This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

SDN-based Service Function Chaining in Integrated Terrestrial and LEO Satellite based Space Internet

Gao Zheng[ℵ], Ning Wang[♭], Peng Qian[¶], David Griffin[♮], Rahim Tafazolli[ℵ]
[ℵ]*5/6G Innovation Centre, University of Surrey, UK*
[♭]*Smart Internet Laboratory, University of Bristol, UK*
[¶]*Department of engineering science, University of Oxford, UK*
[♮]*Department of Electronic and Electrical Engineering, University College London, UK*
[ℵ]g.zheng@surrey.ac.uk, [♭]n.wang@bristol.ac.uk, [¶]peng.qian@eng.ox.ac.uk, [♮]d.griffin@ucl.ac.uk,
[ℵ]r.tafazolli@surrey.ac.uk

Abstract*—Supporting ubiquitous deployment of built-in Internet service with Software Defined Networking (SDN), Network Function Virtualization (NFV), and Low Earth Orbit (LEO) satellite constellations has been widely accepted as one of the key technologies for the next-generation communication services. By integrating terrestrial and space network capabilities, new design features are introduced to existing network ecosystems. For instance, terrestrial Virtual Network Functions (VNFs) can now be hosted on satellites, utilizing satellite highways. This requires expanding the roles of the control units, originally responsible for terrestrial data planes, to include space-based counterparts. As a result, seamless integration of Service Function Chains (SFCs) across satellite constellations and terrestrial control units becomes a challenge due to the topology dynamics caused by high-speed LEO satellites. In this paper, we propose the Geosynchronous Service Function Chaining (GSFC) scheme to facilitate programmable, Internet SFC operations based on LEO satellite network environments. The key idea is to cluster adjacent LEO satellites to represent logical VNF containers at the fixed positions, where the initial VNFs at the region are continuously filled up by the traversing satellite payload functions in a predictable manner. With this design, the ground-based controllers can maintain the space-terrestrial SFCs without being affected by the constantly shifting satellite VNFs, and thereby large-scale and complex recalculation for the routing policies is avoided. The design principle introduces a ground-breaking approach to space Internet protocol stacks, facilitating robust routing for SFC operations across integrated space and terrestrial networks. Our simulation results verify the feasibility of the proposed GSFC-based VNF orchestration mechanism and reveal the trade-offs in both data and control plane performance.

***Index Terms*—Space-Terrestrial network integration, LEO Satellite, Space service function chaining, SDN/NFV in space, NTN routing and addressing design.**

I. INTRODUCTION

Services relying on tailored network functions have become a focal point of research on the next-generation Internet [1]. Supporting these anticipated applications brings the necessity to develop hybrid network systems with ubiquitously offered broadband access via integration between the terrestrial networks and many planned satellite networks, especially for Low Earth Orbit (LEO) satellites. Recent studies, such as [2] have explored the potential of LEO satellite networks to serve as the backbone of a space-based Internet, providing both core connectivity and access. This capability has been further validated by the success of commercial implementations like StarLink. Motivated by these advancements, we envision a scenario in which a global space-based network infrastructure, equipped with diverse service functions on LEO satellite payloads, complements terrestrial communication systems to meet a wide range of application requirements.

Incorporating Non-Terrestrial Networks (NTNs) as a new component of the Internet poses challenges that make it difficult to reuse the conventional terrestrial Internet architecture. This is because maintaining network performance in NTNs requires frequent adjustments to network functions due to the dynamic constellation behaviours of LEO satellites, however the capital and operational expenditures of NTNs significantly exceed those of their terrestrial counterparts [3]. To address the need for such flexibility, Network Function Virtualization (NFV), initially proposed by ETSI [4], is considered a promising solution.

In the context of NFV, network functions are decoupled from specific devices, whereby, the data flows are described by the Service Function Chains (SFCs) without indicating the actual embodied devices [4]. Accordingly, traffic routing in such a dynamic environment makes a critical requirement for high-efficiency network management. Software-Defined Networking (SDN), recognized for its programmable network management capabilities, has garnered increasing attention for its potential applicability in NTN environments [5]. In this case, we envisage distinct research challenges in supporting SDN-based routing for SFCs in the context of space-terrestrial network integration towards the next generation of Internet. In this paper, we aim to advance the state of the art by addressing the following key aspects: (1) tackling the unique technical challenges of orchestrating Internet services in NTNs with highly dynamic network topologies, and (2)

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

enhancing SDN routing and addressing protocol stacks to support time-varying, space-allocated Internet services.

A significant technical challenge in SFC operations lies in the limitations of current NFV orchestration technologies, which struggle to manage the large-scale infrastructure mobility between space and terrestrial network segments caused by the dynamic behaviours of LEO satellite constellations. Although introducing NFV in NTNs to improve the performance of space-terrestrial integrated networks has been well studied [6], [7], to the best of our knowledge, little discussion has been devoted to the implementation architecture per se, especially lacking a comprehensive reference model for orchestrating Virtualized Network Functions (VNFs) among satellites. In conventional terrestrial NFV implementations, topology changes caused by scheduled events, such as device replacements, are typically managed through strategic VNF migrations to maintain system functionality. However, with current NFV technology, completing a VNF migration process can take several seconds to minutes [8]. As a result, directly applying these terrestrial solutions is impractical for space-terrestrial integrated networks, where individual satellites typically provide coverage to terrestrial peers for only a few minutes [9]. Additionally, existing SDN southbound protocols such as OpenFlow [10] are also tailored for static data-plane network topologies, as from the controller's point of view, individual SDN switches are forwarding elements with static identifiers such as IP addresses. Such addresses are physically bound to the hardware, and in the context of LEO satellites, these addresses are always carried by the constellating satellites. As a result, the controller on the ground will not be able to interface static IP addresses while trying to communicate with the constellating LEO satellites that constitute the data plane in space. To leverage the SDN principle into the space-terrestrial integrated networks, our previous work [11] proposed an integration paradigm, where the IP addresses are statically associated with a given geographical area called Virtual Space Grids (VSGs) instead of directly binding to the satellites. Within this framework, a VSG can be viewed as a logical SDN switch with a static but virtual identifier to interface with the control plane on the ground, however, NFVOs and SFCs are not included in the solution.

To facilitate the deployment of SFCs in the constellating LEO satellites, we propose the scheme of Geosynchronous Service Function Chaining (GSFC) that provides a VNF manipulation approach to achieve robust forwarding graphs by taking advantage of the on-payload VNF instances in a predictable manner. This work is extended from [11], in which the VSGs are used as the virtual SDN switches, while in this paper we further leverage the VSGs as the virtual VNF containers and craft a "full-suite" reference implementation architecture. Specifically, instead of directly interfacing the moving satellites in the data plane, terrestrial control units constantly monitor the on-board VNF instances sequentially traversing the VSGs, which are utilized to construct the geosynchronous VNF assignment in space. With the terrestrial control plane viewing a fixed VNF assignment in the space data plane, compulsory operations such as periodical VNF migrations between the satellites to maintain the stability of the space SFCs can be significantly reduced. However, even with a geosynchronous VNF assignment, the varying underlying data-plane topology will still result in frequent changes to the SFC forwarding paths, triggering numerous updates to the routing policies. As such, stabilizing the SFC forwarding policies is necessary, and the key is to decouple the SDN-based flow rules from the underlying data-plane changes. To this end, we further propose a set of lightweight auxiliary mechanisms based on the GSFC framework to enable seamless path switching without being exposed to the control plane on the ground. Overall, the major contributions of this work are listed as follows:

- We propose the GSFC scheme for geosynchronous VNF assignment in constellating LEO satellite networks to ensure data-plane performance robustness against satellite mobility. To our knowledge, this is the first solution that leverages the inherent motion of LEO satellites to consistently maintain localized network service without the need for frequent VNF migration operations. Specifically, we introduce VSG-based virtual containers in the space data plane, where traversing satellites with VNFs on the payload ensure regional VNF availability. This study presents a reference architecture for VNF embedding in LEO satellites.
- We develop a sophisticated solution to address the technical challenge of large-scale network topology instability caused by LEO satellite constellation behaviours. A set of mechanisms is designed for making data-plane changes agnostic to the control plane, substantially reducing the control complexity between the space network segment and the ground. To achieve this, we decouple the SDN flow rules from the underlying data-plane topology by leveraging the VNF as the routing address for the SDN action field. This approach allows flow rules for SFC operations to remain valid despite the time-varying locations of satellites. Furthermore, the VNF forwarding graph is updated in a resolution-based manner, significantly reducing the complexity of policy updates—a critical factor in enabling Internet-scale routing across integrated space and terrestrial networks.
- We build an SDN-enabled constellation emulator that interconnects multiple VNF instances running on independent Virtual Machines (VMs) and conducted extensive simulations to evaluate the data-plane and control-plane performance of the GSFC scheme. The results verify that GSFC effectively avoids not only the VNF migrations between the LEO satellites but also the traffic disruption whenever a forwarding path is changed.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

II. BACKGROUND

Early development of the space and terrestrial communication networks are manually independent, while considering the huge success of the Internet achieved in the last decades, integrating satellite networks into terrestrial networks has become one of the main research topics [12], [13]. Recent works have explored how satellites can extend the coverage into underpopulated areas, offload the terrestrial network traffic [2], play the role of emergency networks without relying on ground infrastructure [14], and provide path diversity, especially for high-speed mobile users [15]. However, implementation approaches are not provided in these works. Further works such as [16], [17] attempt to enable IP-based traffic steering using LEO satellites, however with the conventional TCP/IP routing protocol suite, it is difficult to achieve efficient network management for the time-varying space-terrestrial topology. Some of the works make a breakthrough by signalling innovations, e.g., in [18], a path-aware framework is designed with extra path information in the control signals to enable fast path selections. However, with such a method network management can only be achieved by adjusting the link parameters, which cannot support a comprehensive and direct control of the network.

