Task-Oriented Intelligent Networking Architecture for the Space–Air–Ground–Aqua Integrated Network

Jun Liu, *Member, IEEE*, Xinqi Du, Junhong Cui, *Member, IEEE*, Miao Pan, *Senior Member, IEEE*, and Debing Wei

***Abstract*—As one of the most promising networks, the space–air–ground–aqua integrated network (SAGAIN) has the characteristics of wide coverage and large information capacity, which can meet various requests from users in different domains. With the rapid growth of data and information generated by the Internet of Things (IoT), SAGAIN has received much attention in recent years. However, the existing network architectures are not capable of providing personalized network services according to different task types in SAGAIN. Besides, they cannot deal with many problems in SAGAIN well, such as heterogeneous network disconnection, high network delay, intermittent interruption, and unbalanced network load. In this article, in order to solve the abovementioned problems, we propose a novel architecture for SAGAIN named task-oriented intelligent networking architecture (TOINA). First, we apply the edge-cloud computing technology and network domain division in TOINA to realize intelligent networking and reduce the latency. Second, the task-oriented networking method is proposed to provide personalized network services and increase network intelligence. Third, we intend to leverage the information center network (ICN) paradigm to build the SAGAIN and optimize the content naming rules. Furthermore, a preprocessing layer was added in the network protocol stack to perform the heterogeneous network convergence in SAGAIN. In addition, some security technologies related to network architecture are considered in SAGAIN. This article presents the background, rationale, and benefits of the TOINA for SAGAIN. Besides, a specific case is studied to illustrate the network architecture work process further.**

***Index Terms*—Heterogeneous network interconnection, Internet of Things (IoT), network architecture, space–air–ground–aqua integrated network (SAGAIN), task-oriented intelligent networking.**

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I. Introduction

WITH the development of science and technology, our lives have undergone rapid changes. Accompanied by the development of the Internet of Things (IoT) and the emergence of the concept of the Internet of Everything and the space–air–ground integrated network, the network has become an indispensable part of human life. The new concept of IoT is to connect every single object on Earth through the network for information exchange and communication, and realize intelligent and supervisory functions [1], [2], however, the existing terrestrial network coverage is limited, polar, remote mountainous areas, deep sea, etc., where cannot be served with existing network services [3]. In order to reach a broader scope and expand human activities into space and deep space, scholars have started to develop the space–air–ground integrated network, seamlessly integrating satellite systems, aerial networks, and terrestrial communication. It has become an emerging attractive research topic during the past ten years. On the other hand, oceans occupy about 71% of the Earth's area, and most of the marine resources have not yet been explored. Because the ocean is of great significance in the field of national defense and the IoT for smart ocean is emerging, the underwater network has also been developed, and the underwater networking technology is becoming more and more practical nowadays. All of them promote the formation of the space–air–ground–aqua integrated network (SAGAIN).

SAGAIN is a large-capacity information network capable of information acquisition, processing, and efficient transmission. Compared with the traditional network, SAGAIN has the inherent advantages of extensive coverage and large capacity, and it can be applied to many fields, such as defense missions, marine transportation, emergency rescue, and environmental protection. Therefore, the development of SAGAIN is of great benefit to the human being.

However, there are many challenges in SAGAIN. Multiple tasks running in SAGAIN may have different network performance requirements. It is impossible for SAGAIN to

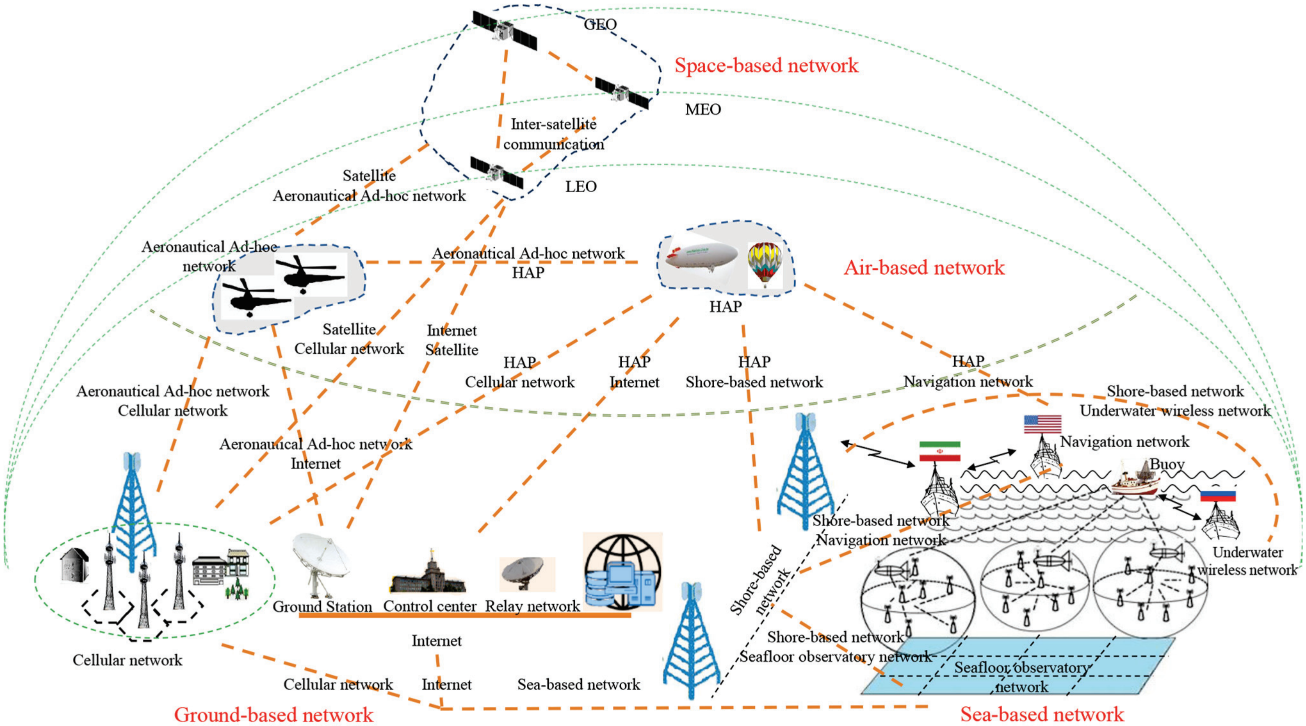

Fig. 1. SAGAIN composition and the communications among the subnetworks.

meet the needs of all tasks in a uniform manner. It can even affect the user experience and lead to an unbalanced load in the network when satisfying another more important requirement. Also, SAGAIN consists of a variety of heterogeneous subnets and the barrier between those subnets directly affects the coverage of SAGAIN. In addition, device mobility and poor communication environment may lead to intermittent network disruptions and prolonged network response latency.

In this complicated situation, the existing network architectures are not suitable for SAGAIN. For example, the traditional TCP/IP architecture [4] cannot solve the link interruption and has the disadvantages of low bandwidth utilization and poor network security. The information center network (ICN) [5], [6], limited by the size and amount of information of SAGAIN, will lead to the explosion of content namespaces. It will also cause a large time overhead for content retrieval, which leads to prolonging the network delay. Besides, the existing network architectures fail to solve the problem of heterogeneous network convergence, and the utilization of network resources is low, and opportunistic transmission [7] is often overlooked. In order to provide more efficient service, it is necessary to design a novel network architecture to adapt to challenging SAGAIN.

The major contributions of the task-oriented intelligent networking architecture (TOINA) we proposed are as follows.

1) We propose a scheme to reduce response delay and implement intelligent networking functions in TOINA by applying the idea of the edge-cloud computing technology and network domain division.
2) A method for task-oriented intelligent networking demand extraction is designed to make TOINA more intelligent, which can provide personalized networking schemes according to task types to meet the requirements of different tasks on networking performance.
3) We employ the ICN paradigm instead of the traditional IP-based structure to build TOINA and optimize content naming rules, which will facilitate mobility management in SAGAIN.
4) A preprocessing layer is designed and added in the network protocol stack to make TOINA achieve heterogeneous network convergence.

