Integrating Satellites and Mobile Edge Computing for 6G Wide-Area Edge Intelligence: Minimal Structures and Systematic Thinking

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Abstract—**The sixth-generation (6G) network will shift its focus to supporting everything including various machine-type devices (MTDs) in an everyone-centric manner. To ubiquitously cover the MTDs working in rural and disastrous areas, satellite communications become indispensable, while mobile edge computing (MEC) also plays an increasingly crucial role. Their sophisticated integration enables wide-area edge intelligence which promises to facilitate globally-distributed customized services. In this article, we present typical use cases of integrated satellite-MEC networks and discuss the main challenges therein. Inspired by the protein structure and the systematic engineering methodology, we propose three minimal integrating structures, based on which a complex integrated satellite-MEC network can be treated as their extension and combination. We discuss the unique characteristics and key problems of each minimal structure. Accordingly, we establish an on-demand network orchestration framework to enrich the hierarchy of network management, which further leads to a process-oriented network optimization method. On that basis, a case study is utilized to showcase the benefits of on-demand network orchestration and process-oriented network optimization. Finally, we outline potential research issues to envision a more intelligent, more secure, and greener integrated network.**

I. INTRODUCTION

In the future, an increasing number of wireless sensors, industrial robots, and intelligent machines will be deployed to free human beings. This stimulates a focus shift of the future sixth-generation (6G) network from serving human beings to supporting various intelligent machine-type devices (MTDs). These MTDs may be employed in disastrous areas for emergency rescue (*e.g.*, vital sign detection). They can also be deployed in remote areas, such as oceans, deserts and forests, for environmental monitoring and resource exploitation. In these harsh areas, constructing terrestrial cellular networks, as in the fifth-generation (5G) system, will be difficult or extremely expensive, due to damaged infrastructures and tough geographical conditions. Instead, a non-terrestrial network via satellites and unmanned aerial vehicles (UAVs), may be used to fill the coverage gap and offer everyone-centric customized services [1].

Despite the advantage of global coverage [2], satellite communications also face their inherent challenges in terms of limited data rate and large latency, which pose difficulty in satisfying the MTDs' service requirements. For example, some MTDs may have to use cloud computing for data processing, due to their limited computing and energy resources on board. However, the bandwidth resources of satellites are limited, and offloading massive data via satellites leads to an unacceptable delay. Furthermore, some MTDs may participate in a time-critical activity, which requires delay-sensitive services. All these issues pose challenges to the use of satellite communications for MTDs, and will inevitably lead to poor user satisfaction ratios [1].

To meet the service demands of these MTDs in an everyone-centric manner [1], edge intelligence is required to replace traditional central cloud computing. Specifically, by enabling artificial intelligence (AI) applications at the network edge, MTDs are endowed with low-latency data processing and decision making capabilities. Mobile edge computing (MEC) is crucial for empowering this edge intelligence paradigm, which may further evolve into a more promising network AI architecture [1]. Current 5G networks have partially used MEC, which shows the benefit of integrating cellular communications and MEC. Thus, it is envisioned that integrating satellites and MEC can support better MTDs in the aforementioned disastrous and remote areas [3] [4]. However, the integration of MEC and satellite networks remains an open issue.

The main contributions of this article are summarized as follows.

- We provide typical use cases of the integrated satellite-MEC network, based on which we discuss the main challenges of satellite-MEC integration.
- We propose three minimal structures for the integrated satellite-MEC network. The complex integrated network can thus be regarded as extension and combination of the minimal structures.
- We design an on-demand resource orchestration framework, which adjusts the network in a hierarchical way. In addition to traditional layers, *e.g.,* network planning and adaptive transmissions, we introduce the minimal structure orchestration layer, which operates at a medium timescale and optimizes the network in a process-oriented manner.
- We present a case study for an extended minimal structure. It is observed that the proposed framework could offer wide-area customized services and significantly improve the network resource efficiency. We also outline

