Service Coordination in the Space-Air-Ground Integrated Network

Yan Guo, Qing Li, Yuanzhe Li, Ning Zhang, and Shangguang Wang

Abstract

The space-air-ground integrated network (SAGIN) is regarded as a promising approach for providing ubiquitous Internet access anytime and anywhere. With virtualization technologies and multi-access edge computing, data transmission and data processing in SAGINs are abstracted as services. Space-air-ground service computing flexibly integrates and manages these services in SAGINs based on service-oriented architecture. However, it is significant but very challenging to provide Internet of Things service with high QoS in space-air-ground service computing due to the distributed service management, and the mobility of both infrastructures and users. Therefore, in this article, we investigate service coordination to guarantee the QoS in space-air-ground service computing. In particular, we first introduce three service coordination scenarios: fine-grained, medium-grained, and coarse-grained service coordination. Then we design a service coordination framework that contains three tiers: edge node tier, service function routing tier, and global control tier. After that, we propose a service coordination approach to reduce the service delay at low cost, which considers the selection with foresight and updates based on threshold. Experimental results show the advantages of our service coordination approach in terms of service delay and cost.

Introduction

With the development of the Internet of Things (IoT) and the emergence of the Internet of Everything, high-level network capacities, such as global ubiquitous access and ultra-reliable communication, are required [1]. At the same time, emerging applications such as augmented/virtual reality, 3D imaging, and autonomous vehicles also bring higher requirements on networks [2]. Although the Internet has experienced unprecedented growth, and wireless networks have developed from 4G to 5G, the gap between demand and supply is becoming more and more prominent. In addition, it is impossible to provide ubiquitous services, especially in rural areas, remote mountainous areas, and isolated islands, by relying only on the terrestrial network due to the limitation of ground infrastructure deployment [3].

The space-air-ground integrated network (SAGIN), as shown in Fig. 1, is regarded as a promising approach for ubiquitous Internet access. The satellite communication network can provide super wide coverage and high capacity. Both the satellite network and the aerial network serve as important complements to the terrestrial network in terms of coverage, flexibility, robustness, and so on [4]. The SAGIN features a large number of network nodes, such as satellites, unmanned aerial vehicles (UAVs), high-altitude platforms, and ground base stations, capable of providing terabit-per-second connectivity. This scale is far beyond other network swarms. Moreover, different network paradigms are supported by various communication standards and communication links, and equipped with different types of network devices. The heterogeneity of different network components leads to high operational and capital expense.

To overcome these issues, a network function virtualization (NFV)- and software-defined networking (SDN)-based SAGIN system has been proposed [5, 6]. With virtualization technologies, the heterogeneous physical resources from different network segments are abstracted into unified virtual resource pools. Then NFV and SDN are applied to manage the abstracted virtual resource flexibly [7–9]. On the other hand, as an emerging network technology, mobile edge computing [10] is regarded as a key technology to reduce processing delay and further promote the quality of service (QoS) for SAGINs. Edge computing servers can be deployed on satellites [11], UAVs [12, 13], and high-altitude platforms [7] and act as edge nodes in the SAGIN. Empowered by mobile edge computing, the nodes in the SAGIN can execute data processing at a unified computing platform.

Based on these technologies, both data transmission and data processing are abstracted as services that can be integrated and managed based on service-oriented architecture. Service computing in the SAGIN, called space service computing or space-air-ground service computing, has many new features of large spatial-temporal scale, dynamic context, and network cooperation. Compared to traditional service computing, space-air-ground service computing has the following features:

1. The services are distributed over satellites, high-altitude platforms, UAVs, and ground infrastructures, which leads to distributed service management. It can further cause high complexity and low efficiency of service provision.
2. Except for the mobile users, the core infrastructures (i.e., satellites, high-altitude platforms, and UAVs) in space-air-ground service computing are mobile with high speed. This mobility features much larger distances and

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velocities than traditional service computing. In such a dynamic context, service continuity guarantee is nontrivial.
3. The in-orbit computing and storage capabilities are limited.
4. For ubiquitous IoT applications in space-air-ground service computing, the QoS requirements are significantly heterogeneous, along with higher requirement for delay.

