Satellite-Terrestrial Integrated Edge Computing Networks: Architecture, Challenges, and Open Issues

Renchao Xie, Qinqin Tang, Qiuning Wang, Xu Liu, F. Richard Yu, and Tao Huang

Abstract

STN has been considered a novel network architecture to accommodate a variety of services and applications in future networks. Being a promising paradigm, MEC has been regarded as a key technology-enabler to offer further service innovation and business agility in STN. However, most of the existing research in MEC enabled STN regards a satellite network as a relay network, and the feasibility of tasks processing directly on the satellites is largely ignored. Moreover, the problem of multi-layer edge computing architecture design and heterogeneous edge computing resource co-scheduling, have not been fully considered. Therefore, different from previous works, in this article, we propose a novel architecture named STECN, in which computing resources exist in multi-layer heterogeneous edge computing clusters. The detailed functional components of the proposed STECN are discussed, and we present the promising technical challenges, including meeting QoE requirements, cooperative computation offloading, multi-node task scheduling, mobility management and fault/failure recovery. Finally, some potential research issues for future research are highlighted.

Introduction

Although the Internet has achieved unprecedented growth over the past several decades, the Internet still cannot achieve global seamless coverage, which makes a large number of populations especially in rural areas and isolated islands unable to enjoy Internet service. Moreover, the current terrestrial infrastructures are susceptible to natural disasters such as earthquakes and hurricanes. Meanwhile, with the emergence of new applications such as holographic communication, Internet of Things (IoT), augmented reality (AR)/virtual reality (VR), 4K/8K, the new network capabilities, including global ubiquitous network access, large-scale machine type communication, and ultra-reliable communication and so on, have been required, which brings many challenges for the current Internet [1].

In response to the above challenges and trends, the satellite-terrestrial network (STN), which interconnects satellites, aerial platforms, as well as terrestrial communication systems, has been attracting a lot of attention [2–8]. In [2], the authors discuss the research advances and open challenges of the space and terrestrial integrated networks. The authors in [3, 4] investigate the integration of satellite networks and 5G networks and pointed out that the adoption of software defined network (SDN) and network function virtualization (NFV) technologies into the satellite domain are the key elements to achieve such integration. The authors in [5, 6] consider applying SDN technology into STN to produce significant promotion of network design and optimization. In [7], the authors study the problem of cooperative transmission in STN. In [8], the authors propose the AI technique to optimize space-air-ground integrated networks (SAGINs) in traffic control.

On the other hand, as an emerging network technology, multi-access edge computing (MEC) [9–11] has the potential to enhance the quality of experience (QoE) of users and reduce redundant network traffic. By extending the cloud computing platform to the edge of the network or even the mobile device itself, the networks can provide users with multi-layer and heterogeneous computing resources, and enable users to obtain computing services anywhere in the world. Thus, the performance of computation tasks is guaranteed.

Being a promising paradigm, MEC is regarded as a key technology enabler to further promote the transmission rate promotion and reduce processing latency for STN. The combination of MEC and STN has also attracted considerable attention [12–14]. Through the assisting of space and aerial, the authors of [12] propose a SAGIN edge/cloud computing architecture for IoT systems. The authors of [13] propose satellite mobile edge computing (SMEC), which integrates the MEC technique in STN-based mobile communication systems. Moreover, a cooperative computation offloading method for the SMEC scenarios is presented. In [14], the authors develop a software-defined STN to manage and coordinate the network, caching and computing resources, and design a deep learning method to solve the joint resource allocation problem.

Although many works have been done toward MEC enabled STN, in most of these proposed works, the satellite network is regarded as a relay network, that is, computation tasks from users are transmitted to remote terrestrial data centers through satellite relay for data processing, while the feasibility of tasks processing directly on the

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satellites is largely ignored. Without loss of generality, task processing directly on satellites can further improve the QoE of users. Moreover, the existing works only consider the basic model of MEC enabled STN, and the design of integrated architecture is still lacking. The multi-layer and heterogeneity of computing resources brought about by this combination have also not been fully considered. Therefore, different from previous works, this article makes a comprehensive study of the satellite-terrestrial integrated edge computing networks (STECN) which consider utilizing the MEC technique to improve the resource utilization and service support capability of STN.

