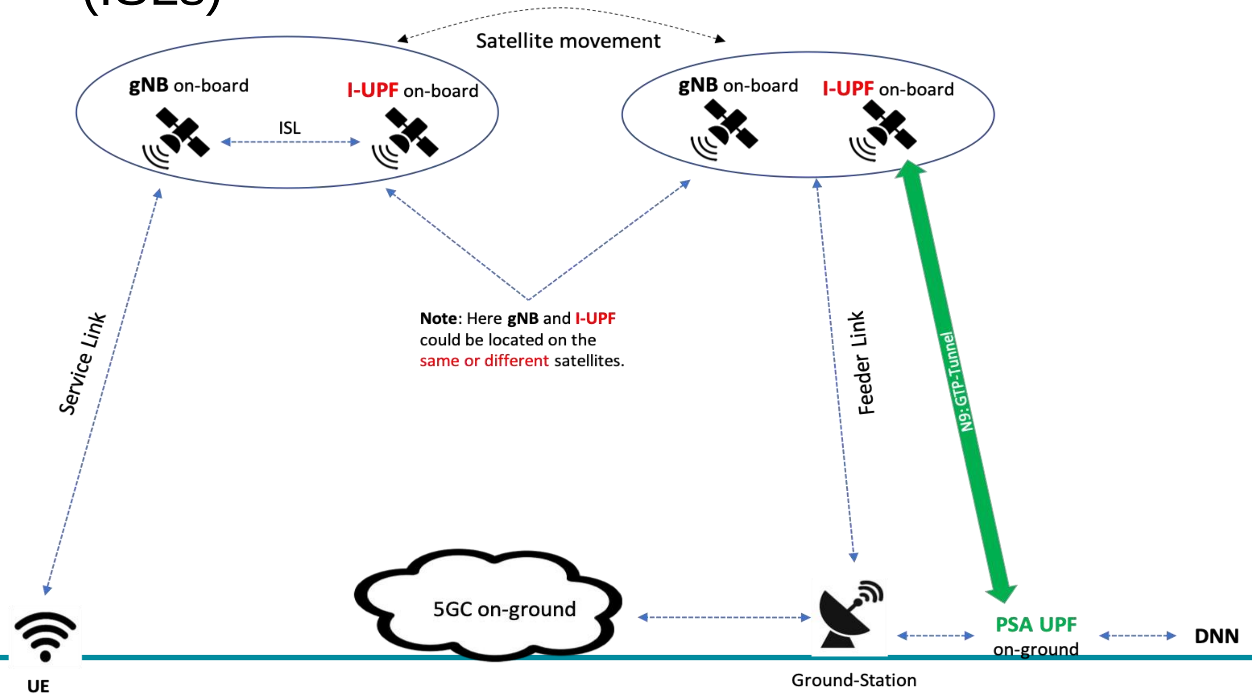


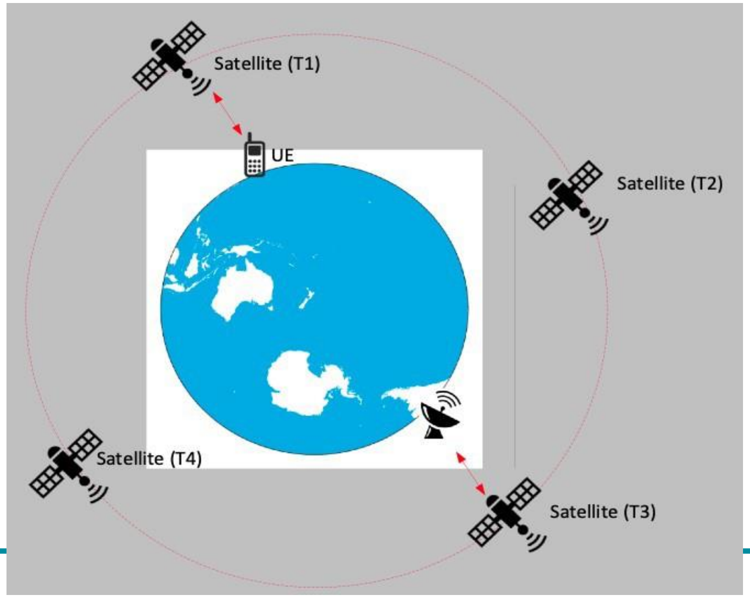
TUDOR i-UPF architecture

Mobile network LEO constellation

- Satellite network being the infrastructure for wireless access and backhaul, it provides the gNB, front haul and back haul transport.
- Satellite w/ regenerative payload (gNB on-board)
- Multi-satellites with Inter-Satellite- Links (ISLs)







