ISFC: Intent-driven Service Function Chaining for Satellite Networks

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***Abstract*—Satellite networks can help extend wider communication coverage and provide more types of services; and introducing service function chain (SFC) to satellite networks can enhance their flexibility and scalability. However, this highly challenges the complexity and efficiency of network service management. In this work, we first present an intent-driven satellite network service management architecture. It provides a user-oriented programmable and customizable service provisioning mechanism, which can improve the flexibility and efficiency in service delivery and provisioning. Furthermore, we elaborate an intent-driven SFC deployment scheme, which is termed as ISFC. The presented ISFC is with the intent parsing, network function virtualization infrastructure point of presence selecting, and the optimal service function path generation. Finally, we provide the ISFC deployment algorithm. And the simulation results show that the presented ISFC scheme can well satisfy user's requirements with much lower delay.**

***Index Terms*—Intent-driven network, network function virtualization, service function chain, satellite network**

I. Introduction

With advantages of global coverage, independence from geographically limited conditions, and diverse service provisioning, satellite networks have found applications in many important fields, such as military, meteorological, and navigation [1]. Despite these considerable advantages, the advanced network technology with the diversified services and huge data scale introduces following challenges to the satellite networks:

1) *Restricted resources*: The onboard computing and storage resources are very limited, which is resulted by the satellite payload technology and the space environment.
2) *Limited scalability*: In terms of cost, the satellite network is constrained by its huge scale, complex heterogeneity, and highly dynamic topology. And it is not easy to adjust the composition of resources according to requirements.
3) *Inefficient configuration*: At present, the management of satellite networks still heavily relies on expert configuration experience. As the number of satellites and types of services extends, the efficiency of manual configuration decreases significantly.
4) *Service provisioning*: With the increasing requests of service types and multi-dimensional resources towards satellite networks, the demands for user-oriented service provisioning is also growing massively.

Thus, it is necessary to reduce the complexity and improve efficiency of satellite network service management. Fortunately, introducing the network function virtualization (NFV) and software-defined network (SDN) towards satellite networks can significantly improve the service stability, network flexibility and scalability while reducing service deployment overheads [2]. Service function chain (SFC), composed of virtual network functions (VNFs) arranged in a certain order, is proposed to compensate for the disadvantages of the VNF independent deployment. It provides a reliable end-to-end service delivery approach to dynamically provision the corresponding network nodes to carry network services according to the requests and the network state [3]. Therefore, a reasonable SFC deployment would improve the efficiency of network management and the deficiency of service provisioning in the satellite network.

To some extent, the implementation of the SFC deployment relies on the SDN [4]. However, the SDNs have certain shortcomings in automated configuration and abstraction of services. To provide a more effective and flexible network service management method, and to better orient users and services, it is necessary to introduce a novel network paradigm, named intent-driven network (IDN).

The IDN can automatically convert user intents into the desired network status through a process of translation, policy generation, verification, optimization, etc. [5]. Meanwhile, relying on network state awareness, the IDN can automatically handle anomalous occurrences to ensure network reliability. And then it has various properties, including advanced abstract network requests, dynamic updates of the network policy, and tailored network service implementation, which simplifies the network management. Therefore the IDN can also provide a user-oriented, efficient and flexible solution for improving the satellite network service management.

In summary, with wider applications of satellite networks, the number of users turning to satellite networks has increased dramatically and the services they can provide have diversified. Therefore, there is an urgent need to design an intent-driven

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satellite network service management architecture to provide a user and service oriented, flexible and efficient satellite network service management method. In addition, in order to maximize the satisfaction of user service requirements, it is necessary to design an intent-driven SFC deployment scheme for satellite networks to ensure the realization of user services and the satisfaction of service QoS.