The main contributions of this article are:

- We analyze what the MEC can do in the STN and give the design principles for deploying the MEC in the STN. Then based on the design principles, we present the architecture of STECN. Moreover, a typical task processing procedure is described in detail.
- We discuss the key functional parts of the proposed STECN architecture and explain each functional part in detail.
- Challenges introduced by STECN architecture such as meeting QoE requirements, cooperative computation offloading scheme, multi-node task scheduling, mobility management and fault/failure recovery process are discussed.
- To fully exploit the benefits of the proposed STECN, some potential issues to be further studied are highlighted, such as efficient trusted protocol, massive user access, high-capacity concurrent signal reliable reception, and so on.

The remainder of the article is organized as follows. In the following section we introduce the STECN architecture. Then the detailed functional components of STECN are discussed. Following that, we discuss the main challenges and open research issues in STECN, respectively. Finally, we conclude the article.

Satellite-Terrestrial Integrated Edge Computing Networks

In this section, we first discuss the advantages of deploying MEC in STN and the design principles for deploying the MEC in the STN. Based on the design principles, we present the architecture of STECN and introduce the typical communication process.

The Advantages of MEC in STN

By deploying MEC in STN, some basic applications can be realized in the network architecture, such as content caching, computation offloading and network services. These applications expand the function of STN and improve the STN's capability.

Content Caching: The explosive growth of user data (especially multimedia data) puts considerable pressure on STN. By caching content in the STN, retransmission of the same content can be avoided, which can greatly reduce the return traffic of STN. By pre-caching the data needed by the application, the corresponding data can be quickly provided to effectively reduce the application delay.

MEC can support STN to provide more sophisticated network services. The topology of the satellite network changes dynamically, so diverse network management services can effectively improve the overall utilization efficiency of STN. The MEC is deployed on STN and can receive the overall information of the satellite network and provide timely feedback.

Computation Offloading: Offloading computation tasks to the remote data center causes not only great pressure on the network transmission but also inevitable delay. Deploying MEC on STN and extending computational capability closer to user devices provides more efficient service guarantees for a variety of delay-sensitive and compute-intensive applications.

Network Services: MEC can support STN to provide more sophisticated network services. The topology of the satellite network changes dynamically, so diverse network management services can effectively improve the overall utilization efficiency of STN. The MEC is deployed on STN and can receive the overall information of the satellite network and provide timely feedback.

Design Principles

Based on the above discussion, combining MEC and STN can expand the function of STN and improve the STN's capability. However, it will make the network structure more complex and the architecture design more challenging. To ensure the good performance of the architecture, the following design principles need to be considered:

Device Heterogeneity Support: In STN, the platform needs to uniformly support different network devices. At the same time, user devices are diverse, such as mobile terminals, terrestrial armored vehicles, drones and so on. The computational capability of these devices varies widely, and the processor architecture is not uniform, such as ARM and x86. The system should ensure the efficient operation of these devices.

Service Continuity: Since both the satellites and the user devices are in high-speed motion, the user device frequently switches the MEC platform with which it communicates, and the offloading of the computation task is greatly affected. Service migration is a common solution. It refers to moving applications providing services to the MEC platforms that are closer to users. The timing of service migration is very important. It is optimal when the user device enters the new MEC platform area. At this point, the impact on QoS is minimal.

Scalability: The network should be able to handle dynamic changes in edge computing nodes and edge computation applications. When a new edge computing node is added, the network can identify the new node and configure it. The network should also support the installation of new edge computation applications to the platform.

STECN Architecture

Based on the above design principles and the typical STN architecture, we design the STECN architecture as shown in Fig. 1. The entire architecture can be divided into four parts: satellite network, terrestrial network, edge computing clusters and user devices:

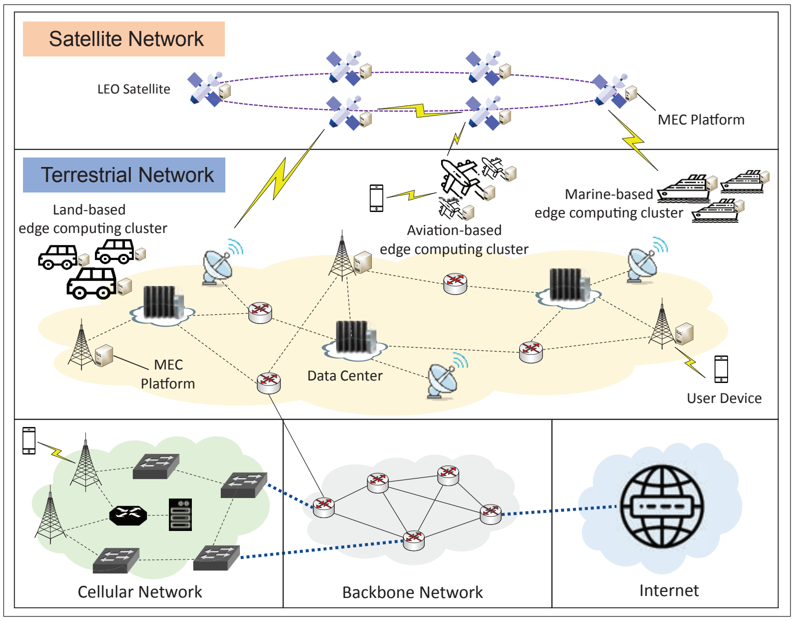

FIGURE 1. System architecture of STECN.

Satellite network is composed of low earth orbit (LEO) satellites equipped with MEC platforms, which can handle computation tasks from user devices. Like clusters, satellites can accelerate task processing through collaboration. Subject to the energy and mobile environment, MEC platforms of clusters and satellites could consider a lightweight management platform such as Docker.

Terrestrial network mainly includes cellular networks, backbone networks, data centers and MEC platforms. The computing resources of MEC platforms in the terrestrial network are more abundant than those in clusters and satellites, so platforms based on cloudlet could be deployed. They can handle computation tasks from the user device through the cellular network, and they can send computation tasks to the data center through the backbone network and the Internet. Data centers have the most computing and storage resources, and they can handle the computation tasks generated by user devices in all networks.

Edge computing cluster includes marine-based clusters, aviation-based clusters and land-based cluster (i.e., vehicle cluster), which is a group of devices with sufficient computing resources. These devices are equipped with the MEC platform and can handle the computation tasks of user devices, and they can improve efficiency through task collaboration.

User devices refer to user devices in the network, such as smartphones, AR/VR devices, and intelligent vehicles. These devices have poor computational capability, so they generate computation tasks and require STECN to handle them.

In STECN, the user device is the edge computing service consumer, while clusters, satellite MEC platforms and terrestrial MEC platforms are the main edge computing service providers. When the task processing pressure of the MEC platform is great, computation tasks can be sent to the data center. According to different scenarios, user devices have different offloading decisions. In scenarios where terrestrial communication facilities are well established, such as urban areas, users are usually offloading to the terrestrial MEC platform because the time delay and cost of offloading to the satellite MEC platform are relatively high. Offloading to a satellite MEC platform is usually the choice when the user device is in a relatively remote area, such as mountainous areas or islands. Devices with edge computing capabilities can form a cluster and then provide edge computing services for other devices. At this point, the user device can choose to offload to the cluster.

Diverse computation offloading options greatly reduce task processing delay and improve network efficiency. For example, in the STN, many services require the satellite to return the image to the terrestrial data center for processing, such as ocean observations and weather warnings. Therefore, these services have high transmission energy consumption and large delay. In STECN, the satellite MEC platforms can realize image recognition and processing. Thus, the satellite can only return the critical part of the image or the alarm information without returning all the observations. And many cache services and IoT services are not well supported in the STN due to excessive communication latency, but they can be implemented in STECN.

Of course, multiple offloading options bring about radio access selection and switching issues. Since a user device has multiple access selections in STECN, the management of multiple radio access is very important. The multiple access technologies are mainly managed by the access control module of the global control plane. The global control plane collects resource and link information of each MEC platform in real-time. When the user device accesses STECN, it interacts with the access control module. The access control module informs the user which platform to access based on the collected information and the performance requirements of the user.

Communication Process

In STECN, the typical task processing procedure is shown in Fig. 2. According to different scenarios and requirements, when the user device generates computation tasks, if the local resources are sufficient, the user device processes them locally. Otherwise, the user device will decide to offload the tasks to the cluster, satellite MEC platform or terrestrial MEC platform according to the cooperative computation offloading strategy. When the clusters and satellite MEC platforms receive computation tasks, they will cooperate with neighboring MEC platforms to handle these tasks when local resources are insufficient. If the clusters and MEC platforms do not have enough resources, they will further offload the tasks to the data center. After processing the tasks, the processing results will be sent back to the user device when necessary.