Therefore, it is very challenging to provide the heterogeneous services in space-air-ground service computing than in traditional service computing. However, the majority of existing works focus on the architecture [8, 9, 11], communication [5–7], and so on. Only a few works study the computing service in SAGINs [14], without considering the coordination of dynamic network and computing resources. To accommodate the diverse services in various practical scenarios (e.g., rural and urban), it is imperative to exploit spatiotemporal service coordination in space-air-ground service computing. Therefore, we investigate the service coordination problem to guarantee the high QoS of services in space-air-ground service computing. We first give three service coordination scenarios in space-air-ground service computing. Then we design an architectural framework for service coordination in space-air-ground service computing. Finally, we propose a service coordination approach that considers the selection with foresight and update based on threshold. Related experimental results show the benefits of our service coordination approach.

The rest of this article is organized as follows. The service coordination scenario is illustrated, followed by the framework for service coordination. Then we introduce the proposed service coordination approach, and perform several experiments to evaluate performance of the proposed approach. Finally, we summarize this article.

Service Coordination Scenarios

The service coordination in space-air-ground service computing is three-fold, as follows.

Fine-Grained Service Coordination

The coordination of the distributed satellite network, aerial network, and terrestrial network has been regarded as a promising approach for ubiquitous IoT applications. With the rapid development of IoT applications, there is a growing demand for global connections to anyone and anything. Although terrestrial wireless networks have made many breakthroughs in network communication technology (i.e., 5G and 6G), terrestrial networks alone cannot meet these needs. The satellite network and aerial network can assist the terrestrial networks to ensure ubiquitous and full service coverage. They can also promote the flexibility and robustness of communication networks, and collectively constitute a proposed beyond 5G network architecture. In addition, with new advanced technologies, satellites and aircraft can provide high data throughput and computing services. Therefore, the satellite network and aerial network can serve as an important complement to terrestrial networks for caching services and computing services, such as multimedia service delivery and satellite remote sensing image preprocessing. In a word, the coordination of distributed networks enables a global coverage and large-capacity network in space-air-ground service computing.

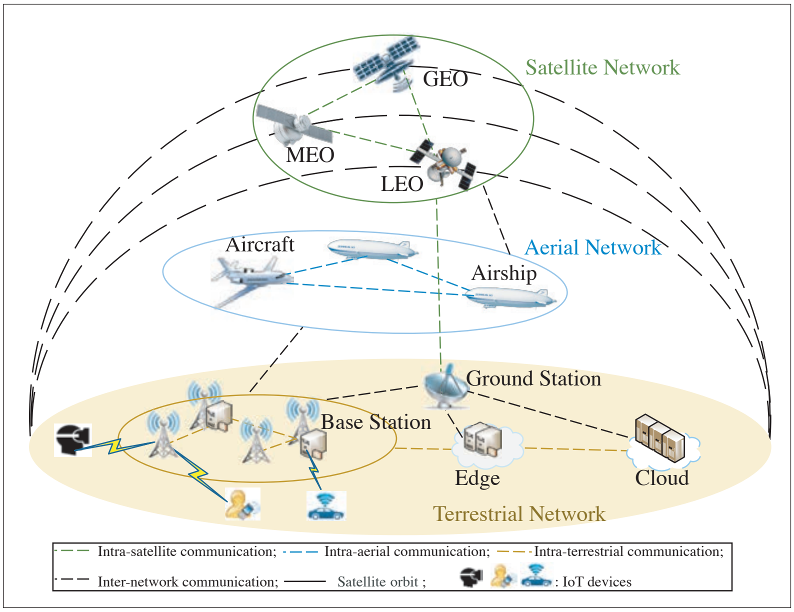

FIGURE 1. The system architecture of a SAGIN for ubiquitous IoT applications.

As shown in Fig. 1, the coordination of three-layered networks can guarantee ubiquitous services for UAVs in emergency rescue. In particular, UAVs can connect with satellite networks and aerial networks for communication and computing when base stations and access points are destroyed, or in areas with patchy terrestrial network coverage such as remote mountainous regions.