The main contributions of this paper are presented as follows:

- **We first introduce the IDN into the satellite networks, and design an intent-driven satellite network service management architecture.** The intent-driven satellite network service management architecture employs a three-layers and two-interfaces model, which consists of application layer, intent-enabled layer, infrastructure layer, northbound interface, and southbound interface. The intent-enabled layer is the foundation layer of the intent-driven satellite network management architecture, enabling intelligent intent analysis and automatic creation of the SFC deployment policy.
- **We propose an intent-driven SFC (ISFC) deployment scheme and the corresponding algorithm.** The scheme is divided into three stages: intent parsing, network function virtualization infrastructure point of presence (VNFI-PoP) selecting, and optimal service function path (SFP) generating. The ISFC deployment algorithm develops the optimal SFP with lower delay under the premise of satisfying the user needs, which synthesizes the available resources and links connectivity of the satellite nodes in the optimal SFP generation phase.
- **We analyze the performance of the ISFC deployment scheme and the proposed algorithm.** Firstly, the results of the intent translation and the policy configuration are given. And then, the performance of the ISFC deployment algorithm is analyzed in terms of the service completion and delay cost. With the satisfaction of the resource constraints, the ISFC deployment scheme can not only satify the service requirements but also with lower delay.

The remainder of this paper is organized as follows. Section II reviews the related work. Section III briefly introduces the intent-driven satellite network service management architecture. Following this, section IV proposes an ISFC deployment scheme and an SFC deployment algorithm for the satellite network. Then we present performance analysis of the ISFC deployment scheme in section V. Finally, section VI provides the conclusion of this article.

II. Related Work

A. Software-defined Satellite Network (SDSN)

A satellite network architecture with flexibility and scalability was designed in [6], in which the SDN controller was deployed on the ground to collect the global network status information. Than a multi-layer SDSN architecture was designed in [7]. The controllers are placed in geosynchronous earth orbit (GEO) and medium earth orbit (MEO). The low earth orbit (LEO) satellites are regarded as the data forwarding layer. Then the management plane, including network operations and control center, is responsible for running various functional modules, such as routing calculations, security policies, and mobility management. With the goal of unified administration and collaborative scheduling in the integrated space-terrestrial network, the SDN and the NFV were adopted in [8] to build the integrated satellite-terrestrial information network architecture. The architecture used the SDN to centralize management and control and the NFV to build a distributed virtual platform. In addition, mobile edge computing was also introduced to improve the quality of service and user experience.

However, due to the large distance between the satellite and the ground, deploying the controller on the ground will significantly increase the propagation delay of the signal, thereby reducing the management efficiency of the satellite network. So it is a tendency to deploy main controllers on GEO satellites to monitor the network status and controllers on the ground stations to backup information.

B. SFC in Satellite Networks

The research on the SFC deployment in satellite networks mainly concentrated on the ground segment. On the other hand, the research on the space segment has only emerged recently. The author in [9] used integer linear programming algorithm to deploy the SFC for the NFV-enabled satellite network. Then using breadth-first search, an SFC deployment algorithm was proposed in [10] to reduce the interstellar delay and to improve the bandwidth utilization, with considering the load balancing. Authors in [11] designed two SFC deployment methods in the satellite networks, which were implemented by the SFP calculation algorithm. Facing the multi-scenario of the space-ground integration information network, a hierarchical multi-domain SFC orchestration framework was proposed in [12]. And a heuristic SFC mapping scheme was provided to deploy the SFC by using a inter-domain path calculation algorithm.

However, we should not only consider the resources of the satellite nodes, the satisfaction of the service requirements also should be taken into account. As a result, it is necessary to develop an efficient scheme for deploying SFCs in the satellite network's space segment.

C. Intent-driven Network (IDN)

The IDN first officially appeared in the draft of the intent standard presented by ONF in 2015 [13]. Following development, the standard and industry fields have successively put forward their concepts and product plans on intent. And then they derived concepts such as *"full intelligent network"* and *"autonomous driving network"*. The key technologies of the IDN include intent translation, policy mapping, consistency check, and intent verification. As the first step in the IDN, the key to intent translation is intent refinement [14]. Then the intent was applied to design the SFC in [15], which provided a formal language of the SFC requests, and solved the problem of SFC design through constrained programming. Furthermore, the flexibility and effectiveness of the network service delivery were enhanced by establishing the SFC request based on the intent.

The IDN converts the user's abstract service requirements into the network configuration, generating and verifying the accuracy of the configuration, and finally changes the network configuration through network automation [3]. It enables more efficient network configuration and allows for unified user-oriented network service management.

