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PERSPECTIVE

Transforming 5G Mega-Constellation Communications: A Self-Organized Network Architecture Perspective

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ABSTRACT With the widespread adoption of 5G as a communication standard, satellite mega-constellations have emerged as viable alternatives and complement terrestrial networks, offering extensive and reliable communication services across a broad spectrum of users and applications. These constellations are already equipped with inter-satellite links and adaptable payloads capable of supporting Radio Access Network (RAN) and core network functionalities, forming complex space-based networks characterized by overlapping layers of multi-orbit, grid-like topologies that undergo continuous, yet predictable, changes—peculiarities not currently addressed within the 5G standards framework. To cope with this technology gap, this paper introduces a novel architecture for 5G services relying on satellite mega-constellations, which adhere to the principles of self-organized networks. This architecture is designed to align seamlessly with 5G service requirements, while also accommodating the unique topological and infrastructural constraints of mega-constellations. In more detail, the paper first outlines the fundamental principles of self-organizing networks that facilitate real-time system adaptation to internal topological shifts and external fluctuations in service demand. Then, we detail a 5G network architecture incorporating these principles, which includes 1) dynamic placement and migration of radio and core network control plane functions, 2) the strategic positioning of the data path, service, and AI decision functionalities to improve end-to-end service quality and reliability, and 3) the integration of dynamically established multi-connectivity options to increase the overall service dependability. These innovations aim for a seamless integration of space-based networks with terrestrial counterparts, creating a robust, cost-effective convergent telecommunication system.

INDEX TERMS 5G, NTN, self-organizing networks, satellite, mega-constellations.

I. INTRODUCTION

With the advent of mega-constellations, a "new space" system model has emerged [1]. On the one hand, the imple-

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mentation of extensive inter-satellite links [2] allows for achieving global point-to-point space-based connectivity, while on the other hand, the evolution of onboard processing capabilities will open the door to supporting various Radio Access Network (RAN) and Core Network (CN) functionality, as well as applications and communication services. As such, this leads to a deep integration of terrestrial and satellite networks, potentially merging them into a unified beyond 5G system [3], [4], and [5].

However, terrestrial telecommunication networks, including 5G, are typically designed with stable backhaul connections optimized for IP-based networks. By contrast, the space segment consists of constantly moving satellites with frequently changing links, a model that diverges significantly from the traditional Internet backbone and telecom operator network structures. Owing to this mobility, addressing based on traditional IP addresses, which embed essential topological information, is ineffective [6]. On the contrary, the space network resembles a complex mesh network, similar to ad-hoc networks, however with predictable satellite positions and links, providing a deterministic topology. Next to satellite mobility, weather conditions may have an important impact on the instantaneously available network capacity, especially concerning the communication links established between space and ground stations, the feeder links, where the data traffic of multiple users is aggregated. Finally, space nodes experience limited computational power in comparison to terrestrial systems, hence being able to support limited telecommunication functions that do not fully replicate the capabilities of their terrestrial counterparts. This necessitates a redesign of the functionality split, to better reflect the resource constraints. Moreover, mega-constellations operate as global networks with a centralized control center which can be reached only with a significant delay, requiring space nodes to self-manage to a significant extent to minimize service interruptions during topological and service condition changes.

In light of the aforementioned potentials of 5G-integrated mega-constellations [7] and the related technical challenges, this paper proposes an innovative approach to achieve self-organizing mega-constellations. In more detail, individual, or adjacent space nodes autonomously decide on various functionalities such as handling of higher RAN and core network data path, aiming to keep topological shifts transparent to the 5G system and prevent the propagation of effects onto terrestrial networks. In particular, one of the main contributions of the paper concerns the extension of a standard 5G system to space, ultimately resulting in enhanced locally managed operational capabilities particularly suitable for space node resources. This approach aims to coherently integrate space and terrestrial subsystems, improving system performance and usability. Notably, unlike the existing literature, our holistic approach comprehensively addresses routing, RAN, core, and service layers, aiming at global system feasibility and self-organization among space nodes instead of punctual optimizations.

TABLE 1. Reference constellation.

Altitude: ~1300 km
Inclination: 50°
Number of Planes: 20
Satellites per Plane: 11
Total number of satellites: 220

We begin in Section II by describing the specific networking attributes of mega-constellations using a reference constellation model, which clarifies the concepts proposed, followed by a discussion on why direct porting of the 5G system to mega-constellations is impractical, outlining the necessary adaptations. Terrestrial 5G systems, designed for centralized management and static topologies, starkly contrast with the dynamic nature of mega-constellation communications. From these a list of key requirements is drawn in Section III followed by the description of the self-organizing concept in Section IV.

Our proposition encompasses a comprehensive high-level architecture spanning devices, space nodes, and their integration with terrestrial networks, acquainting readers with space environment intricacies and laying the groundwork for future 5G and 6G space network detailed specifications as detailed on various network layers in Section V, leading to Section VI where we assess its integration with terrestrial networks. Concluding remarks, we provide in Section VII.

II. BACKGROUND

In this section, we outline the context in which the self-organizing constellations were developed. This includes a detailed description of a reference constellation, a brief evaluation of the limitations of the 5G network, and a concise review of related efforts documented in the literature to give the reader a framework for understanding our developments.

A. REFERENCE CONSTELLATION

In this section, a reference constellation is given as example for providing a basis to exemplify the technologies in the following sections. The constellation was selected to meet higher demands in densely populated areas, generally within +/− 60° latitude with an acceptable number of satellites and an acceptable 5G Non-Terrestrial Networks (NTN) service in terms of link capabilities and delay. Each satellite in this system is equipped with four bidirectional Inter-Satellite Links (ISLs): two for intra-plane connections (north and south), and two for inter-plane connections (east and west). Intra-plane connectivity is continuously maintained with neighboring satellites in the same orbital plane, while inter-plane connectivity changes occur at specific times, such as at the highest latitudes where east and west connections are swapped. The topological and links view of the constellation is depicted in Figure 1 while the specific satellite configuration is included in Table 1.

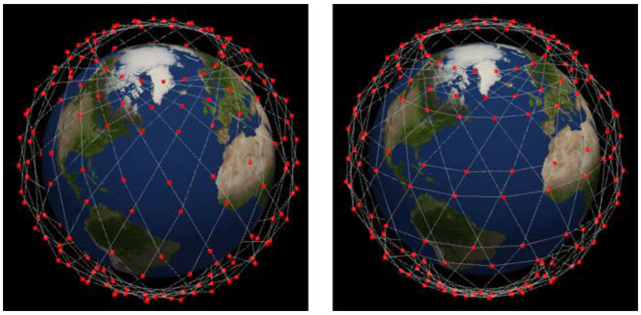

FIGURE 1. Reference constellation view: Orbits view and ISLs viwe.

At any given moment, only a few satellites can connect with the gateways and are selected to realize the feeder links. As illustrated in Figure 2, to establish end-to-end communication, the satellite currently providing the user link has to select one of the multiple data path options through ISLs to reach the feeder link satellite. Due to the presence of the ISLs, the number of gateways can be significantly reduced compared to current systems. Instead of deploying a gateway wherever connectivity happens, gateways can be fewer, complying with the availability and data rate requirements for feeder links regarding the overall capacity of the target constellation and still ensuring the regulatory constraints e.g. legal interception can be met. For obvious reasons, routing policies shall ensure that traffic is routed to the gateway where traffic shall be anchored (e.g., for billing, for legal interception, etc.).

As shown in Figure 2, a satellite currently establishing a user link must choose from multiple potential data paths through ISLs to reach a feeder link satellite. Although many routes can be opened simultaneously, one route is typically optimal in terms of the number of hops and distance, though it may become congested if all traffic is routed through it. Considering the model constellation, the establishment of the shortest path type of routing information can last up to 4.2s, a too high convergence time for routing considering the topology is changing continuously.

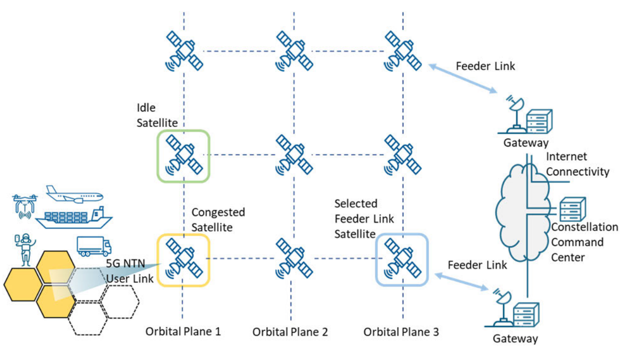

FIGURE 2. Simplified constellation topology.

