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Service-Oriented Resource Allocation in SDN Enabled LEO Satellite Networks

Jingchao He*, Nan Cheng*, Zhisheng Yin†, Haibo Zhou‡, Wenchao Xu‖, Haixia Peng¶,
Conghao Zhou§, Ruqian Zhang*
*School of Telecommunications Engineering, Xidian University, Xi'an, 710071, China
†School of Cyber Engineering, Xidian University, Xi'an, 710071, China
‡ School of Electronic Science and Engineering, Nanjing University, Nanjing, 210023, China
§ Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON N2L 3G1, Canada
¶ School of Information and Communications Engineering, Xi'an Jiaotong University, Xi'an, 710000, China
‖ Department of Computing, The Hong Kong Polytechnic University, Hong Kong, 710000, China
Email:{jchhe, zz}@stu.xidian.edu.cn, dr.nan.cheng@ieee.org, zsyin@xidian.edu.cn,
haibozhou@nju.edu.cn, wenchxu@polyu.edu.hk, c89zhou@uwaterloo.ca, haixia.peng@xjtu.edu.cn

***Abstract*—As an integral component of space-air-ground integrated networks (SAGINs), the low Earth orbit (LEO) satellite networks have displayed immense potential in providing ubiquitous connectivity and broadband mobile communication. However, the intrinsic dynamics of LEO satellites poses unprecedented challenges in network management, multi-dimensional resource scheduling, and service delivery. In this paper, we study the service function chain (SFC) orchestration in dynamic LEO satellite networks, with the aim of achieving flexible and efficient service provision. Considering the service requirements and the load fairness of LEO satellite networks, we formulate the SFC deployment problem as an integer nonlinear programming (INLP) problem. We then introduce a load-aware SFC orchestration algorithm to improve serving capacity and load fairness. Additionally, we address the issue of SFC migration in dynamic LEO satellite networks to ensure service continuity. To minimize the service interruption and network resource wastes, a Tabu search (TS)-based approach is presented to optimize the virtual network function (VNF) migration. Simulation results demonstrate that our proposed approaches outperform the benchmark by a substantial margin in terms of load fairness, without compromising service acceptance.**

***Index Terms*—Low Earth orbit (LEO) satellite network, satellite load, software-defined networking (SDN), service function chain (SFC).**

I. INTRODUCTION

THE space-air-ground integrated networks (SAGINs) have attracted people from both industry and academia for their ubiquitous coverage anywhere and anytime, and have become mainstream in 6G. The SAGIN is composed of space segments, air segments, and ground segments, where low Earth orbit (LEO) satellites play a main role in the space segments and have experienced an unprecedented development [1], [2]. By the end of February 2023, American company SpaceX has launched more than 3,660 LEO satellites and had more than 1 million subscribers as of December 2022 [3]. The deployment of LEO satellite networks provides extraordinary network coverage in remote areas, which enables automotive driving, smart cities, remote Internet of Things, etc [4].

However, as the number of LEO satellites increases, the management and operation of the entire network becomes more complicated and difficult. In terrestrial networks, software defined networking (SDN) is proposed to separate the data layer and control layer and provide centralized network management. On the other hand, network function virtualization (NFV) technology is able to abstract the heterogeneous physical resources and provide a more flexible fashion, i.e., virtual network functions (VNFs), in resource management compared with conventional function-specific middleboxes [5]. Combining SDN and NFV technologies, a programmable, flexible, and scalable network operation and management architecture is proposed that makes full use of the complementary advantages of SDN/NFV technologies and LEO satellite networks and compensates for the inconvenience of traditional dedicated satellite hardware in updating and continuity. Based on the SDN and NFV technologies, the service function chain (SFC) technology is proposed. As service requests like remote sensing, self-driving [6], mobile edge computing (MEC) arrive in networks, they are described into a specific sequenced VNFs chain firstly [7], [8]. Then, these VNFs are embedded on network nodes with transmission links chained together to serve as a network function. Notably, the SFC is customizable to different user requirements, which is a potential solution for future on-demand network serving.

