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Space-air-ground integrated vehicular network for connected and automated vehicles: Challenges and solutions

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Abstract: Unlimited and seamless coverage as well as ultra-reliable and low-latency communications are vital for connected vehicles, in particular for new use cases like autonomous driving and vehicle platooning. In this paper, we propose a novel Space-Air-Ground integrated vehicular network (SAGiven) architecture to gracefully integrate the multi-dimensional and multi-scale context-information and network resources from satellites, High-Altitude Platform stations (HAPs), low-altitude Unmanned Aerial Vehicles (UAVs), and terrestrial cellular communication systems. One of the key features of the SAGiven is the reconfigurability of heterogeneous network functions as well as network resources. We first give a comprehensive review of the key challenges of this new architecture and then provide some up-to-date solutions on those challenges. Specifically, the solutions will cover the following topics: (1) space-air-ground integrated network reconfiguration under dynamic space resources constraints; (2) multi-dimensional sensing and efficient integration of multi-dimensional context information; (3) real-time, reliable, and secure communications among vehicles and between vehicles and the SAGiven platform; and (4) a holistic integration and demonstration of the SAGiven. Finally, it is concluded that the SAGiven can play a key role in future autonomous driving and Internet-of-Vehicles applications.

Key words: space information network; vehicular network; space-air-ground integrated network; autonomous driving; context information; Internet-of-Vehicles

1 Introduction

Due to recent fatal accidents with stand-alone autonomous driving, it becomes evident that safer and more reliable autonomous driving requires effective interaction and collaboration among vehicles and between vehicles and the Road Side Units (RSUs). As a result, ultra reliable and low-latency wireless communication technologies play vital roles. Being connected, vehicles can not only extend their sensing capability to reach blind spots, but also jointly process the sensing data and coordinate their driving decisions, leading to safer autonomous driving and more efficient road traffic. With these great potentials, the paradigm of connected vehicles has been widely regarded as the next frontier of automotive revolution. It has been predicted by International Data Corporation (IDC) that nearly 70% of worldwide or 90% of the United States' new light-duty vehicles and trucks will be shipped with embedded connectivity by 2023. Connected and automated vehicles are particularly important under the complex driving environment in China, where the road is full of mixed traffic such as cars, bicycles, and pedestrians. This is why

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the Chinese government has listed "connected vehicles" as one of the major national engineering projects.

Even though the past decade has witnessed the rapid development of vehicular networks, the proposed technologies for connected vehicles mainly depend on the terrestrial networks and therefore face with huge challenges. For example, the IEEE 802.11p network is not reliable enough due to its random access nature under unlicensed band, and it is also costly to deploy large-scale network infrastructure such as RSUs to support 802.11p. On the contrary, the 4G Long-Term Evolution (LTE) and the corresponding LTE for Vehicles (LTE-V) technologies are now widely available and quite mature, but its typical air-interface transmission latency is in the order of 100 ms, which is clearly not good enough for autonomous driving. In recent days, 5G networks have been developing rapidly worldwide, which commit (in theory) as low as 1 ms air-interface transmission latency. But, it will also face with coverage and reliability issues when it is applied to fast moving vehicles because of frequent handovers. Most importantly, many enabling applications in connected vehicles, e.g., autonomous driving, highly rely on high-precision vehicle sensing, massive data sharing with low latency, and high reliability guarantees, which are challenging for terrestrial vehicular networks.

On the other hand, precise positioning of moving vehicles in the order of 10 cm is also crucial for connected and automated vehicles. It is requested not only by autonomous driving, but also by the coordination and scheduling of the vehicles when they serve as moving computing servers. Again, the terrestrial wireless communication infrastructures cannot provide such highly accurate localization due to multipath fading, Doppler effect, unprecedent blockage, etc.

As the alternatives, the space and aerial networks, such as Geostationary Earth Orbit (GEO)/Low Earth Orbit (LEO) satellites, High-Altitude Platform stations (HAPs), and low-altitude Unmanned Aerial Vehicles (UAVs) platforms, are good at providing unlimited and seamless coverage as well as high-precision positioning services. Therefore, it is highly expected to integrate the terrestrial networks with space and aerial networks to better support the connected and automated vehicles. As a new network concept, the space-air-ground integrated vehicular network ("SAGiven" in short in the sequel) have the potential to provide massive real-time and reliable data sensing, collection, transmission, processing, and distribution as well as tailor-made vehicular information services.