Medium-Grained Service Coordination

Based on fine-grained service coordination, medium-grained service coordination is the coordination of network services and computing services for delay-sensitive IoT applications. Each service delivered to end users is essentially a composite service that consists of both data processing services provided by servers and data communication services offered by network systems. The data processing services are provided by cloud servers and edge servers deployed at the satellite network, aerial network, and terrestrial network. With the development of container technologies and serverless technologies, the complex data processing services are decomposed into a set of lightweight computing service functions that can be deployed and executed individually and flexibly. On the other hand, the NFV- and SDN-based network architecture realizes data communication services as a chain of network service functions that can be deployed on commodity servers, which greatly enhances the flexibility and efficiency of service function chain deployment and operation. Then the network service functions and computing service functions can be selected and orchestrated cooperatively as service components to form a service function hyper-chain (SFHC) for meeting the different requirements of multi-tenant services.

Figure 2 shows an example of emergency rescue service provisioning for UAVs. The service functions have been deployed at the nodes with different processing capacities. In particular, the data processing speed from high to low in proper order are: $N_5 > N_6 = N_4 > N_3 > N_2 = N_8$. When the UAV executes the rescue mission, there are three strategies of SFHC planning schematically. Three strategies ($SFHC_1$, $SFHC_2$, $SFHC_3$) are represented by the solid red line, dotted red line, and dashed red line, respectively. $SFHC_1$ is the strategy with the shortest communication delay and the longest processing delay. On the contrary, $SFHC_3$ is the strategy with the shortest processing delay and the longest communication delay due to the forwarding by satellite. Although the communication delay of $SFHC_2$ is longer than $SFHC_1$ and the processing delay of $SFHC_2$ is longer than $SFHC_3$, the overall delay of $SFHC_2$ is the shortest. If the NSFs and ASFs are selected and orchestrated individually, $SFHC_1$ and $SFHC_3$ may be optimal. The real optimal strategy, $SFHC_2$, can be selected only when the NSFs and ASFs are orchestrated cooperatively.

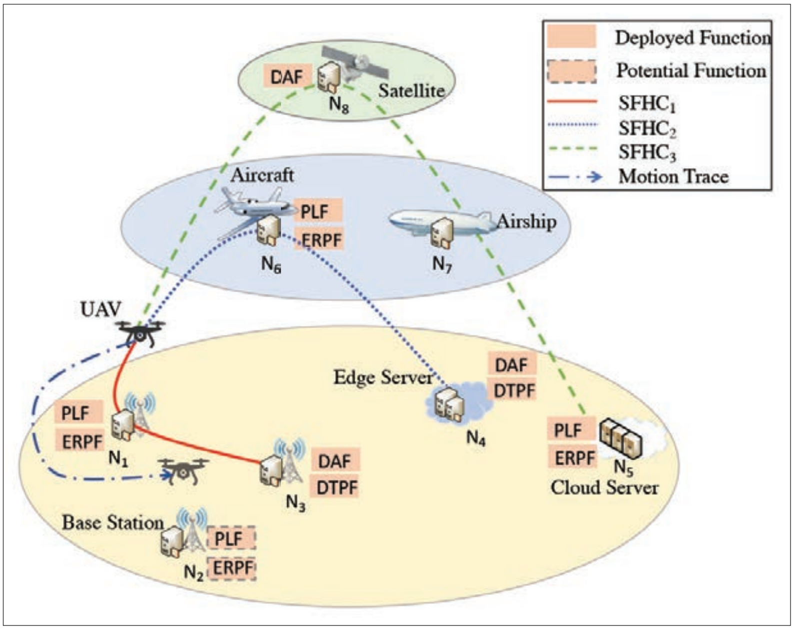

FIGURE 2. An example of emergency rescue service provisioning for UAVs in space-air-ground service computing. The referred service functions are person localization function (PLF), escape route planning function (ERPF), disaster assessment function (DAF), and disaster trend prediction function (DTPF).