Direct control of the space-terrestrial integrated network is believed to be facilitated with the control and user plane separation model of the SDN paradigm, to this end, a number of efforts have been made. For example, preliminary work such as [19] showcases the scenario of directly implementing the terrestrial SDN solutions into the satellites, whereas the flow rule stability becomes an issue as the overhead LEO satellites constantly move away. While [20] propose to directly run an original Space Information Networking (SIN) routing algorithm at SDN controllers, where the routing decisions are pushed to both the LEO satellites and the terrestrial infrastructures. However, such a scheme requires tremendous computation resources. Take the widely used SIN routing algorithm, namely, snapshot sequence algorithm (SSS) [21] as an example, the algorithm divides the time-varying topology into several discrete static topologies, each of which is a snapshot of the constellation topology at a certain moment. Whenever a change is made, a new snapshot will be produced based on which the SDN controller needs to update the routing policies. As a result, the consumption of computation units is considerably large for large-scale networks. Attempts with specifically designed SDN algorithms have also been discussed, e.g., in [22] a Software Defined Routing Algorithm (SDRA) is proposed to provide centralized routing management for the frequent-change LEO satellite network. However, such an integration scheme runs two separated protocol suites for space and terrestrial segments, i.e., bridging the two network segments will require additional functions such as tunnelling or protocol conversion. On the other hand, in [23] the authors develop an integration architecture based on virtual nodes, which allows transmission of the terrestrial-space traffic using the same protocol suite. However, none of the aforementioned works have considered the SFC architecture in the design.

Although many of the recent works such as [24]–[28] have verified the advantage of optimizing the space-terrestrial integrated networks with NFV and SDN, however, these proposed schemes can fully play their roles only under the premise of existing cost-effective VNF manipulation schemes to reallocate the onboard VNFs for the moving satellites. Therefore, we argue that developing an appropriate VNF allocation manipulation scheme is a more fundamental issue for implementing NFV and SDN in space-terrestrial integrated networks.

III. GEOSYNCHRONOUS SERVICE FUNCTION CHAINING

In this section, we describe the design details of GSFC. The key idea is to circumvent the complexity on the control plane in dealing with large-scale and frequent SFC flow rule changes based on the traditional device-oriented flow assignments. In the architecture of GSFC, VNF types are mapped with Virtual Space Grids (VSGs) whose boundaries are determined by a set of space coordinates. Specifically, when a VNF type is assigned to a VSG, it will be instantiated by the corresponding VNF instances that are carried by the traversing satellites. In this way we decouple the VNFs from the satellites and build a dynamic binding relationship between the VNFs and the VSGs. Consequently, the VSGs are converted as the VNF containers which are stationary from the SDN controller's point of view. As a result, the flow rules are made based on the VSGs without caring about the actuarial locations of the VNF instances, and the validity of such flow rules will not be affected by the satellite-level topology dynamic. For clarity, we refer flow rules as GSFC flow rules for the rest of the paper.

A. Network architecture

The architecture of a GSFC-based network is depicted in figure 1, which mainly consists of three parts, namely, the SDN controllers and the NFVO servers on the ground, and the VSGs in the space. The SDN controllers are responsible for updating the routing policies for GSFC operations. To guarantee timely control signal delivery for a large region, the coverage of a controller can be restricted that will divide the network into multiple domains. In this case, flow rule synchronization is required between the controllers which can be achieved by [29], but for clarity this is not further discussed within the paper. Meanwhile, each domain is associate with an NFVO server not only to orchestrate the VNFs, but also to notify the SDN controller belonging to the same domain about the VNF changes. The notification scheme can be realized by the model designed in [30].

On the other hand, the GSFC space network is constructed by a set of VSGs, each of which plays the role of a logical

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

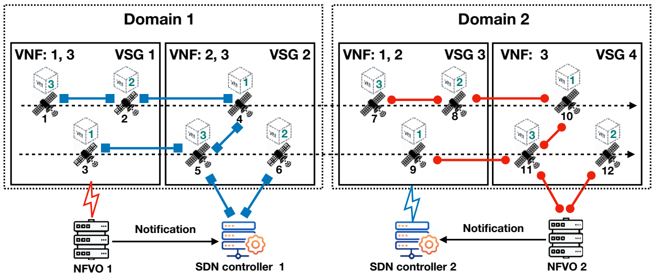


Figure 1: GSFC architecture.

network node. The physical instantiation of the VSGs relies on the traversing satellites, and by extension the logical ports of a VSG are also instantiated by the physical ports on the satellites. Therefore, the designed system requires each VSG to be instantiated by at least one satellite at anytime. In GSFC, the VNFs assignment is VSG-oriented, i.e., the VSGs are regarded as the virtual containers instead of the satellites. As a result, the NFVO will assign each VSG with a set of geosynchronous VNFs, where the initial VNF distribution can be obtain by any VNF allocation algorithms e.g., [31]–[33].

B. Bootstrapping

Once the LEO satellite constellation has been running in the intended orbit, GSFC bootstrapping will be conducted with the aim to enable secure control to the VSGs. To achieve that, control sessions will be created between the VSG-instantiating satellites and the controllers/NFVOs, such that the control signals are deliverable before the data-plane path has been established. Each controller/NFVO is responsible for the VSGs of its assigned domain, where the controller updates the routing policies and the NFVO orchestrates the VNFs. The domain-level and VSG-level topologies are determined in the network planning phase. Together with the satellite constellations, the VSG instantiation information can be calculated and therewith integrated into the satellites' ephemeris, where the satellites' positions over time are recorded. Thereby, the satellites can precisely instantiate the VSGs based on its own location without relying on the controllers. From a controller's perspective, it can also utilize the ephemeris to map its responsible VSGs with the traversing satellites, which are listed as the real-time control targets, i.e., a target list telling the controller which satellites are traversing its control domain.

Figure 1 shows the control session establishment, where the blue lines with solid squares depicted in domain 1 are the SDN controllers' sessions, while the red lines with solid circles depicted in domain 2 are the NFVOs' sessions. Overall, the GSFC bootstrapping scheme is extended from its counterpart introduced in [11], which follows the connect-to-existing-session principle adopted in [34]. Specifically, GSFC bootstrapping follows the listed rules:

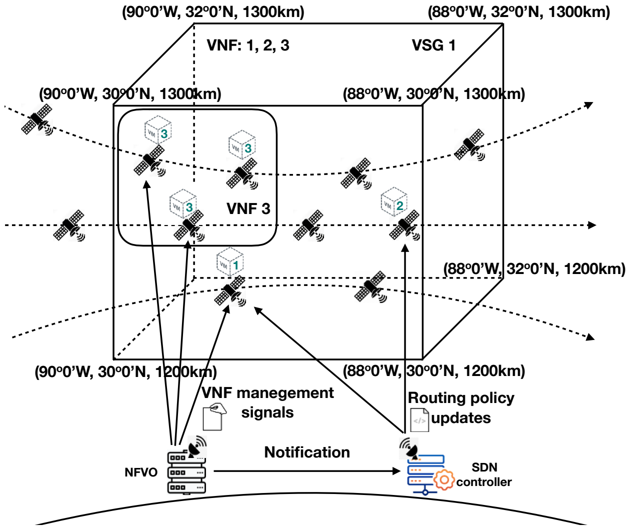


Figure 2: GSFC illustration.

1. When the bootstrap starts, each satellite periodically floods a request-for-control massage on all its ports in order to find connections to a controller.
2. A control session is established if the satellite is directly connected to the controller, or one of its neighbour satellites has established a control session with the controller. Such a flooding only takes place in the beginning when a satellite has not control session and it will not be regularly performed when satellites traverse a VSG.
3. Each satellite has a fixed ID (assigned before launching). The control session will only be established if the satellite ID[1] matches the controller's target list.
4. For VNF orchestration, the satellites can also follow 1-4 to acquire controls from NFVOs.

Once the bootstrap is done, the SDN control signals can be accurately delivered to the VSGs via the established control sessions, and the initial VNF instances can be pushed to the satellites by using the VNF onboarding artefacts [4], [35].

C. GSFC virtual space grids

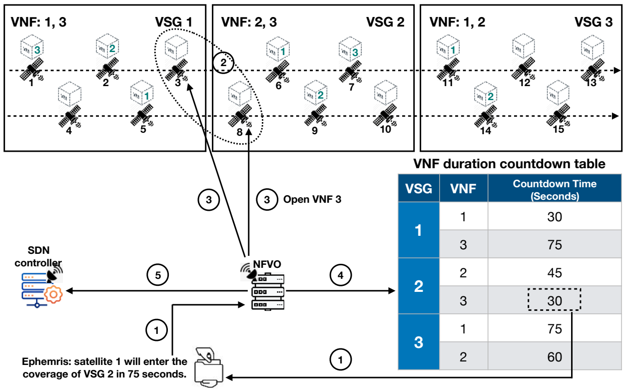
Figure 2 provides a brief illustration of a VSG in GSFC. For simplicity, we set the shape of the VSGs as cuboids, however other shape can be applied without change to the mechanism per se. The position of the VSG is given by the coordinates which consist of the information of longitudes, latitude, and altitude. As shown in the figure, VNF type 1, 2, and 3 are associated with VSG 1 where each VNF type can have one or multiple instances. For the case of a VNF type having multiple instances within a VSG (e.g., VNF 3), the corresponding instances will be grouped to provide service beyond basic routing such as load balancing. Based

---

[1] Authentication credentials in addition to the satellite ID can be deployed to enhance security, but this is not discussed further as it falls outside the primary scope of this paper.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807



VSG	VNF	Countdown Time (Seconds)
1	1	30
	3	75
2	2	45
	3	30
3	1	75
	2	60

Figure 3: Geo-consistency mechanism of the VNFs.

on the design principle of SDN and NFV, the routing policies (including the GSFC flow rules and other essential routing-related tables listed in table I) are generated by the terrestrial SDN controller, while the VNF instances are managed by the NFVO server. Therefore, the NFVO server should notify the VNF allocation changes to the SDN controller that belong to the same domain. On the other hand, because the GSFC flow rules are designed based on a VSG-oriented addressing principle, as a result, each function type in a VNF Forwarding Graph (VNF-FG) is pointed to a VSG instead of a specific satellite. To insert/modify a routing policy, the terrestrial SDN controller can utilize the satellites' ephemeris since the satellites are moving in a predictable manner. Thereby, the SDN controller can push the routing policy updates to the VSG based on the location of the satellites.