However, both space/aerial platforms and ground cellular networks are not specifically designed for connected vehicles and, in most of the time, they are operated independently. In addition, the network functions as well as the network resources of these platforms are heterogeneous in nature and available only in some limited time and location. Therefore, how to efficiently integrate them is the fundamental challenge. For this purpose, innovative design ranging from network architecture to resource management schemes is indispensable.

To tackle the above-mentioned challenges, architecture and protocol design that coordinates the heterogeneous resources from the satellites, HAPs, UAVs, and terrestrial networks requires substantial research efforts. In addition, the SAGiven should adapt itself to the highly dynamic environment, which inevitably needs technologies like software-defined networking, network function virtualization, cross-layer resource management, and reconfiguration. These technologies must also work under incomplete system information due to the large network scale, hence mechanisms like machine learning, stochastic optimization, and game theory can be of great value. To support timely sensing and control for applications like autonomous driving, integration of wireless localization, online inference, and real-time wireless communications that goes beyond the Ultra Reliable and Low Latency Communication (URLLC) in 5G context will be of particular research interests. Finally, securing the operations and communications in SAGiven in a scalable and timely manner will inspire the research of wireless security from a new perspective. Therefore, it is believed that a wide range of studies in the related areas will lead to fruitful outcomes of both practical importance and theoretic merits.

In particular, the key challenges of SAGiven can be categorized into the following three areas: (1)

space-air-ground integrated network reconfiguration under dynamic space resources constraints; (2) multi-dimensional sensing and efficient integration of multi-dimensional context information; and (3) real-time, reliable, and secure communications among vehicles and between vehicles and SAGiven platform. This paper aims at providing a comprehensive survey on the state-of-the-art researches and developments on SAGiven, together with some key solutions for them. We will first give a general literature review of the SAGiven in Section 2 and then move to the detailed reviews of the three fundamental challenges in Sections 3 – 5, in which some up-to-date solutions are also provided. In Section 6, a holistic integration and demonstration of the SAGiven on top of a generic simulation platform with real GEO, UAV, and terrestrial network parameters are provided. In Section 7, a specific design of the SAGiven simulation platform is provided, while its real demonstration is given in Section 8. Key conclusions are drawn in Section 9.

2 Literature review of space-air-ground integrated vehicular network

The SAGiven is composed of three network segments, including space networks, aerial networks, and ground networks.

2.1 Space networks

The space networks mainly consist of network operations control centers, ground stations, and satellites[1], which can be classified into three categories: GEO, MEO, and LEO satellites. The Iridium company has launched 66 LEO satellites that compose a constellation at an altitude of 780 km[2]. The Iridium system is operated to provide global voice and data connectivities for typical mobile users. The Starlink project being constructed by SpaceX has launched 422 satellites to provide global broadband Internet services, whose cost is estimated to be about 10 billion dollars to design, build, and deploy the satellite systems[3]. This project also expects to create a satellite vehicular network, which provides mobile Internet access and dynamic networking for vehicles by using LEO satellites. One major advantage of the space networks is to provide ubiquitous and resilient services due to their global coverage. Some researchers have also proposed to converge the satellite and terrestrial networks to deal with the increasing traffic demands of the users[4], since the next generation GEO satellite systems are expected to achieve Tbit/s aggregated capacity. In Ref. [5], the authors proposed to apply cognitive radio to the satellite-vehicular networks to enhance the spectral efficiency and extend system coverage.

However, the Quality of Service (QoS) of real-time and interactive applications can hardly be guaranteed because of the high signal propagation delay of the satellite-ground links. Thus, towards the vehicular applications that require low latency and high reliability transmissions, the space networks currently mainly provide unidirectional management and control services such as localization, navigation, and high-precision clock synchronization. In Ref. [6], the authors proposed a satellite-ground link planning method to reduce the routing calculation and link switching overhead for navigation systems. In Ref. [7], a cooperative positioning method based on time-division multiplexing is proposed, which not only uses Global Positioning System (GPS) to provide vehicle position information, but also uses a high-precision clock provided by GPS for time slot synchronization. This method can be used for vehicle collision avoidance, emergency braking warnings, and other driving safety related applications. We can see that the space networks can provide macro and global information for vehicular applications. However, due to the cost, the latency, and the network stability, bidirectional interactive applications have not yet appeared. Therefore, the space networks have not really been able to cooperate with the ground vehicular networks.