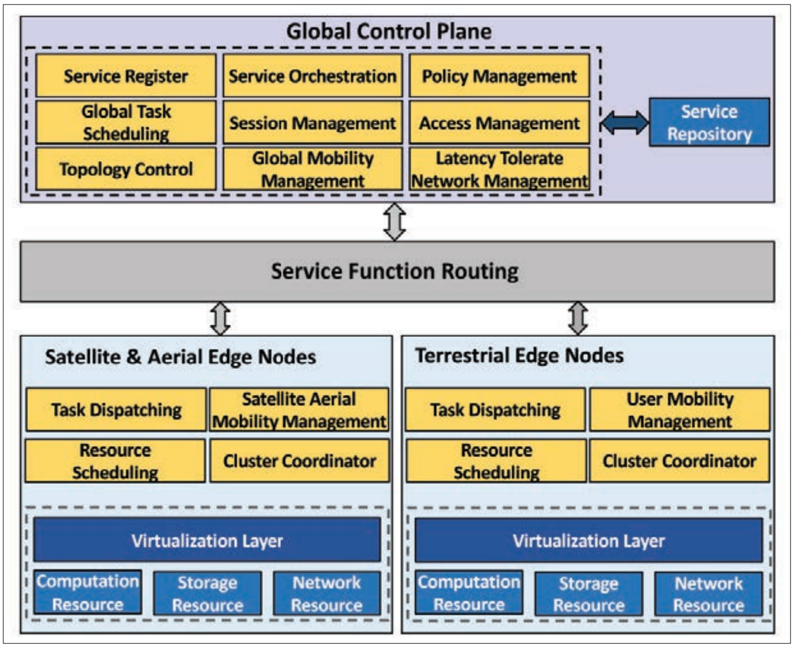

FIGURE 3. The framework for service coordination in space-air-ground service computing.

Coarse-Grained Service Coordination

Coarse-grained service coordination is the coordination of network services and computing services considering mobility. Since both satellites and aircraft are in high-speed motion, the service quality of SFHCs can be greatly affected. In addition to the mobility, the communication and processing (storage) capacities of terrestrial infrastructures are not always stable due to dynamic traffic, especially in disaster areas. The dynamically changing terrestrial infrastructure availability, the motion of satellites and the aircraft, and the mobility of end users are intertwined in space-air-ground service computing, thus making service provisioning more challenging and deserving of thorough investigation. It is significant but very challenging to ensure that moving users can still receive services with high quality in space-air-ground service computing. Service migration can help to deal with user mobility, which moves the service functions closer to users when users change their locations. However, service migration handling service functions individually, without considering other deployed service functions of the SFHC, fails to find the optimal service provisioning strategy and fully utilize the network resources.

The coordination of service functions deployed across the satellite network, aerial network, and terrestrial network plays an important role in guaranteeing QoS. Specifically, service coordination in space-air-ground service computing is mainly to select the optimal SFHC dynamically, taking into account the user mobility, the periodic motion of satellites and the aircraft, and the dynamics in terrestrial infrastructures. For example, when the UAV in Fig. 2 moves away from base station N_1 and reaches base station N_2, it can select the original functions under the new SFCH: $N_6 \rightarrow N_4$ with a long communication delay, or the SFCH: $N_2 \rightarrow N_3$ with service function deployment, or SFCH: $N_8 \rightarrow N_5$. Similarly, if the UAV is still within the coverage of N_1 while the aircraft N_6 moves away from the UAV and N_4, the UAV can still select $SFCH_2$ with longer communication delay, SFCH: $N_7 \rightarrow N_4$ with service deployment, or SFCH: $N_8 \rightarrow N_5$. The overall delay and resource usage of the candidate SFCHs are different and dynamically changing. Therefore, service coordination is to coordinate the functions within different networks to perform real-time emergency rescue service.

Service Coordination Framework

The service coordination framework consists of three tiers, as shown in Fig. 3. From the top to the bottom, the three tiers are global control plane, service function routing, and edge nodes, respectively. In this framework, service function instances run in different edge nodes and form SFHCs with the guidance of service function routing. The global control plane serves as a high-level controller that is in charge of coordinating different nodes and service instances.

The edge node tier consists of satellite edge nodes and terrestrial edge nodes. Each node contains basic infrastructures that provide computation, storage, and network resources. All these resources are provided leveraging virtualization technology via a virtualization layer. Then the virtualized resources are controlled by the management functions. Task dispatching plays the role of an interface to dispatch tasks coming from outside of the node. Then the resources are scheduled according to the dispatching scheme. Both satellite edge nodes and terrestrial edge nodes face mobility challenges. Specifically, the mobility challenge of terrestrial edge nodes mainly comes from user movement, while mobility management in satellites mainly deals with the high-speed mobility of the satellite. The cluster coordinator is in charge of coordinating with other edge nodes in the system.

