Satellite E2E Network Slicing Based on 5G Technology

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Abstract: We investigate the design of satellite network slicing for the first time to provide customized services for the diversified applications, and propose a novel scheme for satellite end-to-end (E2E) network slicing based on 5G technology, which provides a view of common satellite network slicing and supports flexible network deployment between the satellite and the ground. Specifically, considering the limited satellite network resource and the characteristics of the satellite channel, we propose a novel satellite E2E network slicing architecture. Therein, the deployment of the network functions between the satellite and the ground is coordinately considered. Subsequently, the classification and the isolation technologies of satellite network sub-slices are proposed adaptively based on 5G technology to support resource allocation on demand. Then, we develop the management technologies for the satellite E2E network slicing including slicing key performance indicator (KPI) design, slicing deployment, and slicing management. Finally, the analysis of the challenges and future work shows the potential research in the future.

Keywords: satellite communications; E2E network slicing; diversified applications; 5G technology

DOI: 10.12142/ZTECOM.202004005

https://kns.cnki.net/kcms/detail/34.1294.TN.20201117.1128.001.html, published online November 18, 2020

Manuscript received: 2020-10-26

Citation (IEEE Format): J. Zhang, X. Wei, J. F. Cheng, et al., "Satellite E2E network slicing based on 5G technology," *ZTE Communications*, vol. 18, no. 4, pp. 26–33, Dec. 2020. doi: 10.12142/ZTECOM.202004005.

1 Introduction

As an extension and supplement of the ground communication system, satellite communications have the characteristics of global coverage, random access, and large capacity, which can effectively overcome the shortcomings of the ground communication system[1]. Thus, satellite communications have received significant attention from both academia and industry. However, Internet of Things (IoT) and other new diversified application scenarios have different requirements for satellite communications, e.g., data transmission rate and latency. In scenarios where seamless wide-area coverage is needed, satellite systems should provide users with seamlessly high data-rate services anytime and anywhere, even at remote areas. In metropolitan areas where the density and volume of wireless traffic demand are both very high, satellite networks should provide dense hot-spot coverage with high capacity. In scenarios where reliable connections of a large number of widespread low-power nodes, e.g., wireless sensors, are needed, satellite networks should be able to connect millions of devices under the constraints of low power consumption and low cost per device. Extremely low latency and high reliability of satellite networks are required to meet the performance requirements of real-time, reliable and secure communications in some vertical industries such as interconnected vehicles and industrial production control. Unfortunately, traditional satellite communication technology cannot provide different services for diversified applications and it is difficult to meet the above-mentioned requirements.

It is worth noting that by slicing a physical network into several logical networks, 5G network slicing can support on-demand tailored services for distinct application scenarios while using the same physical network. Supported by network slicing, network resources can be dynamically and efficiently allocated to logical network slices according to the corresponding quality of service (QoS) demands[2]. This paper thereby links the satellite communications to 5G network slicing to reap the benefits of both, while meeting the requirements of diversified applications and achieving the isolation between different servers to enhance the flexibility and effectiveness of satellite communication system.

5G network slicing has attracted a lot of research interests[2 – 6]. For example, the authors in Ref. [2] provided a survey on 5G network slicing, which reviewed the state-of-the-art 5G network slicing and presented a framework for bringing together and discussing existing works. In Ref. [3], a user-centric service slicing strategy considering different QoS requirements was proposed based on the software defined network (SDN), and a genetic algorithm was devised to optimize the virtualized radio resource management based on resource pooling. Recently, the network slicing concept applied to satellite network has been introduced. Therein, an extensible network slicing framework for satellite integration into 5G was proposed in Ref. [7 – 8], but it did not focus on the design and deployment of satellite network slicing. To the best of the authors' knowledge, E2E network slicing is not well explored for the satellite system. Motived by this, we investigate the satellite network slicing. However, in 5G network, the dynamic change of slicing resources is mainly affected by the user behavior, while the dynamic change of slicing resources in satellite network is also affected by the behavior of satellite constellation network. Due to the continuous movement of LEO satellite constellation, the satellite channel resources over different regions of the world are different. Thus, the service model and traffic model processed by the satellite are very different. For a single satellite, there is a tidal effect of resource demand. Fortunately, the satellite ephemeris information is known, which provides a good basis for resource demand forecast and resource arrangement. Based on this, we refer to 5G network slice to design satellite network slice, but there are big differences between them. Therein, the characteristics of satellite network slicing, such as limited satellite network resource, fast changing network topology and diversified applications, should be considered.