In cluster and satellite networks, the cooperation of the MEC platform requires the exchange of information. Although exchanging information brings additional costs, it increases the efficiency of cooperation. At the same time, information compression can also be used to reduce the cost of information exchange. Overall, STECN reduces service response time and speeds up task processing, which can improve the user service experience.

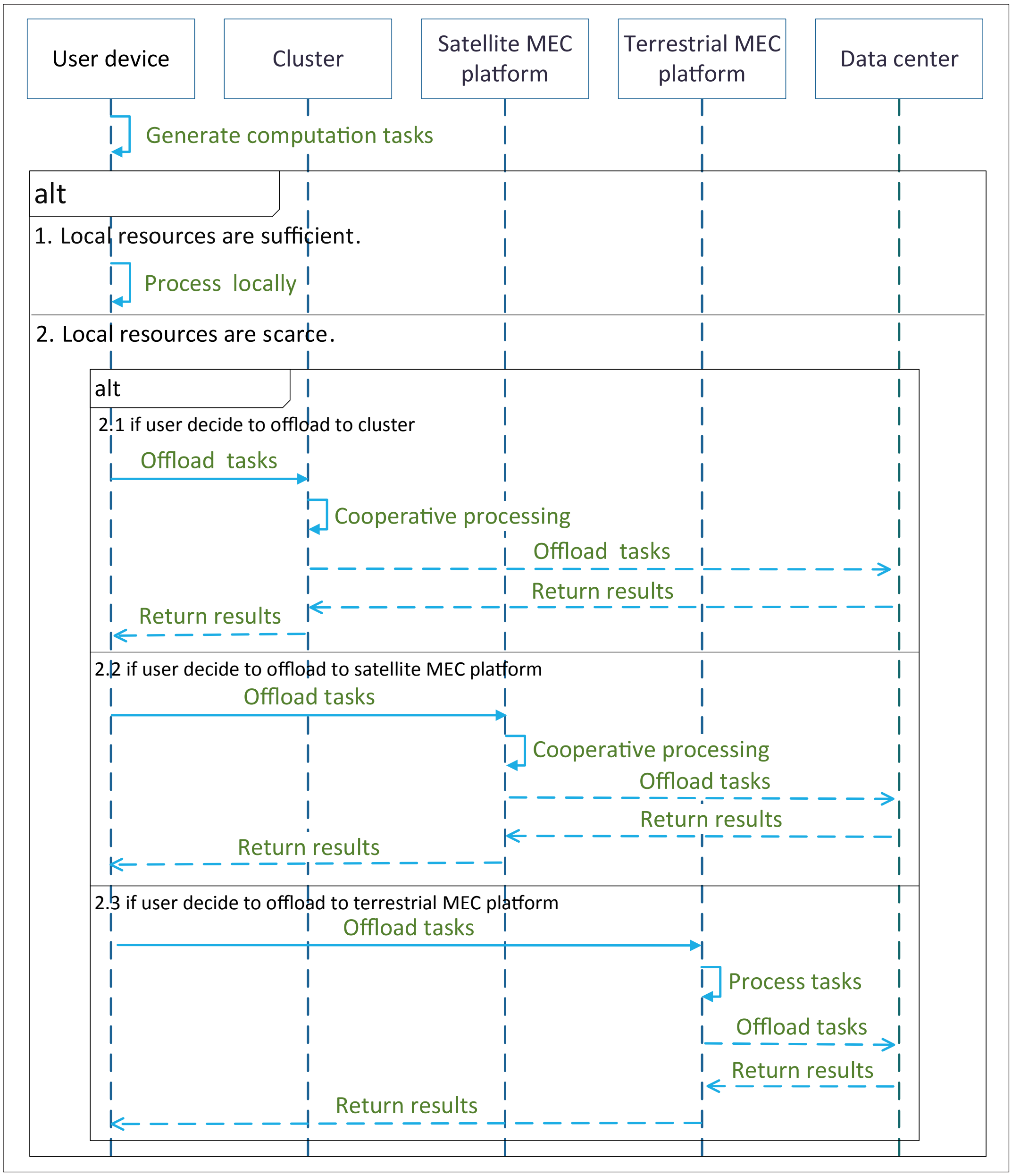

FIGURE 2. The typical task processing procedure

Functional Components of STECN

In this section, we design a management control system to complete the management and control functions of the entire architecture, as shown in Fig. 3. Based on the introduction of STECN in the previous section, we divide the entire management control system into three parts, namely the resource virtualization, Satellite-Terrestrial integrated edge computing networks platform, and the service and application.