In summary, by viewing VSGs as logical network entities, GSFC constructs a VSG-based space SFC system, which aims to reduce the required flow rule updates as well as the VNF migrations. To realize such a system, we specifically design a set of mechanisms which are discussed in the following subsections.

D. *Geo-consistency of the VNFs*

To maintain the geo-consistency of the VNFs, if the loss of a VSG's originally assigned VNFs is foreseeable (e.g., when the last instance of a specific VNF type leaves the VSG and no ingress satellite carries a corresponding VNF instance), the NFVO server will take action to fill the gap.

Figure 3 illustrates the VNF Geo-consistency maintaining mechanism of GSFC. Consider the scenario shown in the figure, where VSG 1 is originally assigned with VNF types 1, 3, VSG 2 is originally assigned with VNF types 2, 3, and VSG 3 is originally assigned with VNF types 1, 2, respectively. A snapshot of the satellite locations of the VNF instances for each VSG is as shown, and we set each satellite has the capacity to host one VNF. When satellite 7 leaves VSG 2, there will be a vacuum period of VNF 3 at VSG 2 until satellite 1 has arrived, therefore, establishing new instances of VNF 3 is required for preserving the VNF consistency. To this end, the NFVO server maintains a VNF duration countdown timetable for each VSG, and it will proactively establish the required VNF instances based on the trajectory of the VNF instantiation satellites. Briefly, the details of our design are show as follows:

1) The NFVO server first determines whether establishing a new VNF instance is necessary. This is achieved by verifying the arrival timeliness of satellites carrying the corresponding VNF instance, using information obtained from the satellite ephemeris. A new VNF instance needs to be established when the countdown time of this VNF at a VSG drops below the arrival time of the earliest ingress satellite carrying the required VNF type.
2) To establish new VNF instances, the NFVO server should check the availability of the satellite within the VSG as well as the ingress satellites, and thereby identify a set of satellites on which the new VNF instances are to be established.
3) The NFVO server now pushes the VNF establishment signal to the target satellites, which can follow the conventional VNF onboarding process [4].
4) Once the new VNF instances are established, the NFVO server will update its VNF duration countdown timetable. In addition, the timer regarding to a specific VNF is also updated whenever a satellite with the corresponding VNF has entered the VSG.
5) Lastly, if the NFVO server fails to find any feasible satellite to host the required VNF instance, it should notify such information with the local SDN controller, and the controller is responsible for further sharing this information with other controllers. In this case, the SDN controllers should divert flows to other paths until the NFVO server has found a solution (The detailed routing process is provided in Section III F and G).

E. *The satellite-VNF resolution mechanism*

A VNF-FG[2] is a set of VNF network forwarding paths which describe the VNF sequences of a service chain. In GSFC, the VNFs are instantiated by the satellites. This will require a satellite-VNF resolution mechanism to ensure the satellites obtaining the VNF instantiations from the NFVO. Since the VNFs are managed by the NFVO, the satellite-VNF mapping will be reported to the SDN controller such that the regarding satellite-VNF resolution updates can be sent to each VSG in a accurate and timely manner with the help from the constellation ephemeris.

Figure 4 depicts the designed satellite-VNF resolution mechanism. As shown in the figure, VSG 1 has 3 instances of VNF type 1 which are instantiated by satellite 1, 2, and 3, meanwhile, the instance of VNF type 2 is instantiated

---

[2] To avoid confusion, for the rest of the paper the term VNF-FG also includes network forwarding path, except where differentiation is required.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

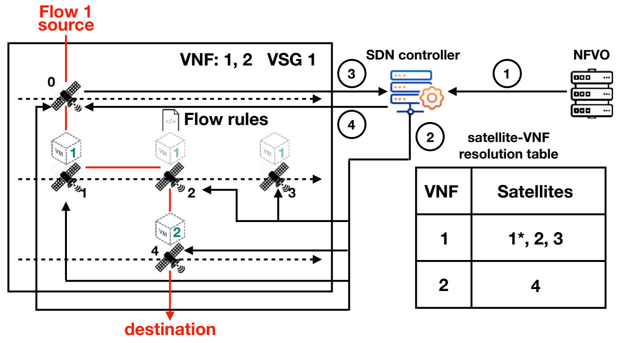


Figure 4: The satellite-VNF resolution mechanism.

by satellite 4. Imagining the following scenario where flow 1 initialed from satellite 0 requires to visit VNF 1 and 2 one after another before it leaves VSG 1. In this case, the interactions between the satellites, NFVO, and SDN controller take the following steps:

1) At any time, the NFVO server keeps the latest satellite-VNF mapping for the SDN controller, i.e., whenever it has opened/removed a VNF instance from a satellite, a notification will be sent to the SDN controller.
2) The SDN controller is responsible for updating the satellite-VNF resolution table to all the satellites within the VSG. In such a scenario, the instantiation satellite IDs (e.g., In VSG 1, satellite 1 is the current instantiation satellite[3] for VNF 1, while satellite 2 and 3 are the standbys, and VNF 2 is currently hosted by satellite 4.) are included. The detailed update scheme is further discussed in section III-H.
3) By the time when flow 1 arriving at satellite 0, the satellite will first lookup its GSFC flow rules. If none of the entries is matched, it will send an inquiry message to the SDN controller for routing information.
4) In response to this inquiry message, the SDN controller replies satellite 0 with the regarding GSFC flow rules.

F. GSFC flow rule action to satellite egress port

In GSFC, the flow rules are decoupled from the VNF instantiation satellites. Specifically, for the action value of a flow rule, instead of directly appointing a specific satellite port, GSFC flow rules use the next-hop VNF as the "egress port". Since the VNFs are bound with the VSGs, therefore the flow rules can be generated without caring the actual VNF instantiatioin satellites. In this case, when a satellite receives a flow, a tailored mechanism to dynamically map the next-hop VNF to a local physical egress port is required. To achieve that, a satellite will rely on its satellite-VNF resolution table in which the up-to-date VNF instantiation satellites are provided. However, the resolution table itself

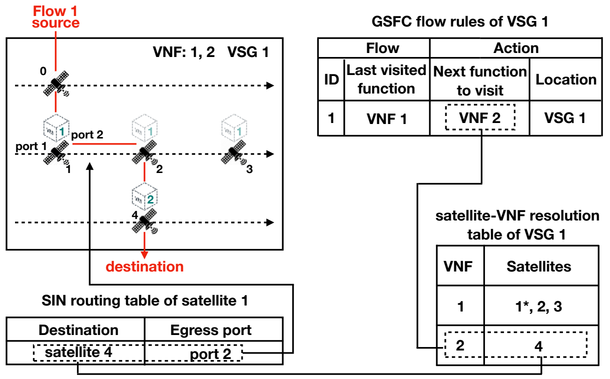


Figure 5: GSFC flow rule to satellite egress port mapping.

does not contain the next-hop port number information but only the next-hop satellite. Therefore, the mapping from the satellites to the actual egress port is required, in which case, the well-developed SIN routing protocols such as [21], [36] can be utilized, whereby the satellite can identify through table-lookup the egress port.

Figure 5 gives a diagram of how a satellite can obtain the egress port based on the GSFC flow rules and the satellite-VNF resolution table. Taking satellite 1 as an example, the VNF-FG of the flow is: Source−VNF 1−VNF 2−Destination. As shown in the figure, to identify the VNF-FG fragment, the flow rule contains a field that indicates the latest VNF that the flow has visited. Based on the action value, satellite 1 knows the next-hop VNF of the flow is VNF 2. In this case, the satellite will turn to the satellite-VNF resolution table which shows VNF 2 in VSG 1 is instantiating by satellite 4. Following that, the satellite will retrieve its SIN routing table provided by a third-party routing protocol to determine to which port it should forward the flow. Here we use the Orbit Prediction Shortest Path First (OPSPF) [36] as an example of the SIN routing protocol implementation, the SIN routing table shows that from satellite 1 to satellite 4, the next-hop satellite is satellite 2 which is directly connected to port 2 of satellite 2. As a result, satellite 1 will deliver the flow to VNF 2 via port 2.

G. Packet forwarding

The GSFC-based routing policy tables are classified into 2 categories, namely, the VSG-based tables (as shown in table I) and the satellite-based tables (as shown in table II). To determine the GSFC routing path, a VSG-level metric is required. For clarity, we assign each VSG and inter-VSG link with a fixed metric for evaluating the cost of the paths where the metric has taken into consideration the VSG's internal constellation dynamics. Such a design is a common strategy to address the time-dynamic properties of the network [37], nevertheless, a dynamic metric design is also an option. Given the VSG-level metric and the VNF allocation, the GSFC

---

[3] The default satellite is labeled with '*', which can be determined based on various criteria such as longest duration, lowest utilization level.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

Table I: GSFC VSG-based routing policy tables

VSG	VSG forwarding base		VSG-Satellite resolution table (UTC 17:25:34)		Satellite-VNF resolution table (UTC 17:25:34)		Terminal registration table	
ID	Destination	Egress VSG port	VSG port	Satellite port	VNF type	Satellites	Terminal	VSG port
1	VSG 2	port 3	port 1:	S1 port 1	1	5	Source of Flow 1	port 2
	VSG 3	port 3	port 2:	S5 port 2	3	1		
			port 3:	S3 port 3	2	2		
2	VSG 1	port 1	port 1:	S6 port 1	1	6	Destination of Flow 1	port 2
	VSG 3	port 3	port 2:	S7 port 2	3	7		
			port 3:	S10 port 3	2	9		

Table II: GSFC satellite-based routing policy tables

Satellite	GSFC flow rules				SIN routing table	
ID	Flow		Action		Destination	Next-hop satellite
	ID	Last visited function	Next function to visit	Location		
5	1	Source	1	VSG 1	S3	Direct-connected
	1	1	3	VSG 2		
3	1	1	3	VSG 2	S5	Direct-connected
					S6	Direct-connected
6	1	1	3	VSG 2	S3	Direct-connected
					S7	Direct-connected
7	1	1	3	VSG 2	S6	Direct-connected
	1	3	Destination	VSG 2		

routing path can be determined with optimization algorithms such as [38], [39].