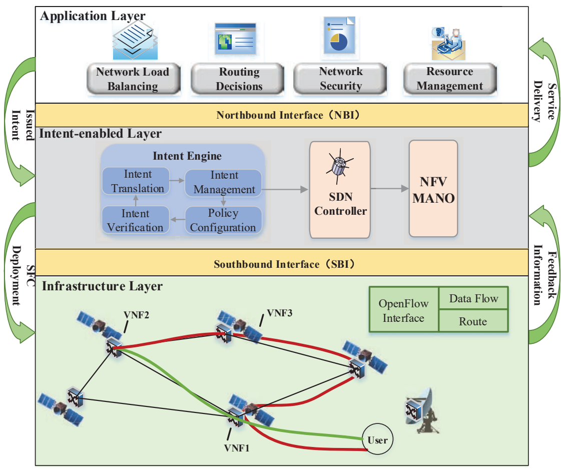


Fig. 1: An intent-driven satellite network service management architecture.

III. An Intent-Driven Satellite Network Service Management Architecture

In this section, we propose an intent-driven satellite network service management architecture, which is depicted in Fig. 1. It employs a three-layers and two-interfaces model. The three layers consist of the application layer, the intent-enabled layer, the infrastructure layer; and the two interfaces consists of the northbound interface and the southbound interface. As the coordinator of the entire network, the network operators can achieve unified planning and integrated orchestration by implementing various management-related applications.

The details of the architecture are described below.

A. Application Layer

It consists of several application services, such as resource management, SFC deployment, and routing management. Then users can input their intents using natural language, templates, or command lines, and then deliver them via the application programming interface, without regard for specific implementation details.

B. Intent-enabled Layer

It includes the intent engine, the SDN controller, and the NFV Management and orchestration (MANO).

The intent engine is the core of the intent-enabled layer. It is responsible for parsing the user's intent, converting it into specific flow classification policies (service function set and access sequence corresponding to distinct data flows, etc.), and sending it to the SDN controller. Specifically, it includes four modules: intent translation, intent management, policy configuration, and intent verification. It supports the customization of the VNF policy repository and the real-time acquisition of network status information through the resource manager. The intent translation module is in charge of refining the service requirements and matching them to the appropriate SFC on demand. The policy configuration is responsible for calculating the SFP of various data flows according to the flow classification policies, and sending it to the service classifier and the service function forwarder to realize flexible flow scheduling.

The SDN controller is responsible for flow control. It can be deployed on GEO, MEO satellites, and ground stations. Based on protocols such as OpenFlow, it sends flow tables to LEO satellites to realize flexible traffic scheduling. Taking into account the link reliability of the global network topology, the GEO is regarded as the master controller to acquire global topology and link information, which will be broadcast to the ground station to complete information backup. As a local controller, MEO assists in managing the entire satellite network and ensures the continuous connection and control of the LEO satellites by the main controller.

The NFV MANO is responsible for managing and orchestrating the underlying resources. In satellite communication networks, service functions commonly exist in the form of middleware. These intelligent entities serve a variety of functions, including performance optimization, security, and address translation. As a result, another usage of NFV MANO is to achieve the entire life cycle management of service function instances, creation, status monitoring, expansion, and deletion.

C. Infrastructure Layer

It consists of physical entities, such as LEO satellites, network operations and control center. While each satellite node has the data forwarding function, it also has the ability to deploy VNFs, such as firewall (FW), performance enhancement proxy (PEP), network address translation (NAT), virtual private network (VPN), duplication, switch [12], etc. Then the VNFs can be subsequently instantiated on suitable satellite nodes to complete service delivery.

D. Northbound Interface

It serves as an intermediary between the application and the intent-enabled layer. It converts the abstract service requirements input by the user similar to natural language into five intent tuples.

E. Southbound Interface

It is used for interacting between the intent-enabled layer and the infrastructure layer, which connects numerous network devices with the NFV. By virtualizing various computing resources, communication resources, and storage resources, the VNF can be deployed flexibly to improve network resource utilization.

The intent-driven satellite network service management architecture decouples of applications and control, as well as separates the data and the control plane. As a major component of the architecture, the intent-enabled layer is a logically centralized control component of the architecture that is employed to achieve comprehensive network service management, including SFC deployment. The intent engine, which is used to automate the transition from requirements to network configuration policies, is a critical component in achieving accurate service delivery. As a result, a user-oriented service deployment method must be developed.

IV. An ISFC Deployment Scheme in Satellite Network

In this section, we design an ISFC deployment scheme in satellite networks. Firstly, we model the satellite networks and the SFC requirements. Secondly, the ISFC deployment scheme and the proposed algorithm are described.

