Bidirectional Mission Offloading for Agile Space-Air-Ground Integrated Networks

Sheng Zhou, Guangchao Wang, Shan Zhang, Zhisheng Niu, Xuemin (Sherman) Shen

Abstract

SAGIN provides great strength in extending the capability of ground wireless networks. On the other hand, with rich spectrum and computing resources, ground networks can also assist space-air networks in accomplishing resource-intensive or power-hungry missions, enhancing the capability and sustainability of the space-air networks. Therefore, bidirectional mission offloading can make full use of the advantages of SAGIN and benefits both space-air and ground networks. In this article, we identify the key role of network reconfiguration in coordinating heterogeneous resources in SAGIN, and study how network functions virtualization (NFV) and service function chaining (SFC) enable agile mission offloading. A case study validates the performance gain brought by bidirectional mission offloading. Future research issues are outlooked as the bidirectional mission offloading framework opens a new trail in releasing the full potential of SAGIN.

Introduction

By interworking the communication and computing resources on satellites, high-altitude platforms (HAPs), unmanned aerial vehicles (UAVs), and terrestrial wireless communication nodes, space-air-ground integrated networking (SAGIN) is expected to exploit the advantages of each component network, as well as provide wide-range and seamless networking services. Many applications that require real-time and reliable data sensing, collection, transmission, processing and distribution across large areas can be supported, such as Earth observation, navigation, smart cities, connected vehicles, and global wireless network coverage.

Recent studies have revealed the great potential of using satellite networks to assist ground wireless networks for ubiquitous access [1], and to handle communication missions that can hardly be accomplished solely by the ground network [2], for example, efficient broadcasting and multicasting for connected vehicles [3]. This mission offloading from ground to space makes use of the wide coverage and reduces the communication delay through fewer hops.

However, the resources in space-air networks are often scarce. The spectrum is limited, and the processing capability is constrained by the computing resources and the power supply on the satellites, HAPs, and UAVs. Under many circumstances, a standalone space-air network can barely accommodate emerging missions calling for a large amount of data acquisition and dissemination, and intense computing tasks requiring real-time processing [4]. To this end, collaboration among multiple satellites from different orbits has been proposed to achieve better resource utilization and accordingly improved performance [5]. In fact, the ground network can also help accomplish the missions in the space-air networks, exploiting its rich spectrum, computing and storage resources, that is, missions originally carried out in space-air networks can be *reversely offloaded* from the space-air to the ground. For instance, computing intensive tasks, such as remote sensing and cooperative monitoring, can be offloaded from space-air nodes to servers on the ground. In coordination with the existing mission offloading from the ground to the space, this bidirectional mission offloading in SAGIN can make full use of the complementary advantages of both space-air and ground networks.

However, the success of bidirectional mission offloading in SAGIN highly relies on abilities to coordinate the heterogeneous resources from satellites, HAPs, UAVs, and ground networks, which is far more challenging than managing resources within individual networks. In addition, to adapt itself to the highly dynamic environment, the integrated network needs technologies like software defined networking (SDN), network functions virtualization (NFV), cross-layer resource management, and network reconfiguration. Recently, SDN has been proposed to realize flexible resource management and resource-mission matching for Earth observation missions [6] and space-assisted connected vehicles [3]. Due to the large network scale of SAGIN, realizing SDN must face the challenges of system information collection. While for agile offloading on both directions in SAGIN, not only do the network functions (NFs) have to be virtualized and matched to the heterogeneous resources, but also the service function chain (SFC) must be planned and optimized with the network management. As a result, a unified framework supporting SAGIN reconfiguration is required.

In this article, we first introduce the concept of bidirectional mission offloading and its potential

Sheng Zhou, Guangchao Wang and Zhisheng Niu are with Tsinghua University, Beijing 100084, China;
Shan Zhang (corresponding author) is with Beihang Univesity, and also with the Beijing Key Laboratory of Computer Networks;
Xuemin (Sherman) Shen is with the University of Waterloo.