Figure 6 provides an example of flow 1's (Source−VNF 1−VNF 3−Destination) hop-by-hop packet forwarding based on table I and II. By receiving flow 1, satellite 5 will first identify the flow as the "Source−VNF 1" fragment and based on the GSFC flow rule, the packets should be forwarded to VNF 1 at VSG 1. From the satellite-VNF resolution table of VSG 1, VNF 1 at VSG 1 is hosted by satellite 5 itself, and thus the data will be passed to the corresponding VM for the service. Following that, satellite 5 will continue lookup the GSFC flow rule for the "VNF 1−VNF 3" fragment, and "the next function to visit" is pointing to VNF 3 located at VSG 2. To acquire the routing path to VSG 2, satellite 5 will turn to the VSG forwarding base of VSG 1 which indicates the egress virtual port from VSG 1 to VSG 2 is port 3. Based on VSG 1's VSG-Satellite resolution table, satellite 5 knows port 3 of VSG 1 is currently instantiated by port 3 of satellite 3. In this case, satellite 5 will forward flow 1 to satellite 3 which is directly connected based on its SIN routing table. When satellite 3 receives flow 1, an identical process will be performed and satellite 3 can forward flow 1 to VGS 2 via its port 3 which is directly connected to satellite 6. From satellite 6's GSFC flow rule, the satellite knows VNF 3 at VSG 2 is the next function for flow 1, and based on VSG 2's satellite-VNF resolution table, the flow should be forwarded to satellite 7 which is directly connected. In satellite 7, flow 1's data will be processed by VNF 3, which is followed by transmitting the "VNF 3−Destination" fragment. For the last fragment, satellite 7 obtains that the destination of flow 1 is attaching to VSG 2 based on its GSFC flow rule. In this regards, satellite 7 will turn to its terminal registration table which suggesting the access VSG port of the destination is port 2 of VSG 2. Finally, from the VSG-Satellite resolution table, VSG 2's port 2 is currently instantiated by satellite 7's port 2, and thus the flow is delivered.

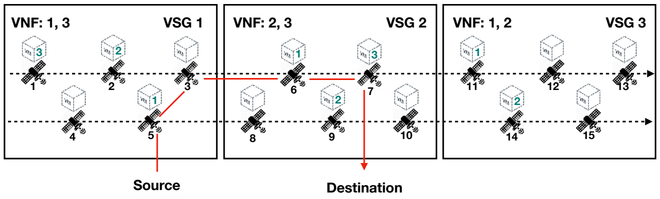


Figure 6: Inter-VSG packet forwarding.

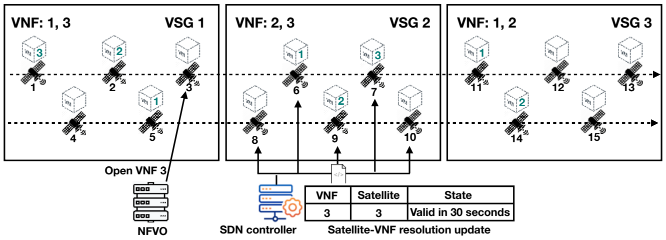
H. Routing policy update mechanisms

The routing policy tables are generated, managed and hosted by different entities. In the context of GSFC, all the satellites within one VSG will share and carry the VSG-based tables of that specific VSG, while each of the satellites hosts its own satellite-based tables. Due to the controller's responsibility for centralized policy management, the VSG-based tables (except the satellite-VNF resolution table) and the GSFC flow rules, are generated and maintained by the terrestrial controllers. In terms of the satellite-VNF resolution table, because of the centralized VNF manipulation principle, it is initialed and managed by the NFVO.

Also, each routing policy table has its own update mechanism. Specifically, updating the VSG-satellite resolution table and the SIN routing table does not need to rely on a terrestrial controller. A satellite can self-update its VSG-satellite resolution table based on the ephemeris because the resolution information is predefined. For the SIN routing table, each satellite will run a unified SIN routing protocol instance such as [36], thereby, timely update is guaranteed by the maturely developed SIN routing protocol suits. In addition, we consider no changes in VSG port settings after the network planning phase due to administrative purposes. Therefore, the terminal

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807



VNF	Satellite	State
3	3	Valid in 30 seconds

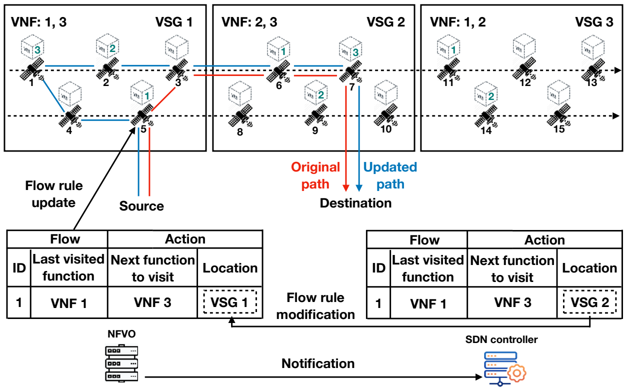
Figure 7: Satellite-VNF resolution update mechanism.

registration table is stable. Updating the rest of the routing policy tables will involve the terrestrial controllers based on a periodic or an event-triggered manner, which are elaborated as follows:

1) Periodic updates: Since the motion of a satellite constellation is predictable, the VSG forwarding base can be periodically updated. The VSG forwarding base contains the routing information at the VSG level, and it needs to be embodied by the traversing satellites. That is, a traversing satellite will execute the VSG forwarding base of a VSG while switching to another when it enters a new VSG. In this case, an LEO satellite needs to acquire the corresponding flow rules before it enters the VSG, and after, that the satellite should activate the new flow rules once it has entered the VSG. In order to achieve seamless data-plane performance, we apply the pre-loading mechanism developed in [11] to proactively renew the VSG forwarding base, where a buffer zone is allocated between two neighbouring VSGs to provide the terrestrial controller to deliver the corresponding updates to the satellites. In this paper, we do not aim to optimize the table/update installation mechanism because it is orthogonal to the difference in design of GSFC as well as conventional LEO satellite networks without geosynchronous VNFs. Therefore, we set the buffer zone size fixed at a safe level.

Specifically, to provide sufficient time for periodical VSG forwarding base installation, the size of a buffer zone should cover its end-to-end installation time, which mainly consists of two parts: i) the signaling propagation time which is proportional to the distance between the target satellite and the controller; ii) the installation time for the VSG forwarding base. The quantified measurement of the two parts are studied in [40]–[43]. Just to name a simple example, considering a scenario where the controller-satellite signaling propagation time is 20 ms [44], and with an SDN-based protocol instance the average installation time per VSG forwarding base entry is 3.3 ms [43]. In such a scenario, the buffer zone should at least provide 350 ms for a satellite if there are 100 entries to be installed/updated. For the orbit with LEO satellites moving at a velocity of 7.8 km/s [45], the edge of the buffer zone need to be allocated 2.73 km ahead from the next VSG or further.

2) Event-triggered updates: For the update requirements related to irregular events, e.g., opening new VNFs instance in satellites, event-triggered updates will be conducted for the corresponding routing policy tables, namely, the satellite-VNF resolution table, and the CSFC flow rules.



Flow		Action	
ID	Last visited function	Next function to visit	Location
1	VNF 1	VNF 3	VSG 1

Flow		Action	
ID	Last visited function	Next function to visit	Location
1	VNF 1	VNF 3	VSG 2

Figure 8: The flow rule update mechanism.

As discussed in section III-E, the satellite-VNF resolution table is managed by the NFVO server but the SDN controller is responsible for sending updates to the satellites based on the centralized management principle. Figure 7 depicts the satellite-VNF resolution updates triggered by opening new VNF instances due to the requirement of geo-consistency. As shown in the figure, VNF 3 of VSG 2 will be invalid when satellite 7 enters VSG 3. Instead of diverting all the traffic in VSG 2 to new paths before satellite 1 has entered VSG 2, the NFVO server decides to open a new instance of VNF 3 at satellite 3 such that potential period of missing VNF 3 at VSG 2 can be avoided. In this case, the SDN controller will proactively send the regarding update to all the satellites in VSG 2, and the update should take effect after a certain time based on the ephemeris. In addition, VNF dynamics caused by satellite mobility will also trigger satellite-VNF resolution updates. For example, when satellite 9 leaving and satellite 2 entering VSG 2, the controller should also update the latest VNF instantiations to the satellites in VSG 2. It is worthy noting that, the controller does not update the dynamics of a passing VNFs. For example, VNF 1 is not assigned to VSG 2, thus, satellite 5 entering VSG 2 will not trigger the satellite-VNF resolution updates with regards to VNF 1.

If VNF geo-consistency cannot be maintained in a foreseeable scenario, e.g., the NFVO server fails to locate a suitable satellite for deploying a new VNF instance, flow diversion becomes necessary. In such cases, the SDN controller is responsible for delivering timely GSFC flow rule updates to the VSGs. Specifically, the SDN controller should recalculate the hop-by-hop VSG path for flows passing through VGSs at risk of losing in-serve VNFs. Upon receiving risk alarms from the NFVO server, the SDN controller proactively pushes updates to the involved satellites. When the NFVO server subsequently identifies available satellites to host new VNF instances, a VSG refilled notification is sent to the SDN controller. At this point, the SDN controller can choose either to restore the original flow rules or maintain the current

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

Table III: Simulation Parameters

Parameter	value
Radius of the Earth	6378 km
Orbit altitude	1100 km
Coverage duration per satellite	5 minutes
Inter-Satellite link delay	12 ms
Terrestrial-satellite link delay	12 - 60 ms
Number of domains	2
VNF migration process time	30 seconds
Number of orbits	3
Number of satellites	48
Number of assigned VNF type per VSG	1 - 3
Number of VSGs	2 - 6
Number of VNFs per SFC	2 - 4
Service processing rate per VNF	200 Mbps

configuration. This decision should consider both routing efficiency and signaling overhead.