Resource Virtualization

The resource virtualization part virtualizes resources such as computing, storage, and networks through SDN and NFV technologies. The resource virtualization completes the basic function implementation of the resource invocation and provides the corresponding interface for use by the upper control plane.

Satellite-Terrestrial Integrated Edge Computing Networks Platform

This part implements the core control functions of the entire STECN. Through the design and deployment of various functional modules, the unified and efficient operation of the entire network architecture is realized. It is mainly divided into four parts: global control plane, LEO satellite edge computing platform, terrestrial fixed MEC platform, and terrestrial mobile edge computing cluster.

Global Control Plane: This control plane is deployed in a remote data center to implement global control functions. The global control plane mainly implements global task scheduling, topology management, service discovery, access control, and program lifecycle management. The global control plane not only collects global information but also implements the transmission and control of specific instructions.

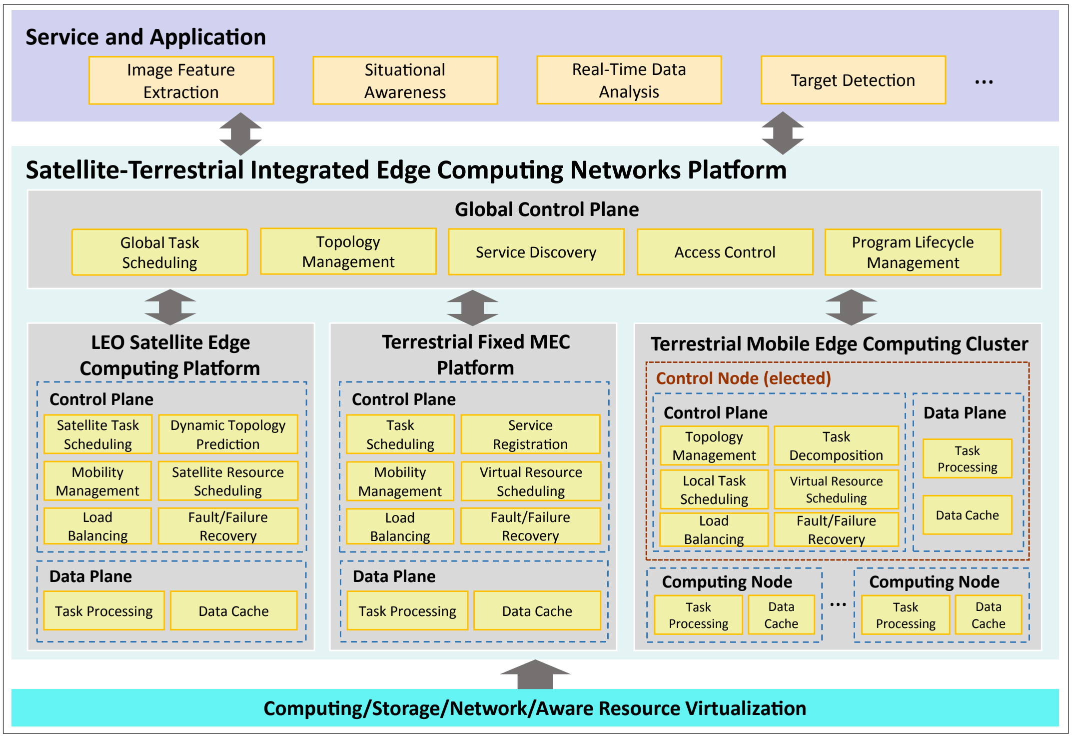

FIGURE 3. The logical functional module of STECN architecture.

LEO Satellite Edge Computing Platform: The LEO satellites edge computing platform has the control plane and data plane. The data plane is responsible for the calculation and caching support. The control plane mainly achieves the necessary control functions of the satellite. When a satellite needs to perform control functions, the platform can wake up the corresponding functional module. In the control plane, on the one hand, it should implement the task of satellite task scheduling, resource scheduling, and load balancing guarantee; on the other hand, it is necessary to deploy functional modules such as dynamic topology prediction, fault/failure recovery, and mobility management to respond to the high-speed movement of the satellite and the dynamic change of the topology.

Terrestrial Fixed MEC Platform: The platform is responsible for processing the computation tasks offloaded by the user devices, and provides computing and caching functions. Besides, it also provides control functions such as task scheduling, load balancing, service registration, fault/failure recovery, and mobility management.