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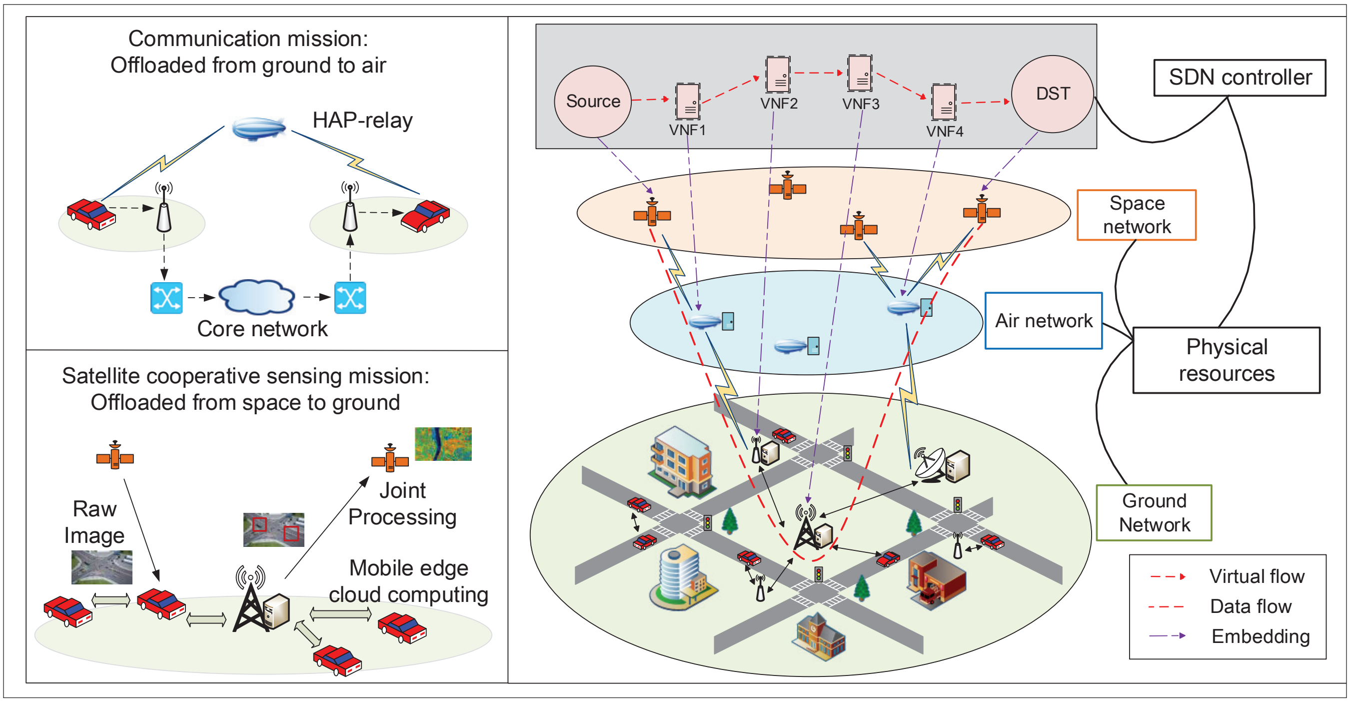

FIGURE 1. Use cases of bidirectional mission offloading in SAGIN, with examples of communication missions offloaded from ground to air and computation missions offloaded from space to ground, respectively. The general concept of VNF embedding and SFC planning for agile offloading is illustrated, with mission offloading from space to ground.

applications. Following the review of the NFV and SFC technologies used in wireless networks, we illustrate how they can be implemented in SAGIN to enable agile bidirectional mission offloading and network reconfiguration. We then elaborate our idea with a case study that addresses SFC and resource provisioning in SAGIN. We conclude the article with an outlook on promising research issues.

Bidirectional Mission Offloading: Making the Best Use of a 3D Network

SAGIN is expected to exploit the complementary advantages of space, air, and ground facilities to provide reliable, high data rate, and cost-efficient services with seamless coverage. An example is illustrated in Fig. 1. Specifically, the facility-rich and low-cost ground network will provide services for the majority population in urban areas, while the large-coverage space-air facilities can help uncovered areas or special events [3]. Based on the distinct features of different facilities, closer collaborations are required to make the best use of this 3D network. To this end, we propose to conduct agile bidirectional computation and communication mission offloading, which can benefit the performance of *both* ground and space-air networks. Specifically, ground missions correspond to missions (mainly communications) originally carried out in ground networks, while the space-air missions correspond to the missions (mainly computation and processing) originally carried out in space-air networks. The label of the missions (ground or space-air) does not change even if they are offloaded in SAGIN.

Ground Missions Offloaded to Space-Air

Flying at altitudes of 17~22 km, HAPs can provide coverage of hundreds of kilometers with low path loss, and have been granted with 600 MHz dedicated bandwidth at 47–48 GHz band for communications by the Federal Communications Commission (FCC). Compared to HAPs, UAVs also enjoy better mobility control in addition to line of sight (LoS) coverage. The battery life, typically 30 minutes to 6 hours, is the main technical concern of UAVs, while energy harvesting technologies can relieve this pressure (https://www.theguardian.com/technology/2015/jul/31/facebook-finishes-aquila-solar-powered-internet-drone-with-span-of-a-boeing-737). The broadband communication satellites (running at low, medium, or geostationary orbits) can provide globally seamless coverage, and the capacity is also improving with technologies such as multiple-beam antennas, and advanced onboard processing and control methods. In addition, the rapid development of space-air technologies greatly reduces the costs of HAPs, UAVs, and satellite communications, and can potentially bring space-air network access into daily life. The Loon Project aims to provide Internet access through HAPs with comparable speed to 4G LTE networks, which was implemented for after-disaster reconstructions in 2017. The Globe Xpress system employs three geostationary-orbit satellites to provide broadband network access for 99 percent global coverage, with downlink and uplink rates of 50 Mb/s and 5 Mb/s, respectively.