2.2 Aerial networks

The aerial networks are constructed with various aircrafts, which carry sensors, transceivers, and processors to provide aerial communication access and data processing services[8,9]. The air networks mainly comprise HAPs, such as airships and balloons, and Low-Altitude Platforms (LAPs), such as UAVs. The HAPs are quasi-stationary aircrafts flying at an altitude of 17 – 22 km in the stratospheric region of the atmosphere[10], which have a wide coverage area, long residence time, and high probabilities of Line of Sight (LoS) connections. Compared with the satellite communication platform, the HAPs have good maneuverability, short communication response time, and low cost. The HAPs are typically deployed for broadcast/multicast services, emergency communications, disaster relief activities, and large-scale temporary events[11]. Some researchers have proposed that the HAPs are expected to be used for navigation and position location, intelligent transportation, and traffic monitoring applications in vehicular networks[12]. Google has begun the "Project Loon" since 2013, using stratospheric balloons to provide Internet access to remote and rural areas lacking coverage[13]. At present, the project is still in the experimental stage, and it needs to launch enough balloons to achieve stable area coverage. The authors in Refs. [14–16] investigated and evaluated the key system parameters such as the path loss and system capacity. It has been proved that the HAPs have the capabilities to provide high-throughput, low-latency network access to the ground users and meet the needs of broadband ubiquitous wireless connections.

With the cost reduction and popularity of quadcopters, low-altitude UAV communication, as an important supplementary part of the ground vehicular networking, has become a hot spot in recent years[17,18]. The UAV communication platforms have the characteristics of low response time, high throughput, highly reliable LoS transmission, and flexible maneuvering due to its close proximity to the ground. In Ref. [19], a vehicular networking platform based on air-ground cooperation is proposed, which forms an air subnet through multiple UAVs to assist ground vehicles to transmit road information. It can be used in emergency situations such as disaster rescue and polluted area investigation, where the ground infrastructures are destroyed. The air-ground channel modeling and delay performance of UAV-assisted vehicular networks is investigated in Ref. [20], which proves that using UAVs to serve as potential relays can improve the vehicular connectivity and data delivery delay performance. UAVs can also work as a temporary cellular base station, the resource allocation and trajectory control of which is studied in Ref. [21]. In Ref. [22], the authors designed and implemented an air-ground vehicular cooperative communication system, using the cameras and GPS information on the UAV to detect obstacles and navigate. The UAV-enabled vehicular communications still have many challenges. First of all, owing to rapid variations of network topologies and link channels, it needs to design effective coordination mechanisms to ensure the sustainability and stability of network services[23]. Moreover, UAVs are limited by the size and load of the fuselage, and their single flight time, communication, and computing capabilities are limited, which requires intelligent deployment and operation mechanisms. Last but not least, multiple UAVs networking and the interference management are also problems worth studying[18].

