Topology Semantic Routing for Mega-Constellations

6G SmartSat

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TABLE OF CONTENTS

ESA Technical Officer: Maria Guta (ESA ESTEC)

Authors: Marius Corici (Fraunhofer FOKUS), Adam Kapovits (Eurescom GmbH), Matthias Britsch (Deutsche Telekom AG), Markus Breitbach (Deutsche Telekom AG), Sebastian Eiser (Airbus), Hauke Buhr (Fraunhofer FOKUS), Nicolas Zunker (Fraunhofer FOKUS), Paulo Mendes (Airbus)

Contact: marius-iulian.corici@fokus.fraunhofer.de
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Executive Summary


Photo: ©ESA - *Mega-constellation coverage.*

Unlike terrestrial networks with almost-static topologies, mega-constellations - consisting of thousands of Low Earth Orbit (LEO) or Medium Earth Orbit (MEO) satellites - form dynamic, grid-like topologies that change predictably and very frequently. The number of topological changes is further increased by the frequent establishment or termination of links to ground stations and due to atmospheric effects (weather) that affect feeder links. These characteristics make mega-constellations significantly different from other networks, requiring new routing strategies.

In networks with frequent topology changes traditional topology-aware routing protocols like Open Shortest Path First (OSPF) or Border Gateway Protocol (BGP) cannot function well, because their convergence times are longer than the time between topology changes. There is insufficient time even for modern protocols like segment routing to distribute new topology information. We present the topology semantic routing as a solution to mitigate the impact of these continuous changes. In contrast to semantic routing, which adapts paths based on application characteristics on top of the results of classical routing, topology semantic routing adapts to network changes using local information. This could be link quality and neighbour status, and allows adjusting the predefined potential available paths in real-time and delay the triggering of routing protocol updates. For example, missing links or nodes are bypassed without network-wide signalling, ensuring proper functioning through using local context.

Furthermore, as the routing is based on potential existing links rather than only the available links, they can be pre-computed in the ground control center and loaded into the system, reducing the need for a classic distributed routing convergence. With this, topology semantic routing reduces the use of satellite compute resources to a minimum while ensuring adaptation and resilience in continuously changing situations through automatically modifying routes based on factors like time-based link availability and environmental conditions. To further increase the efficiency topology semantic routing can be used in combination with existing low-footprint routing solutions, such as pre-defined centralized routing for regular topologies, segment or geographical routing protocols.

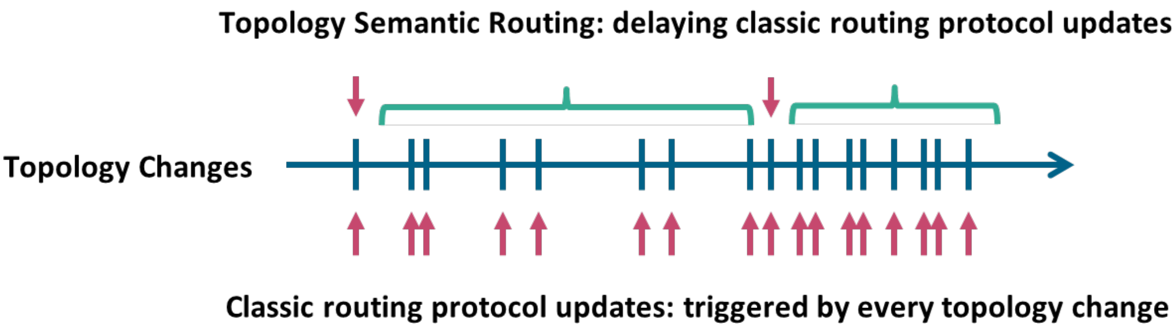

Figure 1 – Topology Semantic Routing enables less frequent routing protocol updates compared to classical protocols to keep the system alive in the face of the extreme number of topology changes

Understanding the context: Mega-constellations

To give the reader an impression of the topology and the specific characteristics that a mega-constellation has, a highly heterogeneous model is described here. The driving factors for the selection of this constellation are:

- Global coverage is targeted with a concentration over European latitudes – any constellation is expected to have a global coverage while at the same time to concentrate on specific areas where most of the users would be located;
- Direct-to-device (D2D) use cases favour lower orbits and lower frequency ranges for link budget reasons, while broadband favours the same low orbits but higher frequency ranges for throughput reasons;
- All orbits are included in order to be able to capture and represent dynamics of a multi-orbit constellation, even though in a realistic use case one, or maximum two would be used.