Recently, several works on SFC have been presented on ground networks and SAGINs. In ground networks, some works mainly concern the resource utilization in optical core networks and cloud-edge synergy scenarios [9]–[11]. In [9], the SFC deployment problem in elastic optical datacenters is investigated. It is modeled as a Markov decision process, and a graph neural network-based algorithm is proposed to minimize the resource utilization. In order to deliver dependable service provisioning in MEC, [10] studies the cost minimization problem. In [11], the SFC deployment problem in a hybrid cloud-edge synergy scenario is investigated to optimize the resource utilization and service latency. Some works are based on the SAGINs [12]–[14]. In [12], the SFC deployment problem is presented to balance the resources of ground networks and non-ground networks in computation and communication. In

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[13], a large-scale heterogeneous SAGIN scenario is considered and federated learning is utilized to cope with the data island problem. To our best knowledge, there are only a few works that investigate the SFC deployment in satellite networks [14]. They mainly consider the resource sharing and competition among each SFC. Then, they formulate the problem as a noncooperative game and utilize the adaptive play algorithm to find the Nash equilibrium. Nevertheless, few works consider the network dynamics and satellite load. In LEO satellite networks, the topology and radio environment are dynamic, which renders previous optimal strategy suboptimal or entirely unavailable, and ultimately impairing the user service experience. However, relying upon the simplistic and mechanical repetition of complete deployment algorithm, whenever the initial strategy is ineffective, will result in abundant resource waste in determination and redeployment of previous embedded VNFs with privacy and customized modules. On the other hand, existing studies overlook the importance of satellite load, as individual satellites carrying overly many services ultimately result in the rapid saturation and diminishment of equipment lifespan, thereby directly impinging upon the stability of the satellite constellation, and in turn, introducing additional operational costs.

In this paper, we investigate the SFC orchestration problem in dynamic LEO satellite networks. To maximize the service acceptance and the fairness of satellite load under limited network capacity and diverse service requirements, the SFC deployment in LEO satellite networks is formulated as an integer non-linear programming (INLP) problem. To solve this problem, we decouple it into the virtual link embedding and VNF embedding, and then provide a heuristic algorithm with low complexity to solve the problem. Considering the dynamics of the LEO satellite network and network resource utilization, we formulate the VNF migration problem to optimize service continuity. A Tabu search (TS)-based algorithm is proposed to minimize the migration cost. Finally, extensive simulations are conducted to evaluate the performance of the proposed algorithms in terms of service reception, fairness of satellite load, and adaption to different types of services.

II. SYSTEM MODEL

Fig. 1 shows an SDN/NFV enabled network architecture, which comprises of three segments: space network segment, ground network segment, and user segment. Particularly, space network segment is composed of LEO satellite constellations and geosynchronous equatorial orbit (GEO) satellites. Ground network segment is responsible for service orchestration, network management, etc., and is primarily composed of satellite ground stations equipped with the satellite gateway and SDN controller. User segment is composed of user terminals that demand various services like remote surgery, holographic communication, etc. In space segment, satellites in LEO satellite constellations are equipped with computation units and communication units to support various network services. GEO satellites are responsible for domain-level network supervision. Incorporated with the GEO satellites, the limited vision and frequent handovers of satellite ground stations can be offset and replaced by a global view of the network. Specifically, the ground stations collect the satellite operation status, locations, user information, and resource utilization periodically. When the service request from user terminals arrives, it is described as the specific SFC on the basic of user requirements, firstly. Then, the SDN controllers decide to accept or reject the arrived service according to the network status. When the service is accepted, the orchestration strategy is generated, otherwise it is blocked. If a service is accepted, the SFC is then embedded on each LEO satellite node, and required network resources are occupied until the service is finished. In the following, we will introduce our network model and service model concretely.

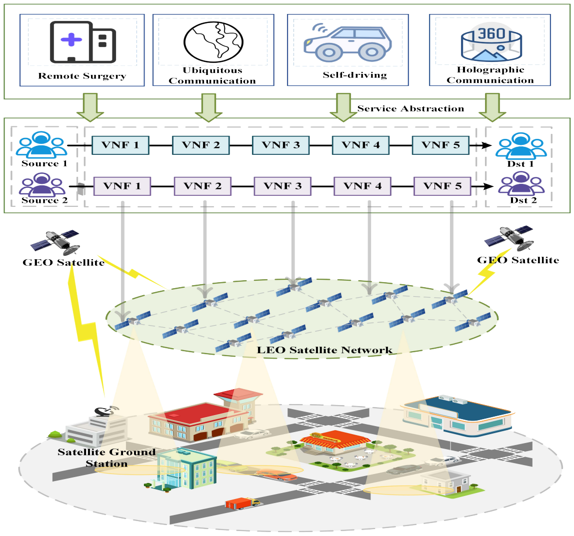

Fig. 1. An SDN enabled LEO satellite network architecture.