Connected to one or more feeder links, the Constellation Command Center (CCC) can receive events and send commands to the constellation's nodes. Due to significant delays and the susceptibility to packet loss and jitter, especially at the transition between terrestrial and space segments, fully centralized decision-making is impractical. For example, in the model constellation a round trip message to the controller has a theoretical minimum maximal delay of 66ms. Thus, space network nodes must be equipped with sufficient knowledge to autonomously handle various situations.

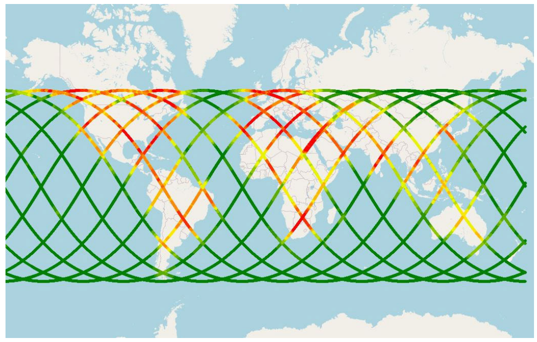

FIGURE 3. Satellite constellation capacity usage (green: 80% of the satellites are idle, red: 10% are congested).

The computational capacity of space nodes is significantly lower than their terrestrial edge counterparts, limited by power constraints, thermal dissipation issues, and the capabilities of radiation-tested hardware from companies like NXP or Versal [8]. Consequently, our mega-constellation functions as a grid of servers with limited capabilities, more similar to a Network on a Chip than to the Internet.

Furthermore, while satellites servicing densely populated areas are highly active and can become congested due to the processing of the user link, neighboring satellites over less populated regions like oceans remain almost or completely idle [9]. As illustrated in Figure 3, 80% of the time a satellite could be idle or have a low resource consumption [10], [11]. This discrepancy offers an opportunity to offload compute tasks from congested satellites to these underutilized ones, despite the challenges of potential packet loss and delays in data transmission and the subsequent need to converge results post-processing.

B. 5G NETWORK AND ITS LIMITATIONS

In this section we provide a short description of the 5G network functionality as designed for terrestrial networks underlining its limitations for space, to enable the reader to understand what is already available and what we have further developed in this paper.

Figure 4 illustrates a typical 5G system architecture that includes an Open Radio Access Network (O-RAN) [12] and a core network subsystem [13]. The User Equipment (UE) is connected through a 5G link to a Radio Unit (RU), which handles analog-digital conversion and sends the digital baseband signal to a Distributed Unit (DU). The DU executes lower layers of the 5G RAN functionality. Multiple DUs connect to a single Central Unit (CU), which manages higher RAN layers. The CU also performs Control Plane (CP) functions,

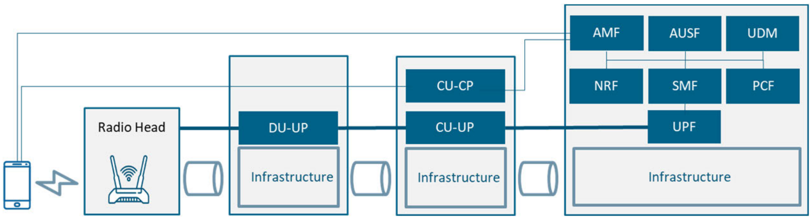

FIGURE 4. End-to-end 5G system.

managing radio resource use by sending commands and receiving information from the UE in real time to prevent communication interruptions.

The RAN is interconnected to a core network that manages device operations in near real-time (x10 ms level) including the authentication and authorization via an Access and Mobility Function (AMF) and an Authentication User Service Function (AUSF). AMF also handles connectivity and mobility management and serves as the communication front-end with the UE for all other core network functions. A Session Management Function (SMF) establishes data paths for UE sessions and allocates QoS resources as indicated by the Policy Control Function (PCF). A Network Repository Function (NRF) selects network function destinations for messages within the core network. User profiles, both static and dynamic, detailing access control permissions and selected network functions serving the UEs, are stored in a User Data Management (UDM) network function.

Additionally, the core network anchors the data path using one or more User Plane Functions (UPFs) that exchange data plane messages with the RAN CU and anchor the user sessions to specific points where the UE's IP address is accessible to the internet.

As the 5G system is specifically adapted for terrestrial applications, deployment atop mega-constellations introduces several challenges that necessitate reassessment within the space context. For instance, the RAN split into DU and CU facilitates vendor diversity but was not intended for environments with limited processing capabilities, like those in mega-constellations. This split requires encoding, transmitting, and decoding messages across a new standard interface, adding complexity. Moreover, the model focuses on deploying numerous radio heads to support concepts like user-centric, cell-free RAN densification, which contrasts with 5G NTN's single-satellite antenna covering a much larger area.

The core network, segmented into various functions, often requires these functions to be grouped during deployment to minimize message exchanges across the network, as most procedures involve multiple network functions like AMF, SMF, and PCF. Grouping functions reduce latency and message traffic, vital for efficient network performance and fitting to the reduced space node resources.

These core networks are designed for millions of connected devices. When collocated, they use standard interfaces involving substantial encoding, decoding, and state information transfer, which is overly complex for the fewer users typical of a constellation.

Lastly, the core network's control-user plane split enables the SMF to select the data plane entities. However, if the data plane is centralized and SMF is placed at the edge, it results in inefficient messaging from edge to central entities. Additionally, the data plane is designed for dependable transport networks and does not account for potential variations due to congestion or availability issues, indicating that the core network lacks awareness and control over the diverse transport paths in mega-constellations, thus failing to adapt QoS resources to backhaul capacities adequately.

C. RELATED WORK

Although self-organized networks have been extensively studied and standardized [12], the primary focus has remained on terrestrial networks, with satellite communications often overlooked. For instance, in [14], authors discuss integrating Low Earth Orbit (LEO) constellations into 5G and Beyond 5G (B5G) systems, predicting the use of distributed processing, sensing, routing, and intelligence via inter-satellite links. Also, in [15] a 3D architecture vision is presented, consisting of terrestrial, aerial, and space planes, each managed by its SON. This setup is enhanced with a self-evolving network layer that interconnects, manages, and handles conflicts between all SONs using AI/ML-based strategies. In comparison, our work represents an essential step towards a more complete architecture, whose baseline is a simpler 5G-based system. In [16], the LEO constellations failures and repositioning are considered, providing algorithms for the autonomous establishment of ISLs and the appropriate selection of channels to avoid interference addressing only the transport network. Also, in [17] an algorithm to cluster a group of nanosatellites in a self-organized manner is presented, enabling one satellite to act as a router towards a LEO transmission network. Here, satellites are mainly treated as information sources rather than actual integral parts of the information transport system, while our approach develops a more comprehensive view of the role that space nodes can play in a full-fledged telecommunication system.

III. REQUIREMENTS

In this section, we address the main technical challenges and key technology requirements that arise in the design and development of self-organizing mega-constellations.

A. TRANSPARENCY TO USER EQUIPMENT (UE)

A key goal is to minimize modifications to the UE to leverage mass-market production and expedite service provision. When considering indirect connectivity via NTN, this poses no significant challenges, as the UE connects to a terrestrial relay with NTN components providing backhaul. However, direct connectivity is challenging due to unique satellite channel characteristics such as larger path loss, over-the-air latency, and Doppler shift as addressed by the existing 3GPP NTN standards.

B. STABILITY TOWARDS THE TERRESTRIAL SEGMENT

Terrestrial IP-based networks are characterized by fixed nodes with stable link characteristics. In contrast, a mega-constellation network with terrestrial and non-terrestrial elements includes orbiting nodes with dynamic adjacent nodes and varying link characteristics (latency, throughput, Doppler shift). Due to orbital movement, the topology of the satellite constellation is regularly and predictably changing, requiring frequent handovers of 5G NTN nodes and feeder links, while due to weather some of the links may be available with limited capacity or interrupted. As such, a mega-constellation is regularly as well as unpredictably changing in relation to its terrestrial segment. To maintain a coherent system, there is a need for dynamic topology adaptations for all of these situations. At the same time, as these changes are very often, it is highly important not to propagate these changes to the terrestrial network counterpart.