Table 1: Summary of the proposed multi-layer constellation. Layers are at different altitudes

Primary Purpose of Orbital Layer	Orbit height [km]	Inclination [deg]	Planes	Total satellites number	Inter-Satellite Links
Direct to Device (D2D), S-band	600	65	12	288	3 to 5
Broadband Ku-band, Ka	1200	60	7	196	3 to 5
Polar extension (D2D + broadband)	1250	80[2]	6	96	3 to 5
Offloading latency insensitive traffic (MEO)	8000	57	3	24	5
Offloading latency insensitive traffic (GEO)	36000	0	1	6	3

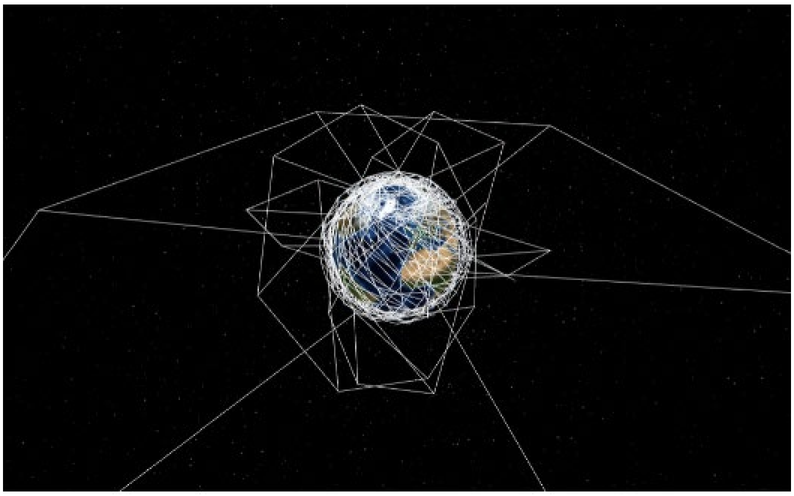

Figure 2 – Visualisation of the example topology: Six regularly spaced GEO nodes span the outermost layer. Three MEO planes (partially forming "rings") connect LEO Satellites and Ground. The dense LEO meshes with highly regular interlinks is visible very close to Earth.

From a routing perspective, this mega-constellation has the following characteristics:

- A grid-like topology in each of the orbital layers
    - without aggregation points that are typical in terrestrial networks
    - with significantly more available routing paths
- Due to the orbital movement of the satellites:
    - topology changes regularly and predictably (depending on the orbit)
    - topology changes can take place in the order of minutes in case of LEO orbits (e.g. in every 4 minutes in the LEO part of our constellation)
    - the grid-like topology of a layer is homo-morphic: the same topology repeats itself but with differently arranged satellites
- The satellite-ground station feeder links need to be established and terminated very frequently
    - due to the orbital movement: added to the repeatable space topologies this would result in practically continuous occurrence of new topologies.
    - due to weather affecting the link capacity
    - there are many routes and many options to select a better feeder link.
- The grid-like topologies of the multiple satellite orbital layers are not co-moving
    - inter-layer links have variable duration, and due to changes in relative distance, non-constant latencies.
    - inter-layer links require additional terminals (or radically different/wider fields-of-pointing) which are hard to motivate for all satellites in a mega-constellation (resulting in a heterogeneous system).
- Compute capacity of the space nodes is very limited, and therefore routing protocols that require minimum resources are highly welcome. Any identifier such as IP addresses cannot encode topology information because the topology changes.