Satellite cloud and application-network coordination

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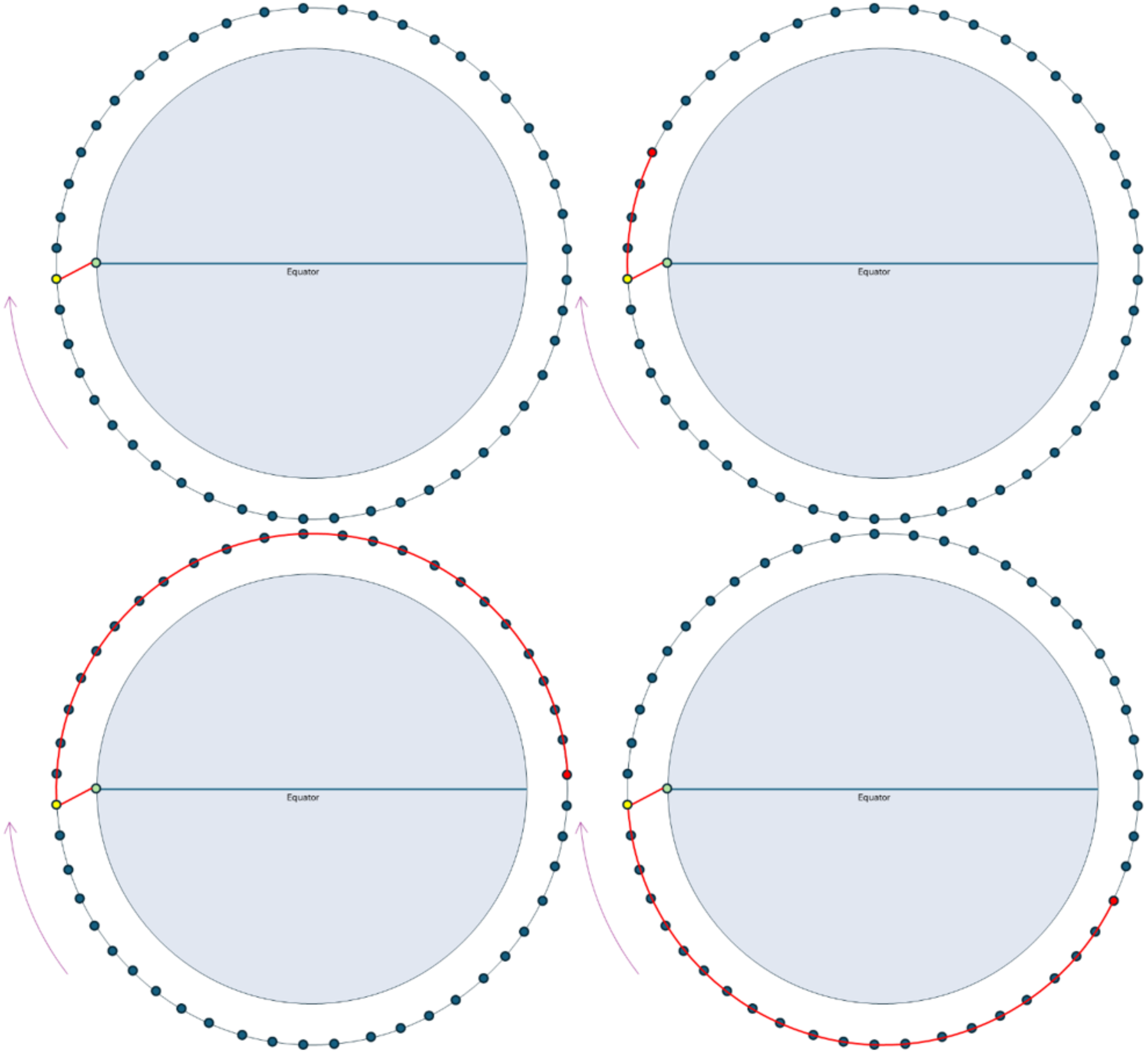
- Model of our Partner LEO constellation
  - OneWeb:
    - 12 orbital planes at an inclination of 87.9°
    - 49 satellites per orbital plane
  - Limit initial model to a single orbital plane
  - Satellites in the same orbital plane are visible for:
    - ~105 mins at the equator
    - ~608 mins in Svalbard
  - Handover between satellites when they drop below 30° elevation