A. Network Modeling

In this paper, we consider a general Walker Star LEO satellite constellation made up of $M \times K$ homogeneous satellites distributed in M circular LEO evenly. Denote the physical network by $G = (\mathcal{F}, \mathcal{E})$, where $\mathcal{F}$ is the set of LEO satellites and $\mathcal{E}$ is the set of physical links between satellites. Without loss of generality, we ignore the network access and consider that each user prioritize to access the nearest network node. We consider each LEO satellite is equipped with four transceivers connected to two inter-orbit satellites and two nearest inter-orbit satellites, individually. The capacity of physical links (n, m) is denoted by $B_{n,m}$, and the channel delay is denoted by $d_{n,m}$, which is expressed as

$$d_{n,m} = distance(n, m)/c, \forall (n, m) \in \mathcal{E}, \quad (1)$$

where c is the speed of light.

The location of satellite n in Cartesian coordinates is denoted by $(p_{x,n}, p_{y,n}, p_{z,n})$, which is expressed as (2), where h is the orbit altitude of satellite n, R_e is the radius of the Earth, α is the inclination angle of satellite orbit, β is the right ascension of ascending node, τ is the true anomaly, and ξ is

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$$\begin{pmatrix} p_{x,n} \\ p_{y,n} \\ p_{z,n} \end{pmatrix} = (h+R_e)\begin{pmatrix} \cos(\xi+\tau)\cos\beta - \sin(\xi+\tau)\cos\alpha\sin\beta \\ \cos(\xi+\tau)\sin\beta + \sin(\xi+\tau)\cos\alpha\cos\beta \\ \sin(\xi+\tau)\sin\alpha \end{pmatrix}. \tag{2}$$

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the argument of the perigee. The distance between satellite n and m is

$$distance(n,m) = [(p_{x,n}-p_{x,m})^2 + (p_{y,n}-p_{y,m})^2 + (p_{z,n}-p_{z,m})^2]^{\frac{1}{2}}. \tag{3}$$

As the communication network node, we omit the energy consumption of re-boosting and focus on the computation and communication, and the load of satellite n is expressed as

$$l_n = \zeta_1 c_n + \zeta_2 b_n, \tag{4}$$

where ζ_1, ζ_2, c_n, and b_n are the energy weights of computation and communication consumption, utilized computation resources, and utilized communication resources, respectively.

B. Service Modeling

As previously noted, the service model utilized in our system is the SFC, which is made up of a sequence of VNFs that are chained together in a predefined manner. To ensure successful service delivery, the sequential and continuous embedding of each VNF on the network node is necessary, and the end-to-end delay must fulfill the user's requirements. We consider the number and types of service requests arriving at the network have been determined before each decision-making interval, which is denoted by $\mathcal{Q} = \{q|q=1,2,...,|\mathcal{Q}|\}$. Two types of services are considered, which are the bandwidth-demand service and the computation-demand service. The sets of source nodes and destination nodes are represented by $\{s_q|q\in\mathcal{Q}\}$ and $\{d_q|q\in\mathcal{Q}\}$, respectively. $\mathbf{v}_q = \{v_i|i=1,2,\ldots,|\mathrm{v_q}|\}$ denotes the VNF sequence of service q. Denote the data flow between VNF i and VNF j by $\mathcal{E}_q = \{(v_i,v_j)|v_i,v_j\in\mathbf{v}_q, q\in\mathcal{Q}\}$.

Let binary variable $x_{v_i,n,q}=1$ if VNF i of service q is embedded on node n, and $x_{v_i,n,q}=0$ otherwise. The solution vector is denoted by $\mathbf{x} = \{x_{v_i,n,q} \mid v_i\in\mathbf{v}_q, n\in\mathcal{F}, q\in\mathcal{Q}\}$. Similarly, binary variable $y^{(n,m)}_{(v_i,v_j),q}=1$ when virtual link (v_i,v_j) of service q is mapped on physical link (n,m), and $y^{(n,m)}_{(v_i,v_j),q}=0$ otherwise. The solution vector is denoted by $\mathbf{y} = \left\{y^{(n,m)}_{(v_i,v_j),q} \mid (v_i,v_j)\in\mathcal{E}_q, (n,m)\in\mathcal{E}, q\in\mathcal{Q}\right\}$. Let the binary variable $z_q=1$ denote the service q is received, and $z_q=0$ otherwise. The solution vector is denoted by $\mathbf{z} = \{z_q \mid q\in\mathcal{Q}\}$.