> Mega-constellations are too dynamic and too grid-like for applying terrestrial routing protocols directly.

How much autonomy network nodes should have? – Centralized vs. Distributed Routing

This trade-off spans between giving each node the complete control (such as in the case of today's Internet routing protocols) and centralized solutions like Software Defined Networks (SDN) where all decisions are taken at the controller and distributed to the nodes.

In distributed routing, nodes cooperate and communicate to understand and develop a routing structure for the network. A large amount of computation is needed for this, and there is delay in the communication. Re-computations are triggered upon every topology change. However, the system is highly robust, being able to adapt to any topology change.

Centralized routing is fast in making decisions especially when the topology of the links is known in advance like the predictable and regularly changing single orbital planes of mega-constellations. Centralized routing can be pre-computed based on the foreseen topologies removing the convergence time. However, any pre-computing can account only for limited anomalous events and with exceptionally large costs. Furthermore, and very importantly, centralized routing always requires a channel to distribute updated routes, so it depends on an already functioning network. For an out-of-band Control and Management Plane (CMP), a secondary, high-reliability system (albeit at low data rate, possibly distributed routing) is needed, to recover from a network failure. For in-band CMP, a network collapse must either be limited by design or another channel must occasionally become available to restore the network (such as Tele-Management/Tele-Control stations).

Please note that both solutions work with most of the routing protocols e.g. routing tables can be computed with OSPF, MPLS labels can be centrally defined or using LDP, and segment IDs can be determined through the system or distributed from a central controller.

Distributed Routing	Centralized Routing with pre-defined topologies
Advantages: • Very robust: No single point of failure	**Advantages:** • No computational burden on the nodes • Single view of the network – fast decisions, global optimum • Can pre-define routing for topologies – very fast in convergence (for expected topology changes)
Disadvantages: • Slow in convergence • Local computing required	**Disadvantages:** • Slow reaction to unexpected events (needs communication with the controller) • A management channel between the controller and the nodes must be available to react to anomalous events • Can not account for all topology changes (too big routing tables) • Still needs a last-resort distributed solution for the establishment of the management channel

Due to the constrained computing capacity and the possibility to pre-define routes, which significantly reduces the convergence time that is critical when the topology changes in minute intervals (e.g. in every 4 minutes in the case of our example LEO low orbit layer), a centralized solution is a direction to explore.

> Centralized Routing is also studied by IETF in the context of terrestrial networks.

What is Topology Semantic Routing?

Topology semantic routing is a concept in which decisions are made based on local real-time interpretation of network conditions, allowing nodes to react independently to topology changes and postponing the signalling of routing changes.

Unlike classical routing which requires routing signalling for every change, topology semantic routing uses localized information, such as link quality and neighbour status, to make simple autonomous decisions. Although the topology is not totally consistent, routing signalling can be postponed until more topology change events can be included. This results in less frequent executions.

Unlike semantic routing, which selects paths from the ones provided by the classic routing based on data flow characteristics, topology semantic routing adapts to real-time network topology context, providing a temporary routing solution until the classical routing signalling is executed.