C. CONTEXT-AWARE PROCESSING

Given that NTN payloads could be idle in areas without users [11]—motivated by the need for global connectivity and orbital mechanics—leads to high inefficiencies. Implementing context-aware processing activates idle NTN nodes temporarily for purposes other than on-ground user connectivity, such as backhauling non-real-time services, optimizing NTN control functions without burdening terrestrial gateways or enhanced security management (e.g. critical data flow isolation or per-country differentiated processing and routing). This approach requires continuous re-optimization of the network based on current topology and immediate needs.

D. THE TRADE-OFF BETWEEN SELF-ORGANIZATION AND NODE COMPLEXITY

Ideally, a mega-constellation would have a full gNB onboard each payload for optimal adaptation and self-organization. However, this setup is complex and costly. A feasible alternative might involve deploying a limited number of advanced NTN nodes with high-capability features interspersed among simpler nodes, balancing network complexity with self-organization capabilities. This could involve a combination of advanced functionalities supported by a denser network of simpler units, such as Remote Units (RUs), achieving an effective trade-off between network complexity and adaptability.

IV. SELF-ORGANIZING MEGA-CONSTELLATION CONCEPT

Self-organized networks are fundamentally characterized by their decentralized control, allowing network nodes to autonomously make decisions rooted in local data, leading to the emergence of overarching system behavior.

This paradigm has been successfully applied in mobile networks, sensor networks, and peer-to-peer networks. A paramount example of its application is the 4G Self Organizing Networks (SON) [18], wherein multiple base stations collaborate synergistically to achieve network goals like increased system performance and service quality via subscriber load balancing and bolstered communication robustness.

The concept of self-organized networks is highly interesting for mega-constellations [16] with repurposable payloads. Given that these constellations experience continuous and deterministic topology changes, there is a stringent requirement for adaptive network reorganizations. Each topological transition necessitates a redefinition of the network paths, including network management. Furthermore, due to the global nature of the network, the reaching of the command center for centralized decisions and new configurations has an extreme delay that would further increase the instability of the system at each topology change.

Further topology changes arise from other external, unpredictable factors such as weather variations, influencing the communication with terminal devices and feeder links to terrestrial ground stations. These introduce drastic shifts in the data traffic inflow next to the fluctuating capacity demand and service expectations of the system users.

As the satellite systems are able to support a fewer number of users than their terrestrial counterpart, their usage patterns are different from traditional terrestrial telecom where due to the law of big numbers makes individual devices contributions insignificant, the only dimensioning being the peak times. As mega-constellations offer connectivity to fewer devices, their resources demand is relatively higher compared to the overall capacity, potentially resulting in unexpected, localized capacity surges, such as in the case of localized public protection and disaster relief actions.

Practically, space nodes have the responsibility of independent operations, potentially communicating information with their neighbors. To facilitate this runtime autonomy, these nodes necessitate high-level goals from the control center, coupled with regular long-delay verifications of whether the goals were met.

Large Language Models (LLMs) can significantly enhance decision-making frameworks for semantic routing and network function placement in satellite mega-constellations. By leveraging their advanced natural language processing capabilities, LLMs can interpret and analyze vast amounts of data in real-time, enabling more accurate and context-aware routing decisions. This semantic understanding allows for dynamic adjustments to network configurations, optimizing the placement of network functions based on current demands and conditions. Consequently, this leads to improved real-time performance, as the network can adapt swiftly to changing scenarios, ensuring efficient data flow and resource utilization. The adaptability provided by LLMs also enhances the resilience of satellite networks, making them more robust against disruptions and capable of maintaining high performance even under varying operational conditions. As an example, in [19] the authors present a digital twin edge network that combines Digital Twin (DT) technology with edge computing, leveraging an over-the-air computation-enabled federated learning architecture to improve UAV performance in IIoT networks. It introduces a device scheduling mechanism that is aware of heterogeneity and energy constraints, optimizing update importance, channel conditions, and computation capacity. This approach significantly enhances test accuracy and energy efficiency, demonstrating robustness in heterogeneous and energy-constrained environments. The paper in [20] discusses the use of multi-modal foundation models (FMs) in 6G wireless networks, highlighting their ability to process and integrate data from various modalities for applications in fields like computer vision and natural language processing. It explores advanced AI techniques such as pipeline parallelism and data parallelism to support the sustainable development of distributed multi-modal FMs, addressing challenges related to computation resources and energy supply. The integration of federated learning with over-the-air computation is emphasized for efficient gradient aggregation, enhancing the performance and adaptability of FMs in 6G networks.

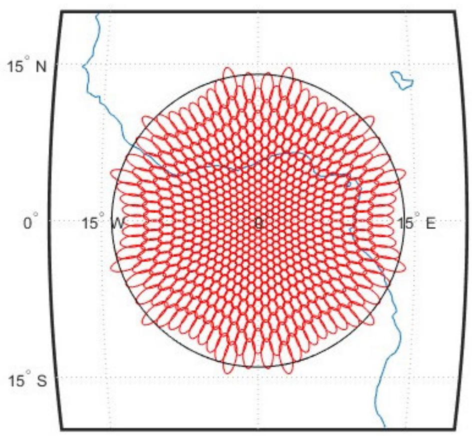

FIGURE 5. 3GPP beam layout for LEO at (0°,0°, 1300Km) with a HPBW 3.64° [22].

V. HIGH-LEVEL ARCHITECTURE DEFINITION

A. BEAMS AND CELLID IDENTIFICATION

Beam management in New Radio (NR) is essentially a cell-level algorithm used within a single cell, encompassing a series of procedures at the Physical (PHY) and Medium Access Control (MAC) layers. These procedures are designed

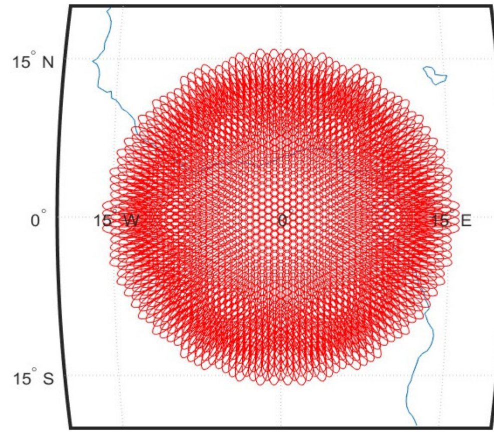

FIGURE 6. Beam footprint layout setting a grid according to the beam radius at Nadir.

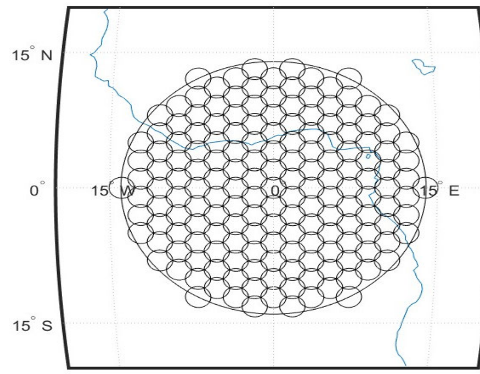

FIGURE 7. Beam layout with uniform footprints.

to establish and maintain an optimal pair of transmit and receive beams for a given link direction, incorporating beam indication, measurement, recovery, tracking, and refinement.

Remarkably, beam management procedures have been originally designed for terrestrial networks to handle multiple directional links. Therefore, for NTN systems where a single NR cell controls multiple NTN beams, the standardized beam management procedure provides a baseline for managing NTN beams effectively [21]. However, due to the characteristics of mega-constellation communications, legacy beam management procedures need a thorough evaluation to determine if adaptations are needed. Several strategies are included in [22], acknowledging that no single solution fits all network configurations. Key influencing factors include frequency reuse, cell mapping, payload architecture, and the bandwidth of the service link. For instance, adopting frequency reuse can minimize inter-beam interference, treated as noise, whereas a full frequency reuse setup would require all beams to operate on the same frequencies, leading to potential interference issues.

Another aspect that deserves some attention is the cell mapping. In the context of mega-constellations, managing NTN beams as individual cells is inefficient due to increased signaling and complex user mobility management. Instead of mapping each NTN beam to a unique physical cell ID (PCI), which necessitates frequent handovers, it is more practical to associate multiple NTN beams with the same PCI. This approach facilitates rapid beam switching, essential for services to airplanes and for dynamic beams in LEO communication systems.