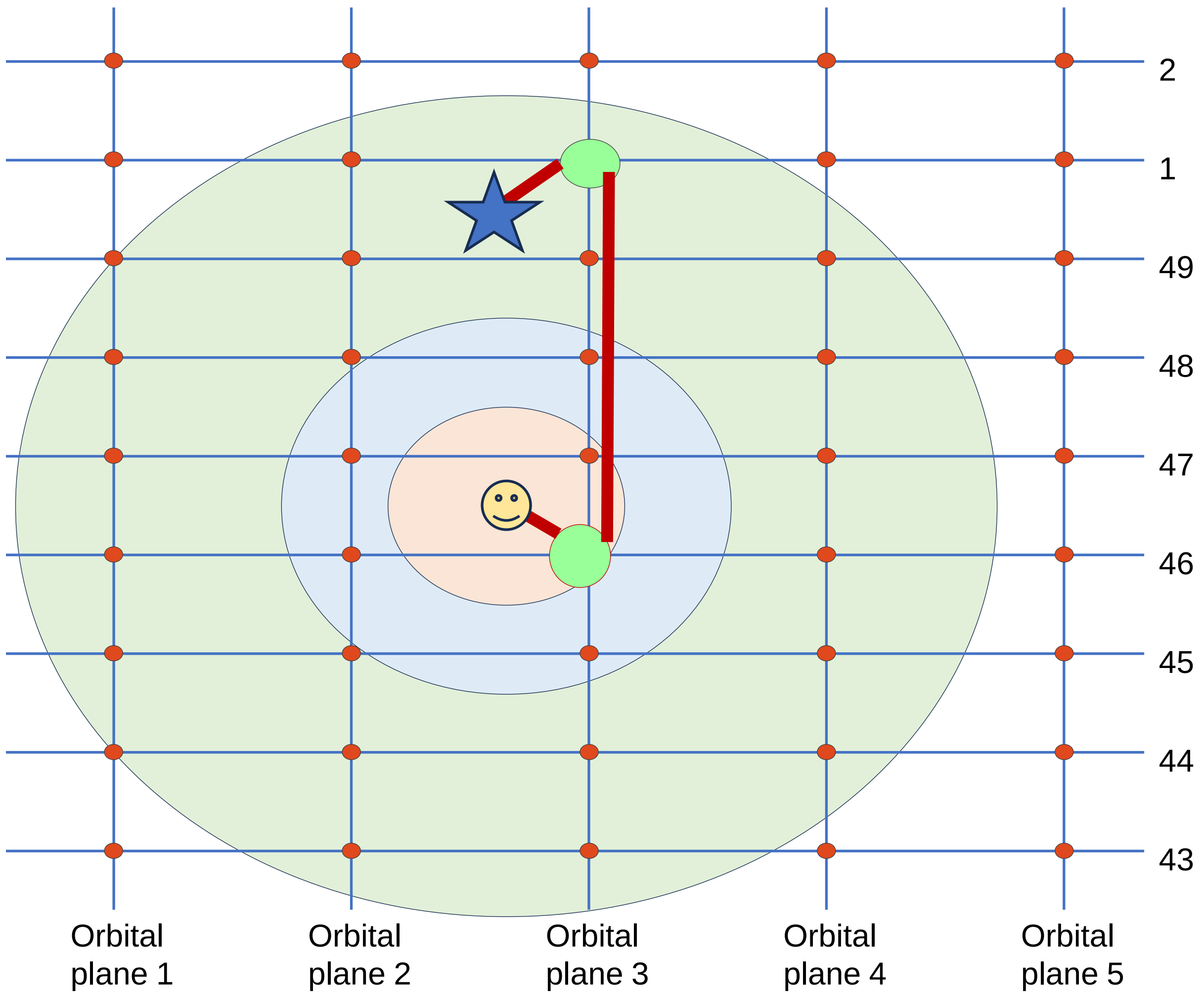
Routing across the satellite cloud

Time: T + 11.15 mins

UE Connected to satellite: 46

Ground Link on Satellite: 1

Number of ISL Hops: 4



Satellite cloud topology and latency

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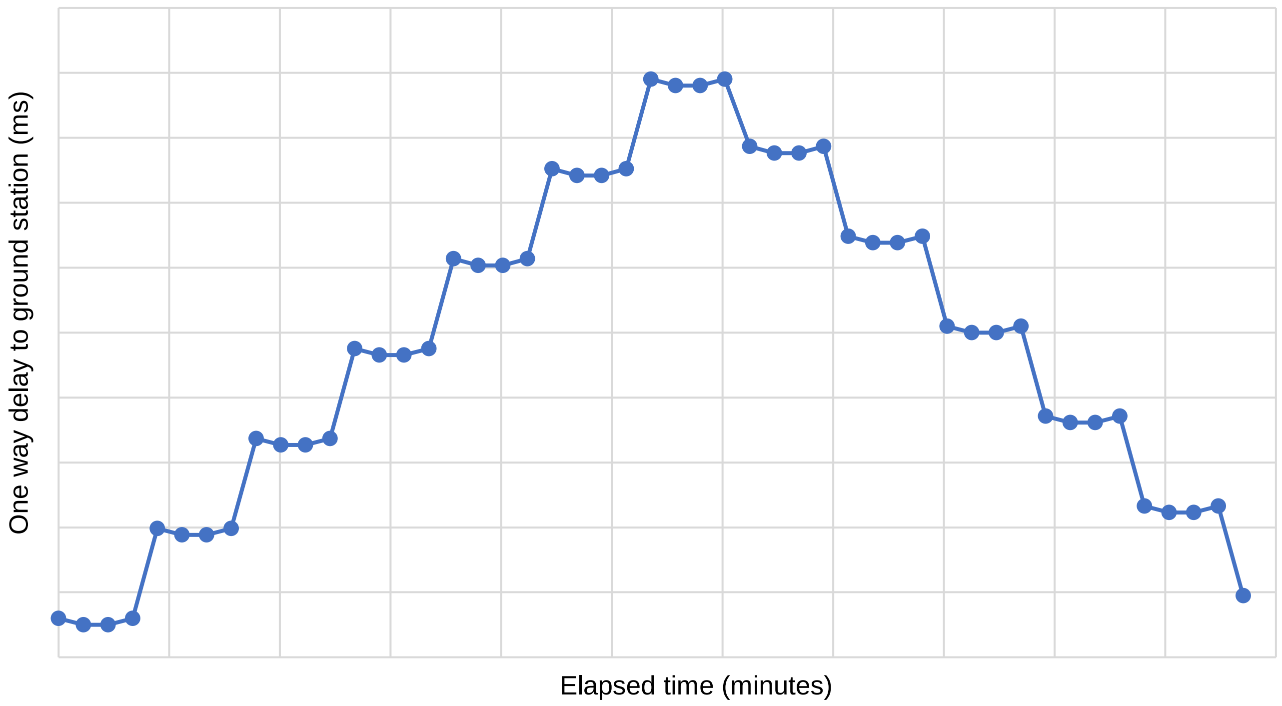
- Modelling of orbits using real OneWeb data
- Emulation environment includes satellite payloads in place
- Investigate inter-orbital plane routing
- Investigate link management to minimise energy usage and maximize battery life



Minimising the satellite cloud energy consumption

- LEO satellites, when exposed to the sun, use solar energy for operation, processing, and communication, and with excess energy they recharge their batteries.
  - However, when satellites are in an area with no sunlight, called eclipse areas, they operate using only their battery power.
- The batteries have limitations on the amount of recharges/discharges, also known as the depth of discharge (DOD) cycle.
  - Therefore, this restricts the useful life of the batteries themselves and also of the satellites.
- The aim is controlling the whole constellation, to find the minimum set of satellite nodes that must be used to meet the actual traffic matrix demand.
- The control system must solve an optimization problem that takes the LEO network topology and traffic matrix as input, and identifies the minimum number of network node links that can be powered on while still guaranteeing full connectivity