The SFC is embedded on the communication networks, whose delay is composed of transmission delay, propagation delay, processing delay, and queuing delay. In this system, the delay of each service is dominated by transmission delay [12], which is expressed as

$$t_q = \sum_{(v_i,v_j)\in\mathcal{E}_q} y^{(n,m)}_{(v_i,v_j),q} d_{n,m}, \forall q\in\mathcal{Q}. \tag{5}$$

III. PROBLEM FORMULATION

In this section, we investigate the SFC deployment in dynamic satellite networks with the consideration of service provision, flow conservation, and network capacity. An INLP problem is formulated to maximize the service acceptance. Then, to maintain the SFC in dynamic LEO satellite topology, the VNF migration problem is studied to minimize the migration costs.

A. Service Provision Constraints

This subsection presents the constraints SFC deployment. Before the service is delivered to the network, the source, destination, and the VNF sequence are all predefined. To ensure that the initial and final VNFs are incorporated in the source and destination, constraints C_1 and C_2 must be met, which are expressed as

$$C_1: x_{v_1,s_q,q} = z_q, \quad \forall q\in\mathcal{Q}, \tag{6}$$

$$C_2: x_{v_{|\mathrm{v_q}|},d_q,q} = z_q, \quad \forall q\in\mathcal{Q}. \tag{7}$$

As a received SFC, the VNFs are limited to embed on only one network node, which is expressed as

$$C_3: \sum_{n\in\mathcal{F}} x_{v_i,n,q} = z_q, \quad \forall v_i\in\mathbf{v}_q, \quad \forall q\in\mathcal{Q}. \tag{8}$$

For each service, the transmission delay must be less than the deadline T_q, which is expressed as

$$C_4: \sum_{(n,m)\in\mathcal{E}} \sum_{(v_i,v_j)\in\mathcal{E}_q} y^{(n,m)}_{(v_i,v_j),q} d_{n,m} \le T_q, \quad \forall q\in\mathcal{Q}. \tag{9}$$

B. Flow Conservation Constraints

The SFC is sequenced VNFs chained by data flow, the flow conservation is critical to ensure the flows in equal to the flows out, which is expressed as

$$C_5: \sum_{m\in\mathcal{F}} y^{(n,m)}_{(v_i,v_j),q} - \sum_{m\in\mathcal{F}} y^{(m,n)}_{(v_i,v_j),q)} = x_{v_i,n,q} - x_{v_j,n,q}, \quad \forall (v_i,v_j)\in\mathcal{E}_q, \forall n\in\mathcal{F}, \forall q\in\mathcal{Q}. \tag{10}$$

C. Network Node Constraints

For each satellite, the computation and communication resources are limited, and the allocated network resources cannot be greater than the node's capacity, which is expressed as

$$C_6: \sum_{q\in\mathcal{Q}} \sum_{v_i\in\mathbf{v}_q} x_{v_i,n,q} c_{v_i,q} \le C_n, \quad \forall n\in\mathcal{F}, \tag{11}$$

$$C_7: \sum_{q\in\mathcal{Q}} \sum_{(v_i,v_j)\in\mathcal{E}_q} y^{(n,m)}_{(v_i,v_j),q} b_q \le B_{n,m}, \quad \forall (n,m)\in\mathcal{E}, \tag{12}$$

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where $c_{v_i,q}$ denotes the computation utilization of VNF i, b_q denotes the communication utilization of service q, and C_n denotes the computation capacity of satellite n. C_6 constrains the computation resource utilization and C_7 constrains the bandwidth utilization.

