Space-air-ground integrated network (SAGIN) in disaster management: A Survey

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***Abstract*—Large-scale natural disasters or public security incidents frequently cause substantial damage to both human life and property, as well as terrestrial communication infrastructure. As a result, this disruption often cuts off communication, leaving the victims isolated from the outside world. Timely completion of Search and Rescue (SAR) operations within the first 72 hours following a disaster is of critical importance, as it can significantly protect human lives and reduce property damage. Note that conducting SAR operations in post-disaster areas requires not only communication support but also computing support. In light of this, it is particularly important to rapidly establish an emergency communication system with computing resources, which offers high reliability, low latency, and high capacity. Such a system is crucial for reducing the threat posed by disasters to human lives. Given the challenges in rapidly restoring terrestrial networks, flexible aerial networks and existing satellite networks emerge as optimal candidates for emergency communications. Meanwhile, the integration of aerial platforms, such as High Altitude Platforms (HAPs) and Low Altitude Platforms (LAPs), can effectively reduce the transmission latency associated with satellite networks and alleviate capacity constraints in terrestrial emergency communication networks. The Space-Air-Ground Integrated Network (SAGIN)-based emergency communication system can utilize the advantages of each segment, including the extensive coverage provided by the space network, the flexibility of the air network, and the high transmission data rates and low latency of the ground network. Consequently, this represents an exemplary paradigm for supporting SAR operations in the future. In this paper, we provide a comprehensive survey of SAGIN-based emergency communication systems, identify key challenges, and discuss promising technologies. Furthermore, future research directions are outlined from multiple perspectives.**

***Index Terms*—Search and Rescue (SAR), emergency communication network, Space-Air-Ground Integrated Network (SAGIN).**

I. Introduction

In recent years, frequent natural and man-made disasters have occurred globally, causing significant loss of life and property. Various disasters, such as earthquakes, floods, hurricanes, tsunamis, landslides, wars, etc., affect millions of people annually [1], [2]. For instance, in 2021, a severe 7.2 magnitude earthquake struck Haiti, resulting in at least 2000 fatalities, 15000 injuries, and direct economic losses exceeding 1.6 billion USD [3]. In the same year, the city of Zhengzhou in China experienced catastrophic flooding caused by extreme rainfall, affecting over 14.7 million people in Henan province, with economic damages estimated at least 15 billion USD [4]. In 2022, Pakistan faced one of its worst flooding disasters in history, which claimed the lives of over 1,500 people, affected more than 33 million [5]. Also, these disasters caused damage to infrastructure, including Base Stations (BSs), fiber optic cables, power supply equipment, and so on.

When a disaster occurs, the most crucial task is to rescue all victims within the critical first 72 hours [6]. Therefore, Search and Rescue (SAR) operations must be conducted swiftly and effectively. In practice, disaster management typically involves two phases: disaster assessment and disaster response. During the disaster assessment phase, data such as high-definition video, temperature, and humidity are collected and sent to the emergency command center. Subsequently, this data can be utilized to assess disaster situations and locate potential victims trapped under debris. For example, the authors in [7] proposed the use of Unmanned Aerial Vehicles (UAVs) equipped with cameras for victim search (VS), implementing an efficient automatic search based on Deep Reinforcement Learning (DRL). Also, the robots equipped with a Wireless Sensor Network (WSN) can be used for VS in post-disaster areas, as discussed in [8]. In the disaster response, an effective rescue plan is formulated based on the data collected during the disaster assessment phase and then executed. Note that in many emergency scenarios, telehealth support is likely to be essential, especially for providing remote diagnosis and medical assistance when victims are in critical condition.

Since disasters typically cause extensive damage to infrastructure, including power systems and BSs, the effectiveness of disaster management cannot be guaranteed. Even if the surviving BSs are operational, the network may potentially face overload issues due to the large number of users in the disaster areas. This will hinder the transmission of information for SAR operations, thereby affecting the effectiveness of SAR activities within the first 72 hours. Therefore, it is crucial to rapidly establish an emergency communication system following a disaster. Only in this way can SAR operations be effectively supported and the loss of life and property significantly reduced [9]. However, the unpredictability of disasters makes it extremely difficult to obtain specific information about the timing, location, and intensity of the disaster. If a disaster occurs in a densely populated area, such as the magnitude 9 earthquake in Japan in 2011 [10] and the severe floods in Zhengzhou in 2021, it poses a tremendous challenge to meet the post-disaster communication needs of millions of people. Therefore, emergency communications have several key characteristics, including uncertain timing and location, complex environments, uncertain capacity, and diverse tasks. It is important to note that emergency communication serves as a temporary and rapid-response mechanism, utilizing available resources to support SAR operations and ensure basic communication needs are met [9], [11], [12].

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Traditional emergency communications have primarily relied on wireless private networks [13], ad hoc networks [14], and satellite networks [15]. Emergency wireless private networks, such as narrowband digital trunking and broadband trunking, are characterised by high reliability and low cost. Police Digital Trunking (PDT) in China, Tetra and Digital Mobile Radio (DMR) in Europe, and P25 technology in the United States are all examples of narrowband digital trunking systems. These systems primarily provide limited voice services [16]. Additionally, broadband trunking can facilitate high-capacity data transmissions, such as video and other wideband services. However, wireless private networks, which rely on pre-existing communication infrastructure, often face challenges in supporting emergency communications following a major disaster. This issue can be overcome by ad hoc networks, which offer benefits such as fast deployment without the need for existing infrastructure, self-organization, and resilience to destruction. However, ad hoc networks also have their own limitations, including restricted coverage and lower capacity, which hinder their ability to provide effective communication services to a large number of users in disaster areas. With the gradual reduction in satellite costs, satellite communication technology has been developing rapidly. As a result, satellite communications have emerged as a promising solution for disaster scenarios due to their long range, wide coverage, resilience to infrastructure damage, and flexibility. These characteristics make them especially valuable in areas where conventional communication infrastructure is compromised. However, the significant transmission delays caused by the high altitudes of satellites can compromise SAR operations that require low latency, such as VS, surveillance, and telehealth services in disaster areas.

Aerial platforms, including UAVs and High Altitude Platforms (HAPs), play a significant role in disaster management due to their flexibility, low cost, and independence from ground infrastructure [17], [18]. Specifically, in post-disaster areas, UAVs can be equipped with cameras to conduct situational awareness (SA), such as monitoring and damage assessment [19]. Additionally, UAVs equipped with radio transceivers can serve as Aerial Base Stations (ABSs), providing timely wireless access to users in disaster areas [20]. However, UAVs have limitations such as limited battery life, restricted coverage, and unstable communication links, all of which adversely affect the Quality of Service (QoS) for user communications. Unlike UAVs, HAPs have greater payload capacity and coverage, making them particularly effective in responding to both natural and man-made disasters [21]. Nonetheless, they also encounter high latency challenges associated with high-altitude flights, which typically range from 17 km to 30 km.

A. Related Surveys

A summary of related survey papers is provided in Table I. Traditional emergency communication systems have predominantly relied on wired infrastructure, which limited deployment flexibility and often resulted in service interruptions during disaster scenarios. For example, the authors in [22] conducted a comprehensive review of wireless technologies, including Wi-Fi, Bluetooth, ZigBee, ultra-wideband (UWB), and satellite communication. They also evaluated the applicability of these technologies in post-disaster environments for tasks such as real-time video transmission and medical data acquisition. In contrast, the advantages of mobile ad hoc networks (MANETs) for rapid deployment in infrastructure-less environments were emphasized in [23], particularly in the context of disaster response operations.

With regard to the application of UAVs in emergency scenarios, the authors in [19] summarized their roles across all phases of disaster management. These include pre-disaster monitoring, communication support during disaster, and post-disaster logistics delivery. Building on this, the integration of UAVs with WSNs was investigated in [6]. In that study, the mobility and flexibility of UAVs were leveraged to facilitate rapid data collection in disaster-affected areas. Furthermore, in [24], UAV deployment was linked to the United Nations Sustainable Development Goal (SDG) 11. In particular, the incorporation of mobile edge computing (MEC) and green energy technologies into UAV systems was shown to contribute to the development of intelligent and environmentally sustainable emergency communication infrastructures.

As a further development, a hybrid space–air–ground (HSAT) architecture was proposed in [2] to enhance communication capacity in post-disaster scenarios. Building on this, a future emergency communication framework was introduced in [9], which integrates maritime networks composed of ship-based and buoy-based nodes with the Space–Air–Ground Integrated Network (SAGIN). This integrated architecture aims to improve emergency response effectiveness in maritime environments by providing resilient and adaptive communication coverage.

However, these studies often overlooked the issue of post-disaster energy supply. In emergency scenarios, power grids are frequently destroyed, making sustainable energy provisioning particularly challenging. In [25], the impact of various disasters on critical infrastructure was analyzed, and hybrid energy solutions such as generators, battery systems, and surviving grid segments were proposed to improve power reliability in affected areas. In contrast, a sustainable energy framework was outlined in [26]. This framework incorporates electric vehicles, renewable energy sources, smart grids, and microgrids to enhance energy resilience during emergencies. Drawing on observations from the 2023 Turkey earthquake, the necessity of integrating green energy with resilient network deployment was emphasized in [27]. A phase-based energy management strategy was also proposed, covering the pre-disaster, during-disaster, and post-disaster stages.

In disaster emergency scenarios, spectrum scarcity and the coexistence of heterogeneous communication platforms often lead to severe interference, making it difficult to maintain stable and high-bandwidth communication links. This challenge is particularly evident in SAGIN, where coordination among multiple platforms is required. In [28], post-disaster network states were categorized into three types: congested, partially functional, and isolated. The necessity of flexible spectrum allocation strategies, such as spectrum sharing, was emphasized to enhance spectral efficiency and mitigate cross-platform interference. Regarding emergency network routing, routing protocols were classified into energy-efficient, hybrid, and anchor-based approaches in [29]. This classification enables the development of more effective routing strategies that are better suited to the resource-constrained conditions commonly encountered in emergency response environments.

From a security perspective, several key challenges in emergency communication networks were identified in [30], including centralization risk, system heterogeneity, and high computational overhead. To address these issues, the use of lightweight authentication and encryption schemes, as well as AI-assisted cross-network security coordination mechanisms, was recommended. These approaches aim to improve the resilience and trustworthiness of post-disaster communication systems. Alternatively, the challenges associated with post-disaster communication at both the physical and network layers were analyzed in [1]. These challenges arise from the integration of non-terrestrial networks (NTNs), such as aerial and satellite platforms, with terrestrial infrastructure.

For computation-intensive scenarios that lack terrestrial infrastructure, such as disaster management, ocean exploration, and the Internet of Remote Things (IoRT), MEC and cloud collaborative architectures were investigated in [31]. In that study, the use of low Earth orbit (LEO) satellites was emphasized for supporting edge computing, while geostationary Earth orbit (GEO) satellites were applied to enable centralized cloud processing, with the goal of improving overall computational efficiency.

TABLE I
RELEVANT SURVEYS

Main Focus	**Ref**
Applications of Wi-Fi, LoRa, 4G LTE, UWB, and satellite communication in emergency scenarios	[22]
Applications of MANETs in disaster response	[23]
Summarizes UAV-based sensing, communication, and coordination roles in emergency and civil safety scenarios	[19]
Integration of WSN and UAV in disaster management	[6]
Systematic review of UAV communications in support of UN SDGs, with a focus on disaster response, agriculture, health, and urban infrastructure	[24]
Survey of hybrid satellite, aerial, and terrestrial networks for emergency communication, with focus on resource management and handover	[2]
Explores future prospects of integrated space, air, ground, and sea networks	[9]
Analyzes the impact of disasters on communication infrastructure and reviews various power supply solutions for maintaining emergency networks	[25]
Resilient Space-Air-Ground-Sea Networks with renewable energy for disaster response, validated in the 2023 Türkiye earthquake	[26]
Explores energy-aware solutions to support sustainable Space-Air-Ground-Sea Networks resilience in disaster areas	[27]
Explores spectrum strategies for post-disaster communication	[28]
Surveys routing protocols for emergency networks	[29]
Reviews security threats and solutions in wireless communications for disaster and crisis response	[30]
Highlights physical and network layer challenges of SAGIN in post-disaster communication	[1]
Surveys emerging computing technologies for SAGIN in infrastructure-limited environments	[31]

B. Contributions

Based on the relevant surveys discussed above, it is evident that while academic interest in SAGIN-based emergency communication networks is increasing, the role of computing resources in post-disaster SAR tasks remains largely underexplored. More critically, the coordination mechanisms driven by the dynamic nature of SAR tasks and emergency scenarios have yet to be adequately addressed. Such mechanisms involve the interaction among multiple platforms, including MEC nodes, cloud infrastructure, and various types of controllers.

More precisely, post-disaster SAR tasks vary significantly across different response phases. During the initial stage of disaster response, tasks such as SA and VS are typically prioritized, whereas in later stages, telehealth and material transport become the primary demands. These tasks impose heterogeneous requirements on network resources, including bandwidth, computational capacity, and latency, and they also vary in terms of service priority. On the other hand, environmental uncertainties such as severe weather conditions or secondary disasters, including aftershocks, can significantly disrupt task execution and node deployment strategies. Therefore, efficient coordination among distributed nodes in SAGIN-based emergency communication systems is essential for adapting to highly dynamic disaster scenarios and warrants further investigation. In fact, cross-platform and cross-layer coordination is a distinctive advantage of SAGIN over traditional emergency networks, as it enables different platforms and technologies to leverage their respective strength in support of diverse SAR operations. This capability underscores the need to develop efficient coordination strategies to fully exploit the potential of SAGIN in complex post-disaster environments.

To this end, this paper provides a comprehensive review of SAGIN-based emergency communication systems, with a focus on system architecture, key challenges, promising technologies, and future research directions. Particular emphasis is placed on integrating communication capabilities across heterogeneous platforms, enabling collaboration between MEC and cloud infrastructures, and coordinating among controllers to support task-driven responsiveness. The main contributions of this work are as follows:

- We summarize the latest representative platforms for the ground, aerial, and space segments in post-disaster scenarios, and outline the main solutions for supporting communication, computing, and energy supply.
- We propose an emergency communication system architecture based on the coordination of multiple platforms, and summarize several key challenges, including interoperability, security, QoS assurance, resource management, and backhaul reliability.
- In light of current technological trends, we outline several promising technologies to support the development of SAGIN-based emergency communication systems, including direct-to-device satellite, AI, RIS, flexible core network (CN) deployment, and quantum key distribution (QKD).

TABLE II
List of Abbreviations

ABS	aerial base station	AD	anomaly detection
AP	access point	BS	base station
CN	core network	CSI	channel state information
DL	deep learning	DRL	deep reinforcement learning
DoS	denial-of-service	GEO	geostationary earth orbit
HAPs	high altitude platforms	ISL	inter-satellite link
IoRT	internet of remote things	IoT	internet of things
LAP	low altitude platform	LEO	low earth orbit
LSTM	long short-term memory	LoS	line-of-sight
MANET	mobile ad hoc network	MEC	mobile edge computing
MEO	medium earth orbit	NLOS	non-line-of-sight
PPDR	public protection and disaster relief	QKD	quantum key distribution
QoS	quality of service	RIS	reconfigurable intelligent surfaces
RL	reinforcement learning	SA	situational awareness
SAGIN	space-air-ground integrated network	SAR	search and rescue
SDN	software-defined networking	SFC	service function chaining
TSN	time-sensitive networking	UAV	unmanned aerial vehicle
VLEO	very low earth orbit	VNF	virtual network function
VS	victim search	VSAT	very small aperture terminal
WLAN	wireless local area network	WSN	wireless sensor network

- We outline several potential future research directions, including the optimal deployment of gateways, the development of effective security strategies, the assurance of QoS for post-disaster SAR tasks, intelligent task scheduling, and the enhancement of backhaul link reliability.