The remainder of this article is organized as follows. Section II analyzes the characteristics and challenges of SAGAIN and introduces the existing networking architectures to determine the networking requirements of SAGAIN. Section III proposes the new network architecture and introduces the basic principles and key technologies of the network architecture in detail. We give the performance analysis in Section IV. Following that, a specific case is studied to illustrate the network architecture work process further in Section V. Section VI concludes this article.

II. Research Background

The development of the space–air–ground integrated network and underwater network technology has promoted the formation of SAGAIN. This section mainly introduces the composition, network characteristics, and challenges of SAGAIN. After that, combined with its properties and the existing network architectures, we analyze the networking requirements of SAGAIN.

A. Space–Air–Ground–Aqua Integrated Network

Fig. 1 shows the composition of SAGAIN and the communication among the subnets in it. Considering the location of the network sits in, SAGAIN is roughly divided into four parts: 1) space-based; 2) air-based; 3) ground-based; and 4) aqua-based networks. These four parts can communicate independently or interconnect across domains. They complement each other to form a global coverage and large-capacity network.

Space-Based Network: SAGAIN consists of a variety of orbiting satellites, which are divided into three categories [3] according to their height: 1) geostationary satellite (GEO, height $= 36\,000$ km); 2) medium-orbit satellite (MEO, 2000 km $\leq$height$<$20 000 km); and 3) near-Earth satellite (LEO, 200 km $\leq$height$<$2000 km). The intersatellite laser communication uses Ka or Ku frequency band which provides high-bandwidth, high-speed communication services. Meanwhile, the satellites also communicate with the ground infrastructures. Presently, the satellite communication technology is relatively mature. For example, both the Beidou satellite system of China and the Iridium system of America have made great achievements.

Air-Based Subnetwork: This is a mobile network composed of aircraft, hot air balloons, etc., providing opportunistic data transmission services. Among them, the high-altitude platform (HAP) is a common air network which is located in the stratosphere about 20 km above the ground. It has a shorter delay than the space network and a larger coverage than the ground network. It can provide wireless communication and complement the terrestrial network [3].

Ground-Based Network: It is mainly composed of the cellular network, terrestrial Internet, mobile *ad hoc* network, and so on. The ground-based network topology is relatively fixed compared with the air-based network although cellphones or vehicle are mobile, the communication link is relatively stable. However, the coverage of the ground-based network is limited, such as polar, remote mountainous areas are difficult to cover.

Sea-Based Network: This subnetwork includes the submarine observation network and underwater self-organizing network. The seafloor observatory network communicates by laying optical cables and cables on the seabed. However, due to the harsh marine environment, the high construction cost, and the difficult maintenance, it is difficult to be deployed on a large scale [8]. The underwater self-organizing network is an extension of the underwater network in wireless communication. It is mainly composed of fixed sensor nodes and mobile ones like autonomous underwater vehicles (AUVs), remote operated vehicle (ROV), etc. It mainly uses acoustic waves to communicate, and has the disadvantages of limited bandwidth and long latency [8].

All these four subnetworks have their own advantages and disadvantages in terms of coverage, communication delay, bandwidth, and link quality. We integrate them to promote the formation of a global SAGAIN. Fig. 1 also identifies the communication among subnets in SAGAIN, such as satellite and terrestrial communication, underwater acoustic wireless network, and shore-based network communication, which is enough to see that SAGAIN is large in scale and capable of supporting multiple business types.

B. Characteristics and Challenges of SAGAIN

Through a detailed analysis of the SAGAIN, we conclude its characteristics as follows.

The Coverage of SAGAIN Is Wide: SAGAIN is made up of four parts. Compared with the traditional terrestrial network, its coverage spans across airspace, terrestrial, and sea areas. It has obvious advantages for the original terrestrial network to realize communication in the sea, air, and remote areas which are difficult to cover [3].

Networks Are Heterogeneous: SAGAIN consists of four domain networks roughly, each of which consists of several subnets specifically. The communication modes, media, and devices of each subnet are different, which affects network delay, communication data rate, etc. As a result, the performance of each subnet network is quite different. SAGAIN is heterogeneous as a whole. As shown in Fig. 1, the shore-based network communicates with the underwater acoustic wireless network. Among them, the shore-based network uses RF to communicate, while the underwater acoustic wireless network uses sound waves as the medium. The network parameters of some representative subnets in SAGAIN are shown in Table I.

SAGAIN Is Fragmented, Dynamic, Clustered, and Weakly Connected: SAGAIN integrates multidomain networks and accesses various types of mobile devices which are always in a high-speed motion state and frequently switching between multiple subnets. They drive the network to be hierarchical and fragmented and the topology is dynamic. While the transmission is clustered under the task driving.

Tasks Requirements Are Various: SAGAIN has the characteristics of wide coverage and large information capacity, so it can be widely used in many fields, such as emergency rescue network, marine transportation, and Earth ocean observation. In a wide variety of scenarios, different tasks have different requirements for Quality of Service (QoS). For example, the emergency rescue network requires real time and reliable response as much as possible, while the Earth ocean observation only requires the throughput and the reliability of the communication.

Terminals Are Subject to Strong Spatiotemporal Constraints and the Mixed Space Is Limited by Multiple Constraints: To improve the utilization of the resource, the terminals will be scheduled to assist with other tasks. For example, the node in the air-based network needs to not only perform the established tasks but also help other nodes to relay data, which will constraint the terminals simultaneously. Moreover, in the complex terrain environment, the low-altitude airspace aircraft is limited, which may affect the aircraft to perform tasks.

The existing mature terrestrial network applies to a single scene, but SAGAIN is far from it. How to organically and efficiently integrate different networks to form an intelligent SAGAIN has the following challenges.

TABLE I
SUBNET NETWORK PARAMETERS IN SAGAIN

Network name		Media	Bandwidth/Hz	Rate/bps	Distance/km	Networking
Space-based	Geostationary Transfer Orbit (GEO)	Ka-band	20-30G	1-10G	36000	Inter-satellite communication uses laser. Satellites use lasers to communicate with air-based and ground-based networks, using C, Ku, Ka, UHF, L, S, X and other frequency bands.
	Middle Earth Orbit (MEO)	Ku-band	10-20G	$< 1.2G$	10000-20000	
	Low Earth Orbit (LEO)	Ku-band	10-20G	$< 3.75G$	< 1500	
Air-based	Aeronautical Ad Hoc network	C	20M	-	< 10	Internal interconnection of air-based networks, and connection with ground-based and sea-based networks. Mainly use RF for communication.
	HAP	Radio	500M	$< 10G$	> 1700	
Ground-based	Cellular network	1G	50M	300K	< 50	Communication between mobile network and terrestrial network. Communication with sea-based network and air-based network. Communication is carried out by radio or by wire.
		2G	50M	800K	< 50	
		3G	145M	15M	50	
		4G	140M	$> 20M$	100	
		5G	1G	10G	50-100	
	WLAN	RF	2.4G	5-10M	< 50	
Sea-based	Underwater wireless network	RF	300	Attenuation	0.01-0.06	Mainly communicate with the shore base station.
		Optical	More than acoustic and RF	Attenuation $> 1G$	< 0.3	
		acoustic	20-50K	10-80K	0.1-1m	
			10K	1-10K	1-100	
	Seafloor observatory network	optical fiber	100M	12800K	-	Mainly communicate with shore-based networks and land-related centers.
	Shore-based network[9]	VHF	200K	13K	50-90	Mainly communicate with seafloor observation network, aeronautical ad hoc network and land-related centers. The media is radio or wired.
		VHF-DSC	300	1.2K	35-50	
		VHF data link	15M	9.6K	-	
		VDES	25-100K	70-300K	90	
		HF	2-3K	2.4K	> 900	
	Navigation network	VHF	200K	$< 10K$	< 100	Mainly communicate with shore-based network and air-based networks, using radio.

Difficulties in Heterogeneous Network Management: The subnets in SAGAIN are very different in terms of the communication environment, not to mention the service requirements. At the same time, each subnet supports different application scenarios, resulting in an uneven transmission load. It is urgent to solve the problems of uniform management and reasonable distribution of network resources.