It is important to remark that the beam footprint layout has a profound effect on beam management. To smooth the impact on the 3GPP standard, the preferred option is to synthesize Earth-fixed beams. The straightforward option is to resort to linear phased arrays. The immediate consequence is that the beams gradually suffer deformation as we move towards the edge of the field of view (FoV), due to the Earth's curvature. An example is represented in the beam pattern of Figure 5. Because of the beam deformation, a uniform grid of beam footprints on Earth must be set according to the beamwidth at the Nadir position, which implies having a large number of beams and large beams overlapping at FoV edges. The resulting overlapping is shown in the beam pattern of Figure 6. The alternative is based on exciting the phases of the radiating elements with a non-linear distribution. In such a case, if the phases are properly designed, uniform beam shapes can be deployed across the FoV, reducing the total number of beams and the beam overlapping. This is illustrated in Figure 7. In exchange, the gain of the resulting beams is reduced in comparison to the linear phased method. It is worth emphasizing that the optimal design calls for in-depth research.

In settings where the satellite power limitations preclude the simultaneous transmission of all NTN beams, implementing beam management is not straightforward and involves careful beam illumination planning. For data transmission, beam illumination strategies can be associated with user scheduling, but beam management needs to handle the delivery of signaling information that is common to all users. In particular, the need to cover the whole FoV applies to the synchronization, the initial access, and the paging. The figure of merit for broadcast signaling is to minimize the number of time/frequency resources that are required to sweep the coverage area of a single satellite.

On the user side, beam management involves tracking both the serving satellite and potential target satellites during handovers, ensuring efficient data transmission and accurate satellite positioning, especially in mobile conditions. Recent releases from 3GPP have simplified these processes, assumed GNSS-capable user equipment, and provided network ephemerides, though challenges remain for operations without GNSS dependency.

B. RAN FUNCTIONALITY PLACEMENT

Before selecting the potential RAN deployment architectures, we must consider the specific constraints and capabilities of the NTN RAN and the impact on the O-RAN functional split models. The primary limitation in our mega-constellation architecture is the feeder link connection to Ground-based gateways. At any given moment, many satellites lack a direct ground connection and must connect indirectly through the ISLs to find a node with a direct connection. To minimize traffic through the mesh network due to limited feeder bandwidth, a regenerative payload architecture is the best option. As shown in [23], the bandwidth for the link is greatly reduced the further up the protocol stack we move our split. We must decide whether it is optimal to split the RAN functionality between multiple satellites and the ground or between one satellite and the ground. A topology with a DU on one satellite, one or more CUs on another, and the core network on the ground may distribute compute tasks evenly but creates the constraint of traffic routing from the DU satellite to the CU satellite before reaching the ground, even if this is not the most efficient path. As illustrated in Figure 8, there are six major split options considered, depending on where the radio parts are placed. Options 1, 4, and 6 propose an integrated RAN on the ground station side, space node, or user side. The integrated model presents minimal overhead if computing and networking resources are sufficient. In Option 1, this depends on the availability of a feeder link on the communicating satellite, which may be rare. In Option 4, satellite resources are limited, requiring all satellites to include RAN functionality. In Option 6, many proxy nodes have to be deployed on the user side. Other options include placing the DU on a space node and the CU either terrestrial or in space (Options 2 and 3) or placing the DU on the ground and the CU in space (Option 5).

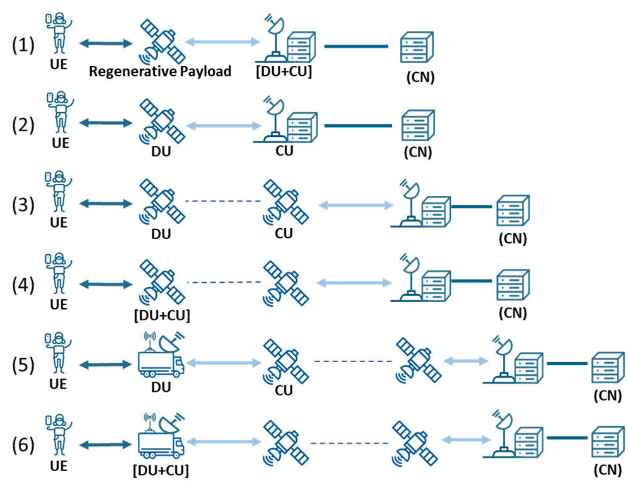

FIGURE 8. Ran functionality placement.

Considering the RAN placement discussion, it follows that there is a wide range of options for placing the DU and the CU. The rationale for implementing RAN functionalities on ground is to reduce the payload energy consumption yet increases the service latency and pose more stringent requirements on the feeder link. This issue is resolved by shifting the RAN functions to space, which is more demanding in terms of onboard processing.

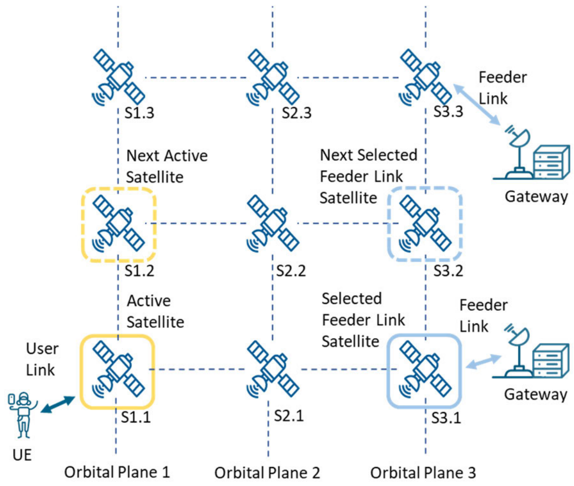

FIGURE 9. Semantic routing.

The continuous topology changes that are inherent to mega-constellations raise the issue of dynamic RAN placement. Dynamic deployment strategies offer more flexibility and adaptability to the network when compared to static deployments. The optimal operation could be selected on the basis of the traffic demand and the available computational resources and power in the payload. Remarkably, dynamic RAN placement is aligned with the functionalities of the O-RAN architecture. Accordingly, the software application deployed in the RAN intelligent controller (RIC) could be in charge of collecting and processing the necessary information from the network to select the most suitable deployment. This data-driven algorithm could be embedded into the non-real-time RIC (near-RT RIC), for closed-loop optimization control in time scales above 1s. The critical aspect to enable dynamic RAN placement is to endow the satellite nodes with flexibility and reprogramability, while complying with the power requirements of payload implementations.

For static deployments, we must select at what level we perform the split. There are two regenerative that have been enabled in the 3GPP, namely the F1 over SRI (Satellite Radio Interface) or the NG over SRI. For this topology, we propose the NG over SRI. This is justified as follows: the nature of a cellular network deployed on a satellite architecture will require many handovers, both for traffic steering/ load balancing and to cope with the fast movement of satellites relative to the ground. This high density of handovers has a large signaling overhead. However, an Xn handover can push the signaling overhead towards the edge, only requiring minimal signaling between the RAN and the core. This Xn handover can leverage the presence of ISL connections between the satellites and greatly limit the communication to the core over the feeder link. This approach requires the CU to be placed on board the satellite.

Several self-organization aspects must be considered for these split options. First, the RAN should be activated only over the target area to conserve resources, based on time-based policies for RAN activation and requiring the signaling of its presence to the core network. Extensive research is however still needed to design efficient mechanisms for RAN activation/deactivation. The main challenges are related to user traffic prediction, the time required to perform (de)activation compared to the satellite velocity, the management of shared resources in networks utilized by several stakeholders (e.g. serving several countries or maritime use cases, etc.), which also depends on the type of interconnection (Wholesale, RAN Sharing, etc.).

Particularly important is the automatic starting of a companion CU, enabling the distribution of CU processing between the main and a companion satellite in options 3 and 5, as well as policies for splitting the load between two CUs. The split between multiple CUs cannot occur below the upper MAC layer, as no appropriate identifier exists to determine the identity of the communicating UE until then. Additionally, the dynamic selection of the CU for the DUs, depending on CU availability and the ability to split communication across multiple CUs, should be considered.

C. SEMANTIC ROUTING

To efficiently route data packets from a satellite serving the user link to one serving the feeder link, as shown in Figure 9, there are multiple potential data paths, with one or more typically being the shortest. While various routing algorithms from the literature can be utilized to establish these paths using pre-defined policies or even complete paths from the control center [24], these fixed routes may not account for dynamic changes as this would intensively complicate the overall routing protocol and endanger its stability. Specifically, routing protocols of today for terrestrial as well as for space networks are considering each topology change as a trigger for re-signaling. We propose to delay this triggers up to a later moment in time, in order to gather more topology changes events within the same routing update and through this to relieve the routing protocol of executing its operations with every topology change, which may happen even continuously mostly due to the handover of the feeder links.