This paper is the first to investigate the satellite E2E network slicing based on 5G technology, including the design of the satellite network slicing architecture and the key technologies of network slicing. The contributions of this paper can be summarized as follows.

- We propose a novel satellite E2E network slicing architecture, where the management domain and service domain are designed in detail in the case of limited satellite network resource and special satellite channel characteristics.
- For the services domain, to support E2E network slicing, the classification and isolation technologies of access network sub-slice, transmission network sub-slice, and core network sub-slice are analyzed and proposed adaptively for satellite communications based on 5G technology.
- For the management domain, we develop the key technologies, including slicing key performance indicator (KPI) design, slicing deployment, and slicing management for satellite communications. Therein, the creation of the satellite network slicing instance is developed in the case of limited satellite network resource.
- The challenges and future work are analyzed in detail, which shows the potential research in the future.

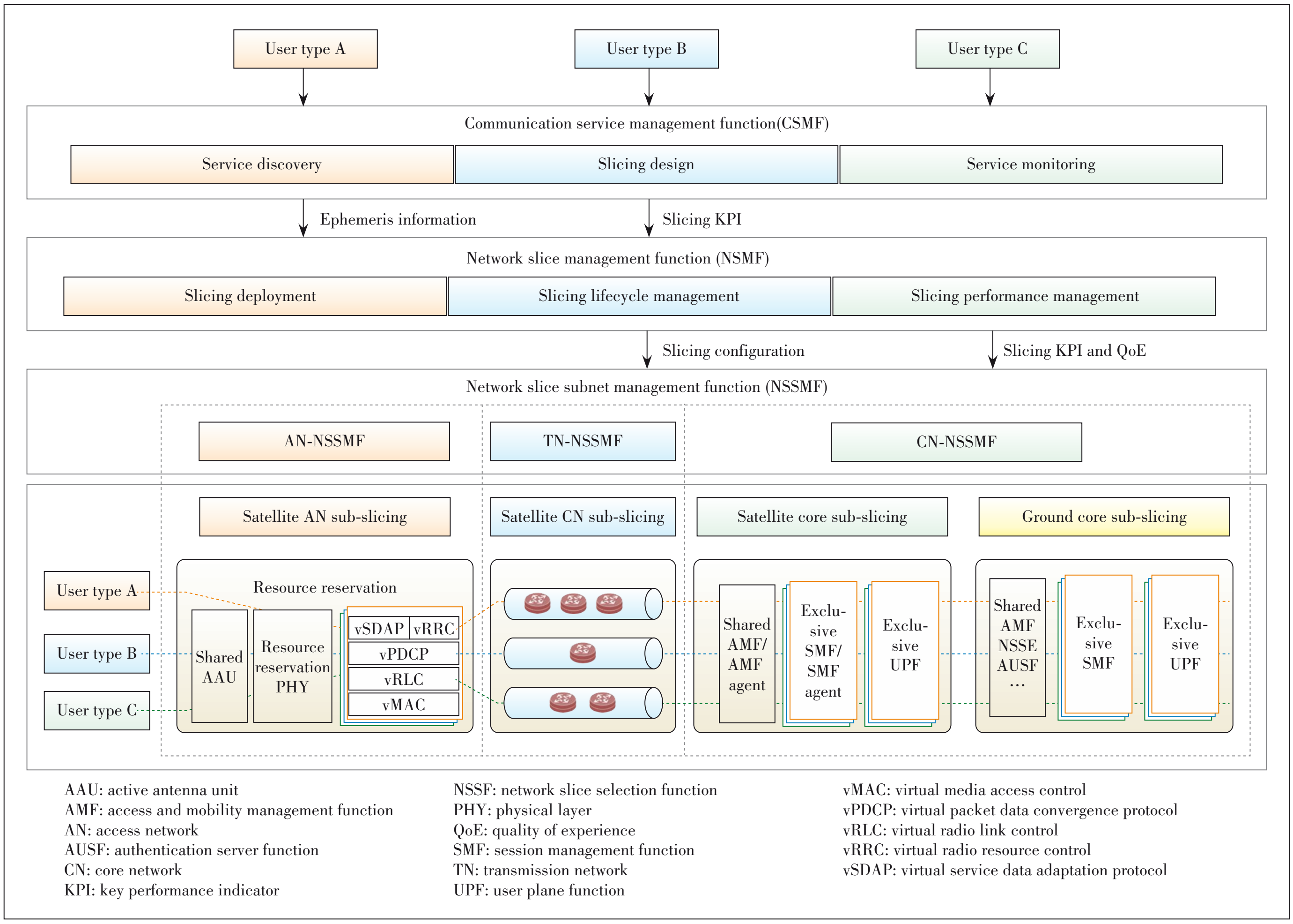
The remainder of this paper is organized as follows. In Section 2, the proposed satellite E2E network slicing architecture is introduced. We investigate the classification and isolation technologies of satellite network sub-slices in Section 3. In Section 4, we present the satellite E2E network slicing management technology. In Section 5, the challenges and future work are presented, and finally, Section 6 concludes the paper.