Terrestrial Mobile Edge Computing Cluster: In a terrestrial mobile edge computing cluster, each node has basic computational and storage capabilities. The control node, which is elected in a cluster, has a control plane. The main task of the mobile edge computing cluster is the collaborative processing of computation tasks. Therefore, in the control plane, it mainly has functions such as local task scheduling, decomposition, load balancing, topology management, fault/failure recovery, and virtualized resource scheduling.

Service and Application

The service and application part provides application support and service assurance. The service and application part allows for the deployment and implementation of multiple applications, including image feature recognition, real-time data analysis, target detection, and more, by invoking the appropriate functional modules and resources. The service and application part is invoked through a variety of standardized interfaces to enable dynamic deployment and management of applications.

Challenges in STECN

The designed STECN architecture can bring various benefits to improve network performance and users' quality of experience, and at the same time, the STECN architecture introduces new challenges, which are discussed in this section.

Meeting QoE Requirements

The ultimate goal of STECN is to provide users with a variety of services and bring convenience to them, so it is crucial to meet the user's QoE requirements.

There are many metrics to measure the users' QoE requirements, such as delay, energy, user privacy and so on. These metrics are also influenced by many practical network factors such as access approaches, throughput, bandwidth, and available edge computing resources. For example, in STECN, users have multiple task access approaches, such as edge computing cluster, MEC platform and data center, and so on. In a different access approach, the status of the communication link and the available resources are different, which may affect users' QoE. To meet the QoE requirements of users, we make a discussion from the following perspectives.

From the perspective of users, different users and tasks have different QoE requirements. For instance, some tasks are delay-intensive, while others are privacy-intensive, and so on. When guaranteeing one QoE requirement for users, other requirements may not be guaranteed. Therefore, user's QoE metrics can be assigned a weight to indicate their importance. When a metric is more important, the weight will be greater, and vice versa.

From the perspective of the whole network, the resources (e.g., bandwidth resource, computing resource, and so on) of the network are limited. Reasonable allocation of limited resources to meet the QoE requirements of multi-users in STECN is also an important issue to be considered.

Cooperative Computation Offloading in STECN

As shown in Fig. 4, users have multiple options to complete their tasks, that is, locally processing, edge computing and data center computing. Cooperative computation offloading between user devices, edge computing platforms and data centers can be an effective way to improve task processing efficiency, but it also brings many challenges.

On the one hand, different computation tasks have different requirements. For example, some tasks are delay-sensitive, some are computation-intensive, and so on. On the other hand, in different scenarios, users can offload computing tasks to different edge computing platforms, which have different characteristics. For example, terrestrial MEC platforms and edge computing clusters are closer to users but the scope of services is limited. A satellite MEC platform has greater coverage but will result in longer transmission delay.

Therefore, when developing a cooperative computation offloading strategy, the demands of the user task and the characteristics of the edge computing platform need to be considered to better meet the user's requirements.

Multi-Node Task Scheduling in STECN

In STECN, due to the limited computing resources of a single MEC platform and cluster node, efficient multi-node task scheduling is essential to further improve network efficiency. MEC platforms in satellite/terrestrial edge networks and edge computing clusters are not identical due to the different characteristics of the two types of systems.

Edge Computing Cluster Task Scheduling: The edge computing nodes in the edge computing cluster are relatively concentrated in a region, so centralized task scheduling may be more effective. In this case, an edge computing node can be elected as a local controller of the cluster utilizing recommendation, and the corresponding task decomposition and scheduling strategy are implemented on the local controller.

MEC Platform Task Scheduling: Compared with the edge computing cluster, the coverage of the satellite/terrestrial network is relatively larger, and centralized task scheduling will result in low processing efficiency and poor resource utilization. Therefore, in the satellite/terrestrial edge network, the task decomposition and scheduling can be carried out directly on the service satellite (the satellite that provides services for users) without the help of a local controller. MEC platform task scheduling can be done in a decentralized manner. Two types of task scheduling can be shown in Fig. 5.