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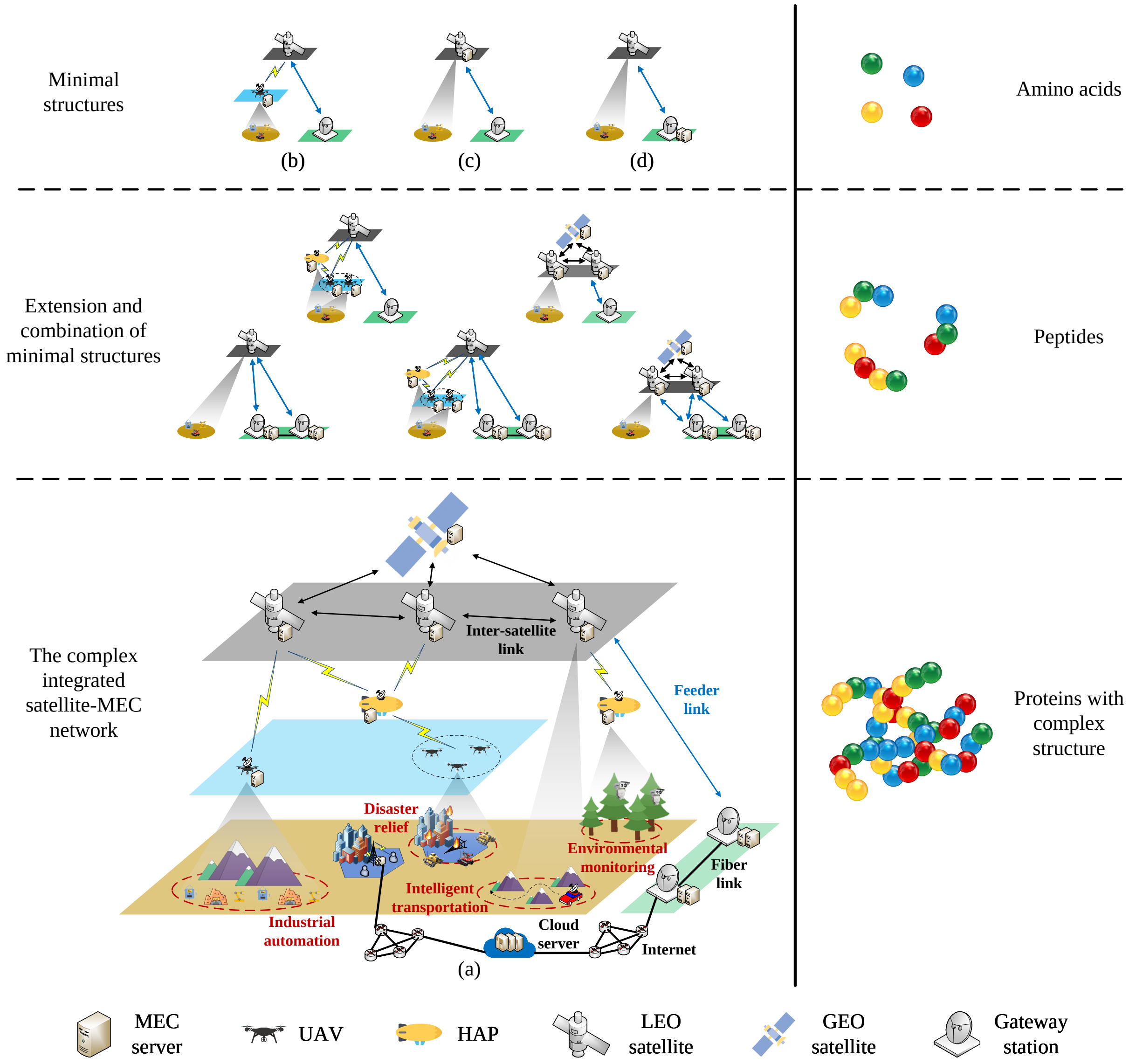

Fig. 1. A systematic view of the integrated satellite-MEC network (left) inspired by the protein structure (right).

future research directions of the integrated satellite-MEC network.

II. Use Cases of Satellite-MEC Integration

The integrated satellite-MEC network is envisioned to support various MTDs in an everyone-centric manner [1]. As shown in Fig. 1(a), we summarize typical use cases in the following.

- **Intelligent environmental monitoring**. In this use case, a large number of fine-grained sensors are widely distributed in remote areas to acquire environmental data. A massive amount of data need to be transmitted and analyzed to detect environmental anomalies (floods, water pollution, forest fire, *etc.*), which can consume excessive communication resources. As a solution, the integrated satellite-MEC network is enabled to provide wide-area coverage for the sensors to allow the massive data to be processed with close proximity to users.
- **Efficient disaster relief**. Natural or man-made disasters (earthquakes, floods, fires, explosions, *etc.*) require that both rescue groups from outside and first responders (*e.g.*, vital sign detectors) from inside take immediate action. However, terrestrial communication infrastructures in disastrous areas are often damaged. When disasters occur, the integrated satellite-MEC network can be rapidly deployed and provide situation information for rescue groups. Meanwhile, they can also assist first responders with real-time decision-making through local computation.
- **Intelligent transportation**. This use case provides vehicles with diverse services, such as automatic control assistance and dynamic path planning. For remote vehicles (*e.g.*, ocean vehicles) and highly mobile vehicles, terrestrial networks are not applicable. The integrated satellite-MEC network can provide ubiquitous coverage for these vehicles. Moreover, they can process the massive data collected by multiple vehicles in real time, which further

enables automatic control assistance and dynamic path planning services.