C. Organization

The remainder of the paper is organized as follows: Section II introduces the architecture of the emergency communication system. Section III outlines key challenges associated with SAGIN-based emergency communication systems, as well as existing works addressing these challenges. Section IV explores promising technologies for enabling such systems. Future research directions are discussed in Section V. Finally, Section VI concludes the paper. For clarity, a list of abbreviations used throughout the paper is provided in Table II.

II. The Architecture of the Emergency System

A. Traditional Emergency Communication Systems vs. SAGIN

1) Traditional Emergency Communication Systems: Traditional emergency communication architectures mainly rely on terrestrial platforms. These include emergency communication vehicles, backpack BSs, and satellite communication systems with very-small-aperture terminals (VSATs). Although widely used, these systems face critical limitations in disaster scenarios. Specifically, ground-based solutions are affected by complex terrain, limited coverage, low flexibility, and high vulnerability to secondary disasters such as aftershocks. Importantly, ordinary user devices cannot directly access satellites. As a result, satellite-based solutions rely on specialized VSATs connected to ground-based access points (APs) to provide wireless connectivity. However, this configuration introduces significant logistical complexity and power demands, making rapid deployment particularly challenging in disaster-affected areas.

These limitations hinder the integration of traditional communication systems with sensing infrastructure in disaster-affected areas and limit their ability to support real-time situational awareness. Another important point is that these systems are poorly suited to distributed computing environments and instead rely heavily on centralized cloud-based processing. This reliance increases the burden on backhaul networks and degrades the transmission efficiency of critical information, including remote medical assistance, resource requests, and command coordination. Moreover, centralized processing delays can significantly impair system responsiveness and effectiveness in time-sensitive SAR operations, such as disaster assessment and VS.

2) SAGIN-based solutions: In contrast, the SAGIN architecture, which integrates space, air, and ground segments, offers several advantages through the use of aerial platforms, particularly UAVs and HAPs. For instance, UAVs improve communication coverage through rapid deployment and flexible payload capacity. In particular, they are capable of carrying wireless transceivers, enabling the immediate establishment of emergency connectivity. HAPs, on the other hand, provide wide-area coverage from high altitudes with rapid activation. This allows them to overcome the deployment and operational constraints of traditional satellite systems that rely on specialized VSATs. Notably, both UAVs and HAPs contribute to improved network resilience by operating above ground level, thereby reducing vulnerability to secondary disasters and terrestrial power outages.

These advantages enable SAGIN-based solutions to achieve deep integration with sensing systems, thereby allowing command centers to rapidly acquire situational awareness data. In addition, the flexibility and wide-area coverage of the SAGIN architecture facilitate efficient task scheduling, intelli-

TABLE III
SUMMARY OF SYSTEM MODELS FOR SAGIN IN EMERGENCY SCENARIOS

System Components	Component Function	Component Distribution	Objective	Key Technology	Ref.
LEO + Tethered UAVs + mobile sensing platform (MSP)	Tethered UAV provides uplink access; LEO offers backhaul and edge processing	TUAVs follow Poisson cluster distribution; LEO in orbit; MSP mobile	Reliable vertical handover for MSP conducting real-time SA	Multi-Attribute Decision Making	[32]
LEO + UAVs + ground users	LEO and UAVs provide wireless access	UAVs follow 3D Poisson Point Process; LEO in orbit; users randomly distributed	Optimize user access mode based on ergodic rate and delay	Evolutionary game theory, replicator dynamics	[33]
LEO + UAV + Ground Devices (GDs)	UAV provides wireless access to ground devices; LEO relays UAV data to surviving BSs	UAV hovers over GDs clusters; LEO in orbit; GDs randomly distributed	Maximize uplink data rate and LEO visibility under UAV energy constraints	Two-stage multi-armed bandit	[34]
LEO + UAV + MANET ground users	UAVs relay ground MANET traffic; LEO enables SDN-based centralized control	UAVs mobile over group-based moving ground users; LEO in orbit	Reduce delay and packet loss via dynamic routing under mobility and congestion	Load balancing algorithm based on multi-dimensional resources	[35]
LEO + UAV + Urban Ground Users	UAV relays urgent user traffic to satellite; LEO provides coverage	UAV in constrained urban airspace; LEO in orbit	Maximize uplink throughput under user priority and network capacity limits	Branch-and-bound heuristic	[36]
LEO + UAV + ground users	UAVs cache and relay content; LEO coordinates access	UAVs hover over clustered users; LEO in orbit; users randomly distributed	Maximize satellite remaining energy	decomposition method	[37]
LEO + UAV + ground users	UAVs relay messages from ground to satellites; LEO provides global coverage	UAVs mobile; satellites in orbit; ground hosts elect cluster heads	Maximize message delivery and network coverage in post-disaster SAGIN	Reinforcement learning	[38]
LEO + UAV-BS + UAV-MEC + ground users	UAV-BS provides communication; UAV-MEC handles local/offloaded computing; LEO bridges to cloud	UAVs cover disaster/rescue zones; users are clustered	Maximize energy efficiency while meeting QoE via joint trajectory and resource allocation	Dinkelbach method and the block coordinate descent	[39]
UAV + ground users	UAV-BS provides broadcast coverage to all users while flying	UAV follows optimized stop-point path; users follow PPP in disaster zone	Maximize energy efficiency under trajectory and power constraints	Dinkelbach method	[40]

gent resource allocation, and improved coordination between communication and computation.

Collectively, these characteristics demonstrate the suitability of the SAGIN architecture for overcoming the limitations of traditional emergency communication systems.

B. Representative SAGIN-Based System Models for Disaster Scenarios

Table III summarizes representative system models of SAGIN designed for emergency scenarios. Specifically, UAVs fulfill multiple roles in disaster scenarios, including serving as temporary BSs to provide connectivity for ground users, acting as relay nodes to forward data to satellites, performing SA tasks, and supporting edge computing and content caching. These capabilities underscore the flexibility of UAVs in deployment, their rapid responsiveness, and their enhanced ability for environmental perception. In parallel, satellites that primarily operate in LEO are responsible for long-range data backhaul, control information transmission, and connectivity to cloud or core networks. Moreover, integrating MEC into satellites helps reduce the burden on backhaul links, particularly in resource-constrained environments. For ground users, data is transmitted either through UAVs or directly to satellites, forming an end-to-end emergency communication link.

C. The Architecture of a SAGIN-Based Emergency Communication System

UAVs, HAPs, and satellites can collaborate with surviving terrestrial BSs and temporary platforms to establish a SAGIN-based emergency communication system, which restores essential services in affected areas, as illustrated in Fig. 1. Specifically, the emergency communication system is composed of three collaborative layers: the ground layer, the air layer, and the space layer. These layers work collaboratively to support a range of SAR operations, including SA, VS, telehealth services, damage assessment, and command and coordination activities. It is worth noting that integrating edge computing nodes into the system, as opposed to relying solely on traditional cloud-based paradigms, can significantly reduce the response time for time-sensitive tasks such as VS and damage assessment. Moreover, it alleviates the bandwidth burden on backhaul links and enhances their reliability. This is particularly important in the aftermath of large-scale disasters, where terrestrial backbone networks may be severely damaged and cannot be promptly restored. In such cases, wireless backhaul serves as a critical solution to maintain communication connectivity between the disaster area and the outside world.

The ground layer consists of various facilities, including surviving BSs, edge servers, emergency communication vehicles, backpack BSs, and temporarily deployed VSATs. These components jointly provide communication coverage and computational capabilities for disaster-affected areas, thereby supporting the execution of on-site emergency missions. Meanwhile, a temporary command center should be rapidly established within the disaster zone to collect real-time SA data and to centrally coordinate diverse post-disaster SAR tasks. This coordination improves the operational efficiency and responsiveness of disaster response efforts. Notably, deployment strategies for the ground layer should be dynamically adjusted to reflect terrain conditions, the severity of infrastructure damage, and specific rescue requirements. This adaptability is essential for addressing the complex challenges of post-disaster environments. More precisely, in flat and accessible regions with relatively intact roads, emergency communication vehicles should be prioritized to rapidly deliver broad communication coverage and on-site computational capabilities. In contrast, in areas with severely damaged roads, complex terrain, or significant non-line-of-sight (NLOS) conditions, portable backpack BSs provide a flexible deployment option. They can be manually transported and set up by first responders to rapidly establish temporary communication links and maintain continuous connectivity. Additionally, in isolated regions where roads are completely disrupted or the situation is critically severe, temporary VSATs can be deployed to establish satellite communication links. These links ensure timely information exchange and support the efficient coordination of rescue efforts involving victims and first responders in such severely areas. Since disasters often damage terrestrial power infrastructure, it is essential to adopt diversified energy supply solutions to ensure the continuous and stable operation of ground-layer components. To this end, a flexible combination of portable generators, battery systems, solar panels, and surviving segments of the power grid can be deployed to address power shortages and enhance system resilience under harsh post-disaster conditions.

The air layer, composed of UAVs and HAPs, plays a vital role in bridging communication and computation between the ground and space segments. A further key responsibility of the air layer is to support critical rescue operations, including real-time monitoring and VS, thereby enabling timely and effective emergency response. For example, UAVs are typically equipped with radio transceivers, edge servers, or sensors, enabling them to perform tasks such as data relaying, local processing, and SA within disaster-affected areas. In particular, when UAVs function as ABSs, they can rapidly provide wireless access to users within their coverage area by leveraging LoS links. Depending on the network topology and task requirements, these UAVs can relay collected data to nearby command centers, HAPs, or directly to satellites. To address the endurance limitations of UAVs, charging stations can be deployed near temporary command centers to ensure sustained operation and continuous support for aerial missions. By comparison, HAPs provide wider coverage and longer operational endurance, making them well-suited for hosting distributed controllers to intelligently manage communication and computing resources within their service areas. In addition, HAPs can serve as relay nodes between satellite and ground networks, thereby facilitating efficient and reliable data transmission. To support long-duration operation, they are typically equipped with solar panels and onboard battery systems, ensuring energy sustainability in post-disaster environments.

The space layer integrates a multi-orbit satellite system comprising GEO (approximately 35,786 km), medium Earth orbit (MEO, 2000–35,786 km), LEO (450–2000 km), and very low Earth orbit (VLEO, 160–450 km) satellites, each fulfilling distinct roles in emergency scenarios. At the same time, satellites positioned at different orbital altitudes are interconnected via inter-satellite links (ISLs). This architecture enhances the resilience of the emergency communication system and facilitates efficient information exchange and coordinated task execution. Specifically, LEO and VLEO satellites can rapidly provide communication coverage to disaster-affected areas through temporarily deployed terrestrial VSATs. These satellites are capable of transmitting critical data such as real-time video, personnel deployment status, and task progress updates to remote command centers, thereby facilitating effective remote collaborative command and control. Moreover, some LEO and VLEO satellites are equipped with integrated edge servers, providing additional computational resources to supplement aerial and terrestrial edge nodes when local processing capacity becomes insufficient. For MEO satellites, including GPS, BeiDou, and Galileo [41], accurate real-time positioning services are provided to victims, first responders, and network nodes in disaster-affected areas. These services assist emergency command centers in managing SAR operations with greater situational awareness. In parallel, GEO satellites, such as Fengyun [42], offer advanced weather forecasting functions, enabling command centers to assess evolving weather conditions within disaster regions and adjust operational strategies accordingly. This capability is particularly important under severe weather conditions such as strong winds, which may adversely affect the stability and safety of UAV operations.

Furthermore, the satellite network can forward time-tolerant data such as environmental monitoring records, rescue operation logs, communication records, and UAV flight logs to cloud computing centers for further processing. In addition to these transmissions, certain tasks, including the training of large-scale AI models for global resource optimization, require the substantial computing and storage capacities provided by cloud infrastructures. Such tasks are often impractical to execute at the edge, particularly in disaster scenarios where local edge nodes are limited and power supplies are frequently unstable. This offloading mechanism effectively reduces the computational burden on local processing nodes, allowing them to focus on time-sensitive emergency tasks such as SA, VS, and damage assessment. Crucially, satellites are typically equipped with advanced solar panels and battery systems that enable long-term autonomous operation, thereby playing a critical role in maintaining stable communication links in post-disaster environments.

D. Space-based Segment

Notably, a centralized controller is deployed on the satellite networks. This controller takes advantage of the satellite's extensive broadcast capabilities to manage communication and computation resources across the entire disaster area. Such centralized architecture enables the coordinated scheduling of distributed resources to better support diverse post-disaster SAR tasks. Given the dynamic and complex nature of disaster environments, SAR operations are inherently heterogeneous. These tasks include SA, VS, telehealth, and communication support for victims, each with distinct communication, computational, and energy requirements. When the disaster response

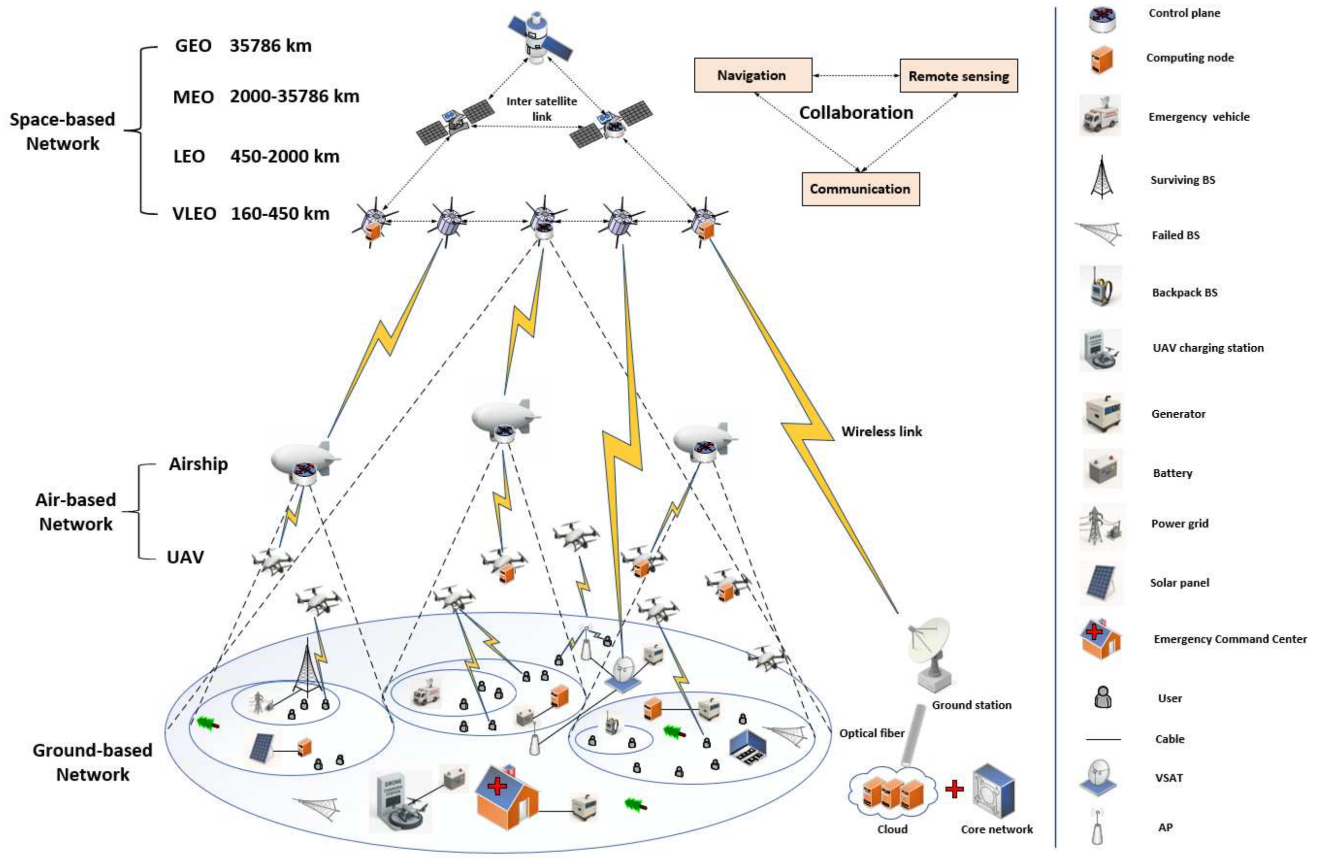

Fig. 1. An architecture of the SAGIN-based emergency communication system.

phase shifts or environmental conditions change in the affected area, the satellite-based centralized controller plays a critical role in system adaptation. This role becomes especially important when secondary disasters further damage the surviving terrestrial infrastructure. Specifically, it dynamically adjusts resource scheduling strategies, enabling timely adaptation to support stable and reliable operation of the SAGIN-based emergency communication system under dynamic conditions.