Time variant networking for LEO satellite

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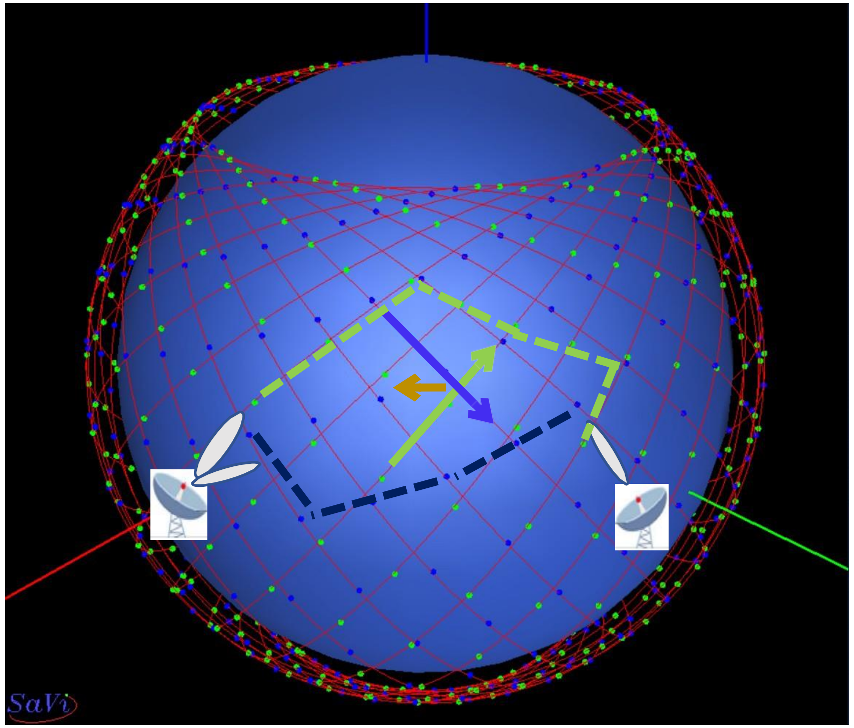
- Predictable Connectivity
  - The trajectory and velocity of a satellite (‘footprint’) are predictable and can be pre-determined
  - Ephemeris: height, inclination, azimuth, time-changed track, etc.
  - 5G case: ‘Predictable’ SAT-based QoS probing optimisation for dynamic backhaul service
- TVN Design Principles
  1. No full-set routing intelligence on satellites
  2. Simplified traffic forwarding logics on-board satellites
  3. Time-limited link connectivity
  4. Predicted traffic demand



Applicability of TVR working group

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- TVR (Time-Variant Routing) Requirements
  - https://datatracker.ietf.org/doc/draft-ietf-tvr-requirements
- It defines the topology model components for resource scheduling
  - Using existing IETF technology where possible, and/or extending for TVR it defines
- Proxies, Nodes, Termination Points, Links, Layering
- Highlights requirements from the use case scenarios, including:
  - Resource Preservation
  - Operating Efficiency
  - Dynamic Reachability
- Defines key TVR terms
  - Visibility
  - Locality
  - Temporality
  - Time-Variability
  - Time Horizon
  - Time Precision
  - Periodicity
  - Continuity
  - Interpolation

TVR Solution work

- Stable TVR Data Model
  - TVR Schedule Definitions
    - Module ietf-tvr-schedule.yang augments the grouping defined in the ietf-schedule.yang with TVR required attributes, and it is meant to be used by other modules.
  - TVR Node YANG Module
    - Module ietf-tvr-node.yang is a device model and designed to manage a single node with scheduled attributes.
  - TVR Topology YANG Module
    - Module ietf-tvr-topology.yang describes a network topology with a time-variant availability schedule.