D. SFC Deployment and Migration Problem

In this model, we optimize the SFC deployment to maximize the service acceptance and fairness of satellite load. Combining with constraints $C_1 - C_7$, an INLP problem is formulated as

$$\begin{aligned} P1: \max_{\mathbf{x},\,\mathbf{y},\,\mathbf{z}} & \sum_{q\in\mathcal{Q}} z_q + \gamma_1 \frac{\left(\sum_{n\in\mathcal{F}} l_n\right)^2}{|\mathcal{F}|\cdot\sum_{n\in\mathcal{F}} {l_n}^2} \\ s.t. & C_1 - C_7, \\ & C_8: \mathbf{x},\,\mathbf{y},\,\mathbf{z}\in\{0,1\}, \end{aligned} \tag{13}$$

where γ_1 is the weight of fairness.

In LEO satellite networks, the satellites move very fast, which changes the network topology and channel status frequently, rendering previously optimal strategy suboptimal or even broken over time. To maintain the SFC status and fulfill users' QoS requirements in such a dynamic network scenarios, the live VNF migration are unavoidable. However, the customized VNFs combine user privacy and dedicated data, and the end-to-end retransmission will bring intolerable delay and communication resource waste. To fulfill users' requirements and minimize the resource waste, we formulate the VNF migration problem as

$$\begin{aligned} P2: \min_{\mathbf{x},\,\mathbf{y},\,\mathbf{z}} & \gamma_2 \sum_{q\in\mathcal{Q}} \sum_{v_i\in\mathbf{v}_q} h_{v_i,q} - \sum_{q\in\mathcal{Q}} z_q - \gamma_1 \frac{\left(\sum_{n\in\mathcal{F}} l_n\right)^2}{|\mathcal{F}|\cdot\sum_{n\in\mathcal{F}} {l_n}^2} \\ s.t. & C_1 - C_7, \\ & C_8: \mathbf{x},\,\mathbf{y},\,\mathbf{z}\in\{0,1\}, \end{aligned} \tag{14}$$

where γ_2 is the weight of VNF migration, $h_{v_i,q}$ is the migration decision of VNF i of service q, where $h_{v_i,q} = 1$ denotes the VNF i will migrate to a new network node, $h_{v_i,q} = 0$ otherwise. The weights of VNF migration and fairness ensure the continuity of each SFC as much as possible.

In P1 and P2, variables **x**, **y**, and **z** are integers, which is an INLP problem. As has been studied before, the problem is non-convex and NP-hard [15], and its optimal solution cannot be found within polynomial time. The topology and channel status of LEO satellite networks are dynamic and unstable, making it inefficient to solve the INLP frequently. Thus, we first decompose the SFC orchestration into virtual link embedding and VNF embedding problems. Then, a load-aware SFC orchestration (LASO) algorithm is proposed to solve the problem. To keep the service continuity and minimize the VNF migration, a TS-based algorithm, named load-aware VNF migration (LAM), is proposed to solve $P2$.

IV. SOLUTIONS OF SFC ORCHESTRATION AND MIGRATION

In this section, we first present a heuristic SFC orchestration algorithm, named LASO algorithm, to obtain the near-optimal solutions to the INLP problem efficiently. Then, we describe our proposed SFC migration algorithm to cope with the inherent dynamics of LEO satellite networks.

Algorithm 1: LASO algorithm

```
Input: Newly arrived service $q$, available physical
       resources, current network topology $G$
Set $\theta \leftarrow 1$;
while $\theta \geq 0$ do
    Calculate the weight of edges in $G$ by (15);
    Utilize the Dijkstra algorithm and obtain the
      shortest path;
    Embed the VNFs of service $q$ by Algorithm 2;
    if $t_q \leq T_q$ and $embeddingIndex \neq fault$ then
        Output the routing path and embedding
          strategy $\pi_e$;
        Break the loop;
    else
        $\theta = \theta - \Delta_\theta$;
Block the service $q$;
```

Algorithm 2: VNFs Embedding algorithm

```
Input: Service requirements, potential path, current
       network status
Output: Embedding strategy $\pi_e$
Choose the candidate network node $CandidatesList$
  with maximal computation resources ;
for VNF $i \in \boldsymbol{v}_q$ do
    if Available resource is enough then
        Embed the VNF $i$ in $CandidateList(i)$;
        update $\pi_e$;
    else
        Set $embeddingIndex \leftarrow fault$ ;
        Break the loop;
if All VNFs are embedded successfully then
    Set $embeddingIndex \leftarrow true$;
else
    Set $embeddingIndex \leftarrow false$;
```