LEO and VLEO satellites operate at significantly lower altitudes compared to MEO and GEO satellites. Owing to their close proximity to the Earth, these satellites are primarily employed to provide communication support and enable on-orbit computing services for time-sensitive applications in emergency response. Up to now, several companies operate in-orbit LEO mega constellations to provide satellite internet services, including Starlink, OneWeb, Globalstar, and so on [43]. Besides, an increasing number of countries have announced plans for LEO satellite constellations. The United Kingdom will collaborate with Spain and Portugal to jointly develop an Atlantic Constellation project aimed at disaster management [44]. Additionally, the China Satellite Network Group plans to launch over 13,000 LEO satellites to establish a global satellite network named "Guowang", which will be crucial for enhancing Internet access in the future [45]. Importantly, the one-way propagation delay for LEO satellites is approximately 5ms, whereas VLEO satellites, owing to their lower altitude, can achieve latency as low as 1ms. Therefore, compared to LEO satellites, VLEO satellites are more suitable for supporting time-sensitive SAR tasks, particularly in telehealth services and remote command coordination. Benefiting from lower deployment costs and improved communication performance resulting from reduced orbital altitudes, several organizations have initiated VLEO constellation projects. For instance, China Aerospace Science and Industry Corporation (CASIC) plans to launch 300 VLEO satellites to construct a global network that will provide significant support for disaster management [46]. Meanwhile, companies such as SpaceX and OneWeb are also planning to launch thousands of VLEO satellites to support seamless and high-capacity communication services [47]. It should be noted that, unlike GEO and MEO satellites, LEO and VLEO satellites orbit the Earth at high speeds of up to 8 kilometers per second and cover smaller areas. As a result, network handover frequently occurs, leading to shorter and less stable link durations.

In contrast, the higher orbital altitudes of MEO and GEO satellites expose them to elevated levels of cosmic radiation, which limits their suitability for on-orbit computing. As a result, these satellites typically serve as relay platforms and leverage their wide-area coverage to offload computational workloads to terrestrial cloud infrastructure. Importantly, cloud computing offers powerful computing and storage resources, making it suitable for complex operations such as large-scale situational awareness analysis, global resource coordination, and AI model training. It also benefits from stable power supplies, which support the continuous updating of AI models. Nevertheless, the long distance between satellites and cloud servers introduces significant communication delays, limiting its application in processing time-sensitive tasks. For example, tasks such as VS require rapid response that is difficult to achieve through cloud-based computing approaches.

Significantly, excessive reliance on cloud computing may increase the load on backhaul links, leading to communication bottlenecks and potentially affecting the transmission of critical data. Such data includes updates on the deployment of emergency personnel, telehealth records, the execution status of rescue operations, and urgent requests for essential supplies such as food, water, and medical resources. Conversely, excessive dependence on edge computing may present limitations. Although edge nodes are physically closer to users, the unstable power supply and limited computing and storage resources in disaster environments make it difficult to support complex tasks such as AI model training. Moreover, coordinating multiple edge nodes increases the system's scheduling complexity and control overhead.

As a result, it is essential to establish an efficient collaborative computing architecture that integrates MEC and cloud computing. This architecture leverages the strengths of both paradigms to enhance the efficiency of SAR operations in emergency response. Specifically, lightweight and latency-sensitive tasks should be processed by individual edge nodes. Tasks with medium computational complexity that still require low latency can be assigned to multiple edge nodes for collaborative processing. In contrast, computationally intensive and delay-tolerant tasks, such as AI model training, can be offloaded via satellite links to remote cloud data centers. This cloud–edge collaborative computing paradigm can more effectively support a variety of critical computing tasks in emergency scenarios, including SAR operations, gateway deployment optimization, and resource scheduling.

E. Air-based Segment

The air network comprises UAVs, airships, and balloons, which are categorized into Low Altitude Platforms (LAPs) and HAPs based on their operating altitudes. The commonly used emergency aerial platforms are shown in Fig. 2. Typically, drones, including tethered, rotary-wing, and fixed-wing types, are considered LAPs [48]. Their flight altitudes range from tens to several thousand meters, depending on the specific type. In contrast, airships and balloons are classified as HAPs. Both types can provide wireless communication and computational offloading services in disaster areas. Unlike LAPs, HAPs operate at approximately 20 kilometers above the ground in the stratosphere, thus they are not affected by atmospheric disasters such as hurricanes. Note that the transmission latency of aerial platforms is lower compared to satellites. As a result, aerial platforms can act as a bridge between the ground and space so as to enhance the quality of satellite-ground links. In emergency scenarios, the flexible deployment, rapid response capabilities, and line-of-sight (LoS) communication advantages of UAVs make them highly effective in supporting SAR operations. However, UAVs have constrained payloads, which limits their battery life. Therefore, they are unable to provide long-duration support for SAR operations. For instance, during the extreme heavy rainfall in Zhengzhou, China, the Wing Loong 1 drone from the Aviation Industry Corporation of China (AVIC) only provided five hours of critical communication coverage in the disaster area [49]. In contrast, HAPs offer longer operational durations and wider coverage area. For example, the "Balloon Project" deployed BSs on HAPs, providing sustained communication services to victims in disaster areas in Puerto Rico [50].

UAVs and HAPs, equipped with radio transceivers and edge servers, can serve as ABSs and edge computing nodes following a disaster, thereby enhancing communication and data processing capabilities. Generally speaking, these platforms can quickly process a large volume of computation-intensive tasks and then relay the information back to command centers. Due to the flexibility of UAVs, various sensors such as cameras and infrared detectors can be integrated to enable real-time data collection from disaster areas. These aerial platforms are used to assist in damage assessment and VS. In this context, many computation-intensive tasks can be offloaded to aerial platforms or satellites with computational capabilities. Furthermore, ABSs can backhaul large volumes of data to satellites or transmit it directly to emergency command centers, depending on the distance from the disaster site to the emergency management center. When disasters strike densely populated urban areas, tens of thousands of people can lose their internet connections. However, the emergency air network, limited by the bandwidth of ABSs, may not be able to provide access to most users in the affected area. To this end, deploying millimeter-wave [51] or terahertz [52] BSs on aerial platforms presents a promising solution. These technologies enable high bandwidth, high data rate, and low latency communications, significantly enhancing the capabilities of the emergency air network. Meanwhile, the compact antenna size required for millimeter-wave and terahertz frequencies allows UAVs to carry these antennas with only a minimal increase in payload, without affecting the operational duration of the UAVs. Moreover, UAVs equipped with high-frequency wireless transceivers can support both multi-beam and narrow-beam communication capabilities. This not only enhances the coverage and communication capabilities but also reduces interference between different platforms.

It is important to note that deploying edge servers or radio transceivers on UAVs increases their payload, which significantly reduces their operating time. This leads to more frequent recharging needs, and lowers the efficiency of post-disaster SAR operations. In contrast, HAPs, with their larger payload capacities, can accommodate both radio transmitters and edge servers without compromising their operational efficiency. Note that HAPs are deployed in the stratosphere, where the environment poses unique challenges, such as extreme temperatures and radiation, to the normal operation of electronic devices [53]. Consequently, electronic devices deployed on HAPs require substantial investments in specially designed equipment to withstand the harsh conditions of the stratosphere. Besides, HAPs offer longer endurance, wider coverage and are less susceptible to adverse weather conditions, such

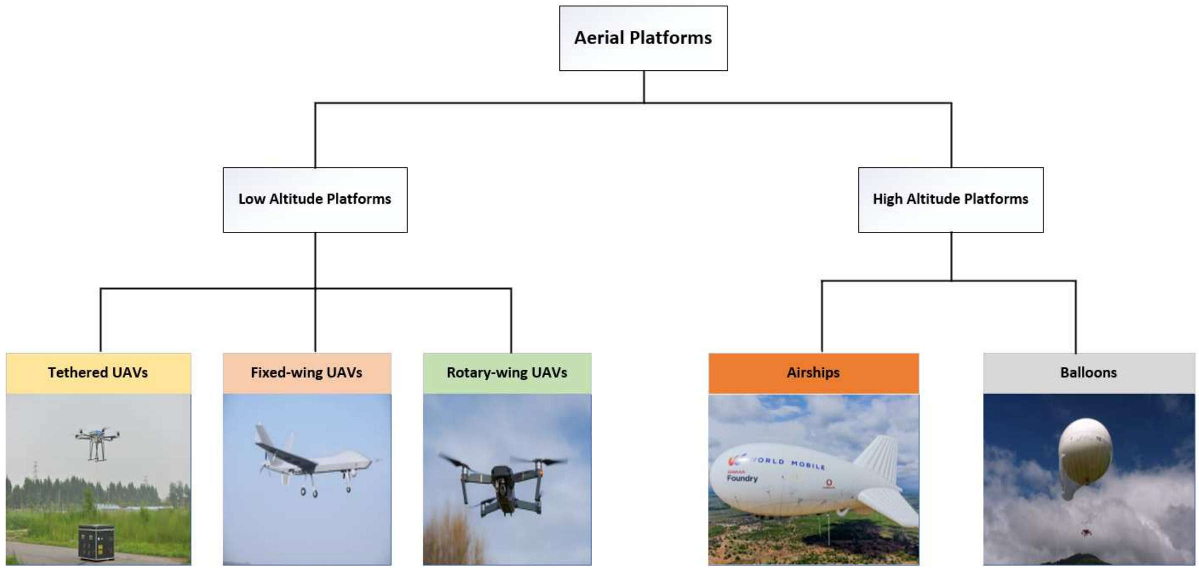

Fig. 2. The diagram of common emergency aerial platforms.

as strong winds. Consequently, distributed controllers can be deployed on HAPs to manage communication and computing resources within their coverage areas. These resources include both UAV-based and terrestrial nodes.

Specifically, following a disaster, command centers may employ the satellite-based centralized controller to pre-allocate resources to distributed controllers. This allocation process considers factors such as victim density and the types of rescue tasks required across different regions. As rescue operations proceed and environmental conditions evolve, the centralized controller can dynamically adjust the resource allocation strategy to better align with current task demands and network status. For distributed controllers, task classification is performed based on specific requirements and priorities, including SA, VS, disaster assessment, telehealth, and communication support for victims. Subsequently, resource scheduling decisions are made by evaluating the real-time operational status of each node, taking into account factors such as current load, remaining energy, latency constraints, computational capacity, and available communication bandwidth. More precisely, distributed controllers assigns tasks to the most suitable nodes based on the priorities of tasks.

For example, time-sensitive and high-priority tasks such as VS, disaster assessment, and telehealth are preferentially allocated sufficient communication and computational resources to ensure rapid response. In contrast, tasks related to maintaining continuous connectivity for victims are assigned to nodes with stable and adequate power reserves, thereby enabling sustained and reliable communication for victims to report their conditions consistently. Besides, the controllers continuously monitors the power consumption of each node and proactively predicts future energy consumption trends, with the aim of preventing critical nodes from experiencing unexpected service interruptions due to power depletion. Particularly for UAV nodes with limited battery capacity, the controller reassigns tasks or migrates them to nodes with lighter workloads or higher residual energy when remaining power approaches a critical threshold. This ensures overall system stability and operational continuity. If a distributed controller on a HAP detects degraded QoS or resource shortages that hinder ongoing SAR operations, the centralized controller in the satellite segment steps in to coordinate cross-region resource reallocation. This hierarchical control mechanism not only minimizes the need for frequent inter-controller coordination, thereby reducing system overhead, but also enables timely cross-regional resource compensation. Therefore, it supports efficient SAR task execution while maintaining overall system stability.

F. Ground-based Segment

Ground networks consist of a variety of heterogeneous networks, including cellular networks [54], MANETs, Wireless Local Area Networks (WLANs) [55], wireless private networks, and so on. Compared to space and air networks, ground networks offer lower latency, larger capacity, and higher data rates due to their proximity to end-users. However, the coverage of ground networks is limited and highly vulnerable to disasters. When a disaster occurs, most terrestrial BSs, edge servers, fiber optic cables, and other infrastructure may stop working. More seriously, it is difficult to restore them within a short time. Meanwhile, the surviving BSs and edge servers might become overloaded due to a surge in user access and computational offloading demands. In such situations, commonly used emergency ground platforms include emergency rescue vehicles and backpack BSs, as shown in Fig. 3. In particular, emergency rescue vehicles equipped with power supplies and radio transceivers can serve as temporary communication BSs, providing wireless access to the affected area [25]. An emergency network solution mentioned in [56] involves Movable and Deployable Resource Units (MDRUs), where power supplies and BSs are deployed in emergency rescue vehicles. These units are capable of rapidly providing flexible communication services to areas affected by disasters. However, the mobility of emergency rescue vehicles is limited by damaged roads. For instance, during the 2008 Wenchuan earthquake in China, emergency rescue vehicles could not drive into the central areas of the disaster zone. As a result, temporary wireless access to this area was provided by communication teams equipped with backpack-based BSs [25]. Therefore, the deployment of emergency communication vehicles and backpack base stations should be determined based on the level of damage and terrain conditions in different areas. For instance, in flat regions with good accessibility, emergency communication vehicles can be prioritized. In contrast, in areas where vehicles cannot easily enter and NLOS conditions exist, backpack base stations should be deployed to provide temporary communication coverage. Despite these efforts, these paradigms face challenges of limited coverage and low capacity, making it difficult to meet the needs of large cities during major natural disasters.