A. Satellite Network Model

Because the satellite network is a time-varying network, deploying SFC needs to find suitable satellite nodes, namely VNFI-PoP, to instantiate the VNFs. Meanwhile, it is also required to generate the optimal SFP that passes through each VNFI-PoP. Then the virtual file system and the virtual network link can be deployed on the satellite network.

The satellite network topology and the SFC requirements model are as follows.

1) Topology Model: The satellite network topology changes dynamically. Therefore, based on the periodicity of the satellite constellation, it is considered that the topology and the link information of the satellite network remain unchanged within a snapshot time. The satellite network can be represented as an undirected graph *P=(N, L, T)*. *N* represents the set of LEO satellites nodes, $n_i \in N$, and i indicates the number of the satellite. The VNFs of different SFCs can be deployed on the same satellite and share its resources. *L* represents the connectivity between satellite nodes, $l_{ij} \in L$, i, j indicate the number of the satellites. *T* represents the snapshot time. In addition, the available resources of the network function virtual infrastructure should be quantifiable. The available storage, CPU, and memory resources of satellite i are represented by $U_s^{P,i}$, $U_c^{P,i}$ and $U_m^{P,i}$, respectively.

2) SFC Requirements Model: For a satellite network service, the VNFs, that are deployed on satellite networks, can be FW, PEP, DPI, NAT, gateway, transit, switch, router, radio VNF, and so on. For any end-to-end SFC for satellite networks, it can be described as gateway VNF - radio VNF - onboard VNF - gateway VNF [9] .

This paper mainly focuses on the SFC deployment in the space segment of the satellite network, so the SFC mentioned in the remainder excludes the gateway VNF.

The SFC is represented by a directed graph *S=(F,LINK)*, which is composed of some specific VNFs in sequence and included in the set *F*, $F = \{f_1, f_2, ..., f_k\}$, and k indicates the number of the VNF in a SFC. *LINK* represents a set of virtual links. Correspondingly, deploying SFC consumes more resources, so the resource of CPU, storage, memory should be considered. $U_c^{S,k}$, $U_s^{S,k}$, and $U_m^{S,k}$ respectively represent CPU, storage and memory resources required by f_k.

B. Intent-driven SFC Deployment Scheme

Different types of network services are implemented by different network functions. That is, the SFC and its VNFs are of different types. SFC deployment is to instantiate, allocate resources, and route for the corresponding VNFs on the underlying physical network. Based on the intent-driven satellite network service management architecture, we design an ISFC deployment scheme to realize the automatic generation of deployment policies. The ISFC deployment scheme consists of three phases, as described in Algorithm 1.

- Phase 1: Intent Refinement

The intent translation module is used to parse and process the service requirements based on Bi-directional Long Short-Term Memory (Bi-LSTM)-Conditional Random Field (CRF). It can get the service configuration parameters and the corresponding VNF type and the sequence of the SFC. Then by looking up the policy repository, it can get the required resources of different types of VNFs. Then relevant parameters of the SFC that complete the network service are gained through the intent engine.

- Phase 2: VNFI-PoP Selection

This phase focuses on selecting the appropriate satellite nodes to deploy VNFs. The satellite-to-ground delay caused by the height of satellite nodes is much larger than that between inter-satellites. Firstly, to reduce the satellite-to-ground delay as much as possible, the ISFC deployment algorithm selects the satellite node that is the closest to the user terminal to deploy the radio VNF (line 2-7). Then, ISFC deployment algorithm matches satellite nodes for each onboard VNF and generates satellite sets that satisfy resource constraints 1 and 2 (line 8-12). The sets can be described, as $OBVNF_1 = \{n_1, n_2, ...\}$, $OBVNF2 = \{n_2, n_3, ...\}$, ..., $OBVNFNum = \{n_1, n_3, ...\}$.