- **Industrial automation**. The exploration and acquisition of industrial materials often take place in rural or remote areas, where multiple sensors and actuators execute their tasks cooperatively. Industrial automation requires that the collected sensor data should be processed in real time to provide instructions for actuators, forming a closed-loop control system. To meet such requirements, the integrated satellite-MEC network can provide communication coverage and real-time computing services for these sensors and actuators.

III. CHALLENGES OF THE INTEGRATED SATELLITE-MEC NETWORK

A. *Unique Characteristics of Service Requirements*

In terms of achieving edge intelligence, it is widely acknowledged that a complementary relationship between terrestrial-MEC and satellite-MEC networks is necessary. In contrast to the terrestrial network, the integrated satellite-MEC network mainly aims at application scenarios in remote or disastrous areas, as discussed before. The service requirements in these application scenarios have these unique characteristics. First, MTDs are expected to be dispersed over extensively wide geographical areas. The spatial distribution of their service requirements is remarkably sparser than that in the terrestrial network. A typical example is the buoys that collect hydrological information for ocean monitoring. Moreover, the temporal and spatial distributions of the service requirements can be heterogeneous and highly dynamic. For instance, industrial automation and efficient disaster relief applications require aggregation of MTDs, and the positions of these aggregates vary over time. These unique characteristics render the system design of terrestrial networks inappropriate due to the low resource efficiency. Therefore, new challenges concerning the integrated satellite-MEC networks' system designs require careful consideration.

B. *Limited Communication and Computing Capability*

In addition to the service requirement characteristics, the inherent limitation in communication and computing capability also poses challenges to the integrated satellite-MEC network. On the one hand, the communication capability of the satellite network is inherently limited. The transmission rate of satellite-ground links is relatively low due to the long propagation distance and limited bandwidth resources. In addition, the number of satellites in the network is restricted. This is because of the high costs of space launch and the limited orbit resources. Specifically, although a single low earth orbit (LEO) satellite is expected to have a similar level of throughput as a 5G base station, the number of satellites in a constellation is remarkably smaller. This makes it difficult for the satellites to satisfy the global service demands. On the other hand, due to the limited capability of satellite communication, MEC servers on satellites and aerial platforms (APs) are necessary in the integrated network for delay-sensitive services. These MEC servers, especially the satellite servers, are under stringent restrictions in terms of size, weight, and power. Moreover, because of the severe electromagnetic radiation in space, the satellite servers need to be radiation-hardened [5]. This requires special design and incurs extra costs. These factors account for the limited computing capability in integrated satellite-MEC networks.

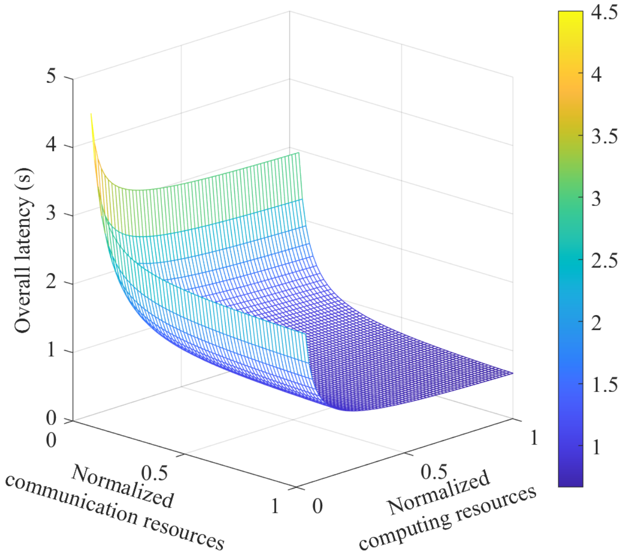

Fig. 2. A schematic diagram of the overall latency of a single offloading task with different communication and computing resources provided.