Instead, we suggest implementing an additional semantic routing layer [25] that adapts based on the locally learned context in each of the nodes, thereby self-organizing the routing in the mega-constellation according to the current situation. Departing from the classic role of semantics to differentiate the flows based on the application requirements, we intend to use semantics to address topology changes in three key scenarios:

1) Regular Handovers of User and Feeder Links: Since the User Equipment (UE) and the Gateway often remain in the same location for extended periods, handovers to subsequent satellites are predictable. Integrating time as a routing parameter can help select the most appropriate path based on the known duration at the UE and the gateway.

2) Impact of Weather on Feeder Links: Bad weather can significantly reduce or interrupt feeder link capacity through which the communication of many UEs is channeled. While for the user link, there are no alternative options, for the feeder link a gateway diversity is an essential solution, requiring a reroute of data traffic to an alternative gateway. This decision can be made by the satellite experiencing poor feeder link conditions or preemptively by neighboring nodes informed of the deteriorating link quality, ensuring that data still reaches its terrestrial destination. In case of a link failure, an immediate mechanism similar to Fast Re-Route [46] can be employed [47]. This way the data traffic which reaches a failed link point can be redirected towards another feeder link without requiring the signaling of the routing protocol.

3) Failures or Congestion Within the Constellation: When nodes or links fail, or temporary congestion occurs due to capacity planning oversights, fast rerouting is necessary until the central command can adjust the routing information to the new conditions. Each node, upon detecting such events, must decide locally on rerouting the traffic to avoid the affected area, utilizing alternative paths by selecting other paths already available in its routing table.

Although semantic routing decisions are based simply on local knowledge rather than the complete constellation context, they are not always optimum, but they allow for fast response to an incident. This speedy decision-making is critical because it avoids the delays inherent in communicating across huge distances in a mega-constellation, making it a feasible method for modifying the system in a timely manner while also delaying the triggering of routing protocol upgrades.

Re-routing data traffic based on local knowledge is typically suboptimal due to decisions made at the last possible node in the data path for carrying out such actions. However, to lessen the rerouting impact in terms of latency and bandwidth consumption, the information can be disseminated to neighboring satellites, allowing for speedier re-routing. This would necessitate the development of a new signaling system that, in some ways, replaces routing signaling.

The trade-off between higher delay and bandwidth utilization against extended signaling depends on the constellation topology. For example, under the constellation model given in Section II-A, such signaling is not required because redirection implies a small number of nodes and only across high-capacity optical lines. However, it may be required for denser constellations.

D. CORE NETWORK FUNCTIONAL PLACEMENT

The deployment of core network functionalities is critically influenced by the location of the RAN network, with three main strategies tailored to enhance efficiency through the interdependent grouping of network functions as illustrated in Figure 10.

1) SINGLE GROUND CORE NETWORK

This approach maintains a central core network to which all ground stations connect. It requires few resources, has simple network management, and integrates seamlessly with terrestrial networks. It is beneficial due to its simplicity and ability to manage all satellite-capable subscribers. Multiple UPFs may be deployed within different ground stations to reduce the end-to-end data path. Still, its major drawback remains the distance of the UPFs from the UEs requiring long delay data paths even for low Earth orbit and a significantly long signaling plane to reach the UEs and the UPFs.

2) SPACE OFFLOADING

- By relocating the UPF to space nodes, this strategy enables the direct connection to space-deployed services and shortens the path between UEs, effectively bypassing extended routing through ground stations. This setup allows for quicker data transfers and reduced latency. Also, the space-UPF functionality can be significantly reduced to conserve the space node resources, by deferring non-essential tasks to be processed asynchronously by terrestrial UPFs.

3) FULLY INTEGRATED SPACE CORE NETWORK

This approach places the UPFs and the entire control plane in space, creating an ultra-secure, reliable connectivity framework without interactions with any terrestrial network. Depending on the RAN's location, UPFs can also be placed at the terrestrial endpoints, for example, to facilitate direct connectivity between globally distributed enterprise locations. However, the communication service requires inputting user profile data from a terrestrial administrative portal into the UDM, potentially synchronizing the communication accounting reports.

Options 2 and 3 require specific self-organizing features, adapting dynamically to operational demands and satellite movements. Space UPFs may be collocated with the RAN CU to minimize data paths for local connectivity, although this arrangement demands frequent handovers due to satellite mobility. An alternative is to maintain a UPF on a single satellite longer, reducing handover frequency but potentially distancing it from its service area, even on the other side of the Earth. A better alternative is to make decisions on the dynamic spawning of new UPFs and whether to have logically localized or orbiting around in the same satellite depending on the 5G system load. This flexibility allows the network to respond to varying load conditions and communication requirements dynamically, adjusting UPF deployment based on real-time data.

Moreover, in Option 3, the complete core network potentially deployed in designated space nodes facilitates enterprise connectivity by allowing direct links across its distributed locations without reliance on external networks where the control plane is less important than increased security and reliability. Additional dynamic deployment of UPFs at ground enterprise locations enables specific APNs for them, and ensure the availability of tailored and secure enterprise data paths.

To be able to make the core network self-organize, a new network function placement functionality has to be added

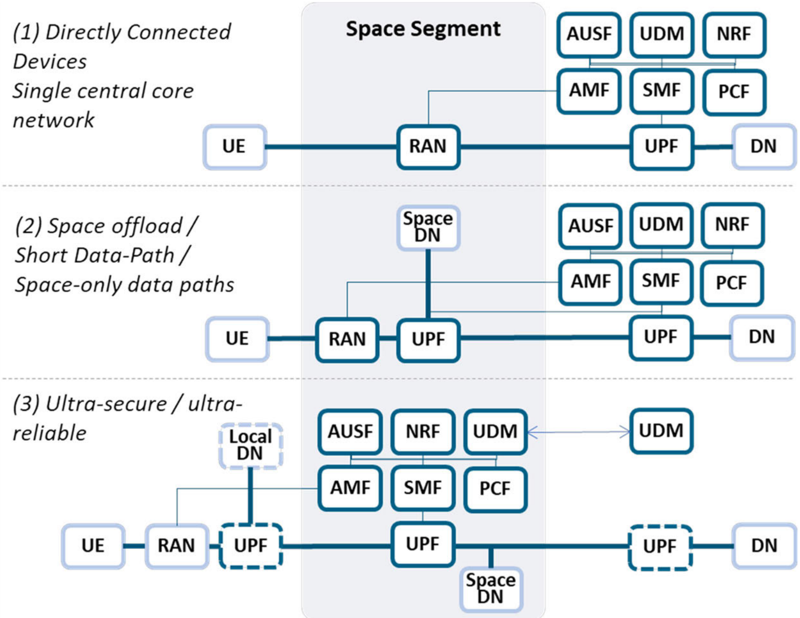

FIGURE 10. Core network functionality placement.

being able to introduce new network functions in the NRF for the control plane as well as the initiation of dynamic UPFs.

E. DYNAMIC RESELECTION OF RAN AND CORE

In the previous sections, we discussed the placement of RAN and core network functionalities. Building on this, we introduce a new self-organizing mechanism to dynamically select network components that serve a UE and manage its data path at any moment.

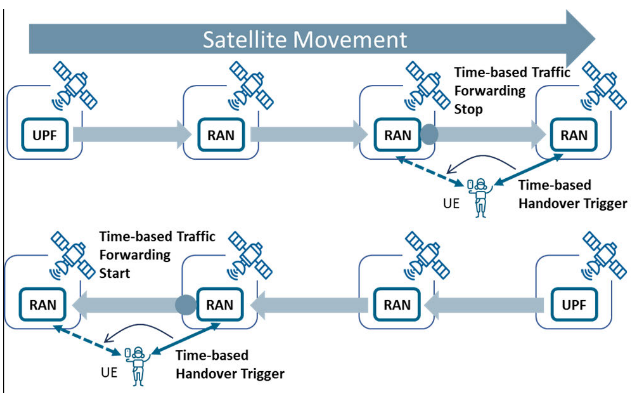

FIGURE 11. DATA PATH STRIP CONCEPT: (A) satellite coming towards UE, (B) satellite going away from UE.