Constraint 1: The available CPU, memory, and storage resources of the satellite node are greater than or equivalent to that required by the VNF that deployed on this satellite node.

$$
\begin{aligned}
U_c^{P,i} &\geq U_c^{S,k} \ \forall f_k \in F, \forall n_i \in N \\
U_m^{P,i} &\geq U_m^{S,k} \ \forall f_k \in F, \forall n_i \in N \\
U_s^{P,i} &\geq U_s^{S,k} \ \forall f_k \in F, \forall n_i \in N
\end{aligned}
$$

Constraint 2: For multiple SFC requirements, the available satellite CPU, memory, and storage resources should be greater than or equivalent to the sum of that required by all VNFs deployed on the node respectively.

$$
\begin{aligned}
U_c^{P,i} &\geq \textstyle\sum_r U_c^{S,k} \ \forall f_k \in F, \forall n_i \in N \\
U_m^{P,i} &\geq \textstyle\sum_r U_m^{S,k} \ \forall f_k \in F, \forall n_i \in N \\
U_s^{P,i} &\geq \textstyle\sum_r U_s^{S,k} \ \forall f_k \in F, \forall n_i \in N
\end{aligned}
$$

- Phase 3: SFP Generation

The SFP generating is the most crucial phase of the algorithm. The depth-first search algorithm is used to search all potential paths between user terminals (line 13-15). The goal of this algorithm is to satisfy service requirements while minimizing

Algorithm 1 ISFC Deployment Algorithm for the Satellite Network

Input: Satellite network represented undirected graph *P=(N,L,T)*, SFC represented by directed graph *S=(F,LINK)*, source node, destination node;

Output: Optimal SFP, delay and the hop of optimal SFP;

1: Initialization;
2: for $f_k \in F$ do
3:   if $k == 1$
4:     for $n_i \in N$ do
5:       Compute the distance between the ground station and the satellite n_i;
6:       Select the satellite n_i with the minimum distance;
7:     deploy the f_1 on the satellite n_i;
8:   else
9:     for $n_i \in N$ do
10:       if available resources of $n_i \geq$ required resources of f_k;
11:         add n_i in the set $OBVNF_k$;
12:       end if
13:   end if
14: for $n_i \in N$ do
15:   $DFSPath(source)$;
16:   $P < -getoptionalpath()$;
17: $WeightSort(P)$;
18: for $p \in P$ do
19:   if $hop \geq VNFnum$
20:     P <- $getOptimalPath(p)$;
21:   end if

the interstellar delay as much as possible. Therefore, the intent-driven SFC deployment algorithm selects the optimal SFP, whose hops are greater than or equivalent to the number of VNFs contained in the SFC and the weight is much smaller than other optional paths (line 16-20). In addition, during the optimal path selecting process, constraint 3 should be also satisfied. The worst case is that the algorithm will traverse all VNFs and satellites, so the cost $O(n^2)$

Constraint 3: VNFs of the same SFC are deployed on different satellite nodes. And the VNF of different SFC can share the resources of the same satellite node.

$$\sum_{n_i \in N} X_i^k = 1, \forall f_k \in F.$$

Finally, the VNF is instantiated on the corresponding satellite node to complete the SFC deployment.

V. Performance Evaluation on ISFC deployment in Satellite Network

In this section, our main purpose is to evaluate and analyze the performance of the ISFC deployment.

A. Simulation Environment

In this experiment, we design a walker constellation using satellite tool kit (STK) to acquire topology information of the satellite network. The constellation consists of 20 LEO satellites evenly distributed in 5 orbits with an altitude of 895.5 km, as well as 1 GEO satellite with an altitude of 36000 km. The snapshot in our simulation environment is 2: 00: 40 on July 31, 2021. The inter-satellite visibility (connectivity) can be obtained through access reports from STK.

We can know that each LEO satellite only establishes communication links with satellites in its own orbit and satellites in adjacent orbits with the same latitude. The inter-satellite delay can be calculated from the inter-satellite distance, which can be also obtained from STK.

We consider that in a snapshot time, satellites have deployed certain VNFs. Therefore, the available CPU, storage, and memory resources of a satellite follow a uniform distribution (20, 70); and the resources required by one VNF of the SFC also follow a uniform distribution (20, 40).

B. Results and Analysis

The user submits the satellite network service requirement through the graphical user interface. The intent can be *"transmit the satellite observation data of Lake Baikal to the Guangzhou ground station, and the return time is: 2:00 on July 31, 2021"*. Then based on the Bi-LSTM-CRF model, the intent translation module correctly parses the declarative service requirement. Then the intent management module matches the corresponding SFC according to the service type by querying the policy repository. The parameters of the translation result are shown in Fig. 2. Then the policy configuration module generates the optimal SFP based on the SFC deployment algorithm, as shown at the bottom of Fig. 2. It shows that the 5 VNFs of the SFC corresponding to the observation data transmission are sequentially deployed on the satellite with node numbers 1, 3, 19, 15, and 16; and the optimal SFP passes through the satellites numbered 1, 2, 3, 4, 19, 15, 16 in turn.