A. SFC Orchestration Algorithm

The SFC orchestration can be decoupled as VNF embedding and virtual link embedding. We primarily focus on finding the optimal routing path with the consideration of satellite load fairness, which is shown in Algorithm 1. Firstly, the available link capacity and the eventual end-to-end delay should meet the service requirements, which is mandatory in our model. To guarantee the adequate channel capacity, we introduce the indicator function into the link weight for each service, which is expressed as $\mathbb{I}\left(b_{n,m} - b_q\right)$, and $b_{n,m}$ is the available bandwidth in link (n, m). We design the weight of physical

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link (n,m) as

$$W_q(n,m)=\frac{d_{n,m}\mathbb{I}\left(b_{n,m}-b_q\right)}{\exp\left(\theta\left(l_n+l_m\right)/2\right)},\forall q\in\mathcal{Q}, \qquad (15)$$

where θ is the load fairness factor and negatively correlated to the load of satellite n and satellite m. The load factor balance the service delay and satellite load. When $\theta=0$, Algorithm 1 will generate the path with the lowest end-to-end delay, and when $\theta=1$, the load of connected satellites is valued.

Employing a greedy approach, Algorithm 2 embarks on VNF embedding. Potential nodes with maximum computational capability are picked for deployment. When the prospective nodes of the produced path from Algorithm 1 are unable to complete all VNFs, the embedding result is marked as fault, and the searching loop continues until the halting criteria is met.

Algorithm 3: LAM algorithm

```
Input: Service $q$, initial embedding strategy $\pi_0$,
       current network status $G$
Output: Migration strategy $\pi_m$
Set $k \leftarrow 1$;
Set $\pi_k \leftarrow \pi_0$;
while $k \leq K$ do
    Set $G' \leftarrow G$ ;
    $migrationList \leftarrow findNeighbors(\pi_k)$;
    $G'.dropNode(migrationList)$;
    Calculate the weight of $G'$ by (15);
    Splice the link of remaining VNFs by Dijkstra
      algorithm in $G'$;
    Embed the migrated VNFs by Algorithm 2 ;
    if $migrationCost(\pi_k) < migrationCost(\pi^*)$ and
      $embeddingIndex = true$ then
        Set $\pi^* \leftarrow \pi_k$;
        $updateTabuList(\pi_k^*)$;
if $\pi^*$ is not $Null$ then
    Set $migrationIndex \leftarrow true$;
    Set $\pi_m \leftarrow \pi^*$;
    return $\pi_m$;
else
    Set $migrationIndex \leftarrow false$;
```

To support the SFC in dynamic network scenario continuously, Algorithm 3 is activated when the initial satellite or the final satellite of a service is not the user's access node. In Algorithm 3, a TS-based migration algorithm is presented to optimize the service continuity and load fairness.

V. PERFORMANCE EVALUATION

In this section, we conduct simulations to evaluate the performance of the proposed algorithm. The LEO satellite constellation is set as a Walker Star LEO satellite constellation where 100 satellites evenly distributed in 10 LEO orbits on the altitude of 2000 km from the Earth. The bandwidth capacity of ISL is set to 100 Mbps and the computation capacity of the satellite is 50 CPU units. The communication and computation requirements of SFCs are distributed in [20, 40] and [5, 20] CPU units. We evaluate the performance of our proposed algorithm and compare it with three benchmarks. The first two benchmarks are to deploy VNFs and migrate them in a greedy manner, i.e. the path with minimal hops (MH) and the path with minimal migration numbers (MMN). The third benchmark is pheromone-based fault avoidance algorithm (PFA) which is referenced form the ant-colony optimization [16]. The simulation is carried out on a computer with 3.0 GHz Intel Core i5-9500 and 16 GB RAM.

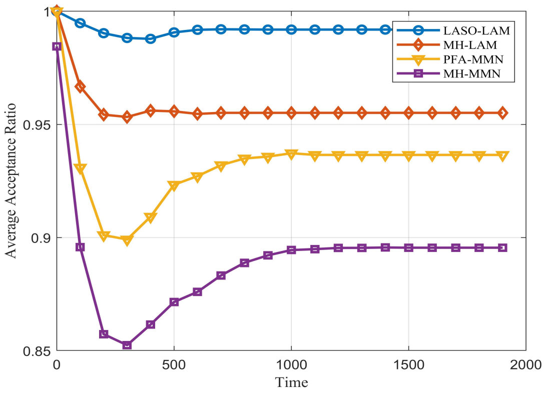

Fig. 2. Comparison of acceptance ratio between proposed algorithm and benchmarks.