2 Design of Satellite E2E Network Slicing Architecture

Network slicing refers to the selection of specific features and functions from the network to customize a logically independent virtual private network (VPN) to serve a certain industry or application scenario. A VPN is a slice, and different slices are isolated from each other. In other words, one physical network can be divided into different logical networks with different functions and characteristics to support different application scenarios separately. Each E2E network slice can provide a set of complete network functions, including access network, transmission network and core network functions[9].

The satellite E2E network slicing architecture includes management domain and service domain, as shown in **Fig. 1**. The proposed satellite network slicing architecture supports the flexible deployment of different functional network elements between the satellite and the ground, which is more flexible than 5G network slicing architecture. At the same time, limited by the satellite resources, the proposed satellite network architecture cuts and optimizes the 5G slice architecture mainly on the slicing management domain.

Network slicing management domain includes communication service management function (CSMF), network slice management function (NSMF) and network slicing subnet management function (NSSMF). NSSMF includes access network slicing subnet management function (AN-NSSMF), transmission network slicing subnet management function (TN-NSSMF), and core network slicing subnet management function (CN-NSSMF). Network slicing service domain includes satellite access network sub-slice, satellite transmission sub-slice, satellite core network sub-slice and the ground core network sub-



▲Figure 1. Architecture of the satellite end-to-end (E2E) network slicing.

slice. Therein, referring to 5G standard, satellite access network sub-slice includes active antenna unit (AAU), distributed unit (DU) and centralized unit (CU). AAU completes RF signal processing, power amplification and satellite cell beamforming by software radio. DU mainly completes the signal processing of physical layer, and CU completes wireless high-level protocol processing in access network. With the virtual machine/Docker deployment mode, it supports the flexible deployment of AAU, DU and CU functions in different scenarios. For example, in a constellation, the master-slave satellite cooperative deployment mode is considered, where only a few master satellites deploy CU, while other slave satellites deploy DU. The cooperation between the master satellite and the slave satellite can realize the complete access network. On the other hand, the satellite core network adopts the micro-service architecture, which decomposes complex functional units into decoupled micro-service functions. Thereby, considering the limitation of satellite network resources, some frequently accessed core network functions can be deployed on satellites according to service requirements, such as access and mobility management function (AMF), session management function (SMF) and user plane function (UPF), while other infrequently accessed core network functions are deployed on the ground, which can meet the service requirements and save satellite resources. It is worth noting that, the capabilities (the size of resources occupied) of access network and core network functional elements in different slices are quite different, which also should be properly designed according to the actual demand.

Network slicing management domain can customize network functions according to the service requirements, and release resources to other virtual networks after the end of slicing life cycle, so as to realize dynamic on-demand distribution and flexible adjustment of network resources. Thus, compared with the traditional one channel best-effort network, the proposed slicing architecture can greatly improve the resource utilization, so it is superior to the traditional network in performance or KPI. However, slicing strategy and slicing technology will also bring additional resource overhead and performance improvement. The trade off between slicing overhead and performance improvement is also a direction worth studying in the future. Network slicing service domain allocates resources by slicing, which can not only isolate the resources required by different application scenarios and enhance the reliability of the network to ensure that the failure of one slice will not affect other slices, but also provide differentiated E2E security mechanisms to meet the different security requirements of various application scenarios.

3 Classification and Isolation Technologies of Satellite Network Slicing

The channel and network resource forms of the satellite and 5G are quite different, which leads to great differences in resource classification and isolation technology, so adaptive optimization and design are needed.