Figure 8 shows such an example where flow 1 (Source−VNF 1−VNF 3−Destination) is assigned to access VNF 3 at VSG 2, while a vacuum period for VNF 3 at VSG 2 is notified to the SDN controller by the NFVO server. In this case, the SDN controller will recalculate the route, and specifically change flow 1's flow rule action from "VNF 3 at VSG 2" to "VNF 3 at VSG 1". The update will be sent to satellite 5 once the calculation has finished, and the result is stored at the SDN controller to provide instant replies to the later access satellites of flow 1.

Overall, by this design, only the VSG-Satellite resolution table needs to be frequently updated due to the constellation dynamic, while other tables are stable unless the consistency of VSGs and/or VNFs breaks. Since the constellation behaviours are predictable, the VSG-Satellite resolution table can be updated in real time based on the ephemeris.

IV. PERFORMANCE EVALUATIONS

In this section, we evaluate the GSFC scheme from both the data-plane and control-plane performance. Although having all VNF types on every satellite provides the best user-end experience, it is impractical due to the high deployment and hosting cost, thus, we do not consider this scenario in this work. The benchmark SFC schemes for comparison in the simulation are namely, Full Migration (FM) and Full Reassignment (FR), where the principles are respectively in line with the benchmarks used in [46] and [47]. Specifically, FM periodically migrates each VNF instance from their host satellite to the next upcoming counterpart, while FR constantly reassigns the flows to new paths based on the latest VNF/satellite locations. Accordingly, we set the migration process time to 30 seconds aligning with the VNF migration instances shown in [8]. For intelligibility, throughout the simulation, we focus on the scenario where the VSGs are set fixed^4, and we do not consider the scenario of satellite failures, because such issue is orthogonal to the difference in design of GSFC and conventional satellite SFC schemes without virtual addressing. Without loss of generality, we apply the walker-type constellation for simulation which is adopted by the Starlink and Iridium systems [48], [49]. The simulated constellation is formed of 48 isometric satellites distributed over 3 orbits, where each satellite is capable of hosting 1 VNF instance, and the coverage duration per satellite is set to 5 minutes [9]. Besides, the radius of the earth is set to 6378 km [48], and the altitude of the LEO satellites is set to 1150 km [2]. The whole constellation is emulated on NE-One [50] with a tailored ephemeris script. In addition, the VNFs are hosted in a set of mutually independent virtual machines that are bridged over with the simulated satellites. Overall, the key simulation parameters are summarized in table III.

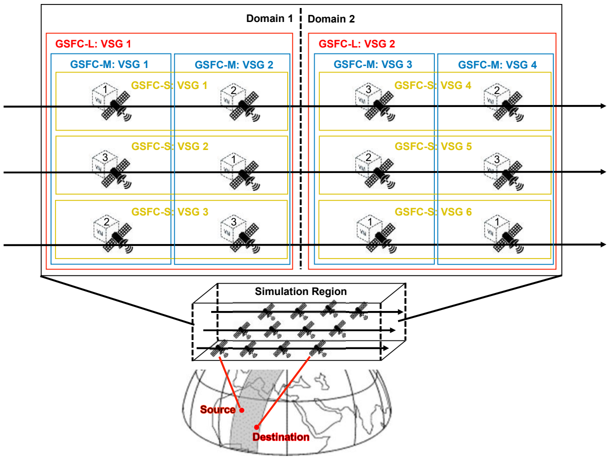


Figure 9: Data/Control-plane simulation diagram.

A. Data-plane performance

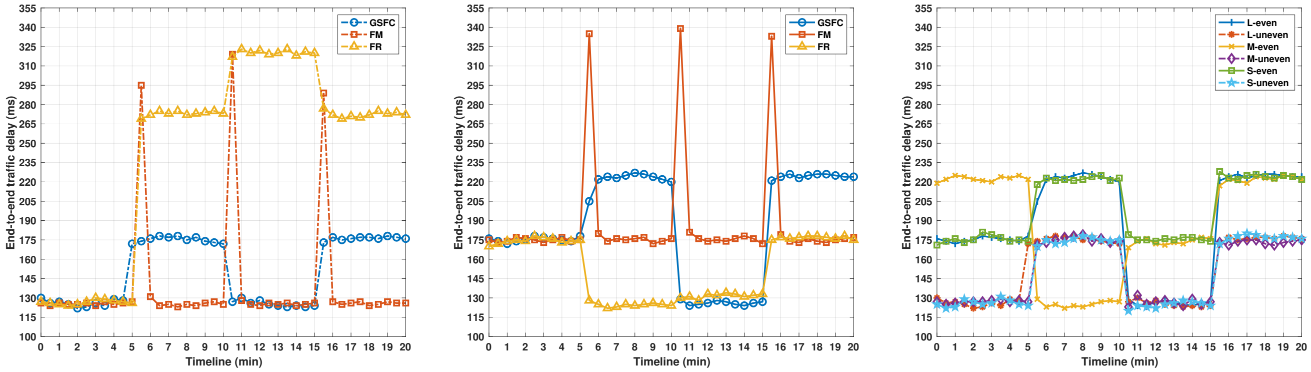
Now we investigate the differences in the data-plane performance between the GSFC and the two benchmark schemes. In this part, the simulations are conducted on a fixed region with multiple fixed VSGs (shown in figure 9). Specifically, we introduce 3 VSG plans, namely, GSFC-S, GSFC-M, and GSFC-L to divide the simulation region into 6, 4, and 2 equal-size VSGs (i.e., a larger VSG number corresponding to a smaller per VSG size), respectively. In this setting, each VSG is assigned with a set of VNFs, and the number of assigned VNFs per VSG is set up to 3.

On the other hand, a simulated flow is described by its source, destination, and the requested SFC. The sources and destinations of the flows are respectively distributed on the left and right bound of the region, which is to simulate the scenario of transmitting a popular flow type from one side of the region to another. The number of VNF per SFC is

---

[4] Dynamic VSG is one of the design options, however, optimization on VSG is out of the main scope of this paper.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.



(a) (b) (c)

Figure 10: Average traffic delay: (a) uneven VNF distribution; (b) even VNF distribution; (c) with different VSG plans.

set to 3 [51]. Considering the data-plane performance of an SFC-based flow is VNF location sensitive, we define two VNF distribution cases, namely, the even VNF distribution and the uneven VNF distribution. As the name suggests, the even VNF distribution has all the 3 VNF types uniformly distributed among the satellites, while for the uneven VNF distribution, VNF instances with the same type have a concentrated distribution. Specifically, for a case with n VNF types, we define the even VNF distribution as the number of repeated VNF types in a row (on both along&cross-track neighboring satellites) is less than n. On the other hand, the uneven VNF distribution is defined as the cross-track neighboring satellites having the same VNF type. Meanwhile, the ISL delay between two neighbouring satellites is set to 12 ms with a 1% fluctuation range introduced to describe the ISL time-varying characteristics, which is in line with [52], [53].

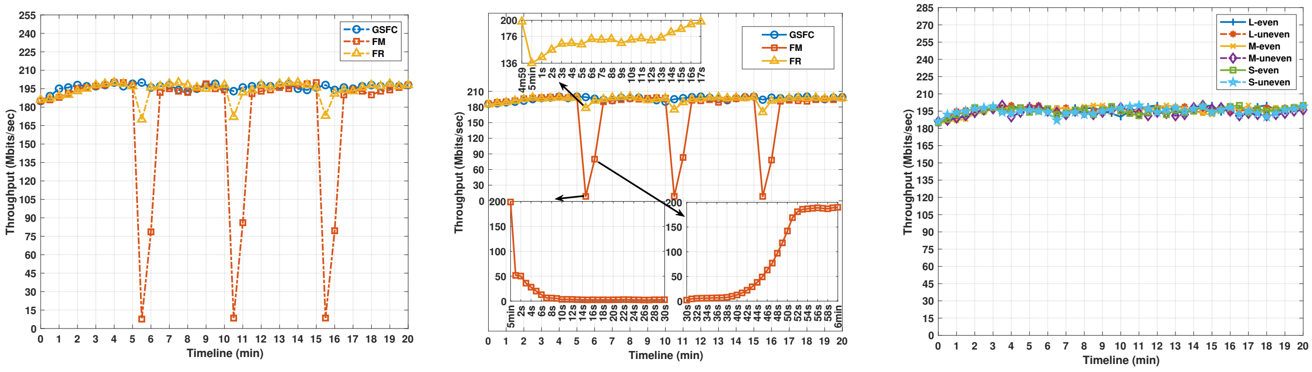
1) Delay: Since the end-to-end traffic delay of a flow varies with the VNF allocation dynamic caused by the constellation behaviours. In this sense, the delay variation becomes one of the key indicators for the transmission stability of the 3 VNF manipulation schemes.

Figure 10 (a) shows the delay variations over time for the uneven VNF distribution case. Such a VNF distribution is typical in the scenario where the frequent-required functions are dissimilar across the region. As shown in the figure, the delay fluctuation with GSFC is between 123 ms and 179 ms, while the FR's counterpart is between 124 ms and 323 ms. This shows that GSFC is less VNF-distribution sensitive compared to FR, because of its VNF manipulation ability. By contrast, FM mechanically restores the VNFs back to their original corresponding region, therefore, its delay performance will not be affected by the initial VNF distribution. As a result, the users will experience a sharply increased end-to-end delay (around 300 ms) when the VNF migrations take place. That is to say, FM can keep the traffic delay at the original level, but with a periodical high migration cost.

Figure 10 (b) shows the delay variations for the even VNF distribution case. This distribution is commonly seen in the scenario where the frequent-required functions are similar across the region. Compared to the previous experiment, FM remains a similar delay variation, because of its VNF-distribution-regardless migration mechanism. FR's delay variation performance in this scenario matches up to GSFC's delay variation performance (both are around ± 45 ms). This makes sense because a reassigned flow from FR has a higher possibility of finding a loop-free path with even distributed VNFs. It is worth noting that, although FR achieves a lower overall delay, it can cause a distinct throughput deduction (details are presented in the next part), due to the path recalculation for the reassigned flows.