The service function routing tier connects all the parts of the system, including edge nodes and the global control plane, together. On one hand, it provides network routing for each service and links the service functions together to form SFHCs. On the other hand, thanks to the flexibility provided by SDN technology, it can easily reform the network topology under the control of the global control plane to adapt to the dynamic network environment.

The global control plane is located at a cloud data center and serves as the central controller of the whole system. It is composed of a service repository and several system control functions. The service repository contains service and application images that are pulled by edge nodes to start a service function instance. System control functions are in charge of the global control of the system. When a new service is deployed in the system, the first step is to register itself to the service register function. Then the relative tasks are scheduled according to the pre-defined policies. Session management and access management are responsible for ensuring the continuity of user sessions and managing user access, respectively. Topology control runs the control plane of SDN devices and manages the network topology of the system. Furthermore, the latency-tolerant network management function works to help edge nodes to deal with situations with different latencies.

The Proposed Service Coordination Approach

In this section, we propose a service coordination approach for space service computing to reduce the overall service delay with low costs.

Our approach is based on the general topology shown in Fig. 2. The satellite network is abstracted as a set of satellite nodes (i.e., N_8) that have large coverage and can connect with all the ground nodes. The aerial network is abstracted as a set of aerial nodes (i.e., N_6 and N_7) that can connect with all the ground nodes except N_5. The ground nodes can be connected to each other by wired or wireless links. The service requests from the UAVs are represented by SFHCs composed of specific NSFs and ASFs. Based on microservice architecture, container technology, and NFV technology, all the NSFs and ASFs are packed into a Docker image, and deployed quickly and flexibly as instance per container on satellite, aerial, and ground nodes.

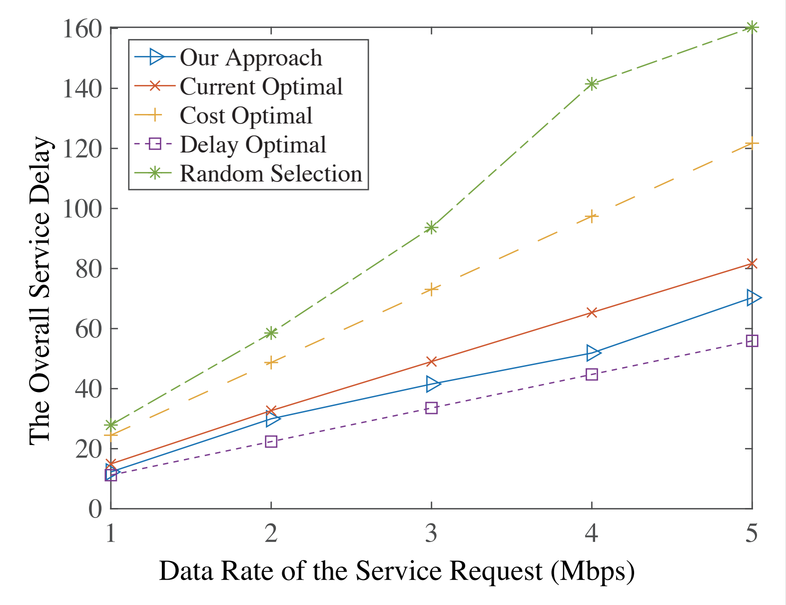

FIGURE 4. The overall service delay of different approaches with respect to the data of a user request.

The objective of the proposed approach is to devise the optimal service coordination strategy with low overall service delay and low cost. The overall service delay contains the data processing delay, data communication delay, and strategy transition delay. The data processing delay of a function is inversely proportional to the computing resource that the node allocates to the function instance. The data communication delay consists of the communication delay between the UAV and its first function instance and the communication delay between each function instance. The communication delay between each pair of ground nodes depends on the number of hops between them. For nodes that are far away from each other, the communication delay of the link between them through a series of ground nodes may be longer than the link through a satellite node. The strategy transition delay is incurred when a new SFHC is selected, because intermediate data (file system and state data) would be migrated to new functions to synchronize instances. The more the functions of the new SFHC change, the higher the strategy delay is. The service coordination cost includes the cost of resource usage and the cost of function deployment. The resource used by each function instance varies, and the resource price of the nodes is different. Therefore, the cost of resource usage depends on both the allocated resources.