3.1 Satellite Access Network Sub-Slice

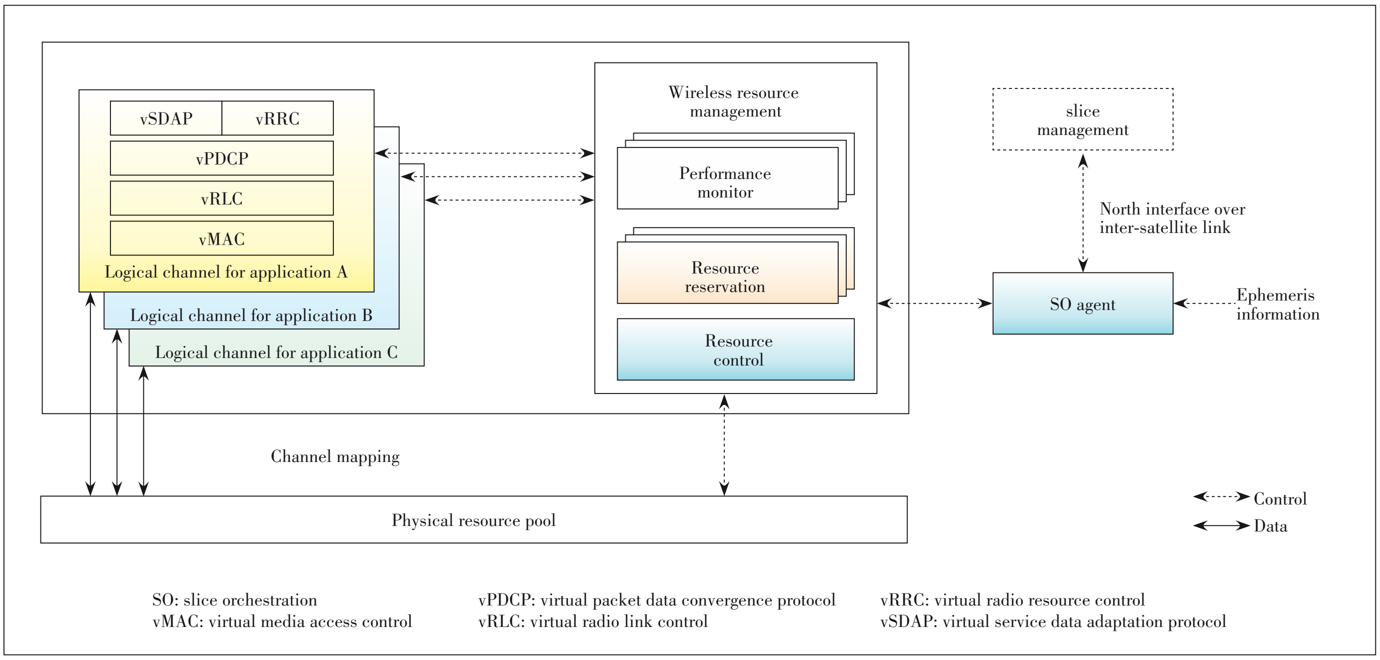
According to the different service level agreement (SLA) requirements of different application scenarios issued by the network slice management platform, the satellite access network sub-slice can be customized utilizing the resource pool reservation and allocation to achieve the isolation of wireless resources, as shown in **Fig. 2**. Different sub-slices of satellite access network can schedule resources and set transmission parameters by configuring the parameters of wireless air interface, so as to obtain reasonable throughput and transmission delay[10].

The slicing method of satellite access network includes QoS priority based schedule, resource block (RB) resource reservation and carrier isolation[11]. QoS priority based schedule can ensure that different services are customized on demand in the case of limited resources, and provide differentiated services for different network. Moreover, when resources are preempted, high priority services can schedule wireless resources first. When resources are congested, however, high priority services may also be affected. Then, RB resource reservation allows multiple slices to share the RB resources of one cell, and allocates a certain number of RB resources to a specific slice according to the resource requirements of each slice. RB reservation supports two working modes, namely static reservation and dynamic sharing. In dynamic sharing mode, the resources reserved for the specified slice can be used for other slice users dynamically when they are idle. On the contrary, with static reservation mode, the resources reserved for the specified slice cannot be allocated to other slice users at any time, to ensure that there are sufficient resources available for specified slice. Finally, in the case of carrier isolation, different slices use different carrier cells. Each slice only uses the wireless resources of their own cell, and the slices are strictly differentiated to ensure their own resources.

3.2 Satellite Transmission Sub-Slice

According to the security and reliability, the satellite transmission sub-slice can be employed by two types of methods, namely the hard isolation and the soft isolation. The hard isolation is physical isolation while the soft isolation is logical isolation. The effect of the soft isolation is worse than the hard isolation, but its cost is lower than the hard isolation[12]. Both hard isolation and soft isolation can be applied alone, and the tradeoff between the isolation effect and cost can be achieved by combining different hard isolation technologies and soft isolation technologies.