The ground network, with well-developed technologies and infrastructures, will take the main responsibility for providing cost-effective access in general. Meanwhile, the ground communication missions can still be offloaded to space-air networks on demand, bringing numerous benefits.

Emerging vehicular communication has posed great challenges for ground networks on high mobility when supporting latency-critical road safety applications. Large-coverage air and space networks can reduce handover frequency, enhancing service reliability. Furthermore, UAVs can even form moving cells to vehicles, providing handover-free network access.

Coverage and Capacity Enhancement: With large coverage and dedicated bandwidth, HAPs are promising to construct low-cost rural area coverage. The satellites can further cover mountains and seas to form global umbrella coverages. In addition to coverage enhancement, the air and space networks can also improve network capacity through large-area broadcast, such as location-based services and vehicle software update.

Mobility Supports: Emerging vehicular communication has posed great challenges for ground networks on high mobility when supporting latency-critical road safety applications. Large-coverage air and space networks can reduce handover frequency, enhancing service reliability. Furthermore, UAVs can even form moving cells to vehicles, providing handover-free network access.

Robustness: Ground networks are vulnerable to disasters, and the recovery is also time-consuming. In comparison, HAPs and UAVs can be rapidly deployed on demand, while the coverage of satellites is robust to disasters.

Wireless Backhauling: As the network densifies, the backhaul will become a key bottleneck. Space-air networks can provide high-speed backhaul access for ground base stations (BSs) through millimeter-wave (mmWave) communications, liberating the wired backhauls. Accordingly, ground stations can be deployed in a flexible plug-and-play manner.

Space-Air Missions Offloaded to Ground

Driven by the need to support diversified missions, space-air facilities will be implemented with onboard processing units for functions like intelligent sensing and information processing. However, the onboard processing units can cause more energy consumption and increased weight. The ground network, especially considering the emerging autonomous driving vehicles, owns abundant computation and storage resources. Accordingly, inverse directional mission offloading enables space-air facilities to make use of ground resources, and promotes the space-air intelligence and sustainability. One such offloading example is shown in Fig. 1. Two satellites are employed to jointly monitor and detect abnormal ground conditions, where one satellite offloads the computation-intensive image processing missions to the ground network. Through mobile edge computing, the BSs and vehicles analyze the raw images cooperatively by utilizing their available general-purpose computation resources. The processing results are fed back to the other satellite to make further analysis and actions. With recent developments of NFV and SDN, space-air NFs are decoupled from the hardware, and thus flexible mission offloading can be made possible, bringing about the following advantages.

Enhanced Sustainability: As computation-intensive onboard processing can cause high power consumption, computation mission offloading can effectively reduce the power consumption of space-air facilities to prolong battery life. In addition, for renewable-energy-powered space-air facilities, computing missions can be dynamically offloaded to ground based on the available battery, energy harvesting rate, and onboard processing load so as to enhance the system reliability and sustainability.

Improved Intelligence: Offloading computation-intensive missions from space-air to ground nodes, either fixed BSs or moving vehicles, for timely processing has a similar effect as enhancing the onboard processing capability of space-air facilities. The enhanced processing capability provides new opportunities to develop space-air intelligence, such as autonomous flying, monitoring/observation, localization, and tacking. Furthermore, the data collected from space-air and ground nodes can be processed jointly to enhance inference and detection precision, for example, in the accurate positioning of UAVs with a high-definition map.

Simplified Facility Design: As missions can be offloaded to the ground, simplified hardware design is possible for space-air facilities. Accordingly, the weights of space-air nodes can be significantly reduced, with enhanced battery life and thus flying sustainability. In addition, the costs of nodes can be reduced, making it feasible to construct large-scale but cost-effective space-air networks. A similar idea has been implemented in ground networks, that is, the architecture of the cloud radio access network (CRAN), where the remote radio head only keeps radio frequency transmission functions, while the baseband processing is conducted in data centers.

Reconfiguration via NFV and SFC: Enabling Agile Mission Offloading

The fundamental issue of bidirectional mission offloading in SAGIN is how to handle diverse missions with heterogeneous resources from space, air, and ground. Also, SAGIN shows high dynamics due to the flexible deployment and mobility of not only air and space nodes, but also ground nodes like vehicles. Thus, a SAGIN should be capable of reconfiguration along with the variations of network status and traffic demands. Flexible reconfiguration requires decoupling NFs from hardware, which can be accomplished by NFV. Moreover, due to the large scale of SAGIN, it is hard to ensure the coexistence of all kinds of resources in need. As a result, the NF for a certain mission cannot be supported anywhere in SAGIN; for instance, observation functions are not supported by ground nodes, while the storage and computing resources may not be sufficient in the space-air nodes. This actually calls for the implementation of SFC on top of NFV, which geographically matches the resource to virtual network functions (VNFs). The signaling overhead for collecting necessary system information for SFC is then vital, and hierarchical control [3], both in space-air and ground networks, is an option to alleviate the overhead. Albeit born within the wireline network, the NFV and SFC techniques enable such agility, whereby the NFs can be orchestrated on demand and embedded based on the resource availability, as shown in Fig. 1 for the offloaded mission from the space-air network to the ground network.