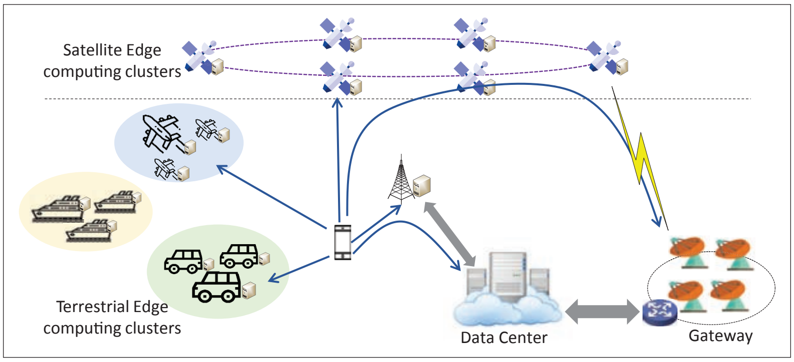

FIGURE 4. Illustrate of computation offloading in STECN.

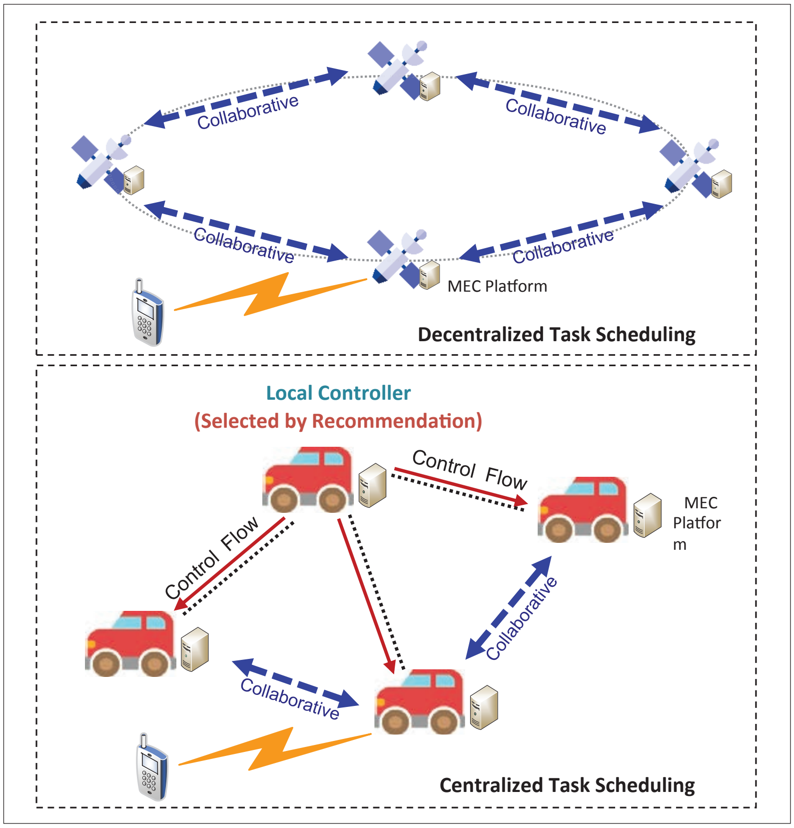

FIGURE 5. Illustrate of multi-node task scheduling in STECN.

Mobility Management in STECN

In STECN's mobility management, how to ensure service continuity is a key issue when the user device moves from one MEC platform to another. Service migration is an effective solution. During the service migration, the original platform sends the application and data to the new platform. The key to service migration is to determine when to migrate. The best case is pre-migration and the migration is completed as the user device enters the new service area. This minimizes the impact of service migration to task processing. Specifically, as illustrated in Fig. 6, there are two situations:

For Satellite Networks: Since the motion of the satellite is periodic, the satellite route at each moment is predictable. The satellite predicts in real-time based on the user device's coordinates and the position of other satellites. The goal is to be able to complete the migration as soon as the user device enters the next satellite area.