The proposed approach is shown in Algorithm 1. The two main principles are to select SFHCs with foresight and update SFHC based on a threshold.

First, we not only compute the utility values of SFHCs, but also predict the long-term utility values of SFHCs. The prediction of utility values is based on the motion traces of satellite and user, the traffic intensity, and the function multiplexing:

- For the satellite nodes of which the motion is periodic and the aerial nodes that are fixed or moving according to pre-set traces, the connect time and duration can be obtained

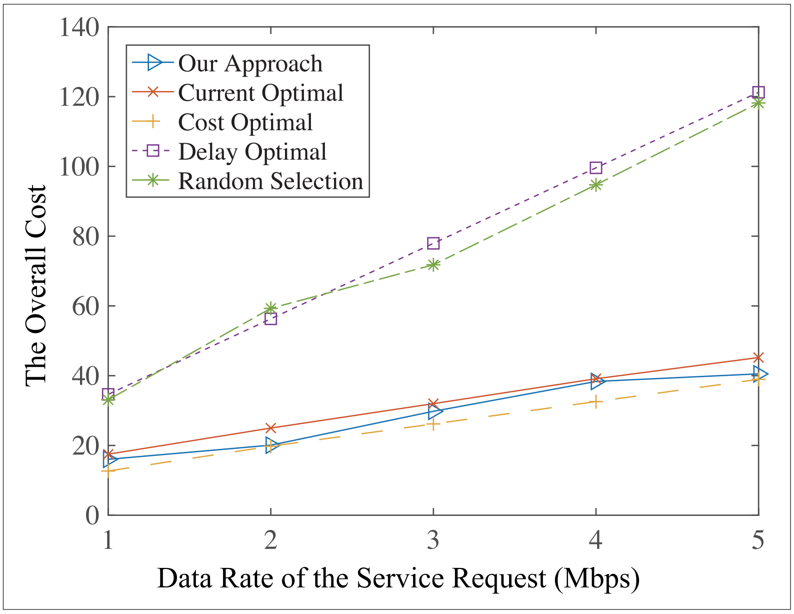

FIGURE 5. The overall cost of different approaches with respect to the data of a user request.

Input: the motion of satellite nodes and aerial nodes $\mathbb{M}$, the computational intensity of all nodes, threshold T
Output: Optimal SFHCs
Long-term utility value computation:
$\mathbb{U} \leftarrow$ Compute the current utility values of SFHCs
$\mathbb{D} \leftarrow$ Compute the duration of connections
$\mathbb{C} \leftarrow$ Predict the computing delay of functions
$\mathbb{U}_d \leftarrow$ Compute the utility of function deployment
$\mathbb{L} \leftarrow$ Predict the location of end users
Compute the long-term utility values of SFHCs according to $(\mathbb{D}, \mathbb{C}, \mathbb{U}_d, \mathbb{L})$
Compute the long-term cumulative utility values of SFHCs
SFHC update:
$g \leftarrow$ Compute the gap between the original SFHCs and the new SFHCs
if $g > T$ **then**
Update SFHCs
end if

ALGORITHM 1. Service coordination approach.

in advance. According to this information, the duration of the connection can be predicted. Nodes with long duration are preferred over nodes with short duration.

- For the ground nodes, the traffic intensity and the resource allocated to the functions are predictable to some extent. The computing delay of the functions in the short term thus can be predicted. Both the current computing delay and the delay in the short term should be considered when selecting the functions.
- For the satellite nodes, aerial nodes, and some of the ground nodes, the computing and storage capacities are limited. The deployed functions would be removed if they are not invoked over a period of time. The function multiplexing can reduce the function deployment cost and improve the resource usage. Therefore, the utility of function deployment is not only the current reward but also the long-term cumulative reward.
- In some particular scenarios, the motion trace of end users is predictable or fixed. The selection of SFHCs should consider not only the current location of a user but also the future location.