NFV and SFC in Wireless Networks

NFV can decouple the network services from the dedicated wireless network hardware, the standardization and implementation of which are provided by the European Telecommunications Standards Institute (ETSI) Industry Specification

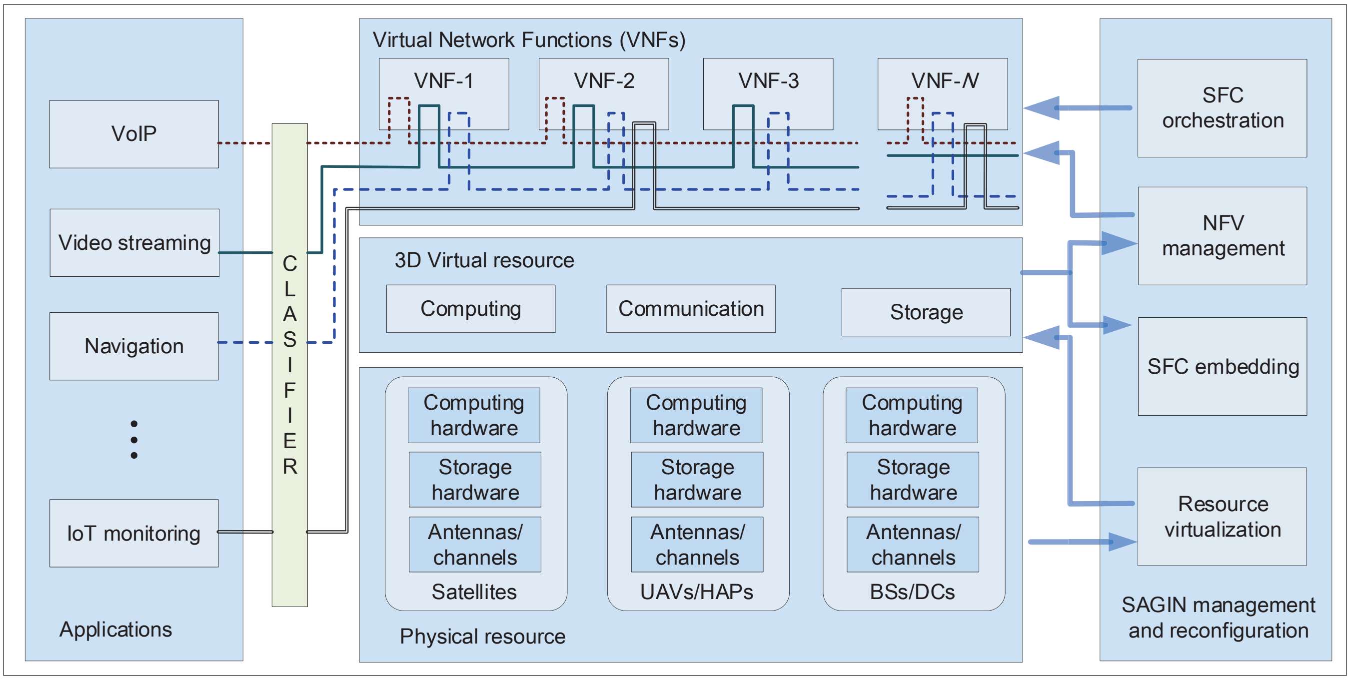

FIGURE 2. SAGIN management and reconfiguration for bidirectional mission offloading.

Group [7]. Using NFV, the traditional NFs are virtualized into software components {as VNFs} that run on universal hardware. The physical wireless network resources, such as radio spectrum, CPU cores, and network infrastructure, are abstracted as virtual wireless network resources and allocated to various VNFs to hold various network services [8]. In this way, the VNFs can be flexibly deployed and reconfigured on different physical nodes, which facilitates network agility and robustness. In addition, better network scalability is achieved because new VNFs can easily be added to support new services. As the VNFs can be shared among multiple service requests, both communication resources and computation resources are utilized effectively. In current IP-based LTE architecture, the NFV can be applied to multiple network segments including radio access networks (RANs), evolved packet core (EPC) networks, and transport networks [9]. In general, the following NFs can be virtualized by NFV:

- RAN functions such as baseband processing functions
- EPC functions such as public data network gateway (P-GW), serving gateway (S-GW), and mobility management entity (MME)
- Security related functions such as firewalls, intrusion detection systems (IDSs), and deep packet inspection (DPI)
- Network optimization functions such as load balancer, traffic control protocol optimizer, and Network Address Translator (NAT)

With the advances in NFV technology, the concept of SFC is defined by the Internet Engineering Task Force (IETF) [10], which also demonstrates the SFC applications in mobile networks. In this paradigm, the data traffic is required to flow through several specific NFs under a specified order for proving the network services with heterogeneous quality of service (QoS), security, and reliability requirements [11]. Conventionally, NFs are implemented using dedicated hardware. This coupling of functions and hardware leads to a static SFC, which typically cannot share the functions with other network services. Thanks to the decoupling of the functions and hardware, NFV technology enables agile SFC and resource sharing by virtual functions.

Reconfiguration in Space-Air-Ground Integrated Networks via NFV and SFC

By decoupling NFs from hardware, NFV and SFC enable agile network reconfiguration to deal with network and traffic dynamics. The framework for network reconfiguration is shown as Fig. 2. Each SAGIN application can be classified based on the QoS demands, whereby the required NFs are orchestrated as an SFC to support the application. The SFC embedding is used to map the NFs of each chain to the SAGIN physical infrastructures through NFV management, which is the main challenge in implementation [12]. NFV enables the flexible placement of VNFs on different physical nodes, which brings dynamic resource allocation problems. The installation and migration problems of VNFs are often NP-hard, and hence nontrivial to solve for large-scale instances. Thus, it is imperative to exploit efficient approaches to obtain optimal dynamic resource allocation. Thus, the resource virtualization function is introduced, whereby the heterogeneous physical resources (e.g., power, spectrum, computation, storage) from SAGIN are abstracted as virtual resources (e.g., transmission rate, computation frequency, cache size). With resource virtualization, the space, air, and ground networks can be seen as unified components, which helps to ease the SFC embedding. The SAGIN demonstrates high dynamics in three aspects: the application and traffic demand variations, the flexible deployment of HAPs and UAVs, and the mobility and availability of space-air and ground nodes. Such dynamics require SAGIN be reconfigured in an agile manner through re-optimizing the relation-

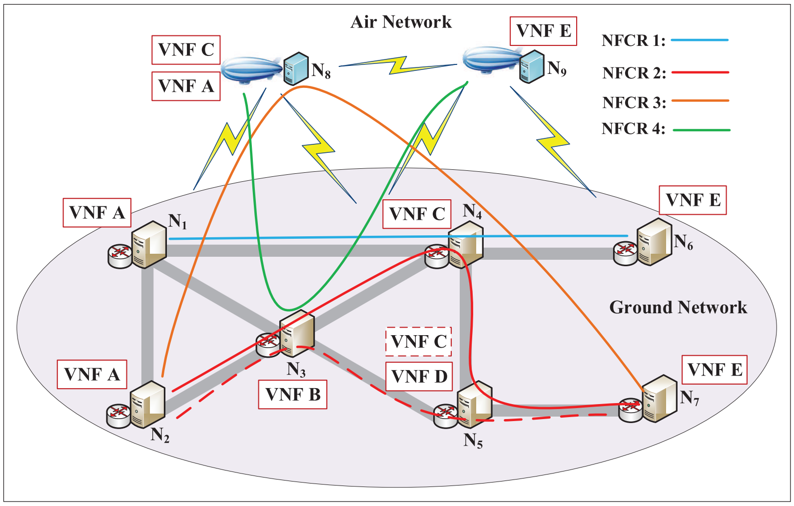

FIGURE 3. An example of a space-air-ground integrated network topology.

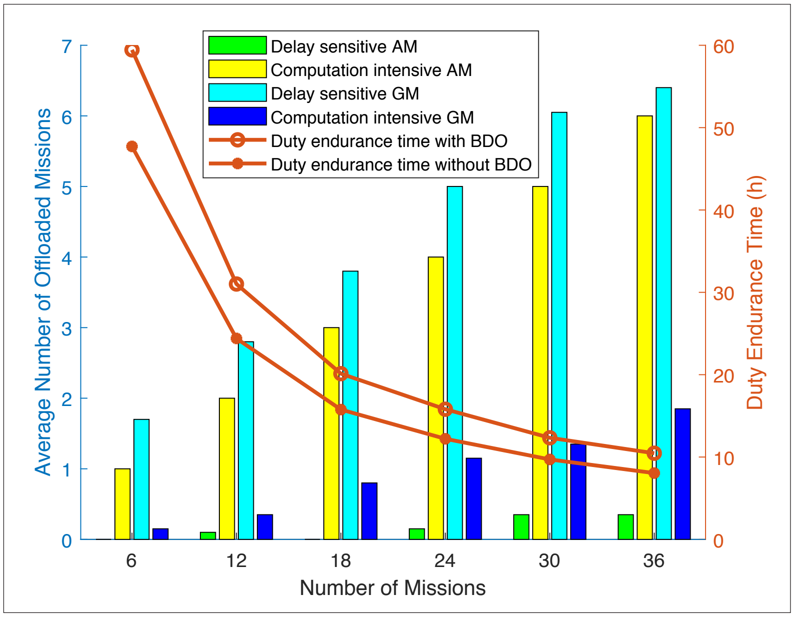

FIGURE 4. Performance of bidirectional offloading (BDO) for air mission (AM) and ground mission (GM).