Figure 10 (c) shows how the delay variations of GSFC are affected by the VSG plans. As shown in the figure, different VSG plans can lead to different delay curves. For the even VNF distribution scenario, the GSFC-S plan will need to regularly conduct proactive migrations to maintain the assigned VNF types because of its smaller VSG size. However, such VNF adjustments can benefit the traffic routing in the way of deploying the VNFs in proper order toward the destination. As a result, the end-to-end traffic delay in this case shows a fluctuation of 50 ms, which is smaller than the other two VSG plans' counterparts. Both the GSFC-M and GSFC-L VSG plans have sufficient VNF instances to guarantee full coverage of the assigned VNF types for each of the VSG due to their larger VSG size, therefore, no VNF migration is triggered in these two cases. Although the three VSG plans achieve a similar average traffic delay of around 187 ms, the delay fluctuation of GSFC-M/L becomes 100 ms, this is caused by SFC's intermediate VNFs being located in the reverse direction of the destination due to no VNF adjustments. On the other hand, for the uneven distribution scenario, the delay curves of the 3 VSG plans show similar behaviours, where the average traffic delay is 150 ms with similar fluctuations between 120 and 180 ms. Such a scenario

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.



(a) (b) (c)

Figure 11: Average throughput: (a) uneven VNF distribution; (b) even VNF distribution; (c) with different VSG plans.

Table IV: Delay by SFC length

No of VNF types per SFC	GSFC-S				GSFC-M				GSFC-L				FM				FR			
	even min	even max	uneven min	uneven max	even min	even max	uneven min	uneven max	even min	even max	uneven min	uneven max	even min	even max	uneven min	uneven max	even min	even max	uneven min	uneven max
2	121 ms	124 ms	122 ms	123 ms	121 ms	225 ms	122 ms	178 ms	122 ms	175 ms	125 ms	176 ms	121 ms	329 ms	122 ms	340 ms	122 ms	176 ms	122 ms	179 ms
3	171 ms	228 ms	120 ms	180 ms	122 ms	225 ms	123 ms	179 ms	124 ms	227 ms	122 ms	178 ms	172 ms	339 ms	123 ms	319 ms	122 ms	176 ms	124 ms	323 ms
4	172 ms	178 ms	175 ms	183 ms	175 ms	278 ms	123 ms	223 ms	176 ms	278 ms	175 ms	228 ms	175 ms	329 ms	121 ms	339 ms	176 ms	279 ms	121 ms	360 ms

happens when none of the VNG plans can fully cover the assigned VNF types without migrations, and the VNFs of the 3 VSG plans converge to an identical distribution.

Overall, we list the minimum and maximum traffic delay of the 3 VNF manipulation schemes in table IV, where the number of VNFs per SFC is set from 2 to 4. Under the same circumstances, a shorter SFC experiences a lower minimum traffic delay because the probability of having a proper-order SFC with 2 VNFs on the shortest path is greater than with 4 VNFs. Compared to the two benchmark schemes, GSFC achieves lower maximum traffic delays in the uneven distribution scenario, and this advantage can be further expanded with a longer SFC. Specifically, the maximum traffic delay of GSFC grows less than 60 ms with SFC's length increased from 2 to 4, while its FR counterpart grows more than 180 ms. The results suggest GSFC can provide lower delay Quality of Service (QoS) in the uneven VNF distribution scenario, especially for long SFCs.

2) *Throughput:* In this part, we present the corresponding throughput variations over time, which should shed light on, to what extent the throughput is affected by the VNF migrations with the 3 VNF manipulation schemes.

Figure 11 (a)/(b) shows the overall throughput variation for the uneven/even VNF distribution case, where the maximum reachable throughput is mainly restricted by the VNF service processing rate. Because the overall throughput curve of each VNF manipulation scheme, has identical behaviours in both of the VNF distribution scenarios, thus, for simplicity, we only present the ”zoom-in” view in figure 11 (b).

As shown in figure 11 (a), with the initial VNF allocation, the throughput curves of the 3 VNF manipulation schemes steadily climb from 185 Mbps to 200 Mbps, which is limited by the service processing rate of the virtual machines. Whereas the VNF migration takes place, the throughput curve of each scheme shows different behaviours. Under the combined effects of the proactive VNF migration and the routing change agnostic to beyond the third layer (i.e., the network layer), GSFC can keep the peak throughput level without caring about the constellation behaviours. For FR, although it fails to achieve a regular delay variation in the uneven VNF distribution scenario, its throughput deduction stabilises at 32%. Lastly, the throughput will drop to near 0 Mbps without proactively migrating the VNFs, which can be verified by the throughput curve of FM.

Further details of the throughput deductions are presented in figure 11 (b). For FR, the throughput deduction is mainly caused by the path recalculation for the reassigned flows. As shown in the figure, the throughput drops to 136 Mbps, and then it gradually climbs back to the full level in the next 17 seconds. This is as expected because the flow control mechanism [54] from the transport layer is triggered, due to its awareness of the flow reassignment events. A similar phenomenon is also found in the FM VNF manipulation scheme. Specifically, the throughput drops to 2.65 Mbps in 10 seconds, which then recovers to 190 Mbps in 44 seconds. The results indicate that, although FR's flow reassignment mechanism causes little impact on the traffic delay, it can greatly affect the throughput performance. Meanwhile, the results also show the significant cost of FM's VNF migration

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

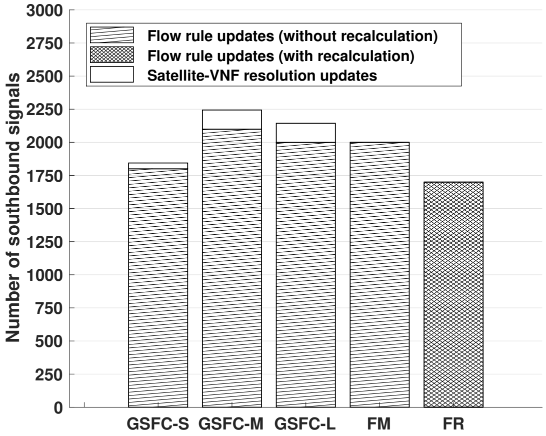


Figure 12: Southbound signalling overheads.

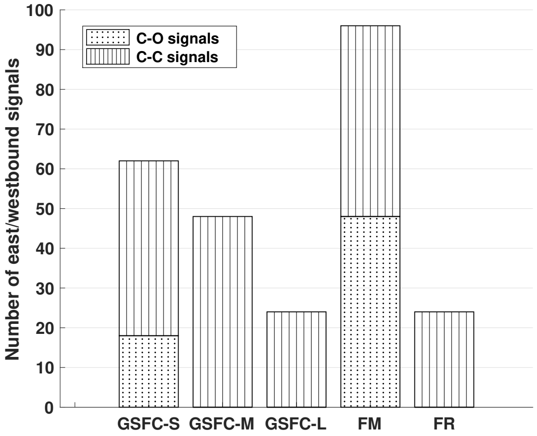


Figure 13: East/Westbound signalling overheads.

mechanism.

Lastly, figure 11 (c) shows the corresponding throughput variations of GSFC with different VSG plans. As the results suggested, the throughput is full as long as with a VSG plan where conducting proactive VNF migration is infeasible. Therefore, GSFC's throughput performance can be considered insensitive to VSG plans.

B. Control-plane performance

Lastly, we analyse the control-plane performance from the aspect of southbound and east/westbound signalling overheads. The results for this part are the aggregated control-plane signals of 100 flows corresponding to the network settings used in the data-plane simulations. For clarity, we do not differentiate the results based on the VNF distribution, as the difference is negligible. In the context of GSFC, control-plane southbound signals are the controller-satellite signals, while the east/westbound signals are the controller-NFVO (C-O) signals and the inter-controller (C-C) signals in the scenario of multi-domains.

1) Southbound signalling overheads: Figure 12 presents the southbound signalling overhead of different types. We note that the southbound signals include the updates of the VSG forwarding base, Satellite-VNF resolution, and GSFC flow rules. Since we do not consider the scenario of satellite failures, thus, the result does not contain VSG forwarding base updates. As shown in the figure, the major overheads are the flow rule updates, where FR requires continuous recalculations for the routing paths to sustain the service, while for GSFC/FM, such recalculations are not required due to their network layer consistency. Although FM also triggers no path recalculation, it relies on heavy VNF-migration jobs. In comparison to the two benchmarks, GSFC introduces the Satellite-VNF resolution updates in an amount of 44, 144, and 144, for GSFC-S, GSFC-M, and GSFC-L, respectively, which accounts for 2.4%, 6.4%, and 6.7% of the total southbound signalling overheads. Nevertheless, the amount of Satellite-VNF resolution updates does not scale up with the increase of flow numbers, because the Satellite-VNF resolution is shared between the flows.

Consequently, at a price of less than 7.9% southbound signalling overheads (1844 updates with GSFC-S compared to 1709 updates with FR), GSFC provides a solution without flow rule recalculations. This is a significant advantage in scenarios with large-scale and complex networking systems because in most cases, finding the optimal SFCs for the flows is an NP-hard problem [6]. While compared to FM, GSFC can reduce the number of VNF migrations without necessarily introducing higher southbound signalling overheads (the detailed reduction in VNF migration numbers is further discussed in the next part).

2) East/Westbound signalling overheads: To investigate GSFC's signalling overheads in the scenario of multi-domains, in this simulation, we divide the simulated region into 2 domains and each one has 1 controller and 1 NFVO.

Figure 13 shows the east/westbound signalling overheads of both the C-O and C-C signals. Since the C-O signals are generated by the VNF migration events, therefore, FR produces no C-O signals. By contrast, GSFC-S produces 18 C-O signals which is 62.5% less than that produced by FM. Moreover, such advantage can be further enlarged by implementing a VSG plan with bigger VSGs, because bigger VSGs can effectively reduce the opportunity of encountering the scenario of missing the assigned VNFs. This can be justified by that both GSFC-M and GSFC-L produce zero C-O signals. Combining the southbound performance, the results suggest that larger VSGs are effective in avoiding VNF migrations, but at the cost of requiring more satellite-VNF resolution updates.