The hard isolation technologies mainly include FlexE interface isolation for layer 1 (L1) and metro transport net-



▲**Figure 2. Satellite access network sub-slice.**

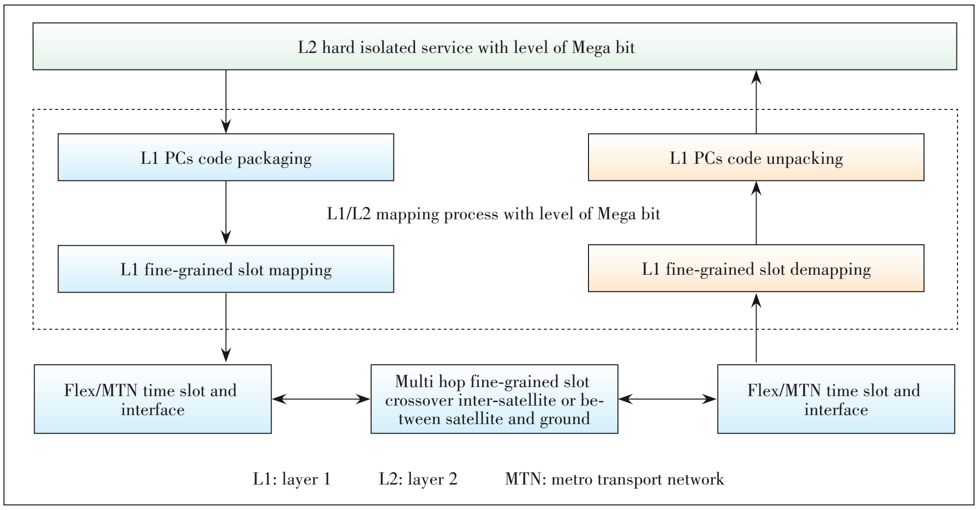
work (MTN) cross isolation for L1 and layer 2 (L2). FlexE interface isolation divides a physical Ethernet port into several Ethernet elastic hard pipes based on time slot scheduling. Thereby, for the network interface, the service can access the network based on the time slot, and for the devices, the statistical multiplexing is based on Ethernet. MTN cross isolation is a cross technology based on Ethernet 64/66 bits code blocks, which achieves time division multiplexing (TDM) based time slot isolation in the interface and devices, so as to achieve extremely low delay and isolation effect. The minimum forwarding delay of single device is 5 – 10 us, which is much lower than that of the traditional packet switching devices. The main soft isolation technology is based on VPN and QoS, which realizes the isolation of multiple services on the same physical infrastructure network. However, software isolation cannot achieve the isolation in hardware and slot, and cannot achieve the isolation effect of physical isolation.

The laser link resources inter-satellite or between the satellite and the ground of LEO constellation are much smaller than the ground optical fiber network bandwidth. Specifically, the ground optical fiber network bandwidth is usually 100 Gbit/s, and the link bandwidth of laser inter-satellite or between satellite and the ground is 5 Gbit/s. Thereby, fine-grained slice isolation is particularly important. In order to support emergency communication and mission critical vertical industry applications, it is necessary to implement fine-grained slice isolation with the level of Mega bit, 10 ms end-to-end transmission delay, and delay jitter with level of millisecond, where the distance variation factor inter-satellite or that between satellite and the ground is considered. Thus, it is suggested to use fine-grained hard isolation technology in satellite constellation transmission network slice deployment, which is shown in **Fig. 3**. Based on Ethernet L1 fine-grained slotting, it supports fine-grained slot hard isolation slicing for L1, and supports direct L1 slot cross for slotted services to reduce forwarding delay. In addition, L2 service mapping processing based on L1 fine-grained timeslot is also needed to support the flexible and efficient mapping of L2 services with the level of Mega bit into L1 slot container to provide the delay jitter with the level of millisecond.

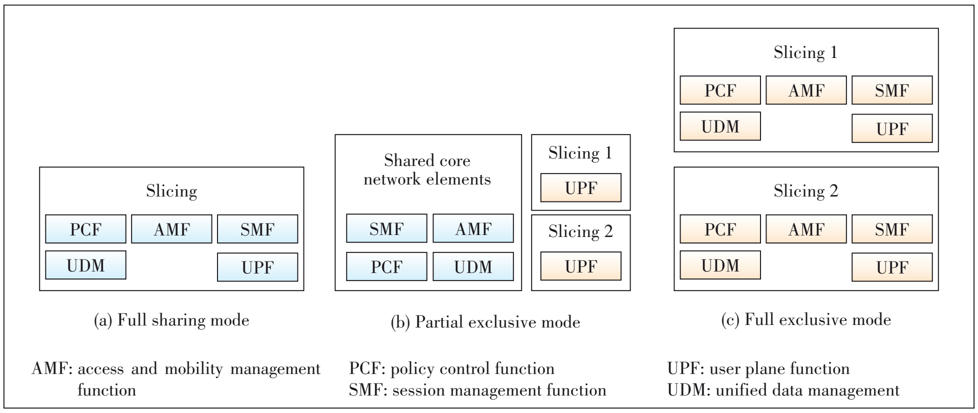
3.3 Satellite or Ground Core Network Sub-Slice