ship between SFCs and physical resources based on the network and traffic status. As such, the SFCs can be better supported with high reliability and resource efficiency. However, the spatial, temporal, and network scales need to be carefully judged to balance SFC embedding performance and reconfiguration costs, mainly caused by system information collection. The entities carrying out SAGIN management and reconfiguration on the right of Fig. 2 can have hierarchical relations and be distributed over SAGIN. We illustrate the basic idea of enabling bidirectional mission offloading with SFC-based SAGIN reconfiguration in the following case study, and then discuss possible research issues in the next section.

A Case Study

SFCs are established and deployed for missions that are offloaded in SAGIN. With NFV technology, NFs are implemented by VNFs, which can be flexibly embedded in both air nodes and ground nodes. We consider an integrated network with two air nodes and seven ground nodes, as illustrated in Fig. 3. Thanks to the large coverage, the air nodes have full connections with the ground nodes. The figure shows four examples of network function chain request (NFCR), which represent resource provision strategies for corresponding missions. NFCR 1 requires VNFs A, C, and E, where VNF C is embedded on node N_4. The traffic of NFCR 1, shown by the blue line, originates from node N_1 and eventually flows to node N_6. NFCR 2 requires VNFs A, B, C, D, and E to complete the mission. The red line shows one chaining strategy of NFCR 2, where the traffic experiences four-hop transmissions. Thus, VNF C is shared between NFCR 1 and NFCR 2, and the computation cost for installation and maintenance of VNF C can be saved. The red dotted line shows another strategy, where the traffic only experiences three-hop transmissions so that the bandwidth cost is reduced, but an additional VNF C instance should be embedded in N_5, which produces additional computation cost. Therefore, there is a trade-off between the computation cost and the bandwidth cost. The required VNFs of NFCR 3, as a ground network mission, are partially offloaded to air nodes, as illustrated by the orange line. The traffic only experiences two-hop transmissions, which effectively reduces the hopping delay, and potential traffic congestion can be avoided in a crowded ground network scenario. Conversely, the VNFs with high computation complexity can be offloaded from the air nodes to ground nodes to save the computation resources and relieve the traffic burden, as shown by the green line.

Here the key issue is the bandwidth and computation resource provision for flexible NF chaining. Thus, the VNF mapping and traffic assignment should be jointly considered. The VNF mapping problem is how to embed the required VNFs to proper physical network nodes. The traffic assignment problem is how to steer the traffic flow through VNFs in a specified order over proper physical links. The major constraint is the resource capacity of the physical network including bandwidth resources and computation resources. The objective is to maximize the number of mission requests that can be successfully served, and minimize the bandwidth and computation cost. This problem can be formulated as a nonlinear integer programming problem, which is solved by the Matlab SCIP toolbox. In the simulation, we consider delay-sensitive and computation-intensive missions that are randomly generated with 3–6 VNFs in both ground network and air network. The bandwidth capacity of links and computation capacity of nodes are uniformly distributed in [80,100] Mb/s and [500,600] giga floating-point operations per second (GFLOPS), respectively. The delay of each hop is set to [10, 15] ms following uniform distribution. Each air node is equipped with a 100 Wh battery that exclusively supplies power for the computation of the missions. Each VNF consumes 0.2 W power for one mission. We assume that the energy is sufficient for the propulsion systems, and that the *duty endurance time*, defined as the time duration in which the energy for processing the missions, is sufficient, depending on the endurance of the computation battery.

The performance of bidirectional mission offloading is shown in Fig. 4. The delay-sensitive missions have more opportunities to be offloaded from the ground nodes. This is mainly because the offloaded missions only experience two-hop transmissions, and the hopping delay can be reduced. However, among the missions from the air network, the computation-intensive missions are preferably offloaded due to the fact that the computation cost is lower in ground nodes, and more computation resources in the air can be saved. The duty endurance time of air nodes decreases with the increase of the number of missions, while the duty endurance time of the air nodes notably increases by bidirectional mission offloading. This is mainly because of reversing mission offloading from air to ground, which leads to the reduction of energy consumption for computation.