Long Network Latency: The network delay is mainly affected by two factors. The first one is the communication distance. The satellites are between 200 and 36 000 km away from the Earth. When the satellite communicates with the base station on the ground, the delay is up to several hundred milliseconds. The second is the transmission speed of the medium. For example, an underwater wireless network uses acoustic waves as the data carrier. Its speed in water is about 1500 m/s, which is five orders of magnitude smaller than the speed of RF in the air (3×10^8 m/s) [8]. Both of these factors significantly prolong the network latency, and it will seriously impact the user experience.

Intermittent Network Interruption: As the network scale continues to expand, more and more devices will access SAGAIN. However, the communication of these devices will be affected by many factors, such as dynamic network topology, energy limitations, and poor communication environment [4]. As a result, it would become difficult to establish and maintain network connections. The network links would likely to be interrupted, and communications might be failed. How to guarantee throughput and reliability in this situation will be especially important.

Network Traffic Has Increased Dramatically: According to Internet data center (IDC) analysis, global Internet data traffic will maintain rapid growth. Traditional TCP/IP-based networks need to establish end-to-end connections for communication, resulting in high link resource occupancy and low bandwidth utilization, which cannot cope with the global data traffic burst. As for other architectures also cannot deal with this problem properly.

Difficulty in Mobility Management: SAGAIN contains multiple types of mobile devices. The movement trajectories of these devices are quite different, and there is also a great difference in the spatial scale. They also have different patterns of movement. For example, some of them like satellites are periodic and predictable to move, and some like AUVs move randomly. If a traditional TCP/IP-based network is used, the IP address identifies not only the identity but also the location. It is complex when dealing with mobility issues. How to access SAGAIN again after moving needs to be further investigated [10].

The Requirements of Different Tasks Cannot Be Met With Uniform Standards: Due to the heterogeneity of nodes, the diversity of tasks and the limitation of resources, SAGAIN cannot meet the needs of serialized tasks in a unified manner.

Therefore, according to the task type, the fragmented subnet needs to be dynamically scheduled to provide on-demand services. Besides, the network situation is perceived in real time. A network change trend can be inferred from the network situation. Finally, the resource scheduling scheme for optimizing the network configuration is given based on the trend of the SAGAIN changes.

Mixed Domain Is Limited by Multiple Constraints: There are some terminals in SAGAIN that undertake multiple tasks simultaneously and are controlled by multiple network domains. We need to implement multidimensional composite control for such terminals. We can refer to the networking in the light of situational guidance to allow multiple network domains to cooperate.

C. Problems Applying the Existing Architecture to SAGAIN

Through analyzing the characteristics and challenges of SAGAIN, we find that there will still be problems if the existing network technologies are used for SAGAIN.

For example, widely used TCP/IP, the premises of it are that there is an end-to-end path during communication, the packet transmission delay cannot be too long, and the packet loss rate should be small [4], which cannot be met in SAGAIN at any time. It will severely impact the performance. Besides, TCP/IP [11], [12] cannot solve the issues of link interruption and node mobility, the bandwidth utilization is not efficient, the IP address is deficient, and the network security is inadequate. Using some "patching" protocols like IPV6 [13], [14] or improved methods like address-driven networks (ADNs) [15], can only solve the specific problems, and it is impossible to deal with the challenging SAGAIN. In the ICN, replacing the network core with a content block, the request and routing are based on it [5], [6], [16]. The adoption of ICN, limited by the scale and a myriad of information of SAGAIN, will lead to the problem of content namespace expansion, and then generate the problem of large time-consuming retrieval of content name and high response delay. The XIA [17] is a general-purpose architecture that replaces the dominant position of IP with new elements and can support different communication modes, providing a unified view to meet various network requirements. However, using the XIA, the complexity of SAGAIN will be increased as the network elements (throughput, mobility, etc.) added.

In addition to the abovementioned network architectures, some network management methods cannot be directly applied to manage SAGAIN. For example, software-defined networks (SDNs) [18]–[22] proposed to separate the control-data planes and made forwarding decision by the centralized controller, which can realize the flexible control of network traffic and make the network more intelligent. Affecting by the large scale of SAGAIN, directly using SDN will overload the centralized controller and even results in the breakdown of the network. Originally designed for the interstellar network, delay tolerant networks (DTNs) [4] proposed to add an overlay network over TCP/IP to ensure normal communication in interrupted or long-delay networks. The lessons learned from DTN should be considered, which can solve the problem of links interruption in SAGAIN.

To conclude, SAGAIN has its inherent advantages of extensive coverage and large capacity, and it can be applied to many fields, such as defense missions, marine transportation, emergency rescue, and environmental protection. Therefore, the development of SAGAIN is of great benefit to the human being. To make SAGAIN highly efficient as expected, we propose a novel network architecture named TOINA which can solve the challenges in SAGAIN and achieve the goals of management of heterogeneous subnets, supporting multiple task types, and providing intelligent and reasonable network services.

III. Task-Oriented Intelligent Networking Architecture for SAGAIN

In this section, we introduce the conceptual architecture of the proposed TOINA for SAGAIN and elaborate the corresponding technological benefits. In accordance with the characteristics and challenges of SAGAIN introduced in the previous section, considered with the existing networking technology, our overall design ideas about TOINA for SAGAIN are as follows.

First, to simplify this large-scale network management, TOINA separates the data plane and the control plane combining with the edge-cloud computing technology. Edge-computing nodes and cloud-computing centers internally carry network controllers, which are mainly responsible for task-oriented intelligent networking demand extraction, opportunistic scheduling transmission, dynamic allocation of network resources, and providing a fast response to terminals.

Second, in order to make the TOINA smarter, a method for task-oriented intelligent networking demand extraction is recommended. Specifically, TOINA should be able to provide a myriad of networking plans that meet the different requirements according to the task type and the network situation.

Third, on the basis of the four constituent networks of SAGAIN, it is subdivided into subnets, which are called domain. This kind of architecture makes it convenient for the management of such a large-scale network. The rules for the division are according to the application scene, service type, geographical location, application density, and other factors. Besides, the range of each domain is different.

Fourth, the entire TOINA is designed based on the ICN to reduce the redundant traffic in SAGAIN and better adapt the mobility scenario. It mainly manifests in abandoning the IP dominant position and concerning the content information nor the location of the terminal. We redefine the naming rules for packets.

Finally, a preprocessing layer is designed and added to achieve heterogeneous network interconnection in TOINA. Besides, to support diverse applications on limited network resources and infrastructure, network function virtualization (NFV) will be adopted.

A. Edge-Cloud Collaborative Computing Framework in TOINA

There are many types of networks in SAGAIN, and the task requirements are different. In order to provide better network services, it is necessary to provide personalized networking

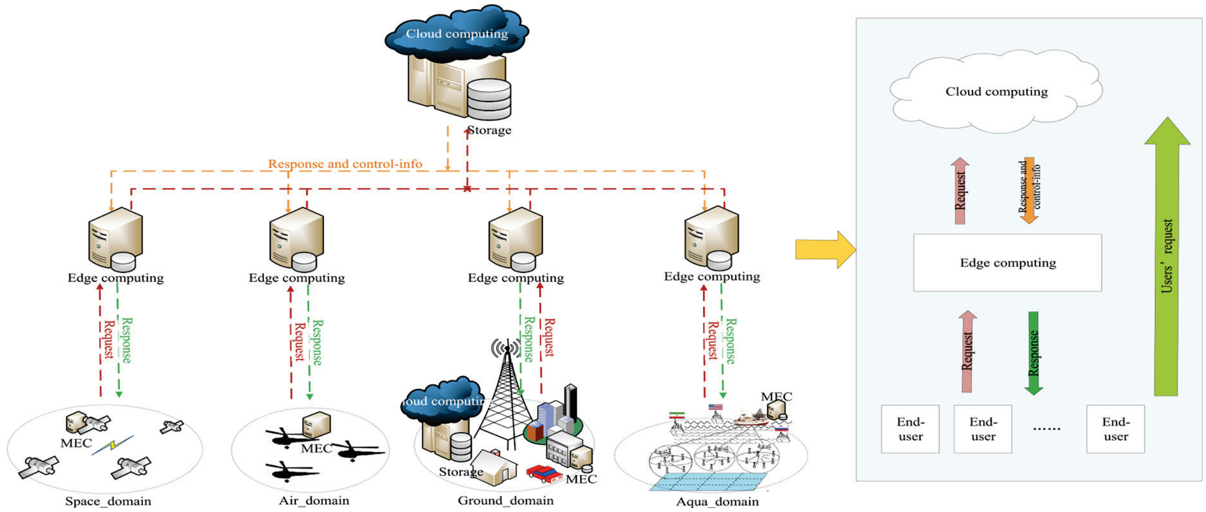

Fig. 2. Information flow diagram in SAGAIN.

schemes according to the task type. Considering the large scale of SAGAIN, TOINA will separate the control plane from the data plane to provide a unified view to meet the needs of diverse tasks. This idea is mainly realized by adding cloud-computing centers and edge-computing nodes in SAGAIN, combined with the edge-cloud computing technology.