Mega-constellations require predictable handovers, as the next satellite in the same orbit naturally follows to provide connectivity. Specifically, the UE can automatically select the next RAN based on network policies, utilizing time-based conditional handovers [26]. This automation eliminates the need for a traditional handover command received from the RAN, thereby removing the handover preparation phase typical in 3GPP technologies. Although this phase traditionally prepares the data path by establishing a tunnel between the source and target RANs to buffer downlink data until the UE handovers, our approach ensures that the data is not lost, but, instead buffered at the target RAN.

For this, we introduce the concept of a "data path strip", a continuous data path along the same orbital plane that connects the UPF and the current RAN, as illustrated in Figure 11. This path transmits all downlink data across the satellites between the UPF and the RAN. The redirection of the data during the handover phase can also be automatically time-triggered, like the conditional handover in the UE, adjusting the forwarding at the precise moment it's needed. For handovers moving towards the UPF (situation A in Figure 11), at the selected time, the target RAN on the data path begins to buffer data, not forwarding it anymore to the source RAN. Conversely, for handovers moving away from the UPF (Situation B in Figure 11), the source RAN will extend the downlink data path to include the next satellite, where the target RAN is located, ensuring continuous data flow.

This forwarding change represents the beginning and the completion of the preparation phase, with no further messages exchanged. However, upon completing the handover, a "Handover Complete" message must be sent to the AMF to update the UE's network location.

This solution prioritizes selecting the RAN in the same orbital plane, which is typically adequate. Occasionally, the optimal RAN may be on a different orbit, necessitating rapid access to the data traffic within the correct orbital plane. If the UPF is fixed geographically, whether on a ground station or a satellite, adjustments to the data path strip at each handover mirror the traffic redirection at the RAN's end of the data path strip.

This self-organizing reselection of the core network data path and RAN handovers simplifies the overall system by leveraging predictable satellite transitions, significantly reducing the number of messages exchanged and the processing required in the nodes. If a handover does not proceed as expected, a standard handover procedure with full messaging is used as a fallback, ensuring the overall system robustness.

F. MULTI-CONNECTIVITY

Multi-connectivity enables the use of multiple communication links to enhance throughput and/or reliability. It adapts transmissions to different QoS requirements, or enables seamless switching for availability and resilience, through soft handovers where two links are simultaneously available, and one may suddenly drop. This feature is particularly beneficial in satellite networks, which can extend reliable coverage of terrestrial networks to rural areas and to enable a backup in case the satellite link line-of-sight is interrupted. Typically, such switches should be transparent to the user [34].

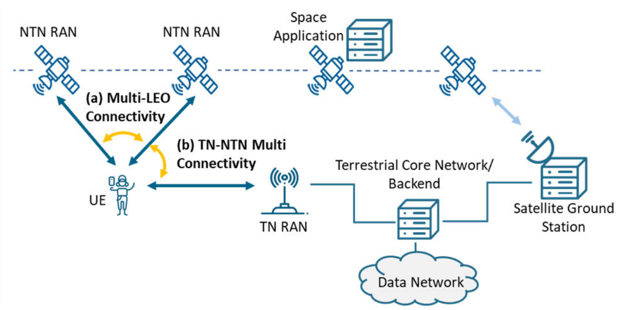

FIGURE 12. Multi-connectivity.

As depicted in Figure 12, we distinguish between two types of multi-connectivity: a) within the mega-constellation and b) between the mega-constellation and terrestrial networks (TN-NTN multi-connectivity). For type a), several implementation strategies are available. These range from low-layer coordination techniques like Coordinated Multi-Point (CoMP) [27] or distributed Multiple Input Multiple Output (dMIMO) [28], which require tight timing and complex synchronization that are highly challenging considering the delays within the mega-constellation, to dual RAN connectivity where the Non-Terrestrial Network (NTN) maintains two separate links that merge before the RAN backend without needing any RAN coordination.

For type b), several solutions can be proposed to provide a user with several communication links, depending on the user's requirements and time to market. As a basis of comparison, roaming is the most well-known solution to extend coverage in rural areas and be used as a back-up communication services. It allows autonomous switching in case the main network (usually the terrestrial one) is not available. Already commercially available for 4G TN and satellite networks (e.g. IoT), it cannot however be considered as multi-connectivity, as conceived by the 3GPP, and does not consider simultaneous access to TN and NTN, nor can guarantee that the user service will undergo no interruption.

In principle, also for case b) the discussed solutions from case a), such as CoMP, dMIMO, but also the dual-connectivity from 3GPP using a primary and a secondary gNB, could be applied. However, the close interaction needed between the serving nodes (in this case, a NTN-gNB and a TN-gNB) requires a deeper integration of both systems and introduces even more challenges on timing and synchronization between the two, e.g., the NTN node in a LEO constellation will be handed-over frequently and introduces a variable propagation delay increasing the need for coordination. A direct link, e.g., an Xn interface, is needed for this which has not yet been specified by 3GPP between TN and NTN systems and requires a detailed investigation for a deeper integration of TN and NTNs in future including also multi-operator setups.

With this perspective, an interesting approach typically involves maintaining distinct RAN connections for the NTN and TN, distributing traffic at a higher layer using technologies like Lower Layer ATSSS [29], Multi-Path TCP (MPTCP) [30], Multi-Path QUIC (MPQUIC) [31] or even at the application level for a dual-SIM (i.e. dual UE) connectivity. While these technologies can operate in an OTT manner (for example thanks to an integrated smartphone/satphone, provided with two radio accesses and two sets of credentials, or through Dual SIM Dual Active), the support of ATSSS functions in the UPF, combined with MPTCP / MPQUIC proxy over MA PDU session, could offer higher performance and reduce the need to accurately sense the performance of each link at the UE side, to spot service degradations. The lack of network information (traffic load, congestion, the capacity of the feeder link, etc.) can lead to poor switching decisions and ping-pong effects could occur if links are unstable. In addition, ATSSS [32] gives TN / NTN operators better visibility on resource utilization, thus allowing enhanced network (re)configuration and adapted traffic management.

Given the notable delay differences between links, it's practical to manage different data flows by developing dedicated bearers and splitting traffic accordingly instead of a transparent data flow unaware split [33].

This higher-layer split is managed by both the UE and the terrestrial aggregation point. The UE, guided by policies and indications from the network—such as UE Route Selection Policy (URSP) from the PCF) — makes independent decisions on which link to use based on the active applications and the current connectivity status.

On the network side, selections are made based on the data path allocated to the bearers from the UPF to the RAN and are further adjusted by semantic routing to avoid congestion or feeder link bottlenecks.

Another not yet standardized aspect of multi-connectivity is the potential to backhaul RAN to UPF via two or more links to ensure enhanced connectivity. In such cases, both the RAN and UPF can divide active bearers across different links and route them to their intended destinations. To facilitate this, the UPF should present two distinct IP addresses to the RAN, enabling the differentiation of bearer routing across the links.

G. DYNAMIC APPLICATION PLACEMENT IN SPACE

Integration of Multi-access Edge Computing (MEC), network softwareization, and virtualization has revolutionized networking by enabling intelligent, secure, and highly reliable systems through software programmability. These technologies foster advanced, intelligent services and applications for end-users [35]. Introducing these capabilities to satellites merges the expansive coverage of satellite systems with the low latency and computational benefits of edge processing. This fusion allows Edge Computing (EC) services and low-latency applications to be globally accessible, spawning new service opportunities and business models [37]. For instance, Earth observation data can be processed directly on satellites, reducing downlink loads [36], or IoT data can be integrated over large areas or provide communication in case of emergencies boosting the overall system resilience and reliability [38].

Enabling EC services on satellites involves trade-offs, including the use of ISL capacity and the inherent limitations in onboard processing and storage capabilities [39]. Similar to the control plane connectivity, two border options are possible for space edge-computing: (i) deploy the EC services on a satellite and, thus, make it reachable through the ISL path or (ii) ''logically'' place it over a specific geographic area and relocate the EC application, following the mega-constellation topology changes. Between these, multiple options are available, such as reduced relocations due to the placement of 2 EC nodes on the same orbital plane, or only due to the skewing of the orbital plane to different longitudes.

In both situations, next to the placement of a UPF in space deployment models, able to assure end-to-end connectivity, there is a need for an additional context handover between the different EC nodes. As such, services with no state or with minimal state should be preferred, as well as a self-organizing option when and how to execute such handovers. Furthermore, data storage can be potentially highly distributed, i.e., data is placed in the easiest-to-reach satellite at the moment of the transmission to be able to reduce the data acquisition delay and to assure its distribution across multiple nodes due to the topology changes. However, in this situation, a mechanism to fetch the data is needed such as a distributed hash table.