Figure 5 compares the performance with and without bidirectional mission offloading. The figure shows that the computation resource cost per completed mission is substantially reduced by bidirectional mission offloading, indicating more efficient resource utilization of the whole network. However, additional bandwidth cost for air-to-ground (A2G) links is introduced. Furthermore, the network with bidirectional mission offloading has a lower blocking rate as a result of more agile resource management enabled by SAGIN network reconfiguration. In summary, the case study validates the feasibility of implementing bidirectional mission offloading in SAGIN via NFV and SFC, through formulating and solving the VNFs mapping and traffic assignment problems. Simulations confirm that bidirectional mission offloading significantly improves the resource utilization efficiency and sustainability of air nodes.

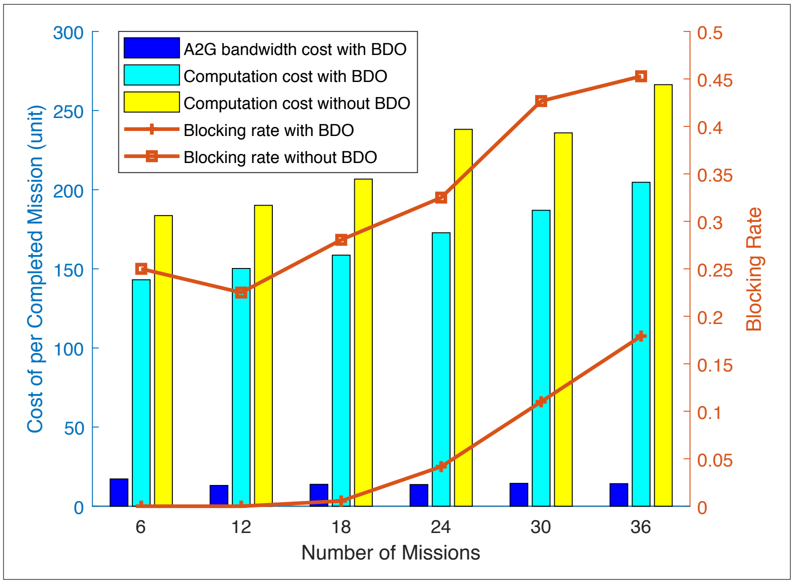

FIGURE 5. Resource cost and blocking rate with or without bidirectional mission offloading.

Research Issues of Bidirectional Mission Offloading

In this section, we highlight key research issues to be solved before realizing the concept of SFC-based SAGIN reconfiguration and supporting bidirectional mission offloading.

Abstraction and Virtualization of Heterogeneous Resources

In SAGIN, the resources include the wireless spectrum, computing processor, storage, observation resources, and so on. Therefore, it is vital to virtualize these heterogeneous network resources as the basis of SDN and NFV in order to enable bidirectional offloading. These heterogeneous resources should have a unified abstraction that satisfies the needs for network virtualization, including flexibility, isolation, and coexistence [11]. Flexibility highly relies on how resources are abstracted. One way is to use the information bits that can be processed (i.e., transmitted, computed, stored, and observed) via various network resources [6]. This approach is mission-dependent, and may not easily be generalized to different missions. For example, tasks can have different computing complexities even if their input bits are of the same amount. In addition, delay performance can hardly be reflected. Here, a possible approach is to sacrifice certain flexibility for better resource virtualization precision. Taking delay as the major performance metric, the effective bandwidth can be used to abstract the real-time transmission capability of wireless resources, and the computation frequency like FLOPS and Dhrystone million instructions executed per second (DMIPS) for computing resources with computing delay as the computation complexity divided by the frequency. As for isolation requirements, computation, storage, and wireless resources in space and air are mostly easy to isolate and slice. Wireless resources on the ground require more research efforts [13]. While the resources in large-scale SAGIN do not in general coexist, jointly optimizing SFC and mission offloading can potentially act as if the resources are available everywhere.

Service Function Chaining and Placement

When the accomplishment of a certain mission spreads over different geographical locations, for instance, the starting points and endpoints of the mission are not at the same spot, or the resources needed to support the mission are not co-located, SFC can plan the component VNFs of the mission and their corresponding virtualized network resources. The placement of VNFs is subject to the geographical distribution of computing, storage, and observation resources, as well as the bandwidth resources that connect them. The resources may also be shared and sliced by multiple VNFs from different missions. End-to-end processing delay of the mission serves as the performance constraint. The corresponding optimization method has been illustrated in our case study. In addition, one key challenge is to exchange the resource information among space, air, and ground networks, which can lead to high signaling overhead. Reducing such overhead can cause imperfect system information or prolong the acquisition delay, either of which can degrade the performance of SFC and placement.