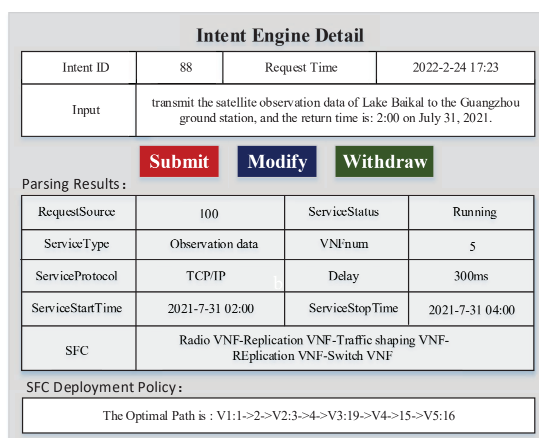
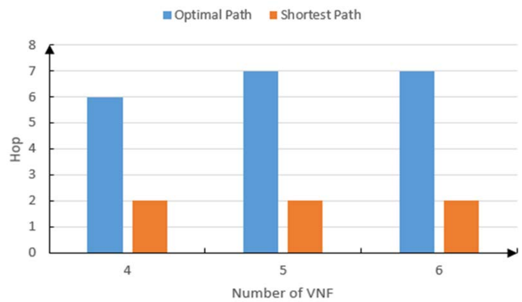
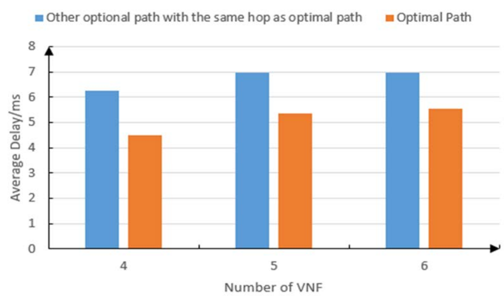


Fig. 2: The translation result and SFC deployment policy.

Then we analyze the performance of SFC deployment algorithm, and mainly focus on whether the service requirement is satisfied, and whether the interstellar delay of the space segment is much lower. To evaluate whether the service requirement is satisfied is to determine whether the hop of SFP is more than or equal to the number of VNF. We set three different types of service requirements, and the number of VNF contained in the corresponding SFC is 4, 5, and 6.



(a) The hop of SFC.



(b) The average delay of SFC

Fig. 3: The hop and delay of ISFC deployment algorithm.

Fig. 3 shows the comparison chart of the hop and the delay, with the determined source and destination points of the data transmission requirement.

Fig. 3(a) compares the hops between the shortest path obtained by Dijkstra algorithm and the optimal path generated by the ISFC deployment algorithm. It can be seen that compared with the number of VNFs, the hops of the shortest path is significantly less than the number of VNFs required, making it difficult to satisfy the demands of SFC deployment. While the optimal path satisfies the requirements of SFC deployment, the hop is only slightly larger than the number of VNFs. When the satellite node resources are sufficient, the ISFC deployment can find the optimal path with the same hops as the number of VNFs.

For comparison, an alternative path with the same hops as the optimal path is chosen to analyze the delay. As shown in Fig. 3(b), compared with the alternative path, the average delay of the optimal path obtained by the ISFC deployment is lower. Because the distance between the across-track satellites located at different latitudes varies, their delay between the across-track satellites differs. Therefore, even if the optimal and optional paths have the same number of satellite nodes, the different satellite compositions make the end-to-end delay different for diverse paths.

In summary, the optimal SFP generated by ISFC deployment can not only satisfy user service requirements but also with lower delay.

VI. Conclusion

In this work, to meet the complex service management and inefficient network configuration in satellite networks, we firstly proposed an intent-driven satellite networks service management architecture. Then, we designed an ISFC deployment scheme, including intent refinement, VNFI-PoP selection, and SFP generation. Finally, we performed our experiment, and the results showed that the proposed architecture provides a user-oriented service management approach that can improve the flexibility and effectiveness in service provisioning and delivery for satellite networks. And the ISFC deployment scheme can not only accomplish the service requirements of users but also with much lower delay.

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