Therefore, we select SFHCs according to the utility value of SFHCs with the long-term reward.

Second, we update SFHC based on a threshold to avoid updating too frequently. Due to the high dynamics of the network, the delay of SFHCs dynamically changes, which may lead to the optimal SFHC continually changing. Also, frequent updating of SFHC may cause misconvergence and uncertainty in practice. Therefore, SFHC only updates when the gap between the original SFHC and the new SFHC is larger than the threshold T.

Based on the above objective and principles, we compute the utility value of SFHCs with the long-term reward, and then update SFHC based on the threshold.

Experiment

In this section, we evaluate the performance of the proposed service coordination approach via extensive simulations. The experimental results show the benefits of our service coordination approach in terms of service delay and cost. Moreover, this approach has been integrated into our Satellite Intelligence Service Platform in China SpaceTY Satellite. It was launched in July 2021 and is carrying out in-orbit test and verification.

Experiment Setup

We consider an area, Pudong New District in Shanghai, which is around 60 km × 20 km. There are about 840 base stations according to Shanghai Telecom's base station dataset [15], which contains the exact location information of 3233 base stations and the Internet access information of mobile users that passed through these base stations. From the base stations in Pudong New District, we select 80 base stations as the placement location for edge servers providing computing and storage capacity. We then deployed 20 instances for each function on base stations, and three aircraft and one satellite randomly.

The satellite node can connect with ground nodes eight times a day for six minutes at a time. The communication delay of unit data between ground nodes is randomly generated in the range (0, 2] ms, the communication delay of unit data from ground nodes to aerial nodes is randomly generated in the range [1, 3] ms, and the communication delay of unit data from ground nodes to satellite nodes is randomly generated in the range [1, 4] ms. The computation resources of each function instance take values within [0.1, 1] GHz randomly.

We compare the proposed approach with four other approaches:

- Delay Optimal: In this approach, we only consider the overall delay, and the user always selects the SFHC with minimum service delay, disregarding the cost.
- Cost Optimal: In this approach, we only consider the cost, and the user always reuses the deployed functions unless the service delay exceeds the requirements.

- Current Optimal: In this approach, we consider both delay and cost, and the user always selects the SFHC with the maximum utility value in the current time slot.
- Random Selection: In this approach, the user selects the SFHC randomly.

Performance Comparison

In this subsection, we compare the proposed service coordination approach and four comparison approaches in terms of the service delay and cost.

Figure 5 shows the performance of all the approaches in terms of the overall service delay with respect to the data rate of service request from 1 to 5 Mb/s. It can be seen that the overall service delay of each approach increases with increasing data rate of service request. When comparing the performance of different approaches for the same data rate of service request, we can observe that the performance of Cost Optimal and Random Selection are worse because they do not consider the service delay. The performance of Delay Optimal is best because it only focuses on the service delay without considering the cost. The performance of Current Optimal and our approach are close, and the latter is better because it considers the impact of future rewards on current selections. In addition, although the service delay of Current Optimal and our approach increases with increasing data rate of service request, the growth rate of our approach is lower than that of Current Optimal.

In summary, the overall service delays of Current Optimal and our approach are close to that of Delay Optimal, and is better than that of Cost Optimal. The overall cost of Current Optimal and our approach is close to that of Cost Optimal, and is better than that of Delay Optimal. The performance of our approach is better than Current Optimal in terms of the overall service delay and cost.

Conclusion

In this article, we mainly investigate the service coordination to guarantee the QoS and service continuity in space-air-ground service computing. We first introduce three service coordination scenarios, and then we design a framework for service coordination. Finally, we propose a service coordination approach to reduce the service delay with low costs. The two principles of the proposed approach are selection with foresight and update based on threshold. The experimental results show that the performance of our service coordination approach is better than the other four approaches in terms of overall service delay and overall cost.

In addition, due to the unique space and aerial environment, there are many fundamental issues that need further research in space-air-ground service computing, including the service deployment, service selection, service composition, service migration, resource scheduling, and more. In our future work, we will also study the intelligent service and service coordination in Interstellar Network 1 or Interstellar Network First.

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