In order to realize the on demand deployment of core network elements between satellite and the ground, the traditional core network element based on complex single unit is decoupled into modular micro services, which can be deployed on virtual machines or Dockers. Thus, the isolation and rapid deployment of core network elements can be realized to support the deployment of core network sub-slice. Based on the combination of part satellite core network elements and part ground core network elements, users can slice the satellite core network sub-slice and the ground core network sub-slice to meet their SLA requirements.

Thanks to the above-mentioned network virtualization and service-oriented architecture[13 – 14], the core network elements support on-demand isolation and the independence of different slices at the same time. There are mainly three types of isolation modes: full sharing mode, partialy exclusive mode, and fully exclusive mode, as shown in **Fig. 4**. With full sharing mode, all network elements are shared by all sub-slices, and its capability is equivalent to that of the traditional network. It is often



▲**Figure 3. Satellite transmission network sub-slice.**



▲**Figure 4. Isolation modes of the core network elements.**

used for general services in public network that have no special requirements for isolation. The partially exclusive mode is that most of the network elements are shared in the sub-slice, and a small number of network elements are exclusive. It can achieve the best balance between isolation requirements and costs, so as to meet the network slicing requirements of most general industries. In the full exclusive mode, each sub-slice owns all the functional network elements, and its ability is equivalent to building a completely dedicated core network. Its isolation is the best, but the construction and operation costs are also the highest. It is suitable for some special industries which need ultra-high isolation and are not cost sensitive.

4 Satellite E2E Network Slice Management Technology

Satellite E2E network slicing management mainly includes network slicing design, network slicing deployment, network slicing lifecycle and performance management[9]. Network slicing design refers to CSMF generating satellite network slice KPI index according to service requirements. Then, NSMF decomposes the KPI index of satellite network slice into access network sub-slice, transmission network sub-slice, and core network sub-slice, namely the network slice deployment. Finally, NSMF completes the network slicing lifecycle management and performance management. It is worth noting that different from 5G network resources, satellite network resources are limited. Therefore more refined resource management is needed, which raises higher requirements for the lightweight of slice management technology and the granularity of resource management. And fortunately, the satellite network behavior can be predicted based on ephemeris information, so satellite network slicing supports resource planning and deployment in advance, and effective slicing planning mechanism can reduce the overhead of slice management.

4.1 Satellite Network Slicing Design

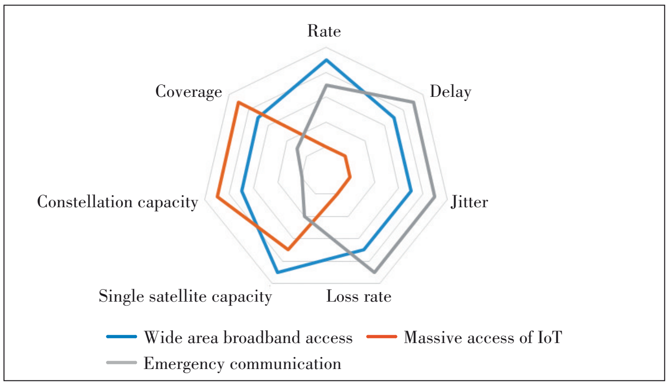
In different application scenarios, the requirements of different services for satellite network slice are also quite different, such as large traffic transmission of wide area broadband access, massive access of IoT and low delay transmission of emergency communication, as shown in **Fig. 5**. Specifically, in the wide area broadband access scenario, the satellite as the supplement of the ground network achieves large capacity and wide area coverage. The typical services of wide area broadband access mainly include high definition video, massive real-time data interaction, etc. These services raise very high requirements for the traffic and transmission rate of network slices, including high transmission rate, high peak rate, large traffic density, service continuity, etc. Secondly, massive IoT mainly includes smart city, environmental monitoring, smart agriculture, intelligent wear and other applications. These applications cover a wide range of applications with a large number of access devices, and have outstanding requirements in low power consumption and mass connection. Thereby, they have high requirements for KPI of network slice coverage, satellite capacity, etc. Finally, the rapid deployment of satellite network can effectively meet all kinds of service requirements in emergency communication scenarios, providing efficient and reliable information transmission. Emergency communications have certain requirements for KPI of network slices, such as delay, jitter, loss rate and rate. To meet the differentiated service requirements in different scenarios, the KPI of satellite network slicing should be properly designed according to the service requirements.