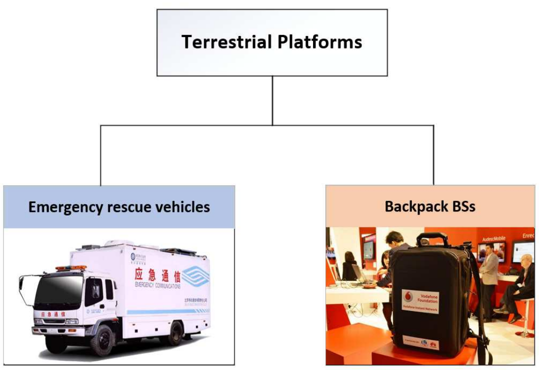

Fig. 3. The diagram of common emergency terrestrial platforms.

In general, post-disaster scenarios can be classified into two situations based on the extent of damage. One scenario involves the destruction of all the BSs, edge servers, and fiber optic cables within the region, creating an "information island" [2], as shown in Fig. 4. In such cases, relying on any existing terrestrial infrastructure to support communication and computing services becomes impractical. Instead, one must depend on temporarily deployed emergency rescue vehicles, backpack BSs, UAVs, HAPs, and satellites to restore network services in the disaster area. The other situation involves partial damage to the infrastructure [28], as shown in Fig. 5. In such cases, if there are surviving infrastructures, they can be utilized to establish an emergency communication network taking the advantages of terrestrial BSs and edge servers. Note that these surviving facilities have sufficient power and computing capabilities to offer high-performance data processing for extended periods. However, terrestrial surviving BSs and edge servers may experience network overload when encountering a large number of user accesses. Therefore, efficiently and intelligently utilising the remaining infrastructure becomes crucial. Notably, if some rescue tasks are not timely addressed due to network issues, the efficiency of SAR operations can be significantly reduced.

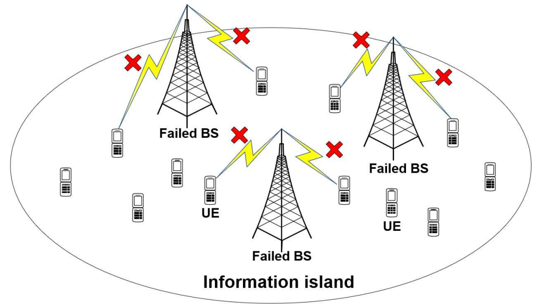

Fig. 4. A post-disaster network scenario where users are completely isolated from BSs.

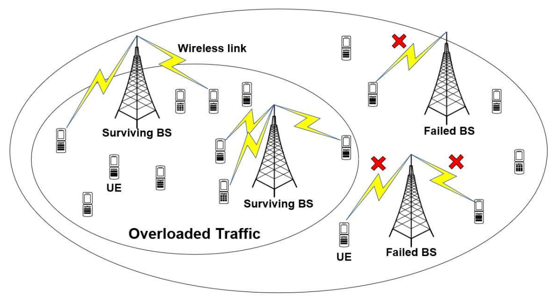

Fig. 5. A scenario where users in the disaster area are connected to surviving BSs.

G. Summary of SAGIN-Based Emergency Communication Systems

Table IV presents a comparison of various networks in the SAGIN-based emergency communication system. To effectively address different types of disasters and overcome the uncertainties of timing, location, and extent of damage, the establishment of an emergency communication network should not rely solely on a single type of network. Instead, it should integrate space-based, air-based, and ground-based network segments to effectively support SAR operations. For example, the European Space Agency (ESA) and Japan are collaborating to integrate 5G and satellite networks. They also plan to connect HAPs and UAVs via this network to build a three-layer heterogeneous architecture spanning ground, air, and space [43]. In summary, integrating these three segments maximizes their respective advantages: space networks provide extensive coverage, air networks offer significant flexibility, and ground networks deliver high data rate and low latency. This integration faciliates the development of a SAGIN-based emergency communication system, offering wide coverage, computational resources and communication capacity, flexible and rapid response, as well as low latency and high throughput.

Fig. 6 illustrates the framework of the SAGIN-based emergency communication system, which integrates communication, computing, and energy management to collaboratively support various post-disaster SAR tasks. Specifically, the system integrates a variety of platforms, including multi-orbit satellites, HAPs, UAVs, surviving terrestrial BSs, emergency communication vehicles, and backpack BSs. Each platform leverages its respective advantages to provide seamless communication coverage and high-bandwidth connectivity in

TABLE IV
COMPARISON OF DIFFERENT NETWORKS

Layer	Entities	Height above earth	Mobility	One-way delay	Advantages	Disadvantages
space	GEO	35786km	static to earth	about 120ms	broadcast/multicast, larger coverage, reliable access	long propagation delay, high cost, high mobility
	MEO	2000-35786km	medium fast	about 70ms		
	LEO	450-2000km	fast	about 5ms		
	VLEO	160-450km	fast	about 1ms		
air	HAP	17-30km	quasi-stationary	medium	wide coverage,low cost, flexible deployment	unstable links,limited capacity high mobility,limited power
	LAP	less than 10km	highly mobile	medium		
ground	Ad Hoc/Celluar	N.A.	mobile/static	low	high rate, low delay	limited coverage

disaster-affected areas. In particular, the close coordination between satellite and aerial networks facilitates the rapid acquisition of situational awareness information and strengthens the integration between edge and cloud computing. To ensure reliable energy supply, the system leverages multiple sources, including surviving power grids, portable generators, batteries, and solar panels. This enables stable communication and computing services under complex post-disaster conditions.

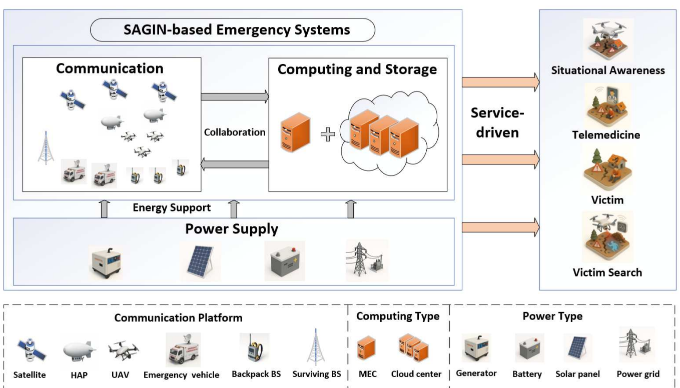

Fig. 6. Framework of the SAGIN-based emergency communication system.

III. KEY CHALLENGES AND EXISTING WORKS

The SAGIN-based emergency communication system is designed to address the limitations of conventional emergency networks, such as delayed response, limited coverage, and insufficient capacity during large-scale disasters. Consequently, such emergency systems present a highly promising solution for providing reliable communication and computing support in diverse SAR operations during disaster scenarios.

However, the inherent complexity and heterogeneity of SAGIN, together with the diverse and dynamic nature of post-disaster SAR tasks, introduces a series of practical challenges for deployment and operation. First, differences in protocols, interfaces, and communication mechanisms across network segments lead to interoperability issues. Second, the multi-layer data transmission process introduces security vulnerabilities, particularly because ensuring the priority of rescue tasks often results in the neglect of security measures. Third, the diversity of access terminals and the varying requirements of SAR tasks impose higher demands on QoS assurance mechanisms. Fourth, the dynamic coordination and scheduling of cross-layer resources, compounded by resource scarcity in disaster scenarios, exacerbates resource management difficulties. Finally, in disaster scenarios where wired infrastructure is damaged or unavailable, wireless backhaul often becomes the primary means of connectivity. As a result, enhancing the overall reliability of the SAGIN-based emergency communication system is a critical challenge that must be addressed.

A. *Interoperability*

In the rapid establishment of the SAGIN-based emergency communication system, the primary step involves resolving the integration challenges of the three distinct segments. Only in this way can interconnection between different segments be achieved, thereby fully leveraging the advantages of each segment. In light of this, it is imperative to address interoperability issues. However, different segments have their own communication protocols, leading to compatibility issues. To address this issue, it is necessary to establish gateway nodes for the SAGIN-based emergency communication network [57]. In particular, these nodes act as intermediaries to connect different segments and facilitate information exchange among the three network layers. However, the deployment of gateway nodes in various locations can impact the security, reliability, and latency of the SAGIN-based emergency communication network. Note that selecting the location of gateway nodes requires careful consideration of factors such as the extent of damage and traffic distribution in affected areas. In this way, the performance of the SAGIN-based emergency communication network can be safeguarded. Additionally, as the number of satellites in orbit continues to grow, relying solely on ground stations as gateway nodes may no longer be efficient. This solution can lead to increased transmission delays and overhead costs when connecting satellites with air and ground networks. This therefore does not meet the requirements of emergency communication networks.

To reduce latency and overhead in emergency networks, future communication paradigms might involve deploying satellite gateways to connect satellites in different orbits via ISLs, thereby effectively supporting SAR operations. It should be noted that varying choices of satellite gateways can lead to different numbers of hops in the communication link, potentially affecting the end-to-end transmission latency and the reliability of the emergency networks. Consequently, selecting the appropriate satellite gateways to serve as intermediaries for the space network must be carefully considered. Typically, gateway placement optimization involves multiple objectives, including minimizing the latency, balancing network load, improving end-to-end reliability, reducing deployment and operational costs, and minimizing overall system energy consumption [58]–[62]. Additionally, gateway nodes can be strategically deployed on UAVs or HAPs to facilitate the connection between ground and space networks. Compared to satellite gateways, HAP gateways offer the advantage of relative stationarity, which reduces the frequency of handover issues. Moreover, HAP gateways provide longer service durations and cover more extensive areas compared to UAV gateways. However, the hardware of gateways deployed on HAPs must adapt to the low-temperature environment of the stratosphere, necessitating the development of special materials to ensure the hardware can withstand the harsh conditions. As a result, this requirement will likely increase the costs. As for UAV gateways, they provide a cost-effective, flexible, and rapid-response solution for emergency communications. However, the high mobility of UAVs can cause frequent changes in network topology. This often results in more handovers, which may compromise the reliability of emergency communication systems. Besides, UAVs have limited battery life, typically lasting only a few hours. This leads to frequent recharging, which may compromise the stability of the network.

B. Security

The SAGIN-based emergency communication system, a three-layer heterogeneous network, is characterized by open connectivity and dynamic topology. These characteristics inherently increase its vulnerability to various security issues. Specifically, in the SAGIN-based emergency communication network, end-to-end communications are typically multi-hop and vulnerable to interference attacks [63], Denial of Service (DoS) attacks [64], spoofing attacks [65], and so on. Note that these vulnerabilities pose a serious threat to the quality of communication links. Particularly, DoS attacks can significantly disrupt communication, thereby hindering the ability of users in disaster areas to access emergency networks. Additionally, time-sensitive tasks such as telehealth [66] and situational awareness may encounter risks of unauthorized tampering during data transmission, which could further compromise SAR operations. In this network, the extensively deployed edge servers are susceptible to malicious utilization by unauthorized nodes. This vulnerability can lead to inefficient utilization of computational resources, leaving these servers unable to deliver the essential computing services needed in the disaster area. However, traditional security measures, such as spread spectrum techniques, directional antennas, and intrusion detection systems, are primarily designed to address the specific vulnerabilities of a single network, whether satellite, air, or ground [67]. As for the SAGIN-based emergency communication network, it is particularly vulnerable to cross-layer and mixed attacks. Consequently, traditional security measures are inadequate. In practice, rapidly establishing an emergency network is usually the primary task in the event of disasters, and network security is often overlooked. Therefore, for the SAGIN-based emergency network, it is crucial not only to ensure the provision of emergency communication services but also to secure each link against potential attacks.

Table V provides a summary of representative studies that address security challenges in SAGIN, with a particular focus on the network and physical layers. Access authentication serves as the first line of security defense at the network layer, which is particularly critical in the SAGIN due to its highly dynamic topology and resource constraints. The authors in [68] proposed a lightweight authentication mechanism based on the Identity-based Multicast Authentication Scheme (IMAS), which integrates identity-based encryption, broadcast authentication, and multicast authentication reuse. IMAS significantly reduces authentication overhead and latency, making it well-suited for dynamic SAGIN environments with frequent LEO satellite handovers. Unlike traditional public key infrastructure-based approaches, it simplifies key management and lowers communication costs, offering an efficient solution for resource-constrained satellite systems. Similarly, an access authentication approach was proposed in [69], which combines IPv6 auto-configuration with signature decoupling to support rapid access for large-scale Internet of Thing (IoT) terminals.

As SAGIN service scenarios evolve toward more intelligent and coordinated architectures, access authentication mechanisms are also progressing toward cross-domain interoperability. For example, a distributed cross-domain authentication mechanism based on a Hashchain structure was proposed in [70], which significantly reduces computational complexity and authentication latency in SAGIN-based vehicular network scenarios. Alternatively, [71] proposed a secure authentication framework that integrates blockchain, federated learning (FL), and fuzzy logic reasoning. Targeting scenarios such as earthquake prediction and post-disaster image recognition, the framework supports end-to-end trusted data collection, authentication, and intelligent decision-making. By leveraging a multi-chain architecture, it enhances the verifiability of model aggregation and the trustworthiness of data sources, offering a practical paradigm for building distributed, intelligent, and collaborative security systems.

Intrusion detection plays a critical role in safeguarding SAGIN, particularly for identifying abnormal behavior and defending against attacks. In recent years, it has attracted increasing attention. [72] proposed the SAGIN-ID framework, which adopts a dual-layer satellite–ground collaborative architecture. The satellite layer performs rapid pre-screening using smart contracts, while the ground layer employs machine learning to achieve high-precision anomaly detection (AD). This solution enhances the system's real-time responsiveness to threats such as DoS attacks. [73] further introduced a FL-based AD mechanism that integrates semi-supervised deep models. This approach enables GEO satellites to perform intrusion detection under low-bandwidth and low-latency constraints, while maintaining detection accuracy and stability in large-scale, unlabeled data scenarios.

To address the emerging security threats posed by quantum computing, the authors in [74] integrated the QKD mechanism into a resource scheduling framework. In this design, cryptographic keys are treated as system resources and jointly scheduled with communication, computation, and caching. This approach not only ensures secure key utilization but also improves task completion rates and system throughput under key-constrained conditions, offering a novel solution for building high-assurance, quantum-resistant scheduling architectures.