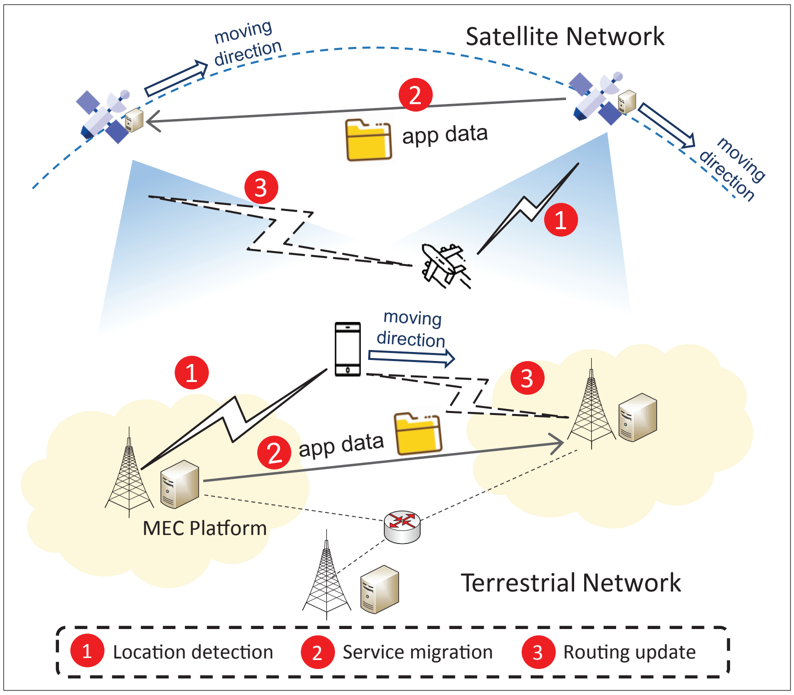

FIGURE 6. Illustrate of mobility management in STECN.

For Terrestrial Networks: Unlike satellites, terrestrial network access points, such as base stations, are fixed. The user device is moving irregularly. Therefore, the optimization of the migration time mainly focuses on the regular induction and trajectory prediction of the user movement [15].

Fault/Failure Recovery

In the process of the computation offloading and co-processing, fault/failure recovery mechanisms are necessary because of some problems such as dynamic change of channel state, insufficient resources, and data corruption. In general, fault/failure recovery can be realized through computation task migration and computation task re-instantiation.

Computation Task Migration: Computation task migration is an effective way to fault/failure recovery. On the one hand, when the channel state suddenly changes due to various factors, the computation task can be migrated to a node with a better link state. On the other hand, when the computing resources of the current node cannot support the processing of the computation task, the computation task can also be migrated to the node with more resources.

Computation Task Re-Instantiation: The re-instantiation is more likely to be used if the computation task cannot be repaired. For example, a container or a node that runs a computation task has a sudden failure. After the user knows the information, the computation request needs to be resent to re-instantiate the task.

Open Research Issues for STECN

To fully exploit the benefits of the proposed STECN, there are still some potential research issues that should be discussed for future study, which can be summarized as follows.

Efficient Trusted Protocol

Given the wide distribution of terminals, prolonged signal propagation, uncontrollable working conditions, and poor maintainability, it is crucial to develop efficient communication protocols suitable for STECN. An efficient communication protocol needs to eliminate the adverse effects of long communication delay and weak terminal processing capacity on the performance of the protocol. A lightweight security protection mechanism is also required to eliminate the adverse effects on information security caused by limited terminal storage capacity, long-term offline of terminals and uncontrollable environment.

Massive Users Access

Driven by more and more new applications, the future STECN faces the enormous challenges brought by massive user access. To overcome this challenge, a key issue to be concerned with in the future is to solve the contradiction between satellite (e.g., long transmission distance and limited resource capability, and so on) and users (e.g., mass connection and low power wide area, and so on) by combining the limited and shared characteristics of satellite resources, so as to meet the casual access requirements of users.

High-Capacity Concurrent Signal Reliable Reception

Another key issue to be solved urgently in STECN is the reliable reception of large-capacity concurrent signals. The satellite has large coverage, and a beam may contain a large number of terminals. Therefore, the occurrence of signal collision is a normal phenomenon, and multiple access methods must tolerate such collisions. Successive interference cancellation (SIC) technology is an effective solution to solve signal collision. However, for large capacity concurrent signals, it may not find the signal without collision. Accordingly, by utilizing signal-to-noise ratio difference and known signal characteristic parameters, the signal with the strongest signal-to-noise ratio can be detected by the signal separation technique. Moreover, through signal reconstruction and signal cancellation techniques, the decoded signal can be eliminated in the original mixed-signal, thereby reducing the impact of collision on system performance.

Conclusions

In this article, we have considered directly empowering satellites with edge computational capability employing MEC to enable users to obtain computing services anywhere in the world, thereby enhancing the QoE of users and reducing redundant network traffic. We have first analyzed the design principles for deploying MEC in STN, then a novel architecture named STECN is proposed. Then, we have presented the functionalities of the mobile edge networks, and develop a management system for STECN. Furthermore, the challenges of the proposed STECN in meeting QoE requirements, cooperative computation offloading and multi-node task scheduling, and so on, are discussed, and potential research directions are highlighted.

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