4.2 Satellite Network Slicing Deployment

Satellite network slicing deployment decomposes the KPI index of network slice into access network sub-slice, transmission network sub-slice and core network sub-slice, and completes the network parameter configuration of each sub-slice. Network parameters include QoS related parameters (delay rate and loss rate, etc.), capacity related parameters (the number of users, the single satellite capacity, and the constellation capacity, etc.), and service related parameters (the coverage area, the application scenario, etc.), and more. The way to reasonably decompose the KPI index of network slice will directly affect whether the slice can meet the service requirements. The KPI decomposition diagram of E2E satellite network slice is shown in **Fig. 6**, where the related network parameters of access network sub-slice, transmission network sub-slice, and core network sub-slice are summarized respectively.

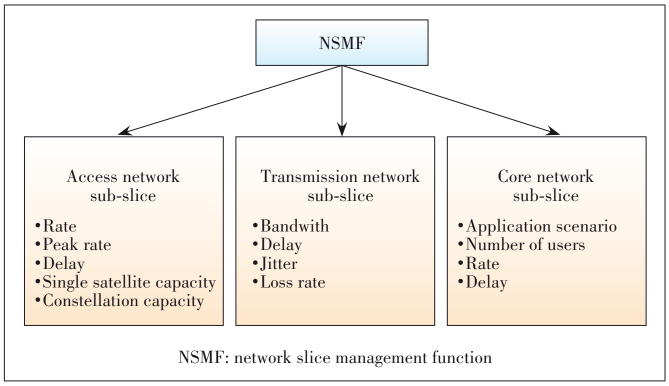
4.3 Satellite Network Slice Management

Network slicing lifecycle management is mainly to complete the creation, update, termination and query of network slice instances. NSMF completes the creation of network slicing instances according to the deployment requirements of access network sub-slice, transmission network sub-slice and core network sub-slice. In **Fig. 7**, the creation of satellite network slice instance is designed to simplify the creation process in the case of limited satellite network resource. Specifically, af-



▲ Figure 5. Requirements of different services in different application scenarios.

ter receiving the request of network slicing creation, NSMF decomposes the KPI of satellite network slice in sub-slices and allocates slice ID. Then, NSFM commands NSSMF to create network sub-slices. After creating the sub-slices, NSSMF returns the results of sub-slices creation and slice creation. Moreover, after receiving the request of network slicing requirement change, NSMF identifies the slice instance to be modified, and generates the corresponding slice instance change requirement to trigger the modification of slice instance to realize the update of network slice instance. If NSMF receives the instruction that the network slice instance is no longer used, and determines that the network slice instance does not contain any network slices, NSMF will delete the network slice instance. At the same time, NSMF supports the query of network slice instance information based on single network slice selection assistance information (S-NSSAI) or network slice instance (NSI) ID, where the instance information includes the service profile, network slice subnet instance (NSSI) information associated with network slice instance, etc.