TABLE V
SUMMARY OF RELEVANT PAPERS ON SECURITY

Main Focus	Network Scenario	Ref
Lightweight authentication for secure access	space-air-ground	[68]
Hashchain-based authentication scheme	space-air-ground	[70]
Lightweight identity-based mutual authentication for IoT	space-air-ground	[69]
Rapid intrusion detection using smart contracts and ensemble learning	space-air-ground	[72]
Semi-supervised anomaly traffic detection via federated learning	space-air-ground	[73]
QKD-secured resource allocation minimizing cryptographic overhead	space-air-ground	[74]
Enhancing SAGIN physical layer security and efficiency via spreading	space-air-ground	[75]
Symbol-level physical layer security	space-air-ground	[76]
Physical layer security via symbiotic co-channel interference	space-air-ground	[77]
Federated learning-enabled approach for earthquake prediction	space-air-ground	[71]

In terms of physical layer security, an enhanced spreading mechanism was proposed in [75] to improve signal confidentiality in high-mobility UAV communications by mitigating the impact of Doppler shifts. In addition, the authors in [76] addressed the practical limitations of finite constellation modulation by developing a dual-layer optimization framework for downlink transmission in SAGIN. This method enhances physical layer security while maintaining low computational complexity, thereby achieving a trade-off between security performance and implementation feasibility. Building on these advancements, [77] introduced a digital twin-assisted symbiotic security framework for SAGIN, in which co-channel interference is leveraged to enhance physical layer protection. To address the non-convex secrecy rate optimization challenge, the authors employed Successive Convex Approximation (SCA). This method significantly improves secrecy performance in complex multi-link scenarios and reflects a broader trend toward intelligent and cooperative security strategies in dynamic networks.

C. *QoS Assurance*

LEO and VLEO satellites in the space segment move at high speeds relative to the ground, whereas UAVs performing SAR tasks, including victim search and surveillance, exhibit variable speeds. In this context, the high mobility of satellites and UAVs can lead to frequent handovers, resulting in QoS degradation in the emergency communication system. Additionally, users in post-disaster areas, including victims and first responders, have diverse and variable demands for QoS. Specifically, users conducting situational awareness need to collect a large amount of data from disaster areas and then send this data to the emergency management center. Consequently, they require high data rates for uplink communications. On the other hand, first responders must download information regarding disaster situations from the emergency command center to effectively conduct rescue operations. As a result, they also require high data rates for downlinks. Note that the SAGIN-based emergency communication network comprises three distinct networks, each with inherent characteristics including coverage, power constraints, and bandwidth. In light of this, it is crucial to select the appropriate network based on the specific needs of different tasks to ensure the QoS demands for each task. In summary, the SAGIN-based emergency communication network is characterized by highly dynamic, heterogeneous, and unevenly distributed resources, as well as complex and diverse SAR tasks. Addressing these challenges requires the development of effective network selection schemes to ensure QoS for users in disaster areas, which have become a significant focus in the field.

Table VI summarizes representative studies on QoS assurance mechanisms in SAGIN. For example, [78] proposed a network selection model based on evolutionary game theory (EGT) and designed to support efficient access decision-making in SAGIN. Although the model is effective in handling multi-user access scenarios, it lacks the capability to differentiate QoS requirements among diverse service types. To address this limitation, the model was extended in [79] by incorporating service-specific QoS requirements. Four typical service categories were defined: Conversational, Interactive Video, Streaming, and Best Effort. Utility functions were developed to represent the specific QoS requirements of each category. These models were subsequently integrated into an EGT-based framework to enable service-aware network selection.

Alternatively, a lightweight QoS-aware access guidance mechanism was proposed in [80], which dynamically adjusts access thresholds to guide a large number of terminal devices in accessing the three-layer SAGIN architecture based on service urgency. By jointly considering QoS urgency, energy consumption, and access success rate, this approach enables a trade-off between network fairness and efficiency under resource constraints. However, the highly dynamic and uncertain nature of SAGIN limits the generalization ability of traditional game-theoretic or rule-based strategies when facing sudden environmental changes. To this end, the authors in [81] introduced reinforcement learning (RL) to develop a vertical handover algorithm. This approach considers key factors influencing network selection, including load distribution, handover fluctuations, and connection reliability. By generating optimal access strategies in an adaptive manner, it enhances both the adaptability of the system in dynamic SAGIN environments.

In the architecture of satellite–UAV-based emergency communication, [33] investigated the problem of multi-user access mode selection. Users' network selection behavior was modeled using a game-theoretic approach, and a utility function was formulated to incorporate both transmission rate and delay cost. This approach facilitates the convergence of users' network selection toward a stable equilibrium, thereby ensuring QoS under resource constraints. In a similar emergency communication architecture, the authors in [32] investigated the network selection problem encountered by UAVs during the execution of SA tasks. The proposed approach ensures that both throughput and latency requirements are satisfied throughout the SA process. Although effective under stochastically generated UAV trajectories, this method does not incorporate trajectory optimization mechanisms, thereby limiting its adaptability to complex and dynamic disaster scenarios. Building upon prior work, [34] formulated UAV network selection as a joint optimization problem of UAV trajectory and LEO satellite selection. A two-stage online learning algorithm was developed to support post-disaster data collection. The proposed method achieves high data rates while minimizing handover overhead, thereby improving adaptability to dynamic and task-driven network environments. To address the limited

TABLE VI
SUMMARY OF RELEVANT PAPERS ON QOS ASSURANCE

Main Focus	Network Scenario	Ref
Network selection via evolutionary game to improve QoS	space-air-ground	[78]
Vertical handover strategy for heterogeneous services	space-air-ground	[79]
QoS-aware network selection for massive MTC access	space-air-ground	[80]
Generative AI-assisted vertical handover for IoT	space-air-ground	[81]
Evolutionary game–based user access mode selection	space-air	[33]
MADM-based vertical handover for real-time SA	space-air	[32]
Joint UAV trajectory and LEO satellite selection for post-disaster areas	space-air-ground	[34]
Joint caching and user selection in emergency scenarios	space-air-ground	[37]

energy availability in emergency environments, [37] proposed an energy-efficient solution that jointly optimizes QoS and power consumption. A dynamic caching policy and an energy-aware user association strategy were developed, supported by a statistical modeling approach based on user distribution. This method maintains service quality while significantly improving satellite energy efficiency.

D. Resource Management

Note that each network within the SAGIN-based emergency communication system has different communication resources, power limitations, and computational capacities. When a disaster occurs, many terrestrial BSs might be destroyed. As a result, a majority of users suddenly handover from ground networks to space or air networks. In this context, network imbalances are prone to occur, thereby reducing the QoS for victims and first responders. More seriously, the efficiency of SAR operations could potentially be decreased. Furthermore, some ABSs, temporarily deployed during emergencies, may overlap with surviving terrestrial BSs and satellite networks, leading to interference issues. On the other hand, computational, communication, and energy resources are all extremely scarce in disaster scenarios. Therefore, in complex heterogeneous emergency communication networks, minimizing interference while maximizing the efficiency of resource utilization is a critical challenge. Effectively addressing this issue is essential to ensure the QoS for both victims and first responders in disaster areas, ultimately enhancing the efficiency of SAR operations. However, the heterogeneity of resources, interfaces, and protocols across different network segments makes unified resource management in SAGIN-based emergency communication systems particularly challenging.

Several studies have addressed resource management in SAGIN, including communication, computation, and energy resources, as summarized in Table VII. Importantly, SAGIN comprises multiple coordinated platforms, and its multi-layered architecture makes it particularly susceptible to cross-layer interference. Accordingly, [82] proposed a two-stage optimization algorithm that jointly adjusts the hovering altitude and transmission power of UAVs within the three-layer network. This approach enhances system throughput while effectively mitigating interference. To further support service differentiation, [83] introduced the concept of Service Function Chaining (SFC), which maps various service types to appropriate network paths and resources. A delay-aware SFC embedding algorithm was developed to enable service slicing and improve the overall service acceptance rate.

With the increasing computational demands of intelligent terminals, research has shifted toward the joint optimization of computation offloading and communication resource scheduling. In emergency scenarios, [39] designed a dual-UAV system in which one UAV functions as a base station, while the other operates as a MEC server. By jointly optimizing UAV trajectory and resource allocation, the system enhances energy efficiency in post-disaster communications. Alternatively, [84] proposed a UAV relay architecture connected to LEO satellites to facilitate IoRT access. A block coordinate descent method was employed to simultaneously optimize user scheduling, power control, and UAV trajectory. Furthermore, [85] introduced a unified framework supporting three-tier task offloading across local devices, UAVs, and cloud servers. By incorporating multi-hop LEO satellite links, the approach effectively balances task completion delay and energy consumption.

Conventional optimization methods often suffer from limited generalization ability and slow convergence in large-scale dynamic environments. As a result, DRL has gained attention as an effective strategy for resource allocation in SAGIN. In [86], a multi-agent DRL framework with a hybrid action space was introduced to jointly optimize multi-task offloading and resource allocation across UAVs and LEO satellites. To improve training efficiency and reduce energy consumption under stringent latency requirements, a feasibility-aided mechanism was integrated into the learning process. This method enhances the adaptability of resource management in SAGIN, thereby improving its applicability in highly dynamic and heterogeneous network environments.

Building upon intelligent service scheduling techniques, [87] proposed a FL–enhanced SFC embedding algorithm, in which model parameters are shared across network domains while local fine-tuning is conducted to capture domain-specific characteristics. This method improves both service acceptance and resource utilization. In a different context, the authors in [88] focused on energy internet scenarios and introduced a queue-based Virtual Network Function (VNF) deployment strategy using a genetic algorithm. By minimizing the maximum queuing delay, the approach enables flexible QoS provisioning for diverse energy services. To support content-driven services in 6G scenarios, a three-sided matching framework involving users, content providers, and SAGIN devices was proposed in [89]. The algorithm was designed to incorporate both user preferences and content delivery quality. System throughput and delivery efficiency are improved, making the approach particularly suitable for personalized service provisioning in heterogeneous SAGIN environments.

E. Reliability

When disasters such as earthquakes and mudslides destroy most of the terrestrial fiber optic cables, rapid deployment of numerous ABS nodes and existing satellite networks still cannot adequately replace traditional fiber networks for data backhaul. Particularly when disasters occur in large urban areas,

TABLE VII
SUMMARY OF RELEVANT PAPERS ON RESOURCE MANAGEMENT

Main Focus	Network Scenario	Ref
Joint optimization of UAV hovering altitude and transmit power	space-air-ground	[82]
Delay-aware SFC mapping for efficient resource allocation	space-air-ground	[83]
Joint optimization of UAV 3D trajectory and resource allocation	space-air-ground	[39]
Joint optimization of UAV trajectory, power control, and user scheduling	space-air-ground	[84]
UAV trajectory, user scheduling, and multi-tier offloading	space-air-ground	[85]
Joint offloading for hybrid cloud–edge computing	space-air-ground	[86]
DRL-based SFC embedding and scheduling to optimize resource use	space-air-ground	[87]
Genetic algorithm–based resource allocation	space-air-ground	[88]
Content-aware resource allocation via three-sided cyclic matching	space-air-ground	[89]

TABLE VIII
SUMMARY OF RELEVANT PAPERS ON RELIABILITY

Main Focus	Network Scenario	Ref
DRL-based traffic scheduling for load balancing	space-air-ground	[90]
Weather-aware satellite routing	space-air-ground	[91]
Robust task scheduling via cross-layer optimization	space-air-ground	[92]
Packet reallocation via ISLs to improve reliability	space-ground	[95]
Collaborative data offloading via ISLs	space-ground	[96]
Routing optimization to reduce delay and overhead	space-air-ground	[97]
Deterministic service framework design for SAGIN	space-air-ground	[99]
Deterministic service assurance in SAGIN via TSN	space-air-ground	[100]

where tens of thousands of people may be trapped, the complexity of the disaster area presents significant challenges to the backhaul capacity of emergency communication networks. In such scenarios, most victims and first responders within the disaster area must rely on satellites or aerial platforms for data backhaul. However, this can lead to severe network congestion and overload, as these systems are designed to handle limited bandwidth. Furthermore, the deployment of ground stations is constrained by high costs and geographical limitations, resulting in a significantly lower number of ground stations compared to satellites. As a result, the limited capacity of feeder links has become a bottleneck in the effective utilization of SAGIN-based emergency communication network, leading to frequent transmission congestion and failures during data backhaul. More critically, these issues pose severe challenges for transmitting time-sensitive tasks such as searching for victims, situational awareness, and telehealth, further reducing the efficiency of SAR operations. Therefore, ensuring reliable transmission for these tasks has become a crucial issue that future emergency communication networks need to address comprehensively.

Several studies have investigated reliability in SAGIN, as summarized in Table VIII. For example, a DRL-based traffic scheduling mechanism was proposed in [90] to improve real-time load awareness and link scheduling in SAGIN. Traffic was dynamically rerouted based on link state information to alleviate hotspot congestion under high-concurrency conditions. As a result, network throughput was improved, load distribution was balanced, and link reliability was enhanced. Additionally, weather-induced degradations in link reliability have been alleviated through the methods proposed in [91].

Due to the inherent multi-hop nature of end-to-end communication in SAGIN, scheduling strategies are required to ensure reliability while minimizing hop count and latency. In light of this, [92] focused on delay-sensitive IoT task scheduling and proposed a robust two-stage algorithm. The algorithm operates within a SAGIN framework enhanced by commercial aircraft serving as aerial access platforms. It models both dynamic topology and task uncertainty, with the objective of jointly optimizing reliable data transmission and end-to-end latency.

ISLs can interconnect hundreds of satellites to form a mega-constellation [93], [94], providing a promising solution to the limitations caused by the insufficient number of ground stations and constrained backhaul capacity. In emergency scenarios, ISLs enable the transmission of large volumes of data across the satellite network to multiple ground stations, thereby preventing traffic congestion that would otherwise result from relying on a single ground station. Moreover, ISLs facilitate data delivery to ground stations that are outside the immediate line of sight of the transmitting satellite. As such, ISLs represent a critical enabler for next-generation satellite systems and play an essential role in the advancement of future emergency communication networks. Specifically, [95] and [96] investigated ISL scheduling strategies in LEO satellite systems to enhance the efficiency and reliability of backhaul links. The former proposed a buffer-limited satellite communication model with a minimum queue length allocation strategy, which dynamically redistributes data packets to mitigate buffer overflow and improve transmission success rates. The latter introduced a coordinated data download mechanism that forwards data to satellites with longer ground contact durations, thereby alleviating resource bottlenecks on individual satellites.

On the ground side, the authors in [97] proposed an enhanced routing protocol based on ant colony optimization. By incorporating node type, geographic position, and energy level into the pheromone design, the protocol supports adaptive and energy-aware path selection. The proposed method improves end-to-end throughput and reduces control overhead. These improvements indicate its potential applicability in energy-constrained and heterogeneous ground access networks.

Time-Sensitive Networking (TSN) [98], a technology developed to support priority-based and reliable transmission of high-priority tasks, has emerged as a promising solution for ensuring deterministic latency in SAGIN architectures. For instance, the authors in [99] incorporated TSN into SAGIN and proposed a deterministic service framework that combines control strategies with service feedback mechanisms. The framework adopts a closed-loop control process to support dynamic Service Level Agreement (SLA) assurance across heterogeneous domains. Building on this work, [100] proposed a hierarchical SAGIN-TSN architecture comprising three layers: ubiquitous networking, multi-domain fusion, and global orchestration. This layered design enhances both the determinism and reliability of service delivery in complex SAGIN environments.