Reconfiguration and Resource Scheduling

The aforementioned SFC-based reconfiguration should be performed at different timescales, depending on the proper decisions that trigger the reconfiguration and the delay required to accomplish the reconfiguration, as illustrated in

Resource	Reconfiguration trigger	Timescale	Scheduling basis
Time-frequency radio	Channel status variations	Seconds to minutes	Interference-aware
Pilots	User mobility	Seconds to minutes	N/A
Backhaul bandwidth	Baseband function splitting	Minutes	Co-design with caching
Computation	New task arrivals	Minutes	Computation task offloading
Storage	Content popularity and requests	Minutes and longer	Content update
Satellite orbit	Position changing/task arriving	N/A	Link scheduling

TABLE 1. Heterogeneous resource management for SAGIN reconfiguration.

Table 1. After the bidirectional mission offloading is established, the supporting SFC may have to be re-planned when the distribution of the network resources is changed, or other triggering events happen as listed in Table 1. Note that the reconfiguration process for replanning the SFC takes time, from collecting the necessary system information, and uploading and downloading the code to space-air nodes and ground nodes, respectively. It is vital to carefully trade off the benefits from reconfiguring as better matching to the resource distribution vs. the delay and overhead incurred. In some cases, merely optimizing the resource scheduling can guarantee the performance of mission offloading with low overhead before reconfiguration is inevitable. In short, the decision of when to perform reconfiguration or resource scheduling should be addressed as an online decision optimization under imperfect system information.

Security and Privacy

When seeking help from other networks via mission offloading, the data and code may be exposed to possibly untrusted entities, which can cause security and privacy threats to users. This calls for mechanisms to perform auto-intoxication in the mission offloading process, and to ensure data privacy and security. In addition, at the lower layer, jamming and eavesdropping from malicious entities should also be addressed, especially for missions offloaded from space-air to the ground. To this end, SFC should also be planned jointly considering the possible threats from jamming and eavesdropping. More interestingly, voiding secrecy threats can also be an important motivation of mission offloading. For instance, the UAVs can help to relay the information of a vehicle to another roadside unit (RSU) if the home RSU is jammed [14].

Summary

In this article, we have elaborated the bidirectional mission offloading framework in SAGIN, which makes full use of the complementary advantages of space-air networks and ground networks. The overall architecture of agile mission offloading, and the enabling network reconfiguration framework based on NFV and SFC, have been introduced and validated with a case study, which demonstrates the substantial performance gain in reliability and cost reduction. Finally, we have identified several key research issues to further exploit the benefits of bidirectional mission offloading in SAGIN.

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Biographies

Sheng Zhou [S'06, M'12] (sheng.zhou@tsinghua.edu.cn) received his B.S. and Ph.D. degrees in electronic engineering from Tsinghua University, Beijing, China, in 2005 and 2011, respectively. He is currently an associate professor in the Electronic Engineering Department, Tsinghua University. His research interests include cross-layer design for multiple antenna systems, vehicular networks, mobile edge computing, and green wireless communications.

Guangchao Wang (wgc15@mails.tsinghua.edu.cn) received his B.S. degree in communications engineering from Beijing Jiaotong University, China, in 2015. He is currently pursuing a Ph.D. degree in electronic engineering at Tsinghua University. His research interests include space-air-ground integrated network reconfiguration and UAV-aided traffic offloading.

SHAN ZHANG [S'13, M'16] (zhangshan18@buaa.edu.cn) received her Ph.D. degree in electronic engineering from Tsinghua University in 2016. She is currently an assistant professor in the School of Computer Science and Engineering, Beihang University, Beijing, China. She was a postdoctoral fellow in the Department of Electronical and Computer Engineering, University of Waterloo, Ontario, Canada, from 2016 to 2017. Her research interests include mobile edge computing, wireless network virtualization, and intelligent management.

ZHISHENG NIU [M'98, SM'99, F'12] (niuzhs@tsinghua.edu.cn) graduated from Beijing Jiaotong University in 1985, and got his M.E. and D.E. degrees from Toyohashi University of Technology, Japan, in 1989 and 1992, respectively. During 1992–1994, he worked for Fujitsu Laboratories Ltd., Japan, and in 1994 joined Tsinghua University, where he is now a professor in the Department of Electronic Engineering. His major research interests include queueing theory, traffic engineering, mobile Internet, radio resource management of wireless networks, and green communication and networks.

XUEMIN (SHERMAN) SHEN [M'97, SM'02, F'09] (sshen@uwaterloo.ca) is a University Professor with the Department of Electrical and Computer Engineering, University of Waterloo. His research focuses on resource management, wireless network security, social networks, and vehicular ad hoc and sensor networks. He is the Vice President of Publications of the IEEE Communications Society. He received the James Evans Avant Garde Award from the IEEE Vehicular Technology Society, and the Joseph LoCicero Award in 2015 and the Education Award in 2017 from IEEE Communications Society. He is a registered Professional Engineer of Ontario, Canada, an Engineering Institute of Canada Fellow, a Canadian Academy of Engineering Fellow, a Royal Society of Canada Fellow, and a Distinguished Lecturer of the IEEE Vehicular Technology Society and Communications Society.