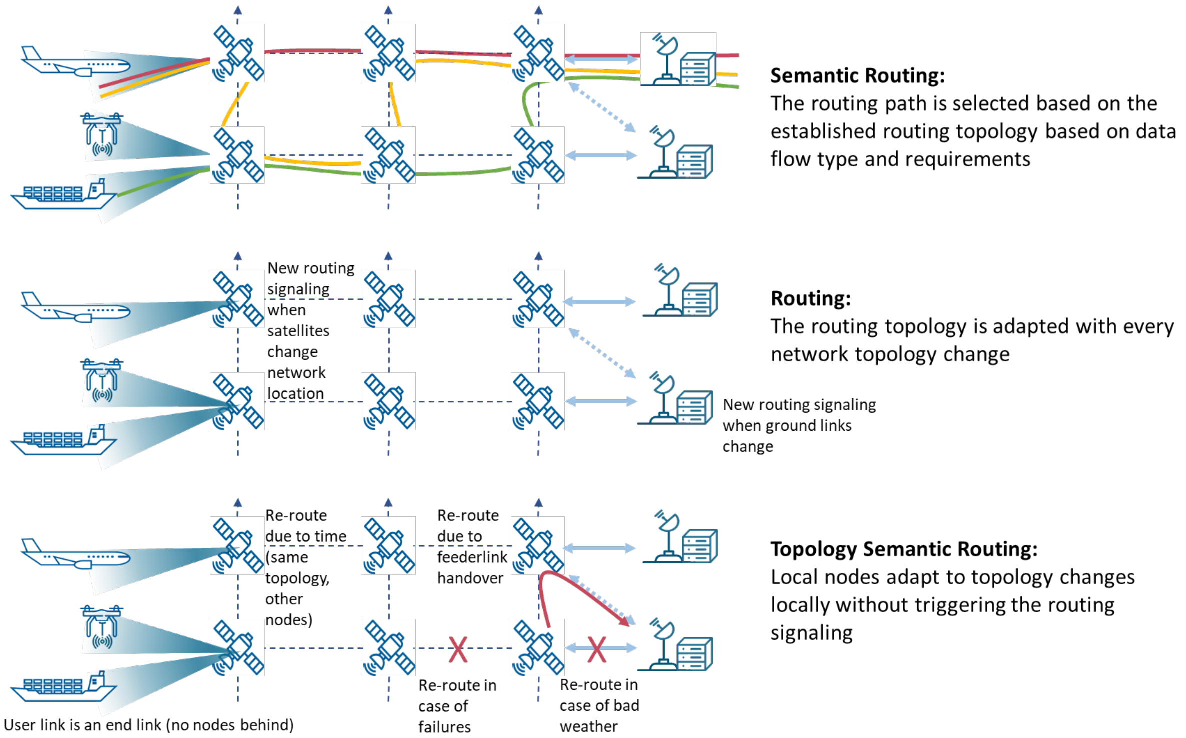

Figure 3 – Topology Semantic Routing is hiding minimal and local changes in topology from the network-wide routing to avoid frequent signalling of routing changes

Topology semantic routing decisions are based on a predefined network topology, established by either distributed or centralized routing protocols. For distributed protocols, an additional adjustment should be made to prevent triggering the signalling when the topology changes. When centralized protocols are used, the topology can contain links that are currently unavailable but have a high probability of becoming active in the near future, such as feeder link connections.

Furthermore, because orbital planes in mega-constellations are homomorphic (recurring the same topology, but with other satellites in the same position), by utilizing time as a semantic parameter, the same established routing rules can be applied in another context (homomorphic routing rules).

> Local decisions to fix such issues in case of failures in terrestrial networks exist: Fast Re-Routing (FRR) is employed to keep the network running until the routing converges again after a failure.

Topology semantic routing eliminates the need to signal changes in topology for short-term or predictable variations, ensuring network stability in the face of frequent changes. Furthermore, it requires minimal decision capabilities in the intermediary nodes but is likely to lead to suboptimal traffic routing.

Topology semantic routing is considered to be especially useful in the following situations:

- Re-route in case of failures – similarly to the FRR method, if a connection or node breaks, the prior node can automatically reroute using one of the many paths available.
- Re-route in case of bad weather (when a feeder link's capacity is reduced or it is interrupted) - topology semantic routing may consider the link momentarily unavailable and select another path, treating weather as a link failure.
- Re-route due to feeder link handover – the routing table should include all the feeder links that may be established in a given time interval. The topology semantic routing will forward the data traffic to the momentarily available feeder links either on the current node or on its neighbour having the feeder link.
- Time-based routing table interpretation – as mega-constellations are homomorphic (have the same topology all the time but cannot guarantee which nodes are in a given position), time can be used as a semantic parameter in interpreting the routing tables.