IV. PROMISING TECHNOLOGIES

Although the SAGIN-based emergency communication network represents the future development trend for Public Protection and Disaster Relief (PPDR), this network still faces numerous challenges as outlined above. Establishing a SAGIN-based emergency communication system requires collaborative efforts and innovations from both industry and academia. Emerging technologies, such as direct-to-device satellite communications [101], AI [102], RIS [103], flexible deployment of CN and QKD [104], are worth integrating into the SAGIN-based emergency network. These solutions greatly enhance the potential for the rapid establishment of SAGIN-based emergency communication network, providing robust support for SAR operations in the future.

A. Direct-to-device Satellite

The high path loss caused by long-distance transmission between space and ground prevents ordinary mobile phones from directly connecting to satellites due to their limited power capabilities. As shown in Fig. 7, deploying VSATs is essential to establish space-to-ground links, which can be challenging in post-disaster areas. Specifically, the large-scale deployment of VSATs may be constrained by power supply limitations and the difficulty of completing deployments within a short time frame. These challenges affect the establishment of emergency networks and reduce the efficiency of SAR operations.

Direct-to-device satellite technology enables mobile phones to connect directly to satellites without the need for intermediary terminals as shown in Fig. 8. As a result, this technology has attracted extensive attention from both industry and academia. For example, Huawei and China Unicom have collaborated to develop mobile phones that can directly connect to the TianTong satellite [105]. Starlink has successfully launched LEO satellites that support direct mobile phone connections and has effectively validated this technology [106]. In summary, direct-to-device satellite technology can facilitate the rapid establishment of the SAGIN-based emergency communication network. In this way, there is no need to deploy VSATs in post-disaster areas, consequently enhancing the efficiency of SAR operations. On the other hand, as more satellites are placed in orbit, this technology has become one of the key technologies for the future SAGIN.

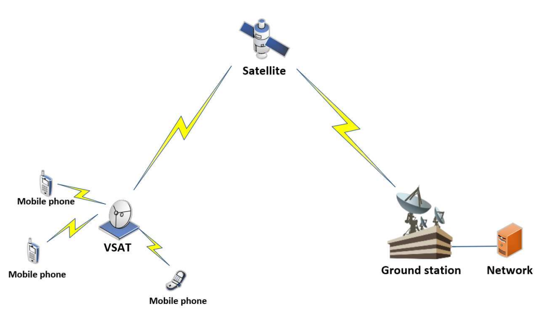

Fig. 7. The schematic diagram of ordinary mobile phone communicating with satellite via VSAT.

Remark: It is worth mentioning that radio spectrum resources are extremely limited. If direct-to-device satellite technology for mobile phones were to be widely adopted, billions of users could connect directly to satellites. This would result in the occupation of a substantial portion of space-to-ground spectrum. This will significantly increase the risk of radio interference. More seriously, such interference would severely impact systems that rely on spatial networks, including aircraft communication, Earth observation, emergency response, and so on. On the other hand, the hardware requirements for mobile phones to achieve direct connectivity with satellites are extremely high. Specifically, the mobile phones must incorporate a module with sufficient transmission power to establish satellite-to-ground links. Consequently, this requirement will significantly increase the size, cost, and power consumption of mobile phones. Finally, enabling direct-to-device satellite communication requires large satellite antennas. These antennas must provide high gain to support reliable signal transmission and reception. As a result, the payload and energy consumption of satellites will increase significantly.

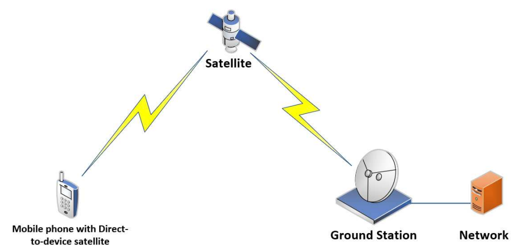

Fig. 8. The schematic diagram of mobile phone with direct-to-device satellite technology communicating with satellite.

B. Artificial Intelligence

The SAGIN-based emergency communication system comprises a variety of heterogeneous and complex network components, including IoT terminals, mobile terminals, ABSs, edge nodes, and satellites from various orbits. Note that in post-disaster areas, power, communication, and computing resources are often scarce and unevenly distributed. Another critical factor is the significant difference in QoS demands between victims and first responders. These factors present substantial challenges to the performance of SAGIN-based emergency communication systems. In this context, the optimisation of such a system, which involves resource management, interference mitigation, user association, security, and handover, poses significant challenges [107]. To this end, AI technologies, including machine learning, deep learning, and RL [108], when integrated into the system, significantly enhance its decision-making and predictive capabilities.

Specifically, supervised learning algorithms such as Support Vector Machines (SVMs) and Recurrent Neural Networks (RNNs) can be applied for communication quality prediction and fault detection [109], [110]. Unsupervised learning methods, including clustering techniques, have shown effectiveness in optimizing user association [111]. RL approaches, such as Deep Q-Networks and policy gradient algorithms, are well suited for solving dynamic decision-making problems. These include resource allocation, trajectory planning for mobile platforms (e.g., UAVs), and handover management in highly dynamic scenarios involving UAVs and LEO satellites [112]–[115]. In addition, transfer learning (TL) facilitates rapid adaptation to data-scarce disaster environments, making it ideal for post-disaster emergency networks. It can be used in tasks such as AD at network nodes and optimization of task offloading strategies [116], [117]. Meanwhile, FL enables privacy-preserving model training and knowledge sharing across distributed platforms. This approach is particularly applicable to the multi-platform collaborative architecture of SAGIN-based emergency communication systems, where both data privacy and distributed intelligence are essential [118]. The integration of these intelligent learning paradigms significantly facilitates the resolution of complex network optimization problems, thereby enabling the rapid deployment of robust and efficient SAGIN-based emergency communication systems in disaster scenarios.

Remark: Importantly, the training of AI models typically relies on large volumes of high-quality data. In disaster scenarios, however, situational awareness data transmitted via satellite backhaul to cloud centers may be vulnerable to physical and network layer security threats. If AI models are trained on unreliable or compromised data, their performance in complex post-disaster environments may be severely affected, which poses a significant concern for practical deployment. In addition, the training of AI models requires substantial computational and energy resources. These resources are often scarce in disaster-affected areas, where rapid response is essential. It is therefore critical to develop coordinated mechanisms for computing and power management to support AI training. Such mechanisms may include collaborative learning among multiple edge nodes or selective offloading to cloud centers, depending on resource availability and task urgency.

C. RIS

Disaster environments are typically highly complex, characterized by uneven distributions of victims and varying degrees of damage across different regions. In particular, certain areas experience extensive destruction and a high concentration of victims, resulting in urgent communication demands, whereas other zones, though sparsely populated, still require reliable connectivity. Moreover, due to factors such as challenging terrain, physical obstructions, or safety risks, the deployment of APs is not feasible in some regions. Even where deployment is possible, a large number of APs can incur high installation and maintenance costs, elevated power consumption, and increased complexity in network management. Nevertheless, ensuring full communication coverage across affected regions remains critical for supporting diverse sub-regional conditions and facilitating the efficient execution of post-disaster SAR tasks. In this context, RISs, owing to their energy efficiency and low maintenance requirements, offer a promising solution for extending communication coverage. Notably, the integration of RISs with UAVs improves coverage flexibility and system responsiveness [119]. Additionally, passive RISs are lighter and consume less power than conventional APs. These advantages help reduce the impact on UAV endurance and conserve energy resources, both of which are especially limited in post-disaster emergency scenarios.

Remark: Although RISs can enhance coverage in emergency scenarios while reducing the number of required APs, their communication performance is limited under long-distance transmission or severely degraded channel conditions. This limitation may hinder their ability to meet high-throughput and reliability requirements. In addition, RIS beamforming relies heavily on accurate channel state information (CSI). In post-disaster environments, where network conditions are complex and channels vary rapidly, acquiring reliable CSI is particularly challenging. This reduces the effectiveness of RIS beamforming, thereby degrading overall network performance.

Meanwhile, the large-scale deployment of RISs still faces several challenges. These include high hardware costs, complex installation site planning, and increased system management complexity. These issues become even more significant in dynamic environments. To this end, it remains essential to explore how to deploy RIS units to expand communication coverage without significantly increasing scheduling complexity. It is also important to investigate how to strategically place RISs to better support ongoing SAR operations. More precisely, this includes determining how many RIS units to deploy, how to choose deployment locations and mounting platforms, and how to identify the appropriate phases of disaster response for RIS deployment. Addressing these problems requires that the command center maintain comprehensive situational awareness of the affected area. Moreover, when RIS is mounted on UAV platforms, the dynamic nature of platform orientation and target positioning introduces additional challenges. These variations complicate beam control algorithms and increase the burden on system-level scheduling.

D. Intelligent Deployment of Core Network

In traditional emergency communication networks, the functions of the CN, including the Access and Mobility Management Function (AMF), Session Management Function (SMF), User Plane Function (UPF), Radio Resource and Broadcast Multicast Control Function (RRBMCF), and Packet Data Unit Session Function (PDUSF), are typically deployed on the ground [120]. In the SAGIN-based emergency communication network, this configuration necessitates frequent interactions between satellites, HAPs and UAVs, and the terrestrial CN, which significantly increases transmission latency. In particular, due to their high orbital speeds, LEO and VLEO satellites frequently encounter network selection issues, which involve multiple handshakes each time. Specifically, each control signaling of the handshake must first be transmitted to the terrestrial CN and then relayed back to the satellite, resulting in higher round-trip delay. These processes not only potentially cause service interruptions but also degrade the QoS for users in the disaster area. In view of this, the traditional deployment of the CN is unsuitable for SAGIN-based emergency communication networks. For this reason, deploying lightweight CN directly on satellites is feasible, which would reduce forwarding and processing delays. Furthermore, this paradigm can be integrated with MEC, thus enhancing support for SAR operations more effectively. Based on these advantages, deploying the CN on satellites has become a key trend for SAGIN-based emergency communication networks.

Remark: It should be noted that deploying the CN on satellites introduces new challenges. Specifically, as a critical element of the network, the CN becomes more vulnerable to various threats, such as cosmic radiation and space debris. It is difficult to maintain the CN if it is deployed on satellites. Moreover, the hardware required for the CN increases the satellite's payload and energy consumption, which can negatively impact overall operational efficiency.

E. QKD

Communications in post-disaster scenarios often involve highly sensitive information, including victims' locations, medical data, and resource allocation plans. Unauthorized interception threatens data confidentiality, while tampering compromises data integrity. Both types of attacks may severely hinder emergency command and rescue operations. Widely used cryptographic schemes, such as the Advanced Encryption Standard (AES) [121] and Rivest–Shamir–Adleman (RSA) [122], offer effective protection in conventional environments. However, their security fundamentally relies on the computational intractability of specific mathematical problems. With the rapid progress of quantum computing, these algorithms may become increasingly vulnerable to future attacks, which introduces significant risks to the confidentiality and integrity of critical communications.

Importantly, QKD is a technique for key generation and distribution based on the principles of quantum mechanics. It enables the secure establishment of encryption keys and thus provides theoretically unbreakable communication security [104]. Due to the no-cloning theorem and the disturbance caused by quantum measurement, any eavesdropping attempt introduces irreversible anomalies in the quantum signals, which can be promptly detected by both the sender and the receiver. Once such anomalies are observed, it is assumed that the key has been compromised. The key exchange process is then immediately aborted, and a new key is negotiated to ensure the security of subsequent encrypted communications. The securely generated keys can be further integrated with classical encryption algorithms to significantly enhance the confidentiality of data transmission. Therefore, this hybrid cryptographic framework achieves both strong security guarantees and high operational efficiency. Especially in emergency scenarios, QKD eliminates the reliance on third-party trust models and enables direct peer-to-peer key negotiation. This not only enhances communication security but also reduces system complexity, which is particularly valuable in dynamic and resource-constrained environments.

Remark: Significantly, QKD imposes stringent requirements on physical transmission conditions, particularly in free-space optical links. Due to limited photon transmission distances and significant channel losses, QKD is inherently constrained in terms of communication range and link stability. Especially in satellite-to-ground links, the long propagation distances and high mobility of nodes, particularly LEO and VLEO satellites, necessitate precise beam tracking mechanisms to maintain reliable QKD performance. Similarly, the mobility and operational variability of UAVs introduces comparable challenges in establishing and maintaining stable quantum links. Furthermore, the integration of QKD increases system complexity and cost. Specifically, the deployment of QKD components such as quantum light sources and single-photon detectors requires higher power consumption, larger payload capacity, and additional system resources. These requirements are especially difficult to meet in emergency scenarios characterized by constrained energy budgets and limited hardware capabilities, particularly on platforms such as UAVs. In light of this, achieving a practical QKD implementation in such environments requires a careful balance among communication security, system performance, and resource efficiency.

More precisely, in future SAGIN-based emergency communication systems, the deployment of QKD should be carefully planned rather than uniformly applied across all communication links. Priority should be given to links that carry highly sensitive information or are particularly vulnerable to eavesdropping. Besides, it is necessary to assess the feasibility and performance implications of deploying QKD across different platforms by considering factors such as power consumption, payload limitations, and platform stability. For example, decisions regarding which platforms should integrate QKD functionality and the appropriate timing for its activation must be addressed systematically. Notably, QKD should be activated only after the emergency communication system has achieved a basic level of operational stability. This is because, during the early stages of disaster response, the command center often lacks comprehensive situational awareness. At this stage, the system's primary objective is to ensure the provision of essential communication services for victims and first responders in the affected area.

V. Future Research Directions

The challenges of SAGIN-based emergency communication systems and the corresponding existing work have been systematically reviewed in Section III. Although substantial progress has been achieved, many existing studies do not specifically focus on emergency scenarios. Building upon previous work, this section explores potential future research directions, with particular emphasis on aligning the unique characteristics of SAGIN with the operational requirements of SAR operations in disaster scenarios. Specifically, SAGIN in disaster scenarios is characterized by high dynamics, resource scarcity, heterogeneous task requirements, and strict time sensitivity. These characteristics arise from rapidly changing environments, damaged infrastructure, diverse SAR needs, and the urgency of rescue operations within the critical 72-hour window. To this end, this discussion highlights five key research areas. First, gateway placement optimization addresses the interconnection challenges among heterogeneous network segments. Second, spatial information security focuses on protecting the transmission of critical and sensitive data. Third, QoS assurance for terminals is essential to support a wide range of post-disaster tasks, including SA, VS, telehealth, damage assessment, and communication for victims. Fourth, task scheduling ensures the efficient allocation and processing of heterogeneous computing workloads. Finally, the reliability of backhaul communication is critical to ensuring continuous wireless transmission of vital information from disaster-affected areas to cloud services and remote command centers.

A. Gateway Placement Optimization

Gateways play a vital role in enabling interconnection among heterogeneous platforms in disaster-affected areas, including emergency communication vehicles, backpack BSs, surviving terrestrial BSs, UAVs, HAPs, and satellites. This integration significantly enhances the flexibility and resilience of the SAGIN-based emergency communication system [123]. The improved interconnectivity further contributes to the enhanced system performance in terms of throughput, latency, packet loss rate, and operational efficiency. As a result, gateway placement has become a critical design concern in such systems. Existing research on gateway placement in SAGIN has primarily focused on optimization objectives such as maximizing throughput or minimizing costs [124], [62]. However, these optimization approaches are often overly simplistic and fail to account for the constraints of complex and dynamic post-disaster scenarios, which limits their practical applicability. In light of this, future gateway deployment strategies in SAGIN-based emergency communication systems should address several critical aspects, as illustrated in Fig. 9. These include sub-region-aware heterogeneous gateway deployment, dynamic adjustment of gateways based on real-time conditions, redundant placement to enhance fault tolerance, and collaborative deployment across multiple platforms to improve system resilience and operational robustness.