Another major challenge lies in space edge computation for near real-time or continuous applications, as often conceived in terrestrial networks. New technologies and capabilities are still required to quickly move data processing contexts from one hardware to another. This challenge is particularly true in mega constellation systems.

H. AI DECISION FUNCTIONALITY PLACEMENT

Recently, AI has gained significant popularity in networking systems, enhancing learning efficiency, reliability, and data security. AI, through its Machine Learning (ML) algorithms, creates a self-organizing system that fits better to the available resources and service requirements. ML can now be deployed in several forms, from centralized to distributed, tailored to different networking infrastructures [40]. AI decision point placement is essential for mega-constellations as the AI algorithms are consuming a significant number of resources while using a large amount of data that has to be gathered and transmitted from different entities in the system [41].

As a single node in space would not have enough free resources after deployment of the active services to support AI decisions, their placement is highly dependent on the capacity to distribute AI decisions. Two options are possible to deploy the centralized decision points on the ground with a lot of computing or distributed through the space with low resources of the nodes however close to where the decisions will be used. This ''edge intelligence'' placement is highly dependent on the type of decision taken:

- Dynamic placement and migration of network functions – enabling real-time optimization of the self-organizing network according to mega-constellation topology changes [42].
- AI-based service optimization – based on allocating dynamic resources to the connectivity service of the users as provided through the RAN and Core network [43].
- Strategic Deployment of Data Path and Applications Functionalities – adapting the end-to-end data paths to edge computing in space.
- Multi-connectivity decision – algorithms placed in the UE for selection between multiple connections.
- Anomaly detection – for determining exceptional situations requiring network management decisions.
- Security –anomalies and potential threats detection, including unauthorized access attempts, distributed denial-of-service (DDoS) attacks, or malicious activities in real-time. Immediate corrective actions are taken, safeguarding the network, and ensuring a secure communication environment for users.

By integrating AI at distributed decision points, the mega-constellation 5G network adapts in real-time to changing conditions, ensuring seamless communication services, enhancing user experience, and maintaining high levels of reliability and security. The decision points can be placed at data centers or edge computing nodes. Data Centers can process large amounts of data through extensive computations. Cloud-based AI facilitates in-depth analysis and long-term planning for network optimization. Moreover, training operations should always be executed at ground data centers as they require large processing capabilities. However, placing AI on the edge computing nodes allows for real-time processing of data, enabling quick decision-making and reducing latency in communication services. Such nodes can be used for inference operations [44].

While data centers are available only at ground stations or on the ground connected through the Internet to the ground station, the edge computing nodes can be placed at different locations regarding the mega-constellation [45]:

- On the ground or flying at the user end of the user link – co-located with 5G users or aggregation – despite reduced latency during the AI operations, the coverage area is very limited and suffers from users' mobility. Also, it has to be assumed that the number of these nodes is extremely high, and their management becomes problematic.
- LEO satellite nodes – LEO satellites orbit at lower altitudes, making them suitable for hosting AI entities. LEO satellites offer low latency and high data transfer rates, making real-time decision-making possible. However, due to their orbiting around the Earth, this delay is not uniform, significantly varying depending on the satellite's location.
- Geostationary Earth Orbit (GEO) Satellites: GEO satellites orbit at high altitudes and remain stationary relative to the Earth's surface. AI entities on GEO satellites can oversee specific regions continuously, ensuring consistent and stable communication services.
- At the ground stations – placing distributed AI decisions at the selected ground stations provides a high level of centralization however very long data paths are equivalent to the cloud computing data centers.

Ultimately a final decision of placement should be adapted to the specifics of the type of algorithm deployed, their delay limitations, and the available resources within the mega-constellation as well as on the parallel AI algorithms deployed.

I. INTEGRATION WITH TERRESTRIAL NETWORKS

As discussed in previous sections, the mega-constellation NTN network's various layers offer the potential for self-organization to enhance service functionality and operation. This capability requires numerous decisions in response to topology changes, including link setups, terrestrial network integration via feeder links, routing within the constellation, and the strategic placement of RAN, core, and application layers in the space network. These decisions aim to establish the user control plane and data plane effectively, avoiding service congestions and achieving the anticipated delays along the data paths.

Terrestrial networks, however, lack the necessary flexibility for such dynamic operations, typically only accommodating failure scenarios with hot-standby options. Thus, integrating terrestrial and space segments should minimally impact terrestrial components by isolating decision-making within the mega-constellation.

Integration models vary due to differing administrative domains, despite all operating under the same 3GPP standards intended for interface-level interoperability, as illustrated in Figure 13:

1) Over-The-Top Backhauling: The terrestrial network (TN) utilizes end-to-end NTN connectivity for backhauling, treating the NTN as an independent service provider for transporting the data between selected locations. The TN manages its data traffic over this connection under specific Service Level Agreements (SLAs), similar to existing satellite network usage. This setup requires no shared authentication, maintaining separate operational control and preventing NTN's self-organizing features from propagating effects to the TN.

2) Virtual Infrastructures: Similar to a cloud networking Infrastructure-as-a-Service (IaaS), TN deploys its network functions directly onto satellite infrastructure, including constellation nodes and satellite operator facilities, allowing TN to manage its network functions independently. However, the antennas of the satellite are pertaining to the satellite network operator and may be shared between multiple virtual terrestrial operators co-existing on top of the same constellation.

In this setup, the placement of network functions within the RAN and core, coupled with semantic routing, could potentially influence terrestrial networks. To mitigate this, semantic routing should be confined to the constellation's gateways, avoiding event propagation to terrestrial systems. This containment might lead to suboptimal routing, particularly for the uplink data traffic through congested gateways due to adverse weather conditions. Redirecting traffic to alternate gateways should be managed solely at the gateway level to prevent impacts on terrestrial routing, necessitating careful planning and sizing of gateway resources and redirection of the data path.

Additionally, the activation, deactivation, and mobility of RAN nodes, along with the positioning of the UPF, will profoundly affect system behavior. The control plane, particularly the Access and Mobility Management Function (AMF) and the Session Management Function (SMF), should incorporate dynamic capabilities to adapt to the changing radio and data plane topologies. Implementing dynamic selection strategies for the RAN and core significantly minimizes the impact on signaling processes.

3) Network of Networks: the NTN operator offers a dynamic type of roaming to the TN operator users. This can be done by the classic roaming network split or by other 6G-oriented sub-networks interoperability or neutral host. To make such a system function, a Service Border Control (SBC) should be added to the network architecture enabling the negotiation of the SLAs, the reporting as well as the discovery and the secure interconnection between the two operators. The SBC is taking the functionality of a large number of network functions that are already standardized for 5G networks.

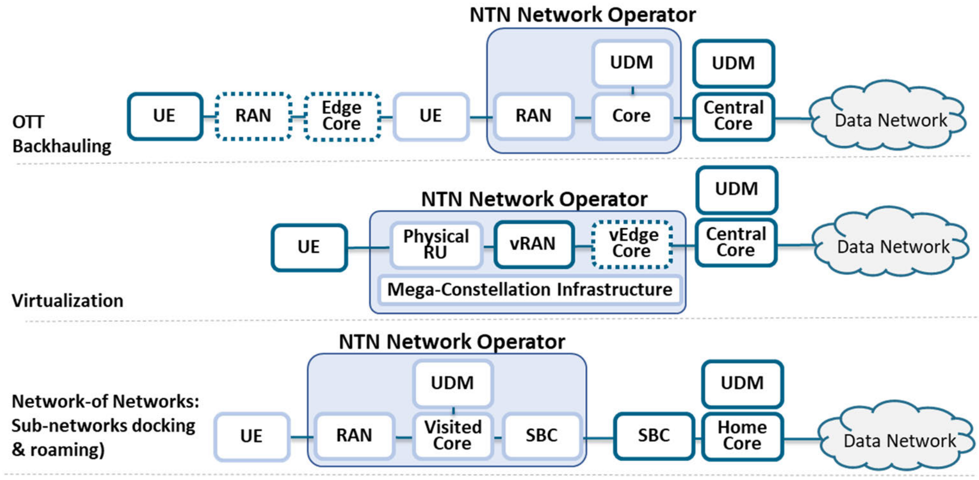

FIGURE 13. TN-NTN integration options.