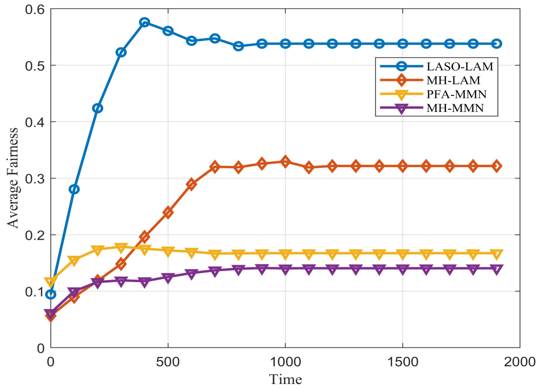

Fig. 3. Comparison of fairness between proposed algorithm and benchmarks.

In Figs. 2 and 3, the service arrival rate is set to 3 per slot, the ratio of bandwidth-demand service to computation-demand service is set to 0.5. Fig. 2 compares the average acceptance ratio of the four algorithms. It can be observed that the LASO-LAM outperforms three benchmarks, and MH-LAM outperforms the PFA-MMN and MN-MMN. The reason is that LASO and LAM utilize the integrated weight of both computation and communication to adapt the multi-dimensional requirements of each SFC. Fig. 3 compares the average fairness of the four algorithms, with the LASO-LAM algorithm initially appearing lower than PFA-MMN but quickly outperforming all three benchmarks. The reason is the services arrive simultaneously in PFA avoids to pass all nodes of the previous infeasible path.

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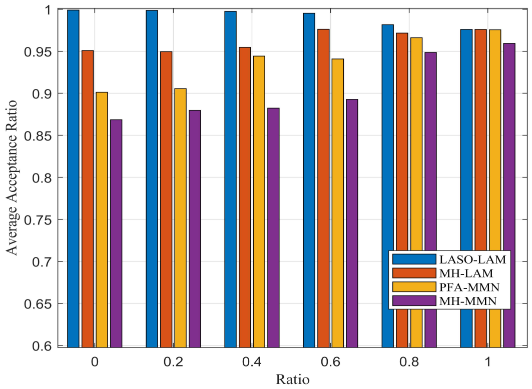

Fig. 4. Service type ratio versus acceptance ratio.

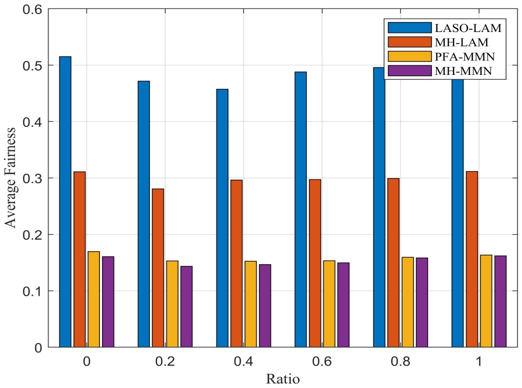

Fig. 5. Service type ratio versus fairness.

Figs. 4 and 5 compare the acceptance and fairness under different ratios of bandwidth-demand service and computation-demand service. The proposed approach beats the benchmarks when the ratio is less than one, which is because our proposed algorithm considers the multi-dimensional network resources concurrently, and too many services with high transmission demands would crowd together and jam. Additionally, Fig. 5 shows that, at the same service ratio, our proposed algorithm achieves twice the fairness value of PFA-MMN and MH-MMN, and nearly 60 percentage points higher than MH-LAM, with the highest service acceptance ratio.

VI. CONCLUSION

In this work, the orchestration and migration of SFC have been investigated in LEO satellite networks to fulfill ubiquitous multi-dimensional service requirements. The SFC orchestration problem is formulated as the INLP problem, and a heuristic algorithm has been proposed to solve the problem with the consideration of satellite load. To support the SFC continuously in LEO satellite networks, a TS-based algorithm has been proposed to minimize the VNF migrations. Extensive simulations have verified the efficiency of the proposed algorithm. Particularly, a greater fairness value is achieved without sacrificing the service acceptance. Our study considers the dynamic LEO satellite scenarios and satellite loads comprehensively and aims to provide guidelines for future on-demand network serving in SAGINs. In the future, we will study the temporal correlation of LEO satellite networks and promote the network resource utilization.