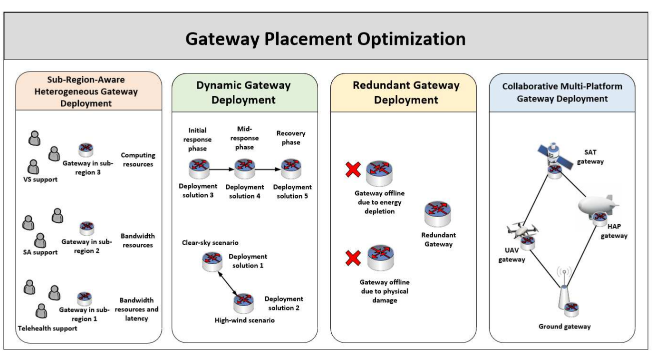

Fig. 9. Optimization framework for gateway placement.

1) Sub-Region-Aware Heterogeneous Gateway Deployment: Different disaster sub-regions often exhibit highly heterogeneous communication and computing demands. Therefore, gateway deployment strategies should be guided by task-specific optimization objectives. For example, areas dominated by video collection terminals require high-throughput transmission; regions engaged in large-scale VS operations demand substantial computational resources; and zones with dense deployments of power-constrained platforms, such as UAVs, necessitate energy-efficient gateway management. Therefore, gateway placement should be adapted to local task characteristics, terminal capabilities, and task priorities to enable demand-driven and resource-aware deployment.

2) Dynamic Gateway Deployment: Disaster environments are inherently dynamic, often characterized by secondary hazards such as aftershocks and strong winds, as well as evolving communication demands across different phases of emergency response. For instance, during the initial phase, the rapid acquisition of accurate and reliable situational awareness is critical. In contrast, in the later stages when UAVs are used to deliver essential supplies, the primary objective shifts to maintaining stable communication links. Consequently, gateway deployment strategies must exhibit dynamic adaptability to accommodate varying task requirements and ensure sustained network performance throughout the entire disaster response lifecycle.

Traditional emergency communication systems often exhibit limited efficiency in timely acquiring situational data, thereby constraining their ability to support rapid decision-making and resource allocation. In contrast, SAGIN-based systems enhance both the scope and timeliness of situational awareness through multi-platform collaboration. For example, MEO satellites can provide precise positioning, remote sensing satellites offer weather forecasting, and UAVs enable the collection of real-time video. Building on these capabilities, future gateway deployment strategies should incorporate AI to enable proactive and adaptive optimization. Such optimization can be achieved by leveraging real-time task requirements, environmental dynamics, and early warning signals. For instance, long short-term memory (LSTM) models can be employed to predict the evolution of disasters based on time-series data [125], [126]. This predictive capability enhances system responsiveness and improves deployment efficiency in complex and dynamic emergency scenarios.

3) Redundant Gateway Deployment: In post-disaster SAR operations, gateways may experience unexpected outages due to prolonged operational durations, battery depletion, adverse environmental conditions, or physical damage. This risk is exacerbated as the disaster becomes increasingly complex, potentially resulting in communication link disruptions. To mitigate this challenge, gateway deployment strategies should incorporate redundancy by provisioning multiple backup gateways along critical routes. Such redundancy enables seamless link failover and ensures continued connectivity in the event of gateway node failure. This design is particularly crucial for tasks that require high communication continuity, such as telehealth, VS, and field rescue.

4) Collaborative Multi-Platform Gateway Deployment: The selection of appropriate platforms for gateway deployment remains a critical research problem. Generally speaking, candidate platforms include ground nodes, UAVs, HAPs, and satellites, each with distinct characteristics and varying suitability under different emergency scenarios. UAVs, for instance, offer high mobility and rapid deployment capabilities. These features make them well-suited for hosting gateways that enable fast interconnection in localized areas and improve system responsiveness and operational flexibility. However, their limited battery life and low transmission power constrain their ability to establish long-distance links with satellite networks. In contrast, HAPs serve effectively as aerial relay nodes, offering long endurance and wide-area coverage. These characteristics make them suitable platforms for hosting gateways that bridge UAV networks with satellite segments. On the ground, VSATs can facilitate interconnection between terrestrial and satellite networks. Nonetheless, in severely affected disaster zones, terrain damage and environmental constraints often hinder the deployment of such ground facilities, reducing their flexibility and increasing installation complexity. In the space segment, satellites gateways enable inter-satellite communication across different orbital layers, including VLEO, LEO, MEO, and GEO, and across functional domains such as communication, navigation, and remote sensing. This is essential for supporting cross-orbit and cross-domain data relay and resource coordination. Accordingly, future gateway deployment strategies should exploit the complementary advantages of multiple platforms to achieve efficient information integration. This approach can also enhance the overall robustness and resilience of SAGIN-based emergency communication systems.

B. Security of Spatial Information

Extensive research has proposed various countermeasures to address a wide spectrum of security threats in wireless communication systems, including message eavesdropping [75], [127], data breaches [128], and unauthorized access [129]. These solutions primarily encompass encryption-based security protocols, access control mechanisms, and advanced anomaly detection techniques. However, the security threats encountered in SAGIN-based emergency communication systems are inherently heterogeneous and dynamic. Unlike conventional wireless networks, such threats are not confined to a specific attack type or restricted to a single network layer. Instead, they may simultaneously affect multiple segments and persist across various phases of the disaster response lifecycle. Consequently, systematically integrating existing security mechanisms into a unified framework remains a critical research challenge. This framework must be tailored to the unique characteristics of SAGIN, the evolving conditions of post-disaster environments, and the operational requirements of SAR missions. Notably, end-to-end communications in SAGIN-based emergency systems often involve multi-hop transmissions, with each hop potentially exposed to different categories of security threats. Furthermore, disaster environments are inherently dynamic, characterized by rapid evolution, unpredictable weather conditions, and varying phases of emergency response, all of which complicate real-time security management. Additionally, the sensitivity of information associated with different SAR tasks varies significantly, resulting in task-specific security protection requirements across the system.

To enhance the security of SAGIN-based emergency communication systems, future efforts should concentrate on several key directions, as illustrated in Fig. 10. First, it is essential to secure communications between nodes to ensure the integrity and confidentiality of each transmission hop. Second, cross-domain trust management systems should be developed to coordinate trust relationships across heterogeneous network segments. Third, dynamic security mechanisms must be designed to adapt policies to changing network conditions and evolving disaster phases, thereby balancing resource consumption with security requirements. Finally, resilient communication mechanisms should be established to guarantee reliable data transmission in the presence of node failures or attacks.

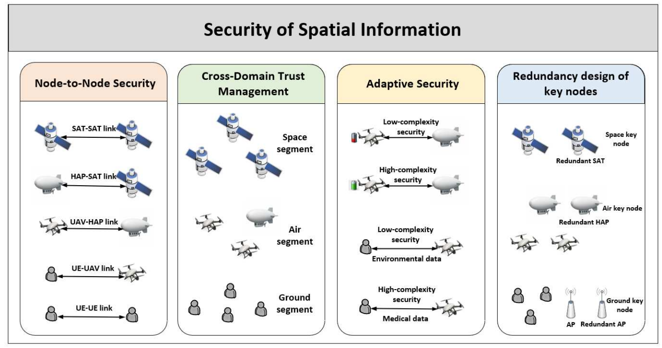

Fig. 10. Security assurance framework.

1) Node-to-Node Security: In the initial phase of a disaster, the emergency command center usually lacks comprehensive situational awareness and therefore prioritizes the rapid collection of critical information over enforcing complex security measures. Consequently, it is essential to adopt lightweight encryption and authentication mechanisms characterized by low latency, low power consumption, and minimal computational overhead. These schemes enable secure hop-by-hop data transmission even under resource-constrained conditions, such as limited UAV battery life or damaged terrestrial infrastructure. Representative examples include ultra-lightweight encryption algorithms such as ICEBERG, LEA, and PRESENT [130], [131], as well as lightweight authentication schemes such as simplified ECDSA [132], which are well-suited for resource-constrained nodes in post-disaster environments.

Furthermore, physical-layer security serves as a critical complementary mechanism for safeguarding communications in heterogeneous network environments. This can be achieved through several techniques. One approach involves the design of secrecy-enhanced reconfigurable waveforms to counter eavesdropping. Another technique is the use of spread spectrum methods, such as frequency hopping and direct sequence spread spectrum, to improve anti-jamming performance [133], [134]. In addition, QKD can be integrated to ensure information security during key exchange. The combination of these approaches contributes to a robust physical-layer security framework, which is particularly valuable for protecting mission-critical links that require high confidentiality and reliability.

2) Cross-Domain Trust Management: SAGIN-based emergency communication systems comprise space, air, and ground segments, encompassing a large number of highly dynamic and heterogeneous nodes. In parallel, SAR tasks in post-disaster scenarios evolve continuously to address changing operational demands. In this context, future research should prioritize the integration of AD techniques [135] into lightweight blockchain-based trust management systems to ensure secure and reliable coordination across heterogeneous network segments. Such systems should be capable of dynamically recording abnormal node behavior, identity authentication outcomes, task execution histories, and resource utilization data across different domains. This capability facilitates rapid identification of trustworthy nodes, continuous monitoring of resource consumption, and validation of task completion. For instance, in the later stages of disaster response, SAR operations increasingly focus on large-scale telehealth services. During this period, the trust management system can promptly verify device authenticity, resource authorization status, and data source integrity.

3) Adaptive Security: Given the dynamic nature of SAR tasks across various phases of disaster response and the continuously evolving post-disaster environments, security strategies must be designed with high adaptability. To this end, future research should explore the integration of RL and various AD techniques. The goal is to enable dynamic adjustment of encryption strength and access control policies based on real-time factors such as node density, link quality, and traffic anomalies. For example, communication links that carry sensitive telehealth data should adopt stronger encryption schemes to ensure the confidentiality and integrity of medical information, such as AES [121]. In contrast, UAV-based environmental monitoring tasks, such as damage assessment, can utilize lightweight encryption algorithms to reduce energy consumption and extend operational duration. Furthermore, when the remaining energy of a UAV drops below a predefined threshold, the system can be reconfigured to operate in an ultra-lightweight encryption and authentication mode. This adaptive paradigm emphasizes basic data protection while minimizing computational load, thereby maintaining essential communication continuity under energy-constrained conditions.

Overall, such mechanisms enable adaptive optimization of security configurations. The adjustment process can take into account multiple factors, including the disaster response stage, weather conditions, environmental complexity, SAR task priorities, link quality, and the energy status of network nodes. Ultimately, this dynamic adaptation seeks to balance security assurance with resource efficiency, thereby enhancing both the resilience and operational performance of SAGIN-based emergency communication systems.

4) Redundancy Mechanisms: Post-disaster SAR operations critically rely on reliable communication infrastructures, where the failure of a single node can result in substantial delays or disruptions in rescue activities. In particular, node or link failures caused by physical attacks or external interference can severely affect the continuity and reliability of communication services. To address these challenges, future research should explore the incorporation of redundancy mechanisms at critical system nodes, including ground command center gateways, aerial HAP relays, and satellites, to improve the resilience and fault tolerance of SAGIN-based emergency communication systems. Such redundancy enables the network to dynamically reconfigure communication links and maintain the transmission of high-priority tasks. These tasks include real-time disaster video streams for SA, VS, and telehealth services, even in the event of partial node failures.

C. QoS Assurance for Terminals

SAR operations encompass a diverse set of tasks, including telemedicine, SA, VS, communication support for victims, and remote command and control. Ensuring QoS for terminals used by first responders and victims is critical to improving the overall efficiency, reliability, and responsiveness of SAR operations. Importantly, each of these tasks imposes distinct requirements on key performance metrics such as latency, bandwidth, computational capacity, and energy consumption. Simultaneously, the platforms involved in SAGIN-based emergency communication systems exhibit substantial heterogeneity. This heterogeneity pertains to available bandwidth, computing resources, transmission delay, link quality, and residual energy. Given these disparities, future research should prioritize the development of efficient network selection strategies capable of accommodating both service-specific demands and platform heterogeneity. In this context, network selection functions as a fundamental mechanism for guiding users toward the most suitable access networks, thereby enabling efficient resource allocation under dynamic post-disaster environments.

Another important challenge lies in designing coordination mechanisms among controllers. Specifically, SAGIN-based emergency communication system architectures that incorporate both distributed and centralized controllers require efficient coordination strategies. These strategies are essential to ensure effective and balanced resource allocation across heterogeneous network segments.

In light of these challenges, future research on network selection in SAGIN-based emergency communication systems should address several critical directions, as illustrated in Fig. 11. First, rapid-response and low-overhead network selection strategies should be developed for distributed controllers to ensure QoS within their respective local areas. Second, effective coordination mechanisms between distributed and centralized controllers should be established to maintain global QoS across heterogeneous network segments. Third, adaptive network selection approaches should be proposed to accommodate evolving network conditions and diverse SAR task requirements in post-disaster environments.

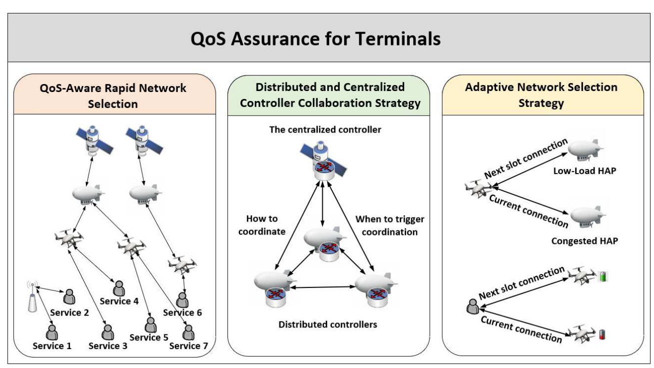

Fig. 11. QoS assurance framework.

1) QoS-Aware Rapid Network Selection: In post-disaster scenarios, SAR tasks are highly diverse, each imposing distinct QoS requirements. At the same time, the operational states of nodes managed by distributed controllers often vary significantly in terms of bandwidth availability, computational capacity, latency, link quality, and residual energy. To enable efficient network selection in SAGIN-based emergency communication systems, distributed controllers that are typically deployed on UAVs or HAPs must first monitor the operational status of each node within their respective management areas. Based on the collected status information and the specific requirements of SAR tasks in the current disaster response phase, the controllers must then make appropriate network selection decisions. Consequently, future research should focus on designing network selection strategies that offer rapid responsiveness while minimizing decision-making overhead. These strategies should leverage real-time node status and task requirements as prior knowledge to ensure the efficient execution of SAR tasks across all phases of disaster response.