> IETF Time Variant Routing (TVR) looks at topologies that repeat themselves to reuse old routing tables. Topology Semantic Routing aims to use the same routing table with different meaning depending on the time, using the homomorphic characteristic of mega-constellations.

Opportunities of a Topology Semantic Layer

Topology semantic routing reduces the need for routing signalling by sufficiently delaying such decisions, which is necessary in a highly dynamic system like mega-constellations.

Opportunities for Satellite Operators:

1. **Handling Dynamic Topologies**: Mega-constellations with thousands of satellites present unique challenges due to their constantly changing topologies. Topology semantic routing enables satellite operators to handle this dynamicity by allowing autonomous routing decisions to be made without constant re-signalling or a very high number of pre-defined large routing tables. This makes deploying and managing routing in mega-constellations much more feasible enabling the deployment of even larger satellite networks.
2. **Efficient Routing in Large Networks:** By adapting routing decisions locally based on real-time network status, very large constellations can remain operational despite frequent changes in link availability, reducing signalling (and its processing) overhead and ensuring more stable connections in such very complex networks.
3. **Simplified Ground Station Connections**: Satellite operators face the challenge of managing the frequent state changing of satellites and ground stations' feeder links, always impacted by changing satellite positions and weather conditions. The topology semantic layer enables operators to control these connections without having to transmit every change throughout the network, hence enhancing overall system reliability and lowering convergence latency.
4. **Resource Optimization**: Topology semantic routing optimizes the usage of limited on-board compute resources of satellites through localized decision-making. This lessens the burden on the satellite infrastructure and makes better use of bandwidth and processing capabilities, allowing the network to adapt dynamically without wasting resources on re-signalling or huge routing table swapping. This is especially true if the topology semantic routing uses only local information (i.e. link and neighbour nodes' status) without any extra communication.

Opportunities for Terrestrial Operators planning to integrate 5G NTN:

5G NTN enables terrestrial mobile network operators to improve coverage in hard-to-reach or underserved areas through satellite connectivity. The adaptation of the topology routing to dynamic satellite links provides the following qualities for terrestrial network operators:

1. **Seamless Network Extension**: Topology semantic routing enables the integration of satellite based 5G networks in terrestrial mobile networks by providing a stable transport layer across all domains despite the dynamic satellite topologies. By containing topology changes within the satellite layer, the terrestrial network is shielded from constant updates, reducing complexity, and maintaining service quality such as knowing where base stations or user plane functions are located, making possible the highly dynamic space network to be abstracted into quasi-static set of network functions.
2. **Reduced Propagation of Topology Changes**: Topology semantic routing's capability to stop frequent topology changes to propagate to the terrestrial networks represents a major advantage for the network convergence. Topology semantic routing makes sure that satellites' constant connectivity modifications are handled locally without necessitating updates to the terrestrial peer network. At the expense of considerable mis-routing this leads to fewer interruptions and a more stable network overall.
3. **Scalable Network Management**: Operators aiming to offer connectivity services across diverse environments would benefit from the improved scalability made possible through the topology semantic routing. They can concentrate on expanding their services without having to cope with high signalling overhead or the complexity of frequent reconfigurations.

6G SmartSat's Approach

In the 6G SmartSat Project we are exploring the possibilities of implementing a sufficiently stable routing to support an integrated 5G TN-NTN system. It is clear from the beginning that classical routing mechanisms cannot function under the conditions of satellite networks' dynamicity, especially in mega-constellations. Therefore, as shown in Figure 4, a new approach for managing the dynamicity is suggested, consisting of five separate development stages.