C. *Complexity of Matching Network Resources with Service Requirements*

Fig. 2 shows a schematic diagram of the overall latency of a single offloading task, varying with the communication and computing resources provided. The resources are normalized, and the latency is obtained by linearly combining the reverse of both resources[1] [6]. We observe that the latency decreases quite slowly with both resources in the resource-adequate scenario. Therefore, configuring proper resources to match the service requirements of an offloading task can considerably improve resource efficiency. For a practical system of multiple offloading tasks, such a resource configuration evolves to a complex high-dimensional backpack problem. For the integrated satellite-MEC network, the hierarchical communication and computing resources, such as the diverse transmission links and the multiple tiers of MEC servers, render it difficult to match the resources with the service demands. Moreover, LEO satellites and aerial platforms are highly mobile in the network, which makes the network resources vary over time. The resource configuration problem becomes even more complex when the time dimension is accounted for.

IV. MINIMAL INTEGRATING STRUCTURES

It is an important but challenging problem to efficiently utilize the limited network resources to meet the wide-area and

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[1] In different use cases, the specific relationship between the overall latency and the network resources can be different.

sparse service demands. To handle this problem, we provide a novel systematic perspective inspired by the protein structure, as shown in Fig. 1. Specifically, we propose three minimal integrating structures based on the location of the MEC server, emulating the amino acids which are the basic elements of proteins. We discuss the characteristics and key problems of each minimal structure. These minimal structures can be extended or combined to form more complex structures, which resembles amino acids forming peptides. In a similar way, a complex integrated satellite-MEC network, corresponding to a functioning protein, can be considered as a nonlinear orchestration of these structures. By figuring out the minimal integrating structures, as well as their extensions and combinations, we can obtain better insight into the complex network.

A. Computing-in-Forward-Link Structure

As shown in Fig. 1(b), this minimal integrating structure consists of an AP equipped with an MEC server, a satellite, a gateway and multiple MTDs. The AP can be a UAV or a high altitude platform (HAP). With MEC deployment, the AP provides local computation services for MTDs. Due to the limitations of APs in terms of size and energy, the central processing unit (CPU) capability of an on-board MEC server is restricted. In addition, the AP can also relay the task data to the satellite, and the task data are further transmitted to a cloud server for computation. This minimal structure can be extended by considering multiple APs.

Compared to satellites, APs can provide high-speed communications, which leads to lower transmission delay. However, the coverage area of an AP is smaller than that of a satellite. From these perspectives, it can be deduced that the computing-in-forward-link structure is suitable for local-area computation services with ultra-low latency requirements. Examples of these services include robotic machine controls in industrial automation and real-time decision making in efficient disaster relief.

For such a minimal structure and its extensions, multiple challenges exist in terms of system design. First, it is of great importance to determine the on-board CPU capability, as well as the capacities of the satellite-AP link and the AP-user link. It should be noted that the capacities of the two links need to achieve a proper fit to improve resource efficiency. Moreover, in the multi-AP case, transmission links might exist among the APs, which further adds to the difficulty of configuring communication and computing resources.

Another challenge is that proper user association plays an important role in the system design of the multi-AP structure. One typical user association scheme is that each AP is equipped with an MEC server, and each user is associated with one AP. Ding *et al.* [7] considered such a scheme and investigated the joint optimization problem of user association, resource allocation, offloading assignment, and transmit precoding. In addition, we can also assume that each user has access to multiple APs and their on-board servers, forming a coordinated multi-point network. Moreover, some of the APs may not carry MEC servers and only serve as relay nodes.

Moreover, in this minimal structure and its extended structures, the APs and the satellites can both be highly mobile. Then, the network topology dynamically changes over time. Therefore, trajectory design of the APs needs to be carefully considered. Besides, the handover problem of APs and satellites requires further investigation to guarantee seamless coverage.

B. Computing-on-Orbit Structure

This minimal integrating structure is composed of a satellite equipped with an MEC server, a gateway and multiple MTDs, as shown in Fig. 1(c). The MTDs' computation tasks can be directly executed at the satellite or further uploaded for cloud computing. The satellite is highly limited in terms of size, weight and energy supply, which places stringent restrictions on the CPU capability of the on-board MEC server. There are several derivatives from this minimal structure. For instance, the space segment can be a constellation of LEO satellites. In addition, a geostationary earth orbit (GEO) satellite and a LEO constellation can coordinately provide edge computing services.

Compared with APs, satellites can provide a much larger coverage to serve more devices. In addition, satellites are in proximity to ground MTDs topologically compared with gateway stations. Therefore, the computing-on-orbit structure can well serve the requirements of computation tasks that span a wide area and require relatively low latency. For instance, path planning for large-area vehicles can utilize this structure to execute their computation tasks.