2.3 Ground networks

Ground networks are the main battlefields of current research on vehicular networks. In Refs. [24, 25], the authors systematically summarized the existing technology and the state-of-the-art of ground vehicular networks. The ground networks are composed of different types of terrestrial communication systems including cellular network, Vehicular Ad Hoc Network (VANET), Wireless Local Area Networks (WLANs), etc. VANET uses Dedicated Short-Range Communication technology (DSRC) based on the IEEE 802.11p protocol and is mainly used for road information sharing, collision avoidance, and transmissions of other safety warning messages[26,27]. Typical communication modes include Vehicle-to-Vehicle communication (V2V) and Vehicle-to-Infrastructures communication (V2I). DSRC technology has a simplified access mechanism resulting in fast connection establishment, low access delay, and high response speed. However, it lacks QoS guarantees and can only offer intermittent and short-lived connectivity. Thus, applications that require high throughput and stable links, such as raw image sharing and video streaming, can not be supported by DSRC. The 3rd Generation Partnership Project (3GPP) has conducted the standardization of LTE-based Vehicle-to-everything (V2X) communications to provide high throughput and highly reliable transmissions for vehicular networks[28]. Together with the evolution of cellular communication technologies, 3GPP has finished three phases of Cellular V2X (C-V2X) standardization. The first standardized C-V2X was introduced in Rel-14, which was completed in March 2017[29]. It introduces sidelink communications for PC5 interface to deliver some V2V safety use cases. In June 2018, the enhanced LTE-V2X (LTE-eV2X) was completed in Rel-15, which brings several features such as carrier aggregation, higher order modulation, diversity, and shorter Transport Time Interval (TTI)[30]. In Ref. [31], based on the Time-Division LTE (TD-LTE), a new protocol called LTE-V is proposed to integrate the centralized and decentralized architectures of cellular-based vehicular networks. With the development of 5G New Radio (NR), NR-V2X is studied as part of Rel-16, which has been frozen recently in July 2020[32]. It introduces vehicle QoS support to meet the ultra-reliability and low-latency communication requirements while maintain the backward compatibility with Rel-14 and Rel-15. C-V2X can be used for remote vehicle monitoring, real-time interaction of environment information, and infotainment systems that require high capacity and reliable communications. However, the communication cost is larger than DSRC. Drive-thru Internet technology is proposed to leverage WLANs to provide short-term Internet access and content distribution services with non-real-time requirements for the passing vehicles[33,34]. In Ref. [35], the authors proposed to utilize idle digital TV broadcasting spectrum to provide high-quality vehicular media streaming access applications for remote and rural areas. Integrating the current multiple wireless access technologies to achieve cross-platform vehicle interconnection is the current development trend and research focus of the ground vehicular network. As the vehicular networks are heterogeneous, dynamic, and large scaled, some researchers are taking efforts to apply Machine Learning (ML) to make both the vehicle and wireless communication highly efficient and adaptable[36]. Moreover, as a new type of network architecture, the Software-Defined Network (SDN) can separate the control plane and the data plane compared to the traditional network. Thus, it can achieve more flexible and efficient dynamic management and adaptation of network resources[37]. In Ref. [38], the authors proposed the SDN-based vehicular network architecture, and leveraged the programmability of SDN to achieve dynamic resource management and service reconfigurations.

We provide a comparison of different network segments in Table 1. Overall, the space networks can provide macro and global information but have expensive construction cost and high propagation latency. The air networks have low round-trip propagation delay, wide coverage, and high probabilities of LoS connections, so they have great potentials to provide delay sensitive applications for autonomous driving in depopulated areas where the ground network is not available. However, their resource capacity is limited due to the load limitations and the link is unstable due to the disturbance of the aircraft positions. The ground networks have high throughput, high reliability, and sufficient computation resources. However, their coverage is limited and the connection suffers from frequent handovers. The ground infrastructures are also vulnerable to natural disasters. We can see that these three network segments have distinct attributes and their own advantages. It has a great potential to achieve the complement of heterogeneous resources by integrating three network segments for vehicular

Table 1 Comparison of different network segments.

Segment	Entity	Altitude (km)	Round-trip propagation delay (ms)	Advantage	Limitation
Space	GEO	35 786	240	Global coverage, well-developed systems	High propagation latency, limited capacity, and high construction cost
	MEO	2000–20 000	13–130		
	LEO	160–2000	1–13		
Air	HAP	17–30	Less than 0.2	Large coverage, LoS transmissions	Limited capacity, link instability
	LAP	Up to 10	Less than 0.1		
Ground	Base Station (BS)	N.A.	Negligible	Sufficient resources, high throughput	Limited coverage, vulnerability
	RSU	N.A.	Negligible		

applications. However, these three segments are still working independently and have different protocols. Thus, the SAGiven urgently needs a collaboration mechanism to coordinate heterogeneous resources in such a large-scale network.

3 Reconfiguration under dynamic space resources constraints

The SAGiven is a multi-layer network composed of satellites, HAPs, UAVs, vehicles, road side units, and base stations. These networks operate independently and have a decentralized architecture. Each of them needs to serve different tasks and is not dedicated to the vehicular networks. Therefore, their available spectrum, computing, storage, and energy resources are highly restricted and dynamically changing with time. Furthermore, the topology of SAGiven changes dynamically, and the resource constraints and link performance have large randomness, making it difficult to coordinate the space, air, and ground resources. The SAGiven is required to provide "immersive" experience for autonomous driving, where the vehicles can perceive, process, integrate, deliver, interact, and share context information from multi-dimensional networks in real time. In order to support the "immersive" experience and to ensure the safe and timely delivery of control information for autonomous driving and intelligent traffic scheduling, it is necessary to integrate and complement the restricted heterogeneous resources to realize the cooperation of different network segments in SAGiven.