1) Edge-Computing in TOINA: With the development of the Internet, IoT, and cloud computing, various novel wireless terminal devices access the network to provide intelligent and convenient services for people. Cisco estimates that by 2020, about five billion devices will be joined to the Internet, and the data generated by people and devices will reach 500 ZB [23]. The demands for IoT applications are continuously rising. But some applications require short delays service, and some involve privacy protection, etc., which challenges the traditional cloud computing paradigm [24], [25]. The concept of mobile-edge computing (MEC) came into being. MEC nodes are to deploy to the edge of the network to serve users, where edges are defined as arbitrary locations on the data source and cloud computing center path [1], [25]. Each edge-computing node has computing resources, network resources, and storage resources, which can assist the cloud center in dealing with tasks.

There are myriads of tasks in SAGAIN. If only adopting the traditional cloud-computing paradigm, it will inevitably cause heavy load in the cloud-computing center, and even cause network bottleneck and paralysis, which will affect the overall performance of the network. Therefore, we adopted the edge-cloud computing technology in our architecture proposed for SAGAIN. Specifically, edge computing and traditional cloud computing [26]–[31] cooperate to jointly complete data collection, processing, analysis, and mining. In this way, TOINA can improve service quality when responding to user requests. Fig. 2 shows the information flow diagram after applying the edge-cloud computing technology. The left side is the actual application scenario, and the right side is the abstracted relationship diagram. It gives an intuitive view of the interaction among the cloud-computing center, the mobile-edge-computing nodes, and the end users. From bottom to top, it is mainly user data and task request information. The other way is the responses and control messages. The requests can be answered by either the edge-computing node or the cloud-computing center.

The edge-computing nodes are responsible for the following functions.

1) They have a storage function. The user data, the processing result, and the forwarding content can be stored locally, and the content storage table (CST) is set to facilitate a quick response to the request. At the same time, the forwarding information in the network domain is temporarily stored. When the network is interrupted, or a fault occurs, the data packet can be quickly forwarded, which improves the availability of the network to a certain extent.
2) They have the computing capacity and extract the task-oriented networking requirements. According to the networking scheme to carry out the corresponding network configuration to ensure the achievement of the task. The network environment is perceived, and dynamic resource allocation is carried out on the managed network.
3) While managing the network and serving terminals, edge-computing nodes are also responsible for interacting with the cloud-computing center and edge-computing nodes in other network domains. It uploads user data to the cloud-computing center and accepts the response data and assigned tasks. Cooperating with the edge-computing nodes in other domains, we realize cross-domain communication, that is, communication between heterogeneous networks.

The advantages of using edge computing are as follows.

1) *Reduce Network Latency:* The propagation delay is $D_{\text{prop}} = \text{distance}/\text{speed}$, where *distance* represents the distance between two communicating entities and *speed* represents the propagation speed of the data carrier. We can get from the formula that the propagation delay is proportional to the distance. When the data are processed, the edge-computing node is closer to the data

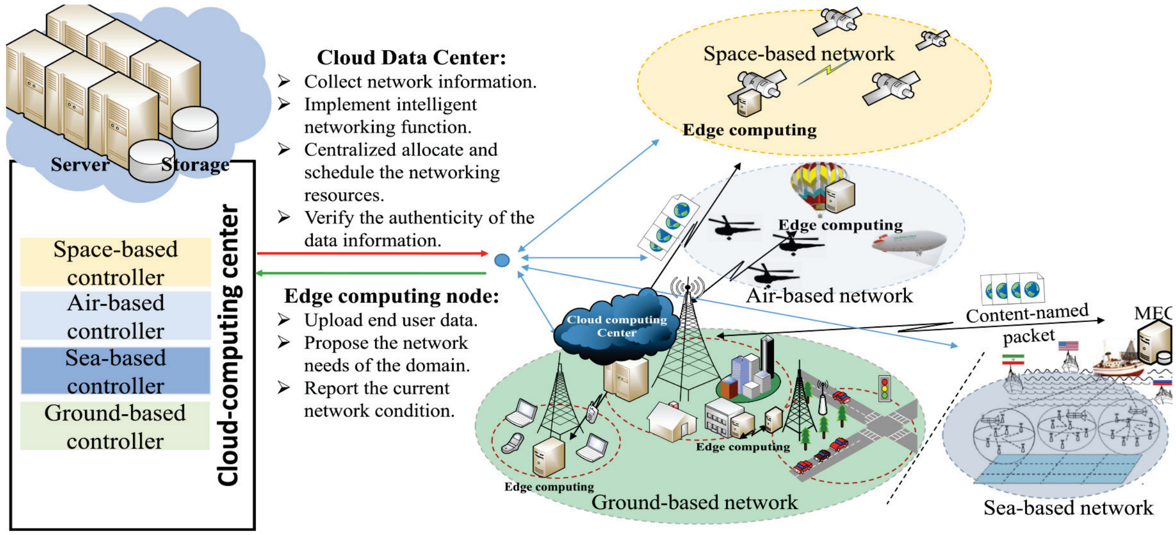

Fig. 3. Deploying cloud-computing center in the ground-based network.

source compared to the cloud-computing center, so the delay of the edge-computing node is shorter.

2) *Balancing the Network Load and Relieving the Pressure of the Cloud-Computing Center:* Since the data are not all uploaded to the cloud-computing center, the bandwidth pressure of the backbone network is alleviated [24], [25].

3) *Improve Network Security:* To some extent, the opportunity for data exposure to the network is reduced, thus reducing the risk of data leakage [24], [25].

2) Deploy Cloud-Computing Center on the Ground-Based Network: Considering the communication technology of the ground-based network is mature, and the communication environment is relatively stable, we analyze that the data flow direction in SAGAIN is convergent. The convergent center is located in the ground-based network. Therefore, we will build the cloud-computing center in the ground-based network, which carries the controller for the whole SAGAIN inside. It is mainly responsible for task-oriented intelligent networking, cooperation with edge-computing nodes in each domain, and providing differentiated services for users.

From Fig. 3, we can see that the cloud-computing center roughly consists of four independent but interactive controllers (corresponding to the four domain networks, respectively). By receiving the network information provided by the edge-computing nodes in each network domain, the cloud-computing center achieves the global control of SAGAIN. In this way, TOINA can meet the service requirements, balance the load, dynamically configure the network, and make efficient use of network resources in SAGAIN.

For example, the application density and network load in the domain of the intelligent transportation network increase significantly during the morning and evening rush hours. Also, traffic information plays a vital role in the application of this area. Wrong or nonreal time traffic information will cause traffic congestions or accidents, threatening the property and life safety of users. In light of the above problems, the cloud-computing center will allocate more network bandwidth and higher priority to the intelligent transportation network domain during the rush hour, which will shorten the network response time.

The above is just one example in SAGAIN. In practice, the cloud-computing center will reasonably schedule network resources according to the characteristics and requirements of different network domains. Besides, the cloud-computing center will handle large and complex tasks that cannot be solved by terminals. In the future, a security control center can be set up here to take charge of identity authentication and other functions to improve network security.

Both of these approaches realize the separation of data and control planes, and TOINA can provide a unified view for diverse applications. They also enable task-based intelligent networking, which is convenient to dynamically configure the network environment and improve the utilization of network resources.