Tidal traffic in LEO network

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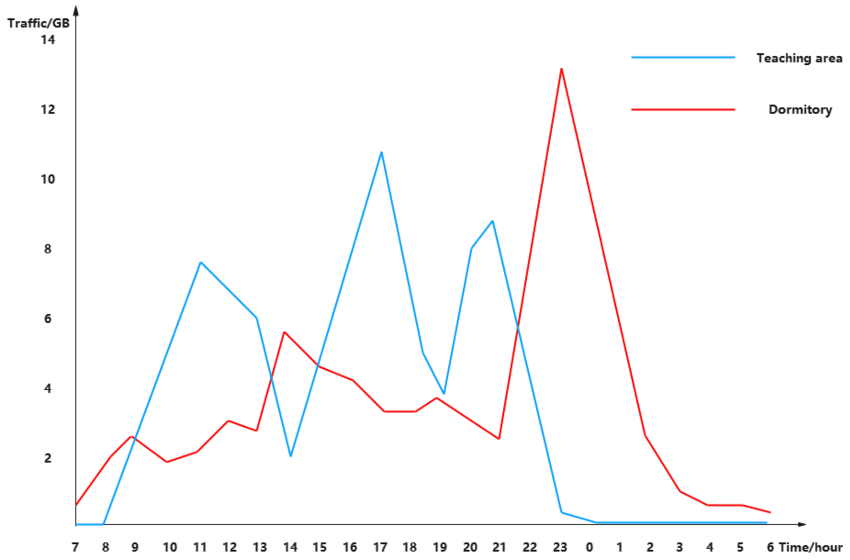
- Tidal Network Example
  - Traffic on the network has an obvious tidal period, including heavy-traffic periods and light-traffic periods
    - Network topology change caused by specific traffic pattern.
  - The time duration of heavy traffic and light traffic are clearly identifiable
    - Residents or employees work specific hours
    - Network change will occur at predictable points
  - The switching time between the heavy-traffic period and the light-traffic period is well established
    - Links can be powered off to reduce energy consumption



Benefits of time variant approach for LEO constellation

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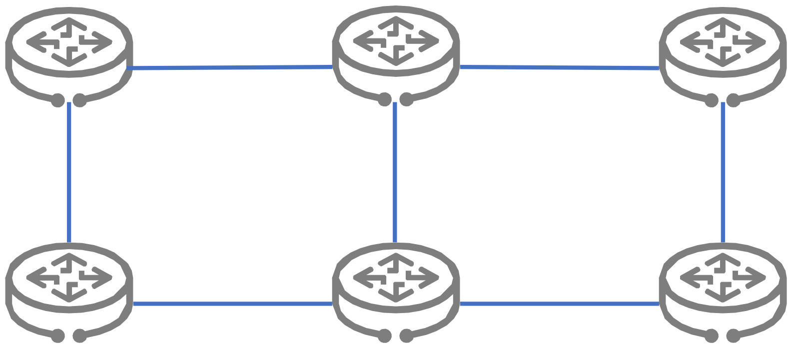
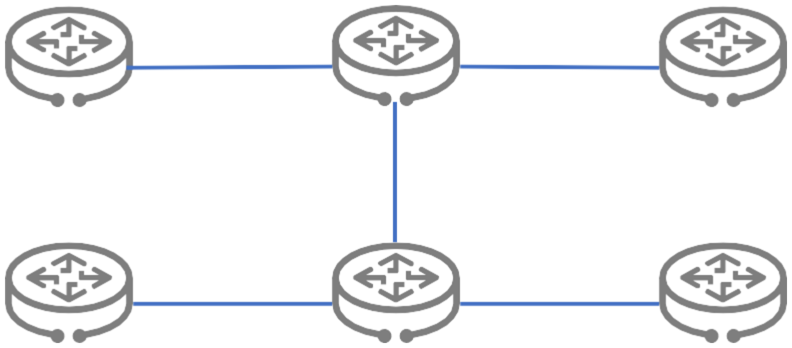
- Benefits of time variant approach for Tidal Network
  - The low tide topology requires less bandwidth to support fewer users
  - Devices and port can be shut down or put to sleep to save energy