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REFERENCES

[1] I. Leyva-Mayorga, B. Soret, and P. Popovski, “Inter-Plane Inter-Satellite Connectivity in Dense LEO Constellations,” *IEEE Transactions on Wireless Communications*, vol. 20, no. 6, pp. 3430–3443, 2021.

[2] N. Cheng, W. Xu, W. Shi, Y. Zhou, N. Lu, H. Zhou, and X. Shen, “Air-ground integrated mobile edge networks: Architecture, challenges, and opportunities,” *IEEE Communications Magazine*, vol. 56, no. 8, pp. 26–32, 2018.

[3] L. Grossman. (2023) Half of all active satellites are now from SpaceX. Here’s why that may be a problem. [Online]. Available: https://www.sciencenews.org/article/satellites-spacex-problem-space-pollution

[4] T. Ma, H. Zhou, B. Qian, N. Cheng, X. Shen, X. Chen, and B. Bai, “Uav-leo integrated backbone: A ubiquitous data collection approach for b5g internet of remote things networks,” *IEEE Journal on Selected Areas in Communications*, vol. 39, no. 11, pp. 3491–3505, 2021.

[5] 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, p. 5824–5838, 2021.

[6] H. Peng, D. Li, K. Abboud, H. Zhou, H. Zhao, W. Zhuang, and X. Shen, “Performance analysis of ieee 802.11 p dcf for multiplatooning communications with autonomous vehicles,” *IEEE Transactions on Vehicular Technology*, vol. 66, no. 3, pp. 2485–2498, 2016.

[7] O. Bouachir, M. Aloqaily, L. Tseng, and A. Boukerche, “Blockchain and fog computing for cyberphysical systems: The case of smart industry,” *Computer*, vol. 53, no. 9, pp. 36–45, 2020.

[8] N. Cheng, F. Lyu, W. Quan, C. Zhou, H. He, W. Shi, and X. Shen, “Space/aerial-assisted computing offloading for iot applications: A learning-based approach,” *IEEE Journal on Selected Areas in Communications*, vol. 37, no. 5, pp. 1117–1129, 2019.

[9] B. Li and Z. Zhu, “GNN-Based Hierarchical Deep Reinforcement Learning for NFV-Oriented Online Resource Orchestration in Elastic Optical DCIs,” *Journal of Lightwave Technology*, vol. 40, no. 4, pp. 935–946, 2022.

[10] J. Li, S. Guo, W. Liang, Q. Chen, Z. Xu, W. Xu, and A. Y. Zomaya, “Digital Twin-Assisted, SFC-Enabled Service Provisioning in Mobile Edge Computing,” *IEEE Transactions on Mobile Computing*, pp. 1–16, early access, 2022, DOI:10.1109/TMC.2022.3227248.

[11] Y. Mao, X. Shang, and Y. Yang, “Joint Resource Management and Flow Scheduling for SFC Deployment in Hybrid Edge-and-Cloud Network,” in *Proceedings - 2022-IEEE Conference on Computer Communications*, 2022, pp. 170–179.

[12] 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.

[13] 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*, early access, 2022, DOI 10.1109/JIOT.2022.3222200.

[14] X. Qin, T. Ma, Z. Tang, Z. Xin, Z. Haibo, and Z. Lian, “Service-Aware Resource Orchestration in Ultra-Dense LEO Satellite-Terrestrial Integrated 6G : A Service Function Chain Approach,” *IEEE Transactions on Wireless Communications*, pp. 1–14, early access, 2023, DOI:10.1109/TWC.2023.3239080.

[15] V. Eramo, E. Miucci, M. Ammar, and F. G. Lavacca, “An Approach for Service Function Chain Routing and Virtual Function Network Instance Migration in Network Function Virtualization Architectures,” *IEEE/ACM Transactions on Networking*, vol. 25, no. 4, pp. 2008–2025, 2017.

[16] K. M. Sim and W. H. Sun, “Multiple ant-colony optimization for network routing,” *Proceedings - 1st International Symposium on Cyber Worlds*, pp. 277–281, 2002.

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