Multiple challenges need to be handled for this minimal structure and its extended structures. One main challenge is that it is not as easy to place MEC servers on satellites as on UAVs or at gateways. First, to implement edge computing on orbit, on-board processing (OBP) capabilities (*e.g.*, modulation/demodulation, encoding/decoding) are necessary on satellites. Besides, the severe electromagnetic radiation in space can induce bit-flips and even cause damage to the satellite payloads. This requires that the servers and the OBP modules should be radiation-hardened [5]. Moreover, satellites are mainly powered by solar energy, which could be limited and discontinuous. Therefore, energy management is a critical issue that impacts the performance of MEC servers on satellites. These factors complicate the minimal structure's system design.

With multiple satellites, the placement method of MEC servers is another important challenge. For instance, we consider the scenario of a LEO constellation providing services. Radiation-hardened MEC servers can be placed on all LEO satellites, which leads to high costs of MEC hardening. Another scheme is that the servers are placed on part of the satellites, while the other satellites merely relay data through inter-satellite links (ISLs). Adopting this scheme can reduce the MEC hardening costs, but the ISL costs will be higher. For the MEC server placement problem, this tradeoff requires careful consideration.

In the extended structure where the space segment is a LEO constellation, there are often multiple satellites in the MTD's line of sight. For more computation-intensive applications, it is an intriguing problem to achieve simultaneous offloading to multiple satellites. Song *et al.* [8] investigated this problem and jointly optimized the task division and the transmission power to each satellite. From another angle, Wang *et al.* [9] proposed a game-theoretic approach to optimize the offloading strategy of multiple users.

Finally, LEO satellites are highly mobile and thus their coverage time can be quite limited. When an offloaded task is computation-intensive, the satellite may not be able to return the computation results in time. In this case, computation migration of MEC servers is a problem worth investigating. The mobility of LEO satellites also leads to dynamic network topology, which makes it difficult to efficiently manage the network resources in this minimal structure.

C. Computing-after-Feeder-Link Structure

As shown in Fig. 1(d), this minimal integrating structure consists of a satellite, a gateway equipped with an MEC server and multiple MTDs. MTDs offload their computation tasks to the gateway through the satellite relay. The computation tasks are executed in the gateway server or they are transmitted to the remote cloud. It should be noted that the MEC server in this minimal structure possesses higher CPU capability compared with the above two minimal structures, since the gateway station allows a larger server size and higher energy consumption. The minimal structure can be extended by considering multiple gateways.

With satellites as relays, the MEC server deployed at the gateway station can meet the demands of large-area computation services. In addition, the CPU capability of the MEC server is higher. However, the communication latency is relatively high since the data may traverse several ISLs before arriving at the gateway. Therefore, this minimum structure is most suitable for wide-area computation-intensive but delay-tolerant services, such as collecting and processing massive sensor data in environmental monitoring.

The computing-after-feeder-link structure and its extensions also raise problems in terms of system design. For instance, the MEC server placement problem is an important challenge. It is typically assumed that multiple gateways work separately. In this case, the CPU capability of each gateway server needs to be properly configured. In addition, the computing resource allocation of each server requires optimization. For instance, Zhang *et al.* [10] proposed a game-theoretic scheme to solve the joint offloading decision and resource allocation problem. Cui *et al.* [11] jointly optimized user association, task scheduling, and resource allocation. Another assumption is that the gateways are interconnected through high-speed fiber links. In this case, the transmission latency among gateways can be ignored, and the problem of server placement degenerates to deciding the total CPU capability of all servers.

The mobility of satellites also has impact on this minimal structure. For instance, the association between satellites and gateways changes constantly, which leads to the handover problem. For example. when an MTD user switches its connected satellite before the gateway server finishes computing the user's task, the handover problem would be coupled with both mobility management and offloading strategies. To return the computation results, the gateway needs to find the user's currently connected satellite, which can be an interesting problem.