We have two unresolved fundamental issues:

(1) How to establish a representation and virtualization method for multi-dimensional heterogeneous resources of SAGiven to enable dynamic reconfiguration and service scheduling?

(2) How to complement heterogeneous resources of different network segments to make best use of their advantages?

In the following parts of this paper, we will introduce the challenges of these two problems and the state-of-the-art researches. We also provide a comprehensive overview of Service Function Chaining (SFC)-based network reconfiguration and bidirectional mission offloading, which are the potential solutions for the above two issues, respectively.

3.1 SFC-based network reconfiguration

The immersive vehicular applications have diverse requirements. The requirements for the coverage, bandwidth, delay, jitter of the communication link, and the capacity of the computing resources vary greatly among applications. It is difficult to satisfy them all through a single design, which brings a great challenge. Network Function Virtualization (NFV) decouples the abstract requirements of an application from specific physical bearers by introducing an intermediate entity, i.e., Virtual Network Function (VNF), which simplifies system design and increases flexibility. NFV technology can customize traditional network functions into software components which are implemented on general-purpose computing hardware[39]. In this way, VNFs can be flexibly deployed or reconfigured on any network nodes as needed, greatly increasing network flexibility and robustness[40]. Moreover, since the network is easily compatible with the newly added VNFs to handle new services, the scalability of the network is also increased.

Some researchers have investigated how to integrate all or part of the SAGiven based on SDN and NFV technologies. In Ref. [41], the authors proposed a software defined satellite-terrestrial network architecture to jointly manage and orchestrate networking, caching, and computing resources. An SDN-based spectrum sharing and traffic offloading mechanism is proposed to achieve the cooperation and competition between satellite and cellular networks in Ref. [42]. Based on SDN, the authors in Ref. [43] proposed a hierarchical network architecture that integrates HAPs, LAPs, and cellular networks to improve the capacity and coverage in a cost-effective manner. In Ref. [44], the software defined SAGiven is proposed to satisfy diverse QoS requirements of emerging applications. Via integration, the network can provide global ubiquitous access, low latency, high bandwidth, and highly reliable communications, and support applications that require large amounts of storage and computing resources.

Nevertheless, how to distinguish different services and dynamically match service demands onto physical resources is still an important issue that has not yet been resolved. Based on SDN and NFV, we propose to apply the concept of SFC to SAGiven, to flexibly implement and reconfigure diverse services with dynamic resource allocation, as shown in Fig. 1[45]. In SFC, the data flow needs to flow through several required VNFs in a specific sequence to implement a specific service. Thus, diverse applications in SAGiven, such as collision avoidance, intersection traffic scheduling, positioning, remote driving, etc., can be identified by different service function chains. Using NFV, the heterogeneous physical resources from different network segments are abstracted into unified virtual resource pools for flexible resource allocation. The SFC technology enables the system reconfiguration, making the service provisioning dynamically adapt to changing requirements. When application requirements change, or resource constraints change (since the computing and communication resources of space/air nodes usually need to be shared with a variety of other existing tasks, and the requirements of these tasks are usually time-varying), the services can be reconfigured simply by updating the software or the SFC deployment. Applying SFC in SAGiven faces two essential issues: (1) how to embed VNFs onto optimal physical network nodes to achieve best resource utilization efficiency; (2) how to route the service data among required VNFs under QoS constraints.

Some researchers are taking efforts to address the SFC deployment and resource allocation issues in traditional wired and cellular networks[46, 47]. In Refs. [48, 49], the VNFs embedding problem in NFV-based wired networks is considered to optimize the operational cost, which is formulated as an integer programming problem. A dynamic-programming based heuristic algorithm is proposed in Ref. [48]. The heuristic algorithm proposed in Ref. [49] is divided into two sub-algorithms, which solve traffic scheduling and multi-path selection, respectively. In Ref. [50], the authors addressed the SFC deployment problem in cellular networks and proposed a heuristic algorithm to minimize the bandwidth utilization. The SFC deployment problem