In the following sections, we propose a method for task-oriented networking requirements extraction and deriving the networking scheme to meet task requirements. This method needs to be jointly implemented by edge-cloud computing, where edge-cloud computing nodes in the network will perform this method in a distributed manner. Fig. 4 is a flowchart showing the execution of intelligent networking by a network controller. We can see that SAGAIN generates a task request and delivers it to the "intelligent networking process according to task type" to create the networking requirements. Meanwhile, "environmental information" such as network situation, is delivered to the "intelligent networking process in the light of network situation" to generate dynamic scheduling information. Then, the above requirements are submitted to the network controller. After collecting various networking requirements, the network controller proposes the network configuration to ensure the successful completion of the task, which mainly includes opportunity-terminal scheduling information, classic network configuration reference, and network parameter configuration. The above parameters will

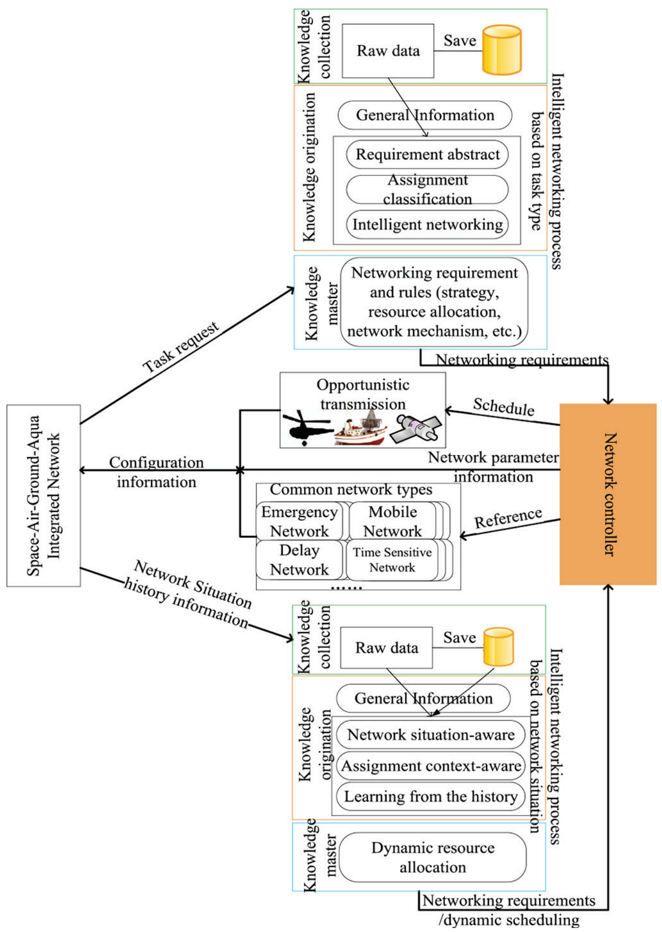

Fig. 4. Network controller performs intelligent networking.

be executed in the network controller to complete the network configuration.

B. Task-Oriented Networking Requirements Extraction

SAGAIN supports a variety of scenarios where different user interest points lead to a high diversity and time variability of user data [32], [33]. Existing networking technologies lack awareness of task types and network situations. Considering the network's dilemma and technology background, we propose a method for task-oriented networking requirements abstraction in TOINA. The main ideas for this method are as follows. First, according to the type of task and combined with machine learning for intelligent networking, the method puts forward networking requirements and solutions to meet the demand. Second, TOINA will perceive the current network situation and dynamically schedule the networking resources to optimize the networking scheme proposed previously.

As shown in Fig. 5, the method for task-oriented networking requirements extraction consists of three main components.

Knowledge Collection: It is mainly responsible for collecting and preprocessing the user data.

Knowledge Origination: This is the core part of the method. It is primarily responsible for extracting networking requirements according to the task type and network situation aware. The processed data will be classified into corresponding task

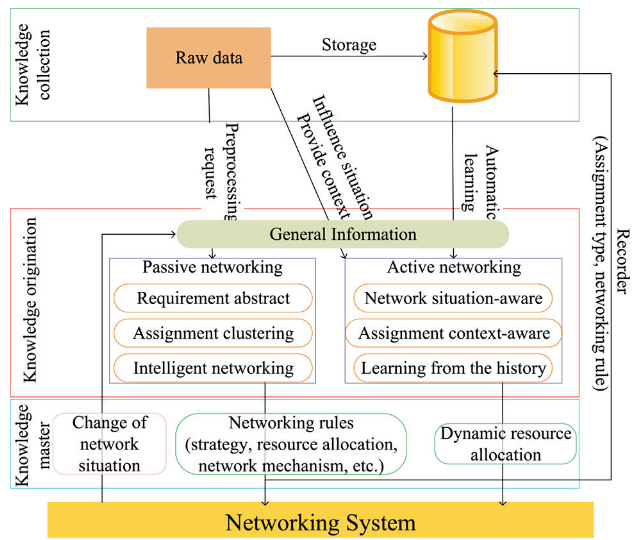

Fig. 5. Task-oriented networking requirements extraction.

types, and then networking requirements will be given to the controller. Besides, sensing the network current situation to schedule network resources dynamically and further optimize network scheme.

Knowledge Master: It is in charge of receiving the above networking requirements, configuring the network, and storing the configuration records. When the network situation changes, the networking solution is revised timely in line with the feedback.

The extraction of networking demands mainly consists of two parts. One part is offering networking requirements according to the task type, and the other is to optimize the networking scheme by sensing the network situation and learning historical data. The details are described as follows.

First, we process the network historical request data set. We transform each data into an m-dimensional data attribute vector $\text{attr} = [x_{i1}, x_{i2}, \ldots, x_{im}]$, which can represent the original data, where x_{ih} is described as an attribute, throughput, date, security, etc. After converting all the data items, they form a data attribute matrix attrs

$$\text{attrs} = \begin{bmatrix} \text{attr}_1 \\ \vdots \\ \text{attr}_n \end{bmatrix} = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix}. \quad (1)$$

Then, we select the characteristics of attrs, to reduce the original data attribute matrix dimension. Finally, by using principal component analysis (PCA), we select j features (throughput, delay, loss rate, interruption, mobility, security, etc.) to represent the networking requirements of the original data. The weight of the selected eigenvalue exceeds 90%, and then gets the following matrix attrs_1, where attr_{i1} indicates the degree of need for each service:

$$\text{attrs}_1 = \begin{bmatrix} \text{attr}_{11} \\ \vdots \\ \text{attr}_{n1} \end{bmatrix} = \begin{bmatrix} x_{11} & \cdots & x_{1j} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nj} \end{bmatrix}, \; j << m \quad (2)$$

$$\text{attr}_{i1} = [\text{throughput, delay, loss}, \ldots \text{disruption, mobility, security}]. \quad (3)$$

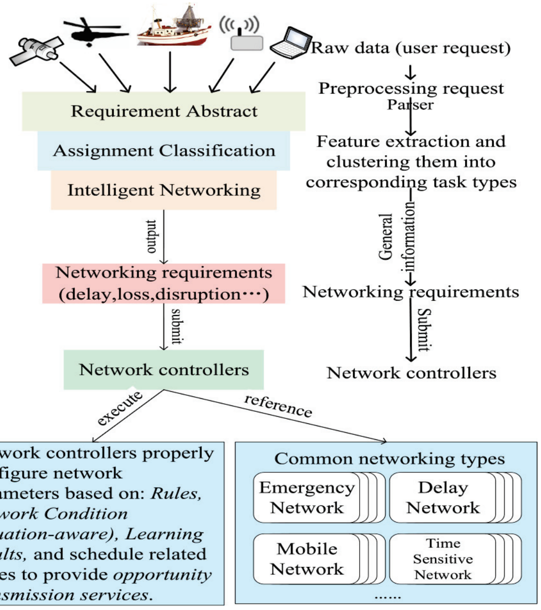

Fig. 6. Knowledge origination working process.