Topology at heavy-traffic period



Topology at light-traffic period

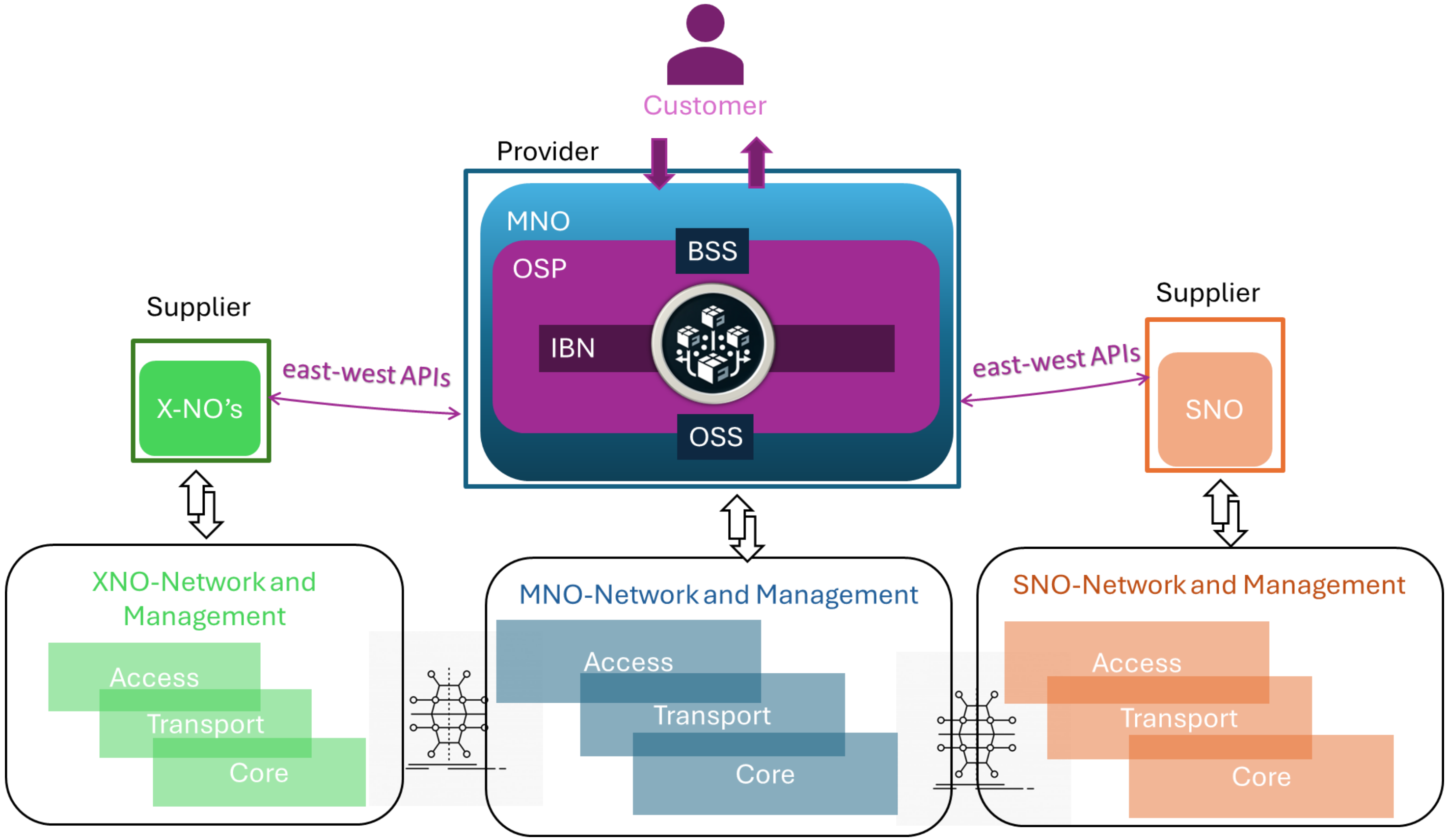
- 14 ports up
- 0 port down/sleep

- 10 ports up
- **4 port down/sleep**

28% Port Power Consumption is saved

Open service platform

- 3D networks span multiple domains
- TUDOR Open Service Platform Architecture:
  - Defines the E-W interactions between suppliers and provider network roles
  - Coordinates end-to-end services to meet customer demands
  - Uses intent-based mechanisms to simplify interactions
  - APIs and templates defined



AI-based control-plane architecture

- Coupling of production networks with an AI training *sandbox*
- Based on Digital Twin with scenario generators
- Current status and plans:
  - Containerised versions of 5G NFs running in the digital twin
  - NF integration with reinforcement learning training (PyTorch/Stable Baselines3)
  - Evaluation of resources needed for training AI control plane components