The SBC enables the simplification of the propagation of effects between the two networks, specifically by letting each function in isolation. As the two networks are optimizing independently, as long as the interconnection points through the SBCs are not changed, the two can operate without propagating any effects. However, the limited computational capabilities of the current satellite payload still constitute a challenge to the targeted independent configuration and isolation.

VI. IMPLEMENTATION FEASIBILITY ASSESSMENT OF THE SELF-ORGANIZING MEGA-CONSTELLATIONS

In this section, we survey a wide range of diverse technology developments, highlighting initial steps taken in different areas with the specific goal of demonstrating that the proposed architecture optimizations we introduced in this article are feasible for further research and development.

A. BEAMS AND CELLID IDENTIFICATION

For the last few years, significant progress has been made to endow satellites with flexibility. The key factor is the implementation of payloads that can be controlled by software and use onboard phased array antennas. The onboard technology advances offer increased flexibility that can be harnessed to control the satellite resources over the coverage area. This feature is essential in satellite systems that cannot simultaneously synthesize all the beams in the FoV, due to power and feeder link limitations. In such a case, associating multiple beams to the same PCI facilitates beam management allows keeping cells alive even without traffic. If the beam illumination pattern within the cell and between cells is carefully designed, the coverage area can be swept with an acceptable level of inter-beam interference. The beam hopping concept has been tested in the DVB-S2X, which defines specific frame formats [48]. Remarkably, 5G NR has not yet specified beam hopping for NTN. The main difficulty lies in ensuring that the periodicity of the system and control information that is common to all users is consistent with the switching rate of the beam pattern, which depends on the beamforming architecture. As part of Release 19, enhancements in the standard will be defined to accommodate satellite payload constraints, e.g., the inability to have all beams active [49].

B. RAN FUNCTIONALITY PLACEMENT

From the perspective of RAN functionality placement, several proposed deployment models have been successfully tested in various satellite projects such as ESA SATis5, 5G GOA, and 5G LEO, utilizing open-source RAN implementations like srsRAN [50] or OpenAirInterface [51]. These projects bolster confidence in deploying network functions on the user links and space nodes. Additionally, numerous functionality splits are currently being assessed in Open RAN architectures for terrestrial and space deployments alike, notably in the SNS JU 6G NTN [52] and TRANTOR [53] projects. However, further advancements in RAN flexibility are necessary to fully leverage companion satellite computational power, such as connecting a single Distributed Unit (DU) to multiple Central Units (CUs) and integrating multiple CUs into the network. Moreover, the automated activation and deactivation of RAN components and their effects on the core network require additional exploration.

C. CORE NETWORK FUNCTIONALITY PLACEMENT

The placement of the core network at ground stations has already been validated in relevant environments during the 5G GOA [54] and 5G LEO [55] projects as a byproduct of RAN testing. For core network functionality placement, an initial proof of concept was developed by Fraunhofer FOKUS using Open5GCore [56] and OpenLanes large-scale network emulator [57]. This demonstration showed that entire core networks or just User Plane Functions (UPFs) could be integrated within satellite payloads alongside srsRAN to validate the functional splits proposed effectively [8]. Moreover, functional splits that position the UPF at the network's edge were highly favored in 5G networks, with numerous demonstrations and products developed in this area. However, beyond this proof of concept, only minimal further development has been undertaken in testing various UPF placement models within such a mega-constellation, which would provide a preliminary overview of the constellation's capabilities for shorter data paths.

D. SEMANTIC ROUTING

In recent years, the development of routing solutions for mega-constellations has seen significant advancements. This includes the creation of new routing protocols tailored for constellations [58], as well as mechanisms for disseminating routing information from the control center to the network nodes [24]. Yet, these proposed algorithms often lead to significant computational demands on intermediary nodes or require extensive storage to accommodate routing information for all possible topologies, which grows exponentially as the constellation expands. A similar challenge has emerged in terrestrial networks, where semantic routing becomes a focal point within 6G advancements [25]. It is anticipated that many semantic routing solutions developed for terrestrial networks will eventually be adapted for space networks, potentially optimizing routing efficiency in terms of both computational resources and storage demands.

E. DYNAMIC RESELECTION OF RAN AND CORE

The robust standardization efforts by 3GPP towards 5G NTN RAN have created a large number of contributions of new research and work items, particularly around using Conditional Handovers (CHO) to eliminate the need for handover commands in predictable scenarios [26]. While this article introduces specific optimizations related to the data path, these aspects have not yet been addressed in the current 5G NTN standardization activities. However, they are expected to be incorporated as the development of the 5G NTN standards continues [59].

F. MULTI-CONNECTIVITY

Multi-connectivity has been thoroughly standardized for terrestrial networks through the Access Traffic Steering, Switching, and Splitting (ATSSS) framework. However, apart from the foundational concepts discussed in this article and a basic handover between terrestrial and satellite networks explored in the ESA SATis5 project [60], there has been limited focus on this aspect. Moreover, the reliability of space links heavily relies on having a clear line of sight, a factor critical for satellite antennas on the ground as anticipated for most 5G NTN user devices and many relay nodes. To date, only Project DAWN [61] has investigated line-of-sight effects for satellite communications, specifically for GEO satellites, which is essential for the successful implementation of multi-connectivity solutions. While ATSSS-based multi-connectivity solutions can be swiftly adapted into prototypes for initial testing, extensive efforts are required to refine user routing policies and tailor multi-connectivity to changing conditions.

G. DYNAMIC APPLICATION PLACEMENT IN SPACE

Dynamic application placement operations in space require the deployment of multiple applications on satellite nodes, as well as the execution of proper management and orchestration frameworks. These operations may mutually impact the system's overall performance. However, the MEC approach could help the platform to consider this potential issue. Indeed, the EC platforms can work in a self-organized way by relocating the processing tasks and reorganizing themselves. This is completely coherent concerning the self-organizing mega-constellation concept so that the platform could be used not only for managing services in a distributed way but also as a platform for the self-management of the network. MEC is part of the 5G system but not considered so far for NTN, to enable MEC services on-board a satellite it must not only host a gNB but also its own UPF to provide a Local Area Data Network (LADN) and the low latency services related to it.

H. AI PLACEMENT IN SPACE-NODES

Driven mostly by the assuring of the privacy of the edge information a very large amount of Distributed Learning (DL) techniques have been developed in the last years such as Federated Learning (FL), Multi-agent Learning, Collaborative Learning, and advanced techniques including multi-agent FL, DL with model split, DL with Meta Learning, and DL with swarm learning enrich the ecosystem, catering to specific characteristics, performance, and user demands making distributing learning a tangible alternative for real-time AI. Several initial steps were taken in this direction specifically from adopting AI algorithms as part of Earth Observation data processing directly into the space nodes. Furthermore, these methods should be further adapted to the mega-constellation environment, as well as to the optimization goals of the 5G NTN system, requiring a coordinated dual critical evolution direction.

I. INTEGRATION WITH TERRESTRIAL NETWORKS

The three proposed interoperability models between space and terrestrial network infrastructures mirror current approaches used between non-public and public terrestrial networks. These models have undergone validation through commercial trials and proof-of-concept environments. However, their efficacy for interoperability with space networks remains unverified. Careful attention should be given to the interoperability with the very small resource nodes which are part of the space networks as well as not to propagate effects between the network, especially in the case of worldwide distributed service interaction points between domains.

VII. CONCLUSION AND FURTHER WORK

In this article, we have outlined the current research and development concerning self-organizing mega-constellations. We started by establishing a model for the mega-constellation, setting the stage for detailed discussions, similar to the 3GPP SA1 characterization of the NTN environment [59]. From this model, we identified the requirements and evaluated architectural elements for an NTN architecture, underlining the role of self-organization in minimizing network communication and enhancing rapid responses to predictable events. This analysis covers beam steering, CellID selection, RAN and core network deployment, routing strategies within mega-constellations, and application deployment.

Additionally, we explored new concepts concerning RAN and core selection and their interoperability with terrestrial networks, which opened various new directions for future research. We also conducted a preliminary feasibility study that supports the significant potential for practical implementation of these concepts showing that initial prototypes were developed in most of the directions and giving confidence that this is the correct way to progress towards optimized TN-NTN systems.

Moving forward, within the 5G Stardust project and beyond, we will continue to refine these architectural elements and develop specific self-organization algorithms. These will be prototyped and validated in relevant environments, utilizing tools such as srsRAN and Fraunhofer FOKUS Open5GCore, alongside other relevant open-source technologies. Our objective is to achieve practical, prototypical implementations for these technologies.

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