In the scenario where the network is divided into multiple control domains, synchronization of routing policies between SDN controllers is essential. Specifically, when a satellite enters a new domain, its routing policies will be managed by the controller of the ingress domain and its payload VNFs will be orchestrated by the corresponding domain NFVO, thus, the controller of the ingress domain should synchronize any

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

corresponding changes to the controller of the egress domain. For GSFC, the information required for synchronization is the VSG-Satellite resolution table, the VSG forwarding base, and the Satellite-VSF resolution table. Since satellite failures are not considered in the simulation, synchronizations for the VSG-Satellite resolution table and the VSG forwarding base will not be triggered because the VSG topology is constant. Accordingly, the C-C signals here mainly indicate the synchronizations of the Satellite-VSF resolution information between the domains.

As shown in the figure, FM and FR have the maximum and minimum number of C-C signals (i.e., 48 and 24), respectively, where FM's C-C signals are fully caused by the VNF migration events, while the FR counterparts are caused by the VNF cross-domain events. In terms of GSFC, the following circumstances hold: 1. If the VSG sizes are sufficiently large to avoid migrating VNFs, and the satellite cross-VSG frequency is as low as the satellite cross-domain frequency (e.g., GSFC-L), the number of C-C signals is minimized; 2. If the VSG sizes are sufficiently large to avoid migrating VNFs, but the satellite cross-VSG frequency is as high as the FM's VNF migration rate (e.g., GSFC-M), the number of C-C signals is maximized; 3. For other cases, the C-C signals are caused by a mix of VNF migration and cross-domain events (e.g., in GSFC-M, 18 C-C signals are caused by the VNF migration events and 26 by the VNF cross-domain events). Consequently, the results suggest that the C-C signalling overhead of GSFC is sensitive to its VSG plan.

V. CONCLUSION

In this paper, we present GSFC, a novel space VNF manipulation scheme designed to support SFCs in space-terrestrial integrated networks within the SDN paradigm. With GSFC, the integration impact on both terrestrial and space data plane networks caused by LEO satellite dynamics is tactfully circumvented from the control plane. This is achieved by clustering adjacent LEO satellites to represent logical VNF containers at the fixed positions, and continuously filling up the initial regional VNFs with the traversing satellite payload functions in a predictable manner. Based on the design, we further develop several mechanisms to not only proactively migrate the VNF instances but also update the routing policies where necessary. The proposed GSFC scheme is evaluated via a set of simulations covering both the data-plane and control-plane performance in terms of end-to-end traffic delay, throughput, routing policy updates, VNF migrations, and synchronization between multiple SDN controllers. The results indicate that GSFC has significant advantages against intuitively migrating all the VNFs or reassigning every flow.

VI. ACKNOWLEDGMENT

This work is supported by the UK Department for Science, Innovation and Technology under the Future Open Networks Research Challenge project TUDOR (Towards Ubiquitous 3D Open Resilient Network) and also ESA TINA project in its early stage. The authors would also thank the members of the 6G Innovation Centre (6GIC) hosted at the University of Surrey.

REFERENCES

[1] H. Tataria, M. Shafi, A. F. Molisch, M. Dohler, H. Sjöland, and F. Tufvesson, “6G Wireless Systems: Vision, Requirements, Challenges, Insights, and Opportunities,” *Proceedings of the IEEE*, vol. 109, no. 7, pp. 1166–1199, 2021.

[2] M. Handley, “Delay is not an option: Low latency routing in space,” in *Proceedings of the 17th ACM Workshop on Hot Topics in Networks*, 2018, pp. 85–91.

[3] P. INFOLYSiS, “A comparative CAPEX Techno-economic Analysis of NFV Applicability on the ground segment of GEO/MEO/LEO Satellite Systems,” *Athens, Greece: INFOLYSIS PC*, 2017.

[4] ETSI, “Network functions virtualisation (nfv); management and orchestration. etsi gs nfv-man 001 v1.1.1,” *[online] Available: https://www.etsi.org/deliver/etsi_gs/nfv-man/001_099/001/01.01.01_60/gs_nfv-man001v010101p.pdf.*, 2014.

[5] M. Vaezi, A. Azari, S. R. Khosravirad, M. Shirvanimoghaddam, M. M. Azari, D. Chasaki, and P. Popovski, “Cellular, Wide-area, and Non-Terrestrial IoT: A Survey on 5G Advances and the Road Toward 6G,” *IEEE Communications Surveys & Tutorials*, vol. 24, no. 2, pp. 1117–1174, 2022.

[6] G. Wang, S. Zhou, S. Zhang, Z. Niu, and X. Shen, “SFC-Based Service Provisioning for Reconfigurable Space-Air-Ground Integrated Networks,” *IEEE Journal on Selected Areas in Communications*, vol. 38, no. 7, pp. 1478–1489, 2020.

[7] X. Gao, R. Liu, and A. Kaushik, “Virtual Network Function Placement in Satellite Edge Computing With a Potential Game Approach,” *IEEE Transactions on Network and Service Management*, vol. 19, no. 2, pp. 1243–1259, 2022.

[8] I. Sarrigiannis, K. Ramantas, E. Kartsakli, P.-V. Mekikis, A. Antonopoulos, and C. Verikoukis, “Online VNF Lifecycle Management in an MEC-Enabled 5G IoT Architecture,” *IEEE Internet of Things Journal*, vol. 7, no. 5, pp. 4183–4194, 2020.

[9] M. Hozayen, T. Darwish, G. K. Kurt, and H. Yanikomeroglu, “A graph-based customizable handover framework for LEO satellite networks,” in *2022 IEEE Globecom Workshops (GC Wkshps)*. IEEE, 2022, pp. 868–873.

[10] ONF, “The Openflow Switch Specification,” *URL http://OpenFlowSwitch.org*.

[11] G. Zheng, N. Wang, and R. R. Tafazolli, “SDN in Space: A Virtual Data-Plane Addressing Scheme for Supporting LEO Satellite and Terrestrial Networks Integration,” *IEEE/ACM Transactions on Networking*, vol. 32, no. 2, pp. 1781–1796, 2024.

[12] J. Liu, Y. Shi, Z. M. Fadlullah, and N. Kato, “Space-Air-Ground Integrated Network: A Survey,” *IEEE Communications Surveys & Tutorials*, vol. 20, no. 4, pp. 2714–2741, 2018.

[13] X. Zhu and C. Jiang, “Integrated Satellite-Terrestrial Networks Toward 6G: Architectures, Applications, and Challenges,” *IEEE Internet of Things Journal*, vol. 9, no. 1, pp. 437–461, 2022.

[14] M. Bacco, L. Boero, P. Cassara, M. Colucci, A. Gotta, M. Marchese, and F. Patrone, “IoT Applications and Services in Space Information Networks,” *IEEE Wireless Communications*, vol. 26, no. 2, pp. 31–37, 2019.

[15] T. Hong, W. Zhao, R. Liu, and M. Kadoch, “Space-Air-Ground IoT Network and Related Key Technologies,” *IEEE Wireless Communications*, vol. 27, no. 2, pp. 96–104, 2020.

[16] L. Wood, A. Clerget, I. Andrikopoulos, G. Pavlou, and W. Dabbous, “Ip routing issues in satellite constellation networks,” *International Journal of Satellite Communications*, vol. 19, no. 1, pp. 69–92, 2001.

[17] G. Zheng, N. Wang, R. Tafazolli, and X. Wei, “Geosynchronous network grid addressing for integrated space-terrestrial networks,” in *2020 IEEE 28th International Conference on Network Protocols (ICNP)*. IEEE, 2020, pp. 1–6.

[18] G. Giuliari, T. Klenze, M. Legner, D. Basin, A. Perrig, and A. Singla, “Internet backbones in space,” *ACM SIGCOMM Computer Communication Review*, vol. 50, no. 1, pp. 25–37, 2020.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

[19] B. J. Barritt and W. Eddy, "SDN enhancements for LEO satellite networks," in *34th AIAA International Communications Satellite Systems Conference*, 2016, p. 5755.

[20] X. Meng, L. Wu, and S. Yu, "Multi-Topology Routing Algorithms in SDN-Based Space Information Networks," *Future Internet*, vol. 11, no. 1, p. 15, 2019.

[21] V. V. Gounder, R. Prakash, and H. Abu-Amara, "Routing in LEO-based satellite networks," in *1999 IEEE Emerging Technologies Symposium. Wireless Communications and Systems (IEEE Cat. No. 99EX297)*. IEEE, 1999, pp. 22–1.

[22] Y. Zhu, L. Qian, L. Ding, F. Yang, C. Zhi, and T. Song, "Software defined routing algorithm in LEO satellite networks," in *2017 International Conference on Electrical Engineering and Informatics (ICELTICs)*. IEEE, 2017, pp. 257–262.

[23] G. Zheng, N. Wang, R. Tafazolli, X. Wei, and J. Yang, "Virtual Data-Plane Addressing for SDN-based Space and Terrestrial Network Integration," in *2021 IEEE 22nd International Conference on High Performance Switching and Routing (HPSR)*, 2021, pp. 1–6.

[24] Z. Jia, M. Sheng, J. Li, D. Zhou, and Z. Han, "VNF-Based Service Provision in Software Defined LEO Satellite Networks," *IEEE Transactions on Wireless Communications*, vol. 20, no. 9, pp. 6139–6153, 2021.

[25] S. Hendaoui, A. Mannai, and N. Zangar, "Cognitive CQI/5QI Based Scheme for Software Defined 5G Hybrid Satellite-Terrestrial Network: Slicing for Ultra Reliability And Video Congestion Offloading," in *2020 International Symposium on Networks, Computers and Communications (ISNCC)*, 2020, pp. 1–7.

[26] M. Jia, L. Zhang, J. Wu, S. Meng, and Q. Guo, "Collaborative Satellite-Terrestrial Edge Computing Network for Everyone-Centric Customized Services," *IEEE Network*, pp. 1–21, 2022.