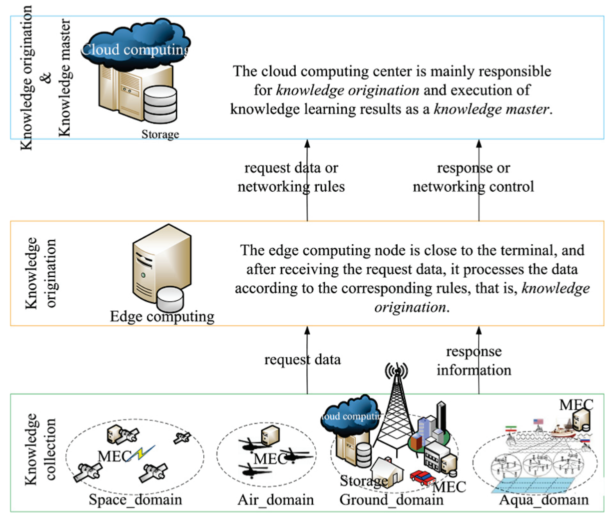

Fig. 7. Implement of task-oriented networking requirements extraction in SAGAIN.

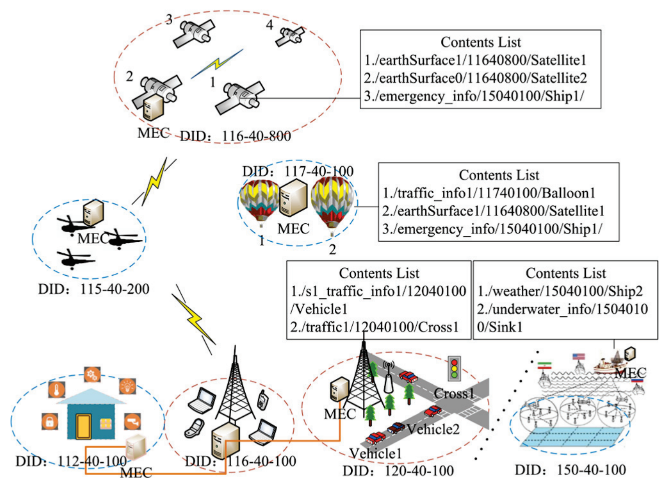

Fig. 8. Schematic of SAGAIN domain division.

Finally, the matrix attr_{i1} is clustered to obtain the network requirement set

$$\text{Require}_{\text{set}} = \{r_1, r_2, \ldots, r_k\}, k << n \tag{4}$$

where $r_i = [\text{throughput}, \text{delay}, \text{loss}, \ldots, \text{disruption}, \text{mobility}, \text{security}]$, each variable $\in$ 0, 1, 2, indicating the degree of dependence on the corresponding service demand. 0 means that the current task for the service request is low; and 2 means to provide such service as possible. Then, map each requirement r_i to the network configuration parameter vector parm_i

$$\text{parm}_i = [\text{bandwidth}, \text{transmission\_rate} \\ \text{storage\_capacity}]. \tag{5}$$

Whenever the data are received, as shown in Fig. 6, the original data are preprocessed to extract the attribute vector data_attr. It is then classified as input to obtain r_i, the networking requirement category most similar to the task demand. The networking requirement for r_i is submitted to the network controller. It appropriately schedules networking resources and completes network configuration based on the obtained network requirement r_i and network situation, combined with common network configuration information.

Besides, the network configuration parameters are returned to the storage and matched with the corresponding task request, to facilitate automatic learning and provide a reference for future task requests.

In practice, we will implement this method in SAGAIN. As shown in Fig. 7, a network terminal is the carrier of the work of the knowledge collection, that is, generating and submitting task requests. Knowledge origination is executed in edge-cloud computing nodes with computing capabilities, which will perform intelligent networking in a distributed manner. The knowledge master is achieved in the cloud-computing center. It presents the reasonable allocation of networking resources and device scheduling. Also, it is aware of the network situation to optimize networking schemes dramatically. In this way, it is possible to provide a differentiated networking scheme for tasks in SAGAIN, which is consistent with the high diversity and time-varying characteristics of user data, making SAGAIN a smarter network.

C. Domanial Autonomy in SAGAIN

To facilitate the management, on the basis of the four constituent networks of SAGAIN, they are subdivided into smaller parts according to the application scene, service type, geographical location, application density, and other factors. Each independent part is called the domain. The range of each domain is not equal, and each domain is given a globally unique domain identification (DID). The naming rule of domain identification DID is as follows:

$$<\text{Longitude} - \text{Latitude} - \text{Radius}>. \tag{6}$$

Taking Fig. 8 as an example, it consists of a smart traffic domain (DID=120 − 40 − 100), an emergency satellite

TABLE II
CL FORMAT

Content list		
CL_ID	*/Content_Name/Domain_ID/Seneor_ID*	Forward direction

domain (DID=116 − 40 − 100), and a navigation domain (DID=150 − 50 − 100) according to the application scenario and service type. Among them, the smart traffic domain and the emergency satellite domain require the shortest possible network response latency, and the navigation domain has lower latency requirements. According to the application density and geographical location, the land mobile network domain (DID=116 − 40 − 100) further was divided. There are multiple domains of this type in SAGAIN, distributed in different locations. The density and coverage range are varied according to the location. The relation between coverage and application density can be modeled as

$$R \propto t/\rho \tag{7}$$

where R represents the radius of area coverage, ρ represents the application density, t is the parameter, and $t > 0$. Specifically, the coverage in the domain is smaller in which the distribution of terminals is sparse, while the density domain is larger.

Each domain uses a uniform network standard. Besides, an edge-computing node is deployed to control the intradomain network, provide intelligent networking, and interacting with other domains. By subdividing the network domain as described above, the TOINA can make load balanced in SAGAIN to avoid resource shortage or waste. TOINA will combine the network resource allocation scheme to make each network domain meet the task requirements to the greatest extent.

D. Naming Rules for Packets in TOINA

SAGAIN is large in scale and contains many terminals with different types. These are accompanied by the problems of traffic surges, dynamic topology, and frequent interruptions of links. In order to solve the above problems, TOINA assumes to enable SAGAIN based on the idea of ICN. The packet format will follow the approach proposed by NDN. Digital signatures are added to the packet to prevent malicious tampering by others, ensuring data reliability and security. Nevertheless, the existing naming rules are slightly modified. The content naming rules we optimized are as follows:

$$/\text{Content\_Name}/\text{Domain\_ID}/\text{Seneor\_ID} \tag{8}$$

where Content_Name is the name identifier associated with the content, Domain_ID indicates the area ID of the node that owns the content, and Seneor_ID indicates the number of the node in the domain.

Each node will maintain a content list (CL), and each item in the list corresponds to a specific content stored in local. This content can be data content generated by the node or retrieved from the network. The standard format for the CL is shown in Table II.

For example, as shown in Fig. 8, Satellite1 in the emergency satellite network domain ($DID = 116 - 40 - 100$)

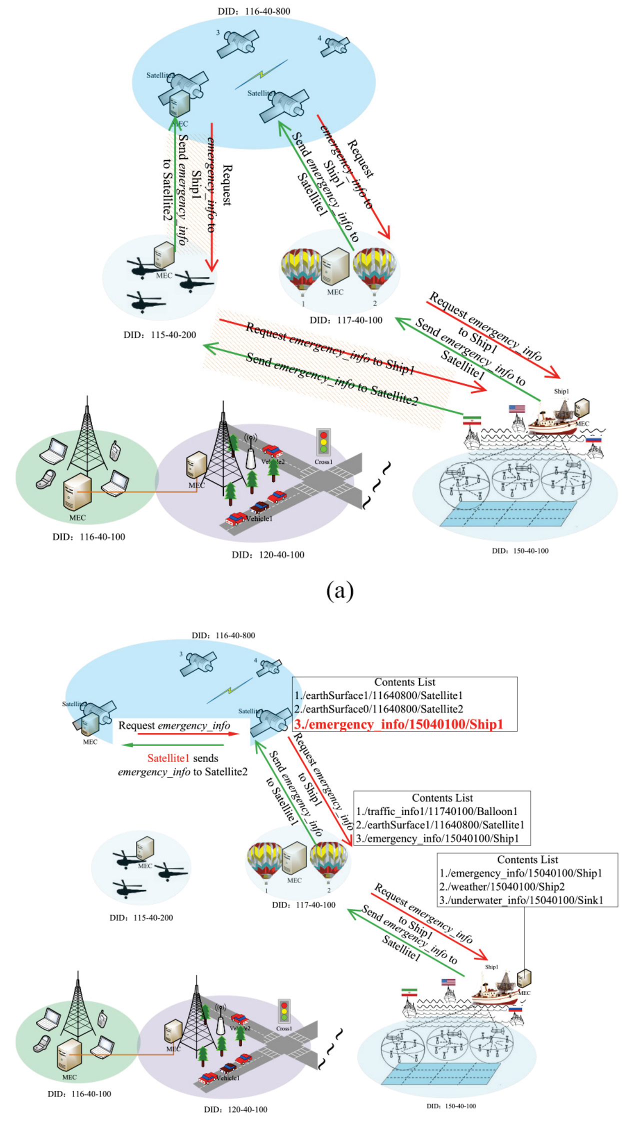

Fig. 9. Comparison of communication based on (a) TCP/IP and (b) TOINA.

shoots a surface image, and names the image "earthSurface1," so add an item "/earthSurface1 /11640100/Satellite1" to the local CL. "/earthSurface0 /11640100/Satellite2" in CL represents the content of the "earthSurface" requested by Satellite1 from the network, and finally receives the content, which is derived from Satellite2. "/emergency_info/15040100/ship1" in CL, indicates Satellite1 requested the content of the navigation network domain.