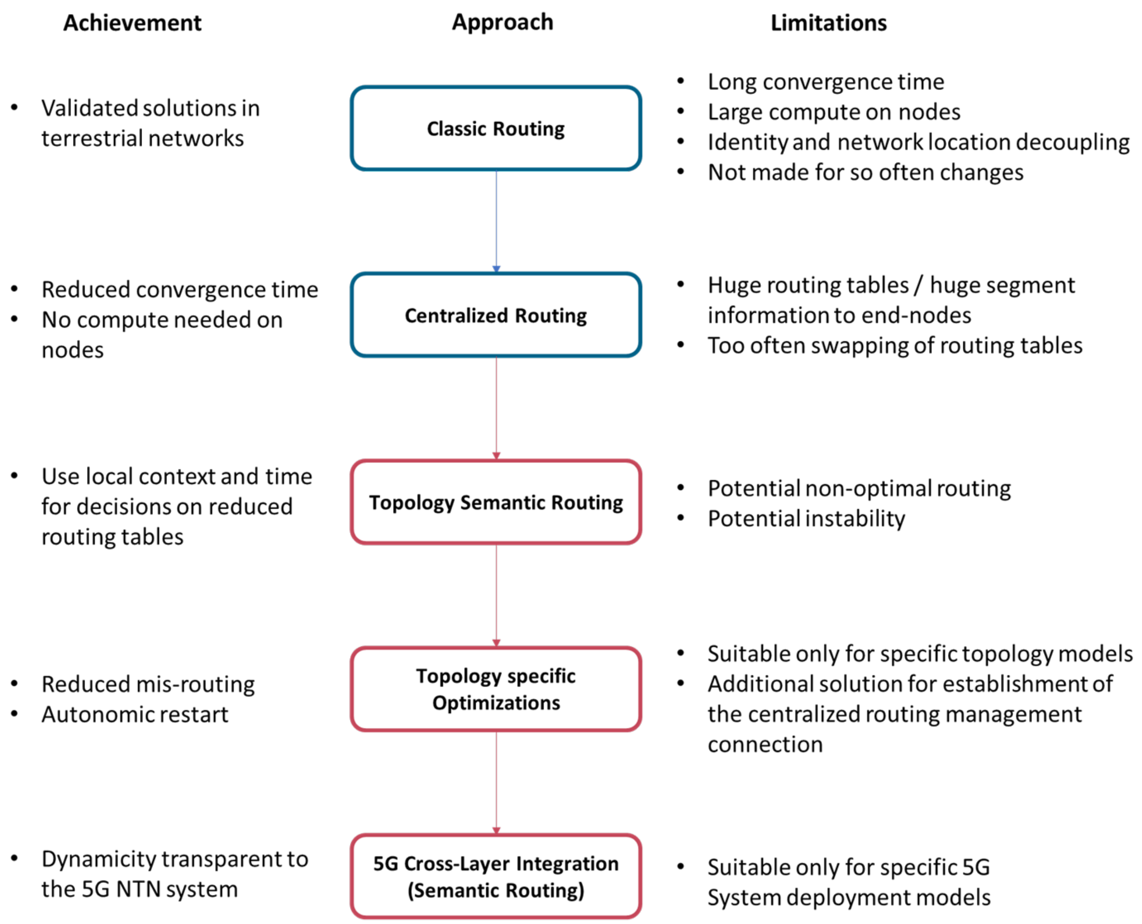

Figure 4 – The 6G-SmartSat Approach

1. **Classical Routing**: 6G-SmartSat starts from classical routing protocols, such as OSPF and BGP, which form the foundational routing layer for establishing basic connectivity across the network. Traditional routing techniques rely on signalling each topology change, ensuring a robust and stable, but very complicated solution for dynamic networks. Nonetheless, such solutions are a good starting point, because they have been validated in commercial environments for many years. The long convergence time, heavy computational requirements at intermediary nodes and the coupling between identity and network location are the main obstacles to simply adapt these solutions to mega-constellations.
2. **Centralized Routing**: Building on the basic connectivity established by classical routing, in centralized routing a centralized controller with a holistic view of the network makes all routing decisions. The centralization enables less resources to be used at the routing nodes and to achieve global optimization. Furthermore, it has the ability to define routes that contain both currently active and potential links, such as feeder connections that may become active under certain circumstances. However, the trade-off between compute and memory leads to huge routing tables or segment IDs that need to be swapped frequently.