For instance, game-theoretic approaches can be applied to model the competitive behavior among multiple nodes under resource constraints, thereby enabling fair and efficient network selection [136]. Techniques such as evolutionary game theory and dynamic replicator equations have been shown effective in coordinating network access among distributed nodes [137]. In addition, multi-criteria decision-making (MCDM) methods, including the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) [32], Analytic Hierarchy Process (AHP), and Simple Additive Weighting (SAW), are well suited for the rapid evaluation and selection of optimal network nodes based on multiple QoS indicators [138]. Furthermore, heuristic optimization algorithms, such as genetic algorithms, can be utilized to derive high-quality and low-overhead solutions for network selection under complex and dynamic resource constraints [139].

Another critical issue lies in the design of appropriate utility functions and weighting schemes. These should account for multiple performance indicators, such as throughput, link quality, computational capacity, latency, packet loss rate, and power consumption. Properly designed utility models facilitate network selection by balancing competing optimization objectives. This, in turn, supports the accommodation of diverse SAR tasks with varying priority levels.

2) Distributed and Centralized Controller Collaboration Strategy: Central controllers deployed on satellites are responsible for maintaining a global view of the system. However, their decision-making capabilities are often constrained by high communication latency and limited real-time responsiveness. In contrast, distributed controllers, which operate based on localized information, can make rapid decisions in response to real-time observations within their respective domains. This distinction underscores the necessity of designing an efficient coordination mechanism that balances local autonomy with global optimization.

Future research should address key challenges, including the timing of coordination initiation, the design of coordination procedures, and the selection of distributed controllers that should interact with the central controller. Specifically, a feasible approach is to allow distributed controllers to manage local network decisions autonomously, while the central controller performs periodic or event-triggered interventions. For example, such interventions can be initiated upon the degradation of QoS to ensure the overall performance of the SAGIN-based emergency communication system.

This collaborative paradigm reduces the overhead associated with continuous coordination. Moreover, distributed controllers can leverage the global situational insights provided by the central controller to promptly adjust their network selection strategies in response to node failures or evolving SAR task requirements. Such coordination enhances both the efficiency and responsiveness of rescue operations.

3) Adaptive Network Selection Strategy: Post-disaster environments are often characterized by rapid and unpredictable changes, including aftershocks, extreme weather conditions, energy depletion of network nodes, and evolving task requirements. To address these challenges effectively, future research should emphasize the integration of AI technologies, particularly RL, AD, and deep learning (DL), into SAGIN-based emergency communication systems to enable dynamic and adaptive network selection. Specifically, AI-driven modules can process heterogeneous real-time data collected from the space, air, and ground segments, including link quality, node status, and task execution feedback. Based on this information, predictive models can be trained to forecast potential disruptions such as network congestion, UAV energy depletion, or changes in SAR task priorities. For example, time-series forecasting models such as LSTM or Transformer can be applied to predict communication bottlenecks and node failures [140], [141], thereby enabling proactive adjustment of network selection strategies.

In addition, AI can support intelligent coordination between distributed and central controllers. By learning coordination patterns and decision outcomes under varying conditions, AI agents can determine optimal interaction timing and coordination strategies. This reduces coordination overhead while maintaining global QoS. Such AI-enhanced coordination is particularly beneficial for enabling decentralized autonomy while preserving centralized control and performance guarantees.

In general, this intelligent and adaptive framework facilitates the development of context-aware, real-time network selection strategies. The integration of AI is expected to significantly improve the responsiveness, efficiency, and resilience of SAGIN-based emergency communication systems in dynamic post-disaster environments.

Significantly, future network selection strategies should incorporate both traditional optimization algorithms and AI-based approaches. Each method presents unique strengths and limitations with respect to adaptability, computational complexity, and resource consumption. While AI models provide strong adaptability and predictive capabilities, their training processes may incur substantial resource costs and exhibit variable durations. Furthermore, in certain scenarios, AI-based methods may not consistently outperform conventional techniques such as the TOPSIS or game-theoretic algorithms. Therefore, future research should investigate how to effectively integrate and deploy different network selection strategies across diverse controllers, taking into account platform-specific characteristics and task-specific requirements.

D. Task Scheduling

Disaster response scenarios involve a wide range of intelligent tasks that require substantial computational resources. Representative examples include VS, damage assessment, and AI model training. These tasks vary significantly in urgency, computational complexity, latency tolerance, and energy consumption. Efficient allocation of computational workloads across the heterogeneous layers of the SAGIN architecture remains a critical challenge, especially given the constrained resources and dynamic conditions typically present in disaster environments. The computing infrastructure in SAGIN spans multiple platforms, including UAVs, HAPs, satellites, and centralized cloud servers. In the absence of effective task scheduling mechanisms, critical tasks may suffer from delays, misallocation, or even execution failure. These issues can significantly compromise the overall responsiveness and effectiveness of the emergency communication system.

Consequently, developing task scheduling mechanisms tailored to SAGIN-based emergency communication systems is essential for improving coordination between communication and computation. By intelligently matching tasks with appropriate computing resources, these systems can enhance responsiveness and maintain service continuity. They also improve the efficiency of constrained resources such as energy and bandwidth. Future research may focus on two key directions. First, context-aware scheduling should be investigated to enable the efficient allocation of diverse task types to appropriate nodes, spanning heterogeneous edge platforms and centralized cloud infrastructure. Second, disaster-aware orchestration mechanisms are required to adapt to the highly dynamic nature of emergency scenarios, including environmental variability and shifts across response phases. Together, these approaches can promote resilient and efficient collaboration among distributed computing nodes operating under uncertainty.

1) Context-Aware Task Scheduling: Future research on context-aware task scheduling should prioritize support for diverse post-disaster computing tasks under dynamic and resource-constrained conditions. A promising direction involves integrating rule-based scheduling [142], RL [143], and lightweight prediction models into a hybrid intelligent scheduling framework. Specifically, rule-based mechanisms are effective in ensuring that high-priority tasks, such as VS and damage assessment, are assigned to nodes with adequate computational capacity and energy reserves. This guarantees timely execution and reliable service delivery.

To handle environmental uncertainty and network variability, RL techniques such as Deep Q-Networks (DQN) and Deep Deterministic Policy Gradient (DDPG) [144], [145] can enable adaptive and long-term decision-making. In addition, lightweight prediction models, including those based on LSTM networks, can estimate key node states such as residual energy, link reliability, and processing workload. These predictive capabilities allow the controller to proactively adjust task allocation and mitigate the risk of service interruption, particularly for resource-constrained platforms such as UAVs.

Overall, this hybrid approach provides a balanced combination of adaptability, responsiveness, and practicality. These characteristics make it well-suited for intelligent task scheduling in disaster response environments that are dynamic, mission-critical, and resource-constrained.

2) Disaster-Aware Orchestration: In future SAGIN-based emergency communication systems, a hybrid orchestration architecture that integrates hierarchical and distributed strategies is anticipated to enable both global coordination and localized adaptability. Within this architecture, a centralized controller deployed on satellite nodes oversees global orchestration functions, especially in the coordination of inter-regional task allocation. At the same time, multiple distributed controllers situated on HAPs are responsible for managing task orchestration within their respective regional domains. Importantly, each HAP-based controller operates autonomously to schedule tasks, monitor local resource availability, and coordinate service deployment across underlying UAVs and edge computing nodes.

To improve adaptability in highly dynamic disaster environments, the orchestration framework can be enhanced through the integration of multi-agent reinforcement learning (MARL) [146] and graph neural networks (GNNs) [147]. Specifically, each distributed controller deployed on HAPs is modeled as an intelligent agent. By leveraging MARL, these controllers can collaboratively learn decentralized orchestration strategies. This reduces dependence on the primary controller and minimizes coordination overhead, which is particularly important in resource-constrained disaster scenarios.

However, when local cooperation becomes insufficient, the system can escalate orchestration requests to the primary controller. Leveraging its global perspective, the primary controller can subsequently reallocate resources across domains to restore system stability and ensure service continuity. Notably, this mechanism significantly reduces the risk of orchestration failure caused by disruptions in post-disaster environments, such as sudden weather changes, aftershocks, or regional power outages. These factors can severely impair the coordination capabilities of distributed controllers, leading to degraded system performance if not properly mitigated.

Within each domain, task dependencies and resource topologies are modeled as dynamic graphs. For example, GNNs are applied to extract structural features from these graphs. This approach enables more effective and context-aware task scheduling. The orchestration process also considers task-specific constraints, particularly the latency requirements of different SAR operations. In addition, it takes into account real-time node states, including workload, energy availability, and link reliability. Based on these factors, the controllers can generate adaptive orchestration plans that are capable of meeting the diverse computational requirements of post-disaster missions.

E. Reliability of Backhaul Communications

Disasters frequently damage terrestrial fiber-based backhaul infrastructure, resulting in network isolation in affected areas. In such cases, these regions become solely dependent on satellite wireless links to backhaul large volumes of critical information to the outside world. During the backhaul process, the wireless segment is typically structured as a multi-hop routing system. It includes uplinks from APs in disaster-affected areas to the satellite layer, followed by downlinks from satellites to ground stations. Notably, the introduction of ISL technology further transforms the satellite segment into a multi-hop architecture [148], [149]. Although multi-hop routing enhances backhaul flexibility and resilience, it may also introduce significant end-to-end latency. This poses substantial challenges for the reliable transmission of time-sensitive information, such as real-time video streaming and rescue command coordination. Furthermore, as the wired node in the backhaul process, the ground station may experience a sudden influx of heterogeneous data with varying priority levels, potentially resulting in network congestion. This congestion can delay the transmission of high-priority information to remote command and cloud centers, thus compromising the reliability of backhaul communications.

As shown in Fig. 12, a reliability assurance framework is proposed for backhaul communication. Specifically, future research should prioritize the development of intelligent backhaul routing protocols. These protocols should be capable of dynamically optimizing the trade-off between hop count and key performance indicators (KPIs), such as throughput and latency, particularly under constrained and evolving network conditions. Meanwhile, the design of priority-aware congestion control mechanisms at ground stations should be explored to ensure the timely delivery of high-priority data. Enhancing routing efficiency in the wireless domain and improving traffic management at the wired interface can significantly increase the overall reliability of the backhaul link. This, in turn, ensures robust and continuous connectivity between disaster-affected areas and cloud or emergency command centers.

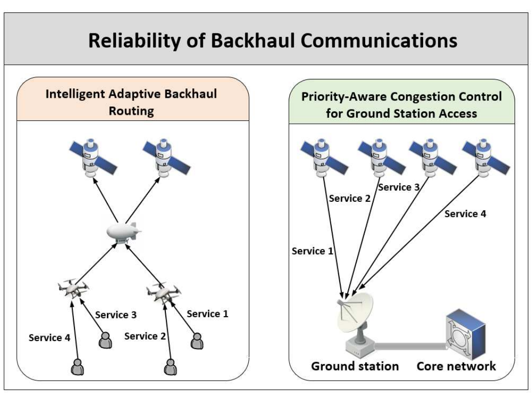

Fig. 12. Reliability assurance framework for backhaul communication.

1) Intelligent Adaptive Backhaul Routing: During the backhaul process, in which data is transmitted from APs in disaster-affected regions to ground stations, excessive transmission hops can significantly increase end-to-end latency and elevate security risks. On the other hand, if all APs select paths with fewer hops, traffic congestion may occur at specific intermediate nodes, which can degrade the overall reliability of the backhaul link. To address these challenges, future research should explore the application of AI techniques such as RL and GNNs. These methods have demonstrated strong potential for predictive and adaptive routing in complex network environments [150], [151]. Specifically, by utilizing historical traffic patterns, real-time metrics (e.g., link quality, congestion), and task priorities, these methods can construct routing paths that support the reliable delivery of heterogeneous, time-sensitive data in SAGIN-based emergency communication systems. Furthermore, heuristic optimization algorithms such as ant colony optimization (ACO) and genetic algorithms (GA) can be employed to provide efficient solutions for multi-objective routing problems under stringent latency and bandwidth constraints [152], [153]. These algorithms can be further enhanced by incorporating QoS utility functions that simultaneously account for latency, hop count, and throughput requirements across different SAR tasks.

Overall, the integration of predictive AI models and resource-aware heuristic routing algorithms is essential for the future design of backhaul communication strategies. Such integration can substantially improve the resilience and responsiveness of wireless backhaul links, thereby enabling them to meet the stringent performance requirements associated with disaster response operations.

2) Priority-Aware Congestion Control for Ground Station Access: In the wired segment of the backhaul link, particularly at ground stations, a substantial volume of data may be concurrently received from disaster-affected regions. This high traffic load can lead to severe network congestion, especially considering the limited number of operational ground stations. The situation is further complicated by the dual-use nature of these facilities, which simultaneously support both emergency communication services and regular satellite internet operations. Additionally, the heterogeneity and varying priority levels of post-disaster data pose significant challenges to ensuring the timely transmission of critical information from ground stations to remote command centers.

To this end, future research should explore the integration of TSN mechanisms into ground stations within SAGIN-based emergency communication systems. Particular emphasis should be placed on the development of time synchronization protocols [154] and priority-aware traffic scheduling strategies [155], tailored to the dynamic operational requirements of SAR tasks. Given that the urgency of information varies across different phases of disaster response, static scheduling schemes often prove insufficient. Accordingly, dynamic priority assignment strategies should be adopted based on real-time SAR task context, urgency levels, and data types, including video streams, voice communications, and sensor data. These strategies are essential to ensure the timely and efficient transmission of mission-critical information.

In addition to ensuring the timely transmission of high-priority data, future research should explore the design of lightweight TSN protocol stacks tailored for deployment at ground stations. It should also investigate adaptive queue management mechanisms that can prevent the starvation or loss of lower-priority yet essential data flows. Another promising direction lies in the development of collaborative TSN architectures that coordinate traffic shaping and queuing strategies across multiple ground stations [156]. Such architectures can support distributed load balancing of backhaul traffic, particularly in scenarios where congestion at a single ground station becomes a bottleneck for mission-critical tasks.

VI. Conclusion

This paper provides a comprehensive review of the latest representative platforms across the space, air, and ground segments to support the communication and computing requirements of post-disaster SAR tasks. It also examines the coordination mechanisms among these platforms, including complementary communication, MEC–cloud collaboration, and inter-controller coordination. These cross-segment and cross-platform coordination strategies help address fundamental limitations of traditional emergency networks.

Key challenges in SAGIN-based emergency communication systems are further identified, including interoperability, security, QoS assurance, resource management, and backhaul reliability. Building on current trends in wireless communication and the dynamic nature of post-disaster scenarios, the paper highlights five promising technologies: direct-to-device satellite communication, AI, RIS, intelligent deployment of CN, and QKD. Integrating these technologies into the SAGIN architecture can enhance networking efficiency in emergency contexts, particularly with respect to communication coverage, security, and resource scheduling.

Finally, future research directions are outlined from a system-level perspective, focusing on five critical areas: gateway deployment optimization, information security, terminal QoS assurance, task scheduling, and the reliability of backhaul communications. These directions are critical for the advancement SAGIN-based emergency communication systems.

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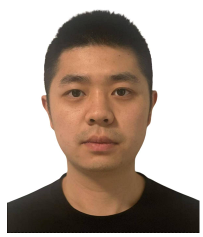

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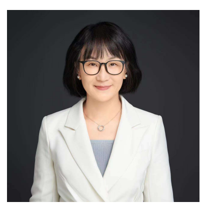

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