Using the request-receive-cache content mechanism can reduce the traffic overhead in the network. We give an example, compared with communication based on the TCP/IP network, to explain the benefits of TOINA in detail. The example is about Satellite1 and Satellite2 successively requesting emergency_info at Ship1. (This process mainly considers data transmission and ignores the establishment of connections.)

Fig. 9(a) shows the communication based on the TCP/IP network. First, Satellite1 requests to Ship1 based on the IP address, and the forwarding path is $IP_{\text{satellite1}} - IP_{\text{ballon1}} -$

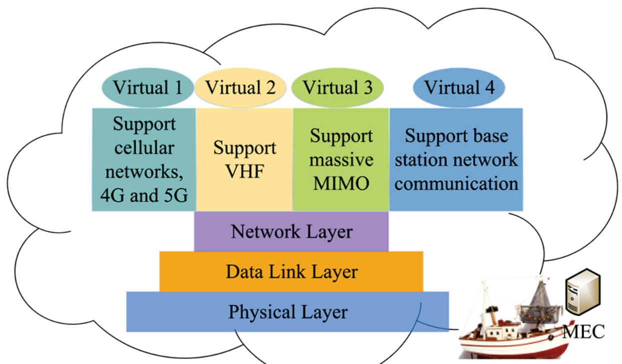

Fig. 10. NFV implementation diagram.

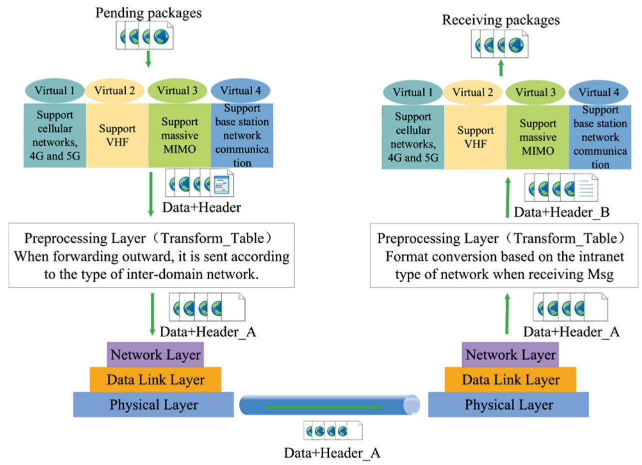

Fig. 11. Working principle of the preprocessing layer.

IP_{ship1}; later Satellite2 requests the same content as Satellite1, and the forwarding path is $IP_{\text{satellite2}}-IP_{\text{airplane1}}-IP_{\text{ship1}}$. If we use TOINA, based on content, to complete the same task, the process is shown in Fig. 9(b). First, when Satellite1 requests, the forwarding path is Satellite1—Ballon1—Ship1. The participating terminals will temporarily store emergency_info locally. Satellite2 later requests the content again, which can be provided directly by its neighbors, Satellite1. In this way, Satellite2 does not need to repeat cross-domain communication with Ship1, which reduces the redundant traffic in the whole network and shortens the delay.

In practice, such similar examples occupy a large proportion. Based on the content, TOINA does not need to establish and maintain the end-to-end connection or consider the reliability of the long-distance transmission links, which simplifies the communication, save the network resources, and shorten the delay.

E. Heterogeneous Network Interconnection in TOINA

SAGAIN covers diverse networks, such as cellular networks, underwater sensor networks, and intersatellite networks. These heterogeneous networks have discrepancies in media, network architecture, and protocol, but the current architecture is firmly entrenched [34]. Therefore, the new network architecture not only needs to solve the problems existing in the current network but also needs to solve the problem of network compatibility and heterogeneous network interconnections.

In terms of the actual use of the network, it is to transfer data between users. That is, in the process of communication, users only care about the data content itself but not which strategy is employed to transmit. In order to better support the communication between heterogeneous networks, first, we adopt the concept of NFV in SAGAIN. Second, we set the preprocessing layer in the protocol stack of the edge-cloud computing node to realize the conversion of packet formats among heterogeneous network domains.

NFV is to support differentiated communication applications on the same network infrastructure, that is, terminals in the network domain can run multiple types of applications [16], [35]. As shown in Fig. 10, the same network infrastructure can support underwater acoustic wireless network, base station network, very high-frequency (VHF) communication, and multiple-input–multiple-output (MIMO) communication. Specifically, different network protocols can also be employed for communication.

Besides, at the edge-computing node, we add a preprocessing layer to its protocol stack. Its primary function is to convert the format of the data packet between the subnetworks. In brief, it is in charge of striping the header information of the packets in the source subnetwork domain, extracting the content itself, and then encapsulating the content to the type of the target subnetwork. Later, the update packet will be forward. By adding the preprocessing layer, the TOINA realizes the management of heterogeneous networks in a uniform way. Furthermore, it separates the upper application from the lower network. Specifically, the application terminal only needs to consider the content itself without the implementation details of the underlying network. The working principle of the preprocessing layer is shown in Fig. 11. By adding the preprocessing layer, TOINA realizes the conversion of the packet header and applies this method in different types of networks, which makes communication between heterogeneous networks accomplished.

All in all, there are three main advantages of TOINA compared with the existing network.

1) It enables SAGAIN and controls the areas that cannot be reached before.
2) It provides intelligent and flexible services and allocates the resources on demand ensuring efficient execution of tasks.
3) It has high compatibility and scalability, which conforms to the rapid development of the network.

IV. Performance Analysis

In this section, we evaluate the performance of our proposed architecture TOINA in five aspects.

Network Delay: Here, we mainly discuss the propagation delay and it can influent the total network delay. Specifically, some edge computing nodes are deployed nearby the users and the propagation delay of it is shorter than the cloud center. Besides, the terminal requests are based on content rather

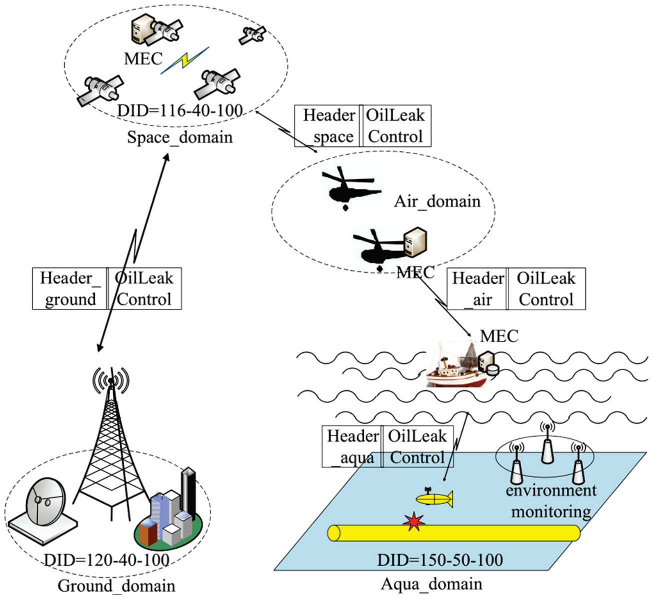

Fig. 12. Case study for the TOINA.

than the IP address, which is easier and more quickly to be responded by surrounding qualified nodes.