V. ON-DEMAND NETWORK ORCHESTRATION

A. Medium-Timescale Network Orchestration

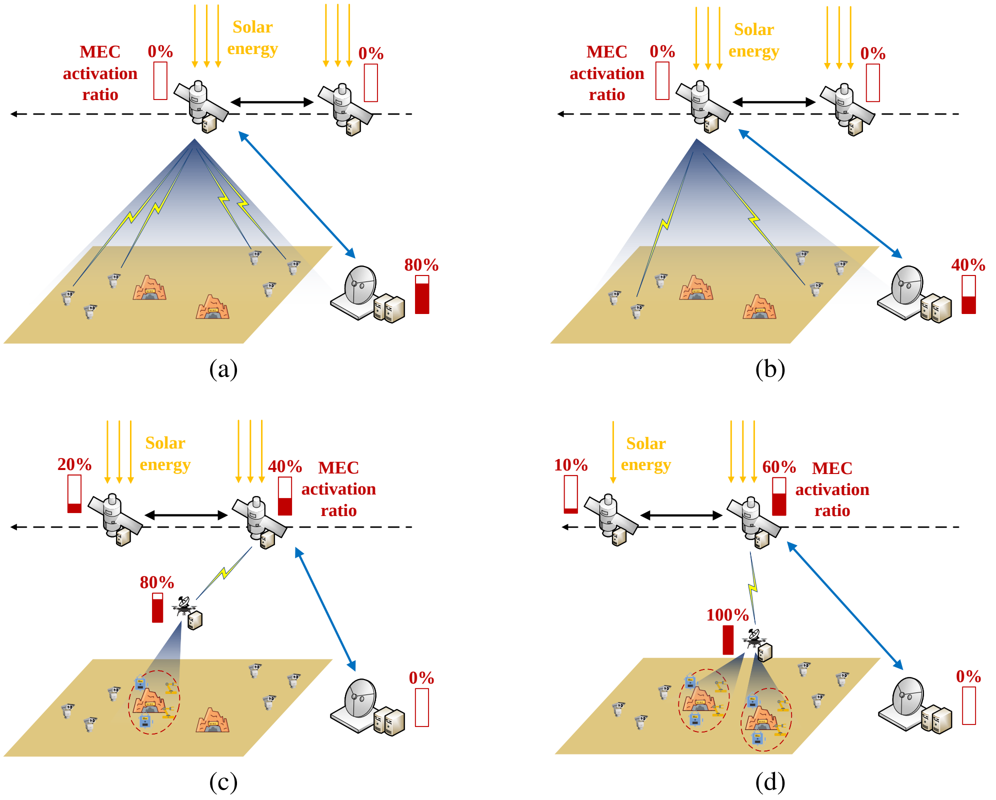
On-demand adjustments of the integrated satellite-MEC network are of great importance for providing wide-area customized services [1]. As illustrated before, the temporal and spatial distributions of MTD users are sparse. In addition, the communication and computing capability of the integrated network are rather limited. Through dynamically adjusting the network to match the changing service requirements, the resource efficiency can be substantially improved. Because of this, the network can fully utilize its limited resources to provide ubiquitous services.

The current 5G network is mainly adjusted at two different timescales. First, mobile network operators conduct network planning at the timescale of months or years. Network planning adjusts communication and computing infrastructures, such as the number of satellites and the CPU capability of satellite servers. The second is the timescale of milliseconds or less, which is close to the channel coherence time. At such a timescale, the transmission parameters are adjusted, such as channel estimation and beamforming.

However, the service demands often change at a medium timescale (*e.g.*, minutes or hours), in terms of number, spatial distribution and service type. Besides, the available energy resources and network resources in the network could also vary at a medium timescale, due to the mobility of APs and LEO satellites. Both network adjustments in the 5G network are incapable of matching these changes. Therefore, novel medium-timescale network adjustments need to be introduced in the integrated satellite-MEC network. Moreover, the network can be viewed as a nonlinear orchestration of the three minimal structures, as illustrated above. Therefore, we will establish an on-demand network orchestration framework, which adjusts the minimal structure orchestration at medium timescales to match the varying service requirements. Specifically, this can be achieved by adjusting the activation ratios

TABLE I
COMPARISON OF NETWORK ADJUSTMENTS AT DIFFERENT TIMESCALES

	Timescale	**Adjusted parameter**
Network planning	months/years	Number of satellites, number of gateways, satellite-user link capacity, ISL capacity, on-board CPU capability
Minimal structure orchestration	minutes/hours	Activation ratios of servers, activation ratios of ISLs, spot beam management, deployment of UAVs
Adaptive transmissions	milliseconds	Encoding/decoding, modulation/demodulation, channel estimation, beamforming



(a) (b) (c) (d)

Fig. 3. An instance of dynamically adjusting the minimal structure orchestration at a medium timescale to offer everyone-centric customized services.

of certain transmission links and MEC servers for instance. Table 1 summarizes the network adjustments, as well as their corresponding timescales and adjusted parameters.