[27] C. Yuan, T. Peng, K. Zhang, H. Shu, and W. Wang, "Dynamic Mapping Service Function Chains in a Logical Segmented LEO Constellation," in *2023 IEEE 98th Vehicular Technology Conference (VTC2023-Fall)*, 2023, pp. 1–6.

[28] J. He, N. Cheng, Z. Yin, H. Zhou, W. Xu, H. Peng, C. Zhou, and R. Zhang, "Service-Oriented Resource Allocation in SDN Enabled LEO Satellite Networks," in *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*, 2023, pp. 1–6.

[29] A. Panda, W. Zheng, X. Hu, A. Krishnamurthy, and S. Shenker, "SCL: Simplifying Distributed SDN Control Planes," in *14th USENIX Symposium on Networked Systems Design and Implementation (NSDI 17)*, 2017, pp. 329–345.

[30] X. Yao, H. Wang, C. Gao, F. Zhu, and L. Zhai, "VM Migration Planning in Software-Defined Data Center Networks," in *2016 IEEE 18th International Conference on High Performance Computing and Communications; IEEE 14th International Conference on Smart City; IEEE 2nd International Conference on Data Science and Systems (HPCC/SmartCity/DSS)*, 2016, pp. 765–772.

[31] P. Zhang, Y. Zhang, N. Kumar, and M. Guizani, "Dynamic SFC Embedding Algorithm Assisted by Federated Learning in Space–Air–Ground-Integrated Network Resource Allocation Scenario," *IEEE Internet of Things Journal*, vol. 10, no. 11, pp. 9308–9318, 2023.

[32] G. Sallam, Z. Zheng, and B. Ji, "Placement and Allocation of Virtual Network Functions: Multi-Dimensional Case," *IEEE Transactions on Mobile Computing*, vol. 22, no. 7, pp. 4195–4211, 2023.

[33] G. Zheng, A. Tsiopoulos, and V. Friderikos, "Optimal VNF Chains Management for Proactive Caching," *IEEE Transactions on Wireless Communications*, vol. 17, no. 10, pp. 6735–6748, 2018.

[34] S. Sharma, D. Staessens, D. Colle, M. Pickavet, and P. Demeester, "Automatic bootstrapping of OpenFlow networks," in *2013 19th IEEE Workshop on Local & Metropolitan Area Networks (LANMAN)*, 2013, pp. 1–6.

[35] OSM, "Open Source MANO," *[online] Available: https://osm.etsi.org*, 2024.

[36] T. Pan, T. Huang, X. Li, Y. Chen, W. Xue, and Y. Liu, "OPSPF: Orbit Prediction Shortest Path First Routing for Resilient LEO Satellite Networks," in *ICC 2019 - 2019 IEEE International Conference on Communications (ICC)*, 2019, pp. 1–6.

[37] B. Barritt, T. Kichkaylo, K. Mandke, A. Zalcman, and V. Lin, "Operating a UAV mesh & internet backhaul network using temporospatial SDN," in *2017 IEEE Aerospace Conference*, 2017, pp. 1–7.

[38] H. Yang, W. Liu, J. Li, and T. Q. S. Quek, "Space Information Network With Joint Virtual Network Function Deployment and Flow Routing Strategy With QoS Constraints," *IEEE Journal on Selected Areas in Communications*, vol. 41, no. 6, pp. 1737–1756, 2023.

[39] Y. Mao, X. Shang, Y. Liu, and Y. Yang, "Joint Virtual Network Function Placement and Flow Routing in Edge-Cloud Continuum," *IEEE Transactions on Computers*, vol. 73, no. 3, pp. 872–886, 2024.

[40] A. R. Curtis, J. C. Mogul, J. Tourrilhes, P. Yalagandula, P. Sharma, and S. Banerjee, "DevoFlow: Scaling flow management for high-performance networks," in *Proceedings of the ACM SIGCOMM 2011 Conference*, 2011, pp. 254–265.

[41] S. Jain, A. Kumar, S. Mandal, J. Ong, L. Poutievski, A. Singh, S. Venkata, J. Wanderer, J. Zhou, M. Zhu *et al.*, "B4: Experience with a globally-deployed software defined WAN," *ACM SIGCOMM Computer Communication Review*, vol. 43, no. 4, pp. 3–14, 2013.

[42] A. D. Ferguson, A. Guha, C. Liang, R. Fonseca, and S. Krishnamurthi, "Participatory networking: An API for application control of SDNs," *ACM SIGCOMM computer communication review*, vol. 43, no. 4, pp. 327–338, 2013.

[43] X. Jin, H. H. Liu, R. Gandhi, S. Kandula, R. Mahajan, M. Zhang, J. Rexford, and R. Wattenhofer, "Dynamic scheduling of network updates," *ACM SIGCOMM Computer Communication Review*, vol. 44, no. 4, pp. 539–550, 2014.

[44] SpaceX, "The Starlink Project," *URL https://www.starlink.com*.

[45] G. Swinerd, *How Spacecraft Fly: Spaceflight Without Formulae*. Springer Science & Business Media, 2008.

[46] J. Li, W. Shi, H. Wu, S. Zhang, and X. Shen, "Cost-Aware Dynamic SFC Mapping and Scheduling in SDN/NFV-Enabled Space–Air–Ground-Integrated Networks for Internet of Vehicles," *IEEE Internet of Things Journal*, vol. 9, no. 8, pp. 5824–5838, 2022.

[47] M. Ghaznavi, A. Khan, N. Shahriar, K. Alsubhi, R. Ahmed, and R. Boutaba, "Elastic virtual network function placement," in *2015 IEEE 4th International Conference on Cloud Networking (CloudNet)*, 2015, pp. 255–260.

[48] G. Stock, J. A. Fraire, and H. Hermanns, "Distributed On-Demand Routing for LEO Mega-Constellations: A Starlink Case Study," in *2022 11th Advanced Satellite Multimedia Systems Conference and the 17th Signal Processing for Space Communications Workshop (ASMS/SPSC)*, 2022, pp. 1–8.

[49] M. Guan, T. Xu, F. Gao, W. Nie, and H. Yang, "Optimal walker constellation design of LEO-based global navigation and augmentation system," *Remote Sensing*, vol. 12, no. 11, p. 1845, 2020.

[50] Calnex, "NE-One," *URL https://itrinegy.com/*.

[51] L. Tang, X. He, P. Zhao, G. Zhao, Y. Zhou, and Q. Chen, "Virtual Network Function Migration Based on Dynamic Resource Requirements Prediction," *IEEE Access*, vol. 7, pp. 112 348–112 362, 2019.

[52] T. Taleb, D. Mashimo, A. Jamalipour, N. Kato, and Y. Nemoto, "Explicit Load Balancing Technique for NGEO Satellite IP Networks With On-Board Processing Capabilities," *IEEE/ACM Transactions on Networking*, vol. 17, no. 1, pp. 281–293, 2009.

[53] Q. Chen, L. Yang, X. Liu, B. Cheng, J. Guo, and X. Li, "Modeling and Analysis of Inter-Satellite Link in LEO Satellite Networks," in *2021 13th International Conference on Communication Software and Networks (ICCSN)*, 2021, pp. 134–138.

[54] E. Altman, F. Boccara, J. Bolot, P. Nain, P. Brown, D. Collange, and C. Fenzy, "Analysis of the TCP/IP flow control in high-speed wide-area networks," in *IEEE CDC*, 1995.

Gao Zheng is a Research Fellow in Future Network Intelligence at the University of Surrey. He carried out this work as a work package leader for the EAS TINA and UK TUDOR projects. He holds a PhD degree in Informatics from King's College London. His research interests include future Internet technologies, space and terrestrial network integration, network function virtualization, software defined networking, multi-sense networking, and network optimization.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.

This article has been accepted for publication in IEEE Journal on Selected Areas in Communications. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/JSAC.2025.3528807

Ning Wang joined the Smart Internet Laboratory, University of Bristol as a full professor in August 2024, and previously he was a full professor at the 6G Innovation Centre (6GIC) at University of Surrey where this work was conducted. He received the PhD degree in electronic engineering from the Centre for Communication Systems Research, University of Surrey. His main research interests include future networks, multimedia networking, network management and control, and QoS/QoE assurances.

Peng Qian received the B.Eng. degree from the Nanjing University of Posts and Telecommunications (Nanjing, China) in 2008, the M.Sc. degree (Hons.) in 2013, and the Ph.D. degree in 2018 from the University of Surrey, Home of 5G/6G Innovation Centre. He has worked as senior research software engineer of UK5G, EPSRC NGCDI and EU-SPIRIT projects, to conduct research, implementation and deployment of holographic video streaming application in next generation network infrastructure. He was involved in the field of the telecommunication industry from 2008 to 2012. From April 2024, he joined the Computer Infrastructure team of Oxford University, as a senior research software engineer for EU-SmartEdge project. His research interests include Web and extended reality content streaming and acceleration, mobile edge computing, and next-generation Internet and routing protocols.

David Griffin is a Principal Research Associate in the Department of Electronic and Electrical Engineering, UCL. He has a BSc from Loughborough University and a PhD from UCL, both in Electrical Engineering. His research interests are in the use of classical and machine-learning algorithms for management and control of multiservice networks, optimisation of edge networks for delivering high-performance, low-latency applications and novel Internet routing paradigms combining network and service metrics.

Regius Rahim Tafazolli Fellow of Royal Academy of Engineering, IET, WWRF and Regius Professor of Electronic Engineering, Professor of Mobile and Satellite Communications, Founder and Director of 5GIC, 6GIC and ICS (Institute for Communication System) at the University of Surrey. He has over 30 years of experience in digital communications research and teaching. He has authored and co-authored more than 1000 research publications and is regularly invited to deliver keynote talks and distinguished lectures to international conferences and workshops. He was advisor to the Mayor of London (Boris Johnson) on London 2050 Infrastructure.

Authorized licensed use limited to: University College London. Downloaded on January 22,2025 at 23:36:19 UTC from IEEE Xplore. Restrictions apply.
© 2025 IEEE. Personal use is permitted, but republication/redistribution requires IEEE permission. See https://www.ieee.org/publications/rights/index.html for more information.