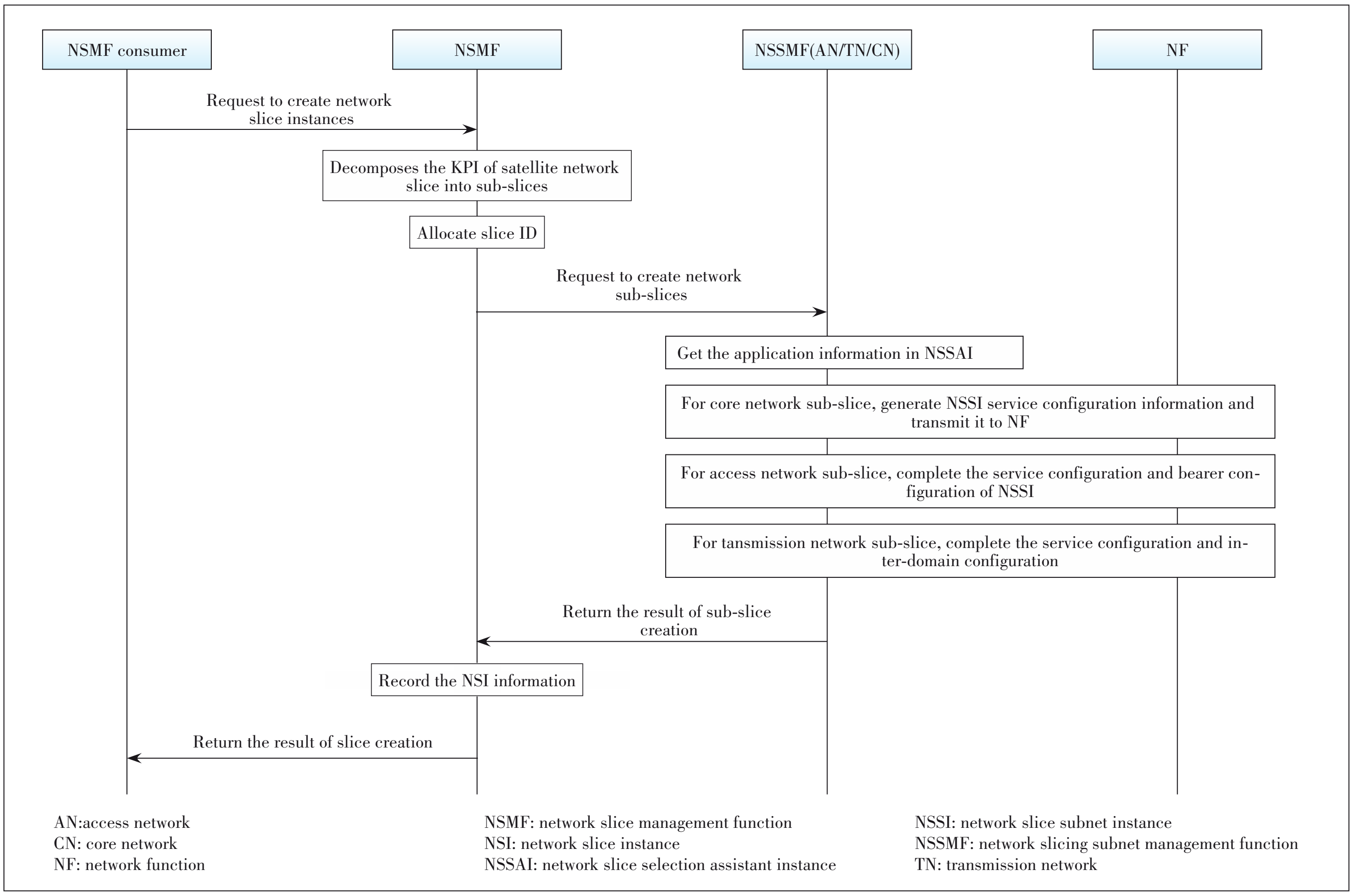


▲Figure 6. Key performance indicator (KPI) decomposition of end-to-end (E2E) satellite network slicing among sub-slices.

The performance management of satellite network slicing is mainly to collect the performance data reported by the sub-slices of NSMF, summarize the performance data of each domain, and generate performance index. At the same time, after the slice creation, NSMF can check whether the current slice meets the user's performance requirements. If the requirements cannot be met, NSMF can improve the slice performance by modifying the capacity of the slice instance or the slice configuration.

5 Challenges and Future Works

5G network slicing has already received a lot of attention.



▲Figure 7. Satellite network slice instance creation.

The research on the satellite E2E network slicing is just beginning, but it is an interesting topic for future research. In this section, we elaborate on several significant challenges that need to be addressed to fully realize the satellite E2E network slicing based 5G technology in the future. First, the base band unit of the access network is difficult to be virtualized, especially when the satellite resources are limited, resulting in low resource isolation between sub-slices. To this end, slice awareness can be considered to support network slicing in access network. Specifically, when the slice is established, the access network divides and reserves the resources according to the slice type, which can guarantee the time-frequency resources for transmission. Secondly, the dynamic deployment strategy of core network elements between the satellite and the ground is another important factor restricting the efficiency of network slicing, which has not been well studied in both academia and industry, but it is an interesting research direction. Finally, there is no mature scheme for satellite network slicing design. The key is to design typical satellite application scenarios, complete the quantification of service SLA, and map model and strategy between service SLA and network slicing KPI.

6 Conclusions

We have presented what we believe to be the first scheme of the state-of-the-art satellite E2E network slicing based on 5G technology to provide customized services for the diversified applications. To this end, we present a common satellite network slicing architecture to support the flexible deployment of the network functions between satellite and the ground. Then, on the one hand, for the slicing service domain, the sub-slices of access network, transmission network and core network are designed including the classification and the isolation technologies based on 5G technology to support resource allocation on demand. On the other hand, for the slicing management domain, slicing KPI design, slicing deployment and slicing management are developed in satellite E2E network slicing. Finally, the challenges and potential research are presented in detail to give a view of future work.

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