Fig. 3 depicts an instance of medium-timescale minimal structure orchestration for four constant time periods. As shown in Fig. 3(a), multiple environmental sensors require updating their data for analysis in the first period. In this case, the activation ratios of gateway servers are high, while the satellite servers are turned off to save energy. Such a network adopts the computing-after-feeder-link structure. The second period sees a decrease in the number of transmitting sensors, as shown in Fig. 3(b). Therefore, the activation ratios of gateway servers are lowered. Fig. 3(c) shows that some mineral occurrences start exploiting resources in the third period. To provide industrial automation services, some satellite servers are turned on, and a UAV is dispatched for delay-sensitive computation offloading. The network is then adjusted to a combination of the computing-in-forward-link structure and the computing-on-orbit structure. As depicted in Fig. 3(d), in the fourth period, the activation ratios of servers on the UAV and its connected satellite are further increased to adapt to the increase in service demand. Meanwhile, the MEC activation ratio of the other satellite is lowered as the received solar power decreases.

B. Process-Oriented Network Optimization

For medium-timescale network orchestration, some network parameters are adjusted over different time periods, which matches the change of service requirements. However, these parameters, such as the MEC activation ratio in Fig. 3, remain fixed during a time period. This requires that the parameters should be optimally designed to maximize the system performance of the entire period. To address this problem, we propose a process-oriented optimization method, where the process refers to a medium-timescale period. The design of this type of method is challenging, since the accurate process information can be difficult, if not impossible, to acquire. For instance, the process duration is much larger than the channel coherence time. Therefore, the full channel state information (CSI) during the process is considered random, and thus cannot be obtained accurately. To address this challenge, one promising direction is to introduce external information to assist the optimization. For instance, the large-scale CSI of the whole process can be conveniently acquired from a pre-established database, referred to as a *radio map* [12]. Process-oriented optimization can be conducted based on the large-scale CSI. Likewise, we also need a large-scale model that characterizes the service requirements, which is worth further investigation.

VI. A CASE STUDY

In this section, we will provide a case study on process-oriented joint optimization of power allocation and offloading decisions in an extended computing-in-forward-link structure [13].

As illustrated in Fig. 4, the system consists of a gateway, a satellite, a swarm of UAVs each equipped with an MEC server, a data center and multiple MTDs. This indicates

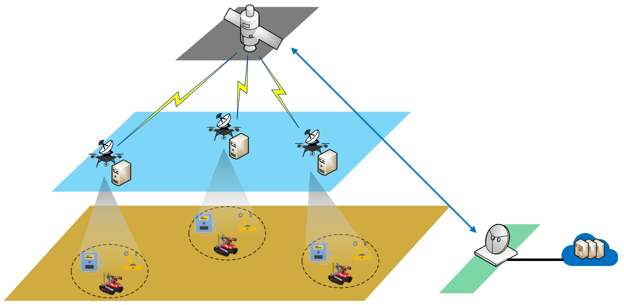


Fig. 4. The system model of the case study on process-oriented optimization.

that the system adopts an extended computing-in-forward-link structure with multiple UAVs. Each MTD is associated with the nearest UAV. Additionally, each MTD has one computation task, which can be processed at the UAV server or further uploaded to the data center. The task offloading process is designed under a process-oriented framework. Specifically, the whole process is divided into multiple segmentations. The power allocation and offloading decisions of each MTD are jointly optimized prior to the process to minimize the overall communication and computing latency.

The simulation parameters of this case study are listed as follows [13]. There are 56 MTDs and 7 UAVs in the considered system. The positions of the devices and UAVs are generated in a heterogeneous manner. The height of the UAV swarm is 3 km. For each MTD, the maximum transmit power is 2 W. The data rate of the MTD-satellite link is set as 9.6 kbps, and the maximum rate of the UAV–satellite link is set as 2 Mbps. The MTD-UAV link adopts a composite channel model, where Nakagami-m small-scale fading is considered. For each MTD-UAV link, the carrier frequency is 5.8 GHz, and the bandwidth is 1 MHz. The throughput of the MEC server for each MTD is 6 Mbps.

The proposed process-oriented optimization scheme is compared with other schemes. A simple scheme is considered first, where we only use the satellite for communications. Furthermore, a traditional state-oriented scheme is also compared [14]. In contrast to our proposed scheme focused on the whole process, this state-oriented scheme aims to minimize the latency of each state, or in this case, each segmentation [13]. From Fig. 5, we can observe that the proposed scheme has better performance compared with the satellite-only scheme. This suggests that the on-demand adjustment of minimal structure orchestration, in this case deploying UAVs with MEC servers, leads to better system performance. Moreover, the proposed process-oriented optimization scheme also outperforms the traditional state-oriented scheme. This suggests that process-oriented optimization can provide a performance gain despite the limited process information.