Resource Utilization: In TOINA, we propose to dynamically configure the network resource, which can avoid the shortage or idleness of the network resource. It can schedule some terminals to provide opportunistic transmission after finishing their own assignments. In addition, there is no need to establish an end-to-end connection, that is, the use of the link resources is more flexible and the redundant traffic is greatly reduced.

Robustness: In terms of robustness, we mainly achieve rapid recovery from the link interruptions and avoiding network paralysis. Using the request-receive-cache mechanism, participating nodes temporarily save the forwarded content. It can be retransmitted by the near nodes to complete the communication when the link interrupted. In TOINA, we use edge computing nodes to manage the SAGAIN in a distributed manner. When a failure occurs, its influence is local and the number of involved terminals is small.

Security: First, the packet is authenticated with a digital signature. It can determine the source of the information and is nonrepudiation. Its value will change if the content changed. Because of that, digital signatures ensure the message integrity. Second, the edge computing nodes in TOINA response the user more closely, reducing the risk of data exposure. They can provide a seamless network access services for mobile terminals in SAGAIN, avoiding the packet being intercepted in the middle. Finally, the requests are based on content, not location. That is the specific servers cannot be located and unable specific nodes, reducing the risk of Denial-of-Service (DoS) attacks.

Compatibility: The incremental design of the protocol stack enables format conversion between protocols and is compatible with many firmly entrenched architectures. Both of them will improve the compatibility of TOINA.

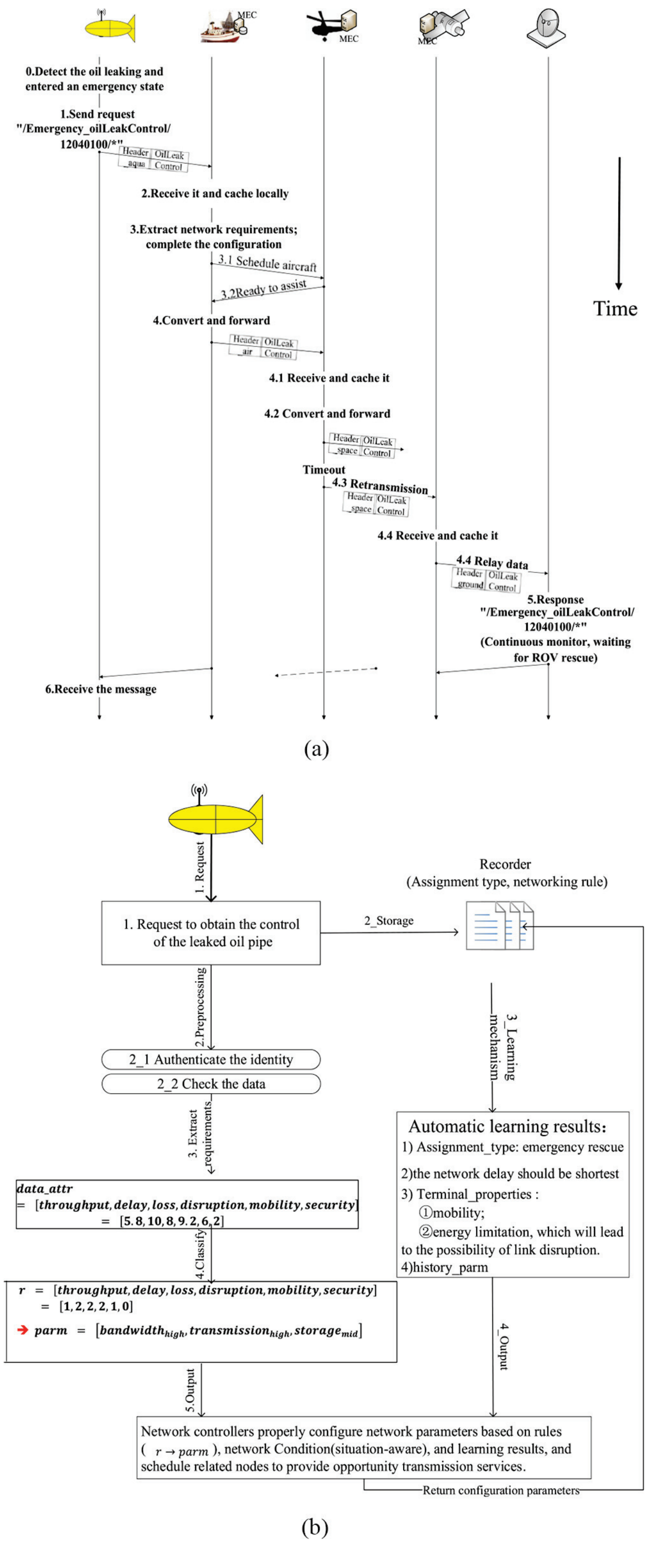

Fig. 13. Details of emergency network. (a) Interaction among terminals. (b) Process of requirements extraction.

V. Case Study

Through the introduction, we have a certain degree of understanding the TOINA proposed for SAGAIN. The following will take an example to deepen the recognition of it.

As shown in Fig. 12, there are two types of underwater scenarios. One is underwater environment monitoring (completed by fixed sensor nodes), and the other is an underwater survey, which is mainly responsible for investigating whether the oil pipes laid on the seafloor have leaked oil. This task is mainly assisted by AUV.

It is important to control the oil spill as soon as possible because it will pollute the ocean environment. Fig. 13(a) depicts the interaction among the terminals in response to this emergency task.

When the oil pipe suddenly leaked, the AUV detects the situation and entered an emergency state. The AUV sends a request "/Emergency_oilLeakControl/12040100/*" reporting the information about the leak of the oil pipe to the shore control center for further instructions.

After receiving the request, the sink node (work as an edge-computing node and contain the controller) preprocesses and verifies it, and executes the method of requirements extraction. The process of it is shown in Fig. 13(b). After that, the task is defined as follows.

1) The task type is emergence condition.
2) The network delay should be reduced as much as possible.
3) The property of the terminals participated is mobile and energy limited, so the interruption should be considered.
4) The opportunistic relay transmission can be carried out with the aid of the aircraft. Finally, the task is allocated with high bandwidth and transmission rate, and some capacity storage.

Then, the sink node will perform network configuration based on all collected information. To provide low-latency communications, the task will be completed with the help of SAGAIN. Besides, the controller schedules some network resources of the underwater environment monitoring network, to provide sufficient network resources for the emergency network.

After finishing the intelligent networking, the next step is to execute the task. The sink node checks the local CL to determine the forwarding direction according to the request, converts the request packet format, and forwards it to the aircraft to relay the request to the satellite. Later, the satellite sends the request to the land control center for further command. When the control center receives the message, it will give the command for AUV and deploy the ROVs to fix the pipe. This reply is sent back to AUV according to the original path. During the above process, the participating nodes temporarily save the message for quick retransmission in case of a link interruption.

VI. Conclusion

In the era of the IoT with massive information, SAGAIN with large scale and extensive coverage has become one of the most promising networks. It can be applied to many fields, such as defense missions, marine transportation, emergency rescue, and environmental protection. Therefore, the development of SAGAIN is of great benefit to the human being. In order to make better use of this network system and further promote the development of the IoT, this article analyzes the characteristics and challenges of SAGAIN. Combined with the existing network architectures, we propose a new network architecture named TOINA for SAGAIN and analyze its performance. The TOINA mainly solves the problems of intelligent networking, heterogeneous network interaction, intermittent network interruption, long latency, and load unbalance. However, how to effectively manage the namespace, make routing decision, ensure the network security, and other issues remain to be further studied and resolved.

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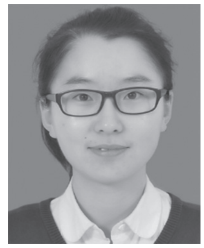

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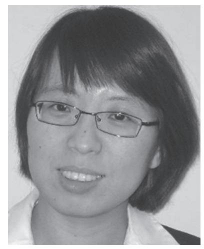

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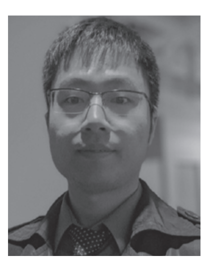

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