From this step on, 6G-SmartSat goes further than existing research by formalizing the routing adaptations.

3. **Topology Semantic Routing**: First, we introduced the topology semantic routing, a shift towards localized minimal decision-making. Here, routing decisions are based on real-time localized context, such as link quality and neighbour status, eliminating the need for network-wide routing updates. This layer reduces the dynamicity and frequency of global routing updates in mega-constellations by enabling nodes to make independent decisions to adjust to topology changes. Like any semantic decision, due to the reduced context knowledge many data packets may be mis-routed. The next stages concentrate on fixing this.
4. **Topology-Specific Optimizations**: At this stage, particular optimizations are applied based on the unique characteristics of the network topology, including:
    - the horizon of information - how far the topology semantic knowledge is transmitted either being processed on the local node or also by the neighbours.
    - how often the routing protocol signalling has to be triggered - how many topology changes and of which type the system can handle.
    - Homomorphic topology – routing tables can be made smaller by utilizing the same table adding a time parameter. Paths within the homomorphic constellation do not change, routing protocols do have to signal between edge nodes.
    - Feeder link protection - consider weather patterns in addition.

    Although these optimizations further improve the routing method especially by reducing the size of the large routing tables and decisions of the topology semantic routing, they come at the expense of assuming certain topology models, not being able to function anymore for the general case.
5. **5G Cross-Layer Integration (Semantic Routing)**: In this last stage we plan to merge the 5G system with the semantic routing and the topology specific optimizations, to accomplish end-to-end optimization and use the terrestrial semantic routing optimizations through converging network layer decisions with application layer requirements. A more responsive and adaptable network is made possible, for example by steering data flows according to service type, such as low latency applications or ultra-secure communications to be able to maintain a specific service layer agreement.

As in situ analysis of mega-constellations routing is not possible, the 6G-SmartSat solution will be incorporated into the OpenLANES large-scale network emulator (www.openlanes.net), providing the chance to verify a complete 5G system under close to real-life conditions.

Summary and Conclusions

In our whitepaper we introduced the concept of topology semantic routing for mega-constellations aiming to reduce the need for routing information updates caused by space systems dynamicity. The topology semantic routing addresses a major issue in routing: how to handle high dynamicity without overburdening the system with re-signalling. It works with both centralized solutions with routing tables in the nodes or with segment routing like solutions with routing tables at edge nodes. Topology semantic routing can combine within a coherent system multiple optimizations described in the literature for routing within mega-constellations, such as congestion avoidance on specific links, feeder link protection against bad weather, and geographical routing solutions, providing a potential foundation for a consistent commercial solution.

In order to make the solution efficient, the specificities of the constellation, the network types, and the 5G TN-NTN integration model need to be fixed and appropriately considered.

Trade-offs Recap

- Mega-constellations are too complex and their topology changes too dynamically and frequently for traditional routing protocols to function.
- Centralized routing represents a good option for reducing routing signalling, convergence time, and processing on space nodes at the cost of extensive memory usage (very large routing tables)
- Topology semantic routing is reducing the excessive memory usage at the cost of requiring some, rather minimal processing in the nodes.
- Topology semantic routing can hide the dynamicity in autonomous decisions, making the interoperability between mega-constellations and terrestrial networks manageable.
- To reduce suboptimal routing and the very unlikely artificially created congestions, a topology and services-related cross-optimization should be further considered.
- Validation using the OpenLANES toolkit is foreseen to prove the effectiveness of the solution and the potential to integrate 3rd party research results.

> There is no network so dynamic as a multi-layer mega-constellation. Even large ad-hoc networks are changing less often, although in a less predictable manner. If handling dynamicity works in these networks, solutions can be easily adapted (simplified!) also for terrestrial nomadic and mobile networks.

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