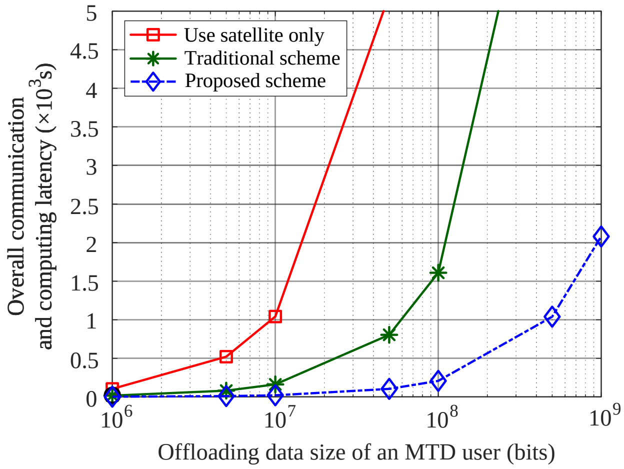


Fig. 5. Latency comparison of different schemes.

VII. Open Research Issues

Integration with AI: In the integrated satellite-MEC network, the introduction of the on-demand network orchestration framework raises many problems hard to model. AI-based algorithms can be of great assistance to solving these problems. On the other hand, the integrated satellite-MEC network can support AI-based applications in a ubiquitous and low-latency manner. Therefore, the integration of AI and the network can be an important issue.

Security: Security issues require careful consideration in the integrated satellite-MEC network. The inherently large coverage of satellites renders the network susceptible to adverse cyber-attacks. In addition, medium-timescale network adjustments are introduced in the network, which raises new security risks. Therefore, corresponding security measures need to be taken. For instance, blockchain-based methods can be considered to enhance network security. A seminal effort can be found in [15], which has proposed a blockchain-enabled air-ground integrated network to support the digital twin applications. Further investigations on this topic can be considered accordingly.

Coordination with navigation and sensing: In addition to communication and computing, the satellite system also has navigation and remote sensing functions. The coordination between the integrated satellite-MEC network and these functions is an interesting problem. Such coordination enables the network to open up new applications that require a comprehensive sensing-communication-computing capability.

Green network: Automated vehicles and MEC servers are widely and densely deployed in the integrated satellite-MEC network. This leads to a huge amount of energy consumption and carbon emission. Therefore, having a greener solution is an important issue. Considering the network characteristics, such as dynamic topology, innovative techniques need to be developed to achieve a greener network.

VIII. Conclusions

In this article, we have considered the integration of satellite communications and MEC to efficiently support MTDs in an everyone-centric manner. First, we have provided typical use cases of the integrated satellite-MEC network and the challenges of network design. Then three minimal integrating structures from a systematic perspective have been proposed.

To improve resource efficiency, we have established an on-demand network orchestration framework and a process-oriented optimization method. We have then conducted a case study, which shows that medium-timescale network orchestration and process-oriented optimization provide a tremendous performance gain in terms of latency. Finally, we have briefly outlined potential research directions for more intelligent, more secure, and greener satellite-MEC integration.

ACKNOWLEDGMENTS

The work of Yueshan Lin, Wei Feng and Ning Ge were supported by the National Key Research and Development Program of China under Grant 2020YFA0711301, and the National Natural Science Foundation of China under Grant U22A2002. The work of Ting Zhou was supported by the Program of Shanghai Academic/Technology Research Leader under Grant 21XD1433700. The work of Yunfei Chen was supported by King Abdullah University of Science and Technology Research Funding (KRF) under Award No. ORA-2021-CRG10-4696. The work of Cheng-Xiang Wang was supported by the National Natural Science Foundation of China under Grant 61960206006, the Key Technologies R&D Program of Jiangsu (Prospective and Key Technologies for Industry) under Grants BE2022067 and BE2022067-1, and the EU H2020 RISE TESTBED2 project under Grant 872172.

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Citation on deposit: Lin, Y., Feng, W., Zhou, T., Wang, Y., Chen, Y., Ge, N., & Wang, C. (2023). Integrating Satellites and Mobile Edge Computing for 6G Wide-Area Edge Intelligence: Minimal Structures and Systematic Thinking. IEEE Network, 37(2), 14-21. https://doi.org/10.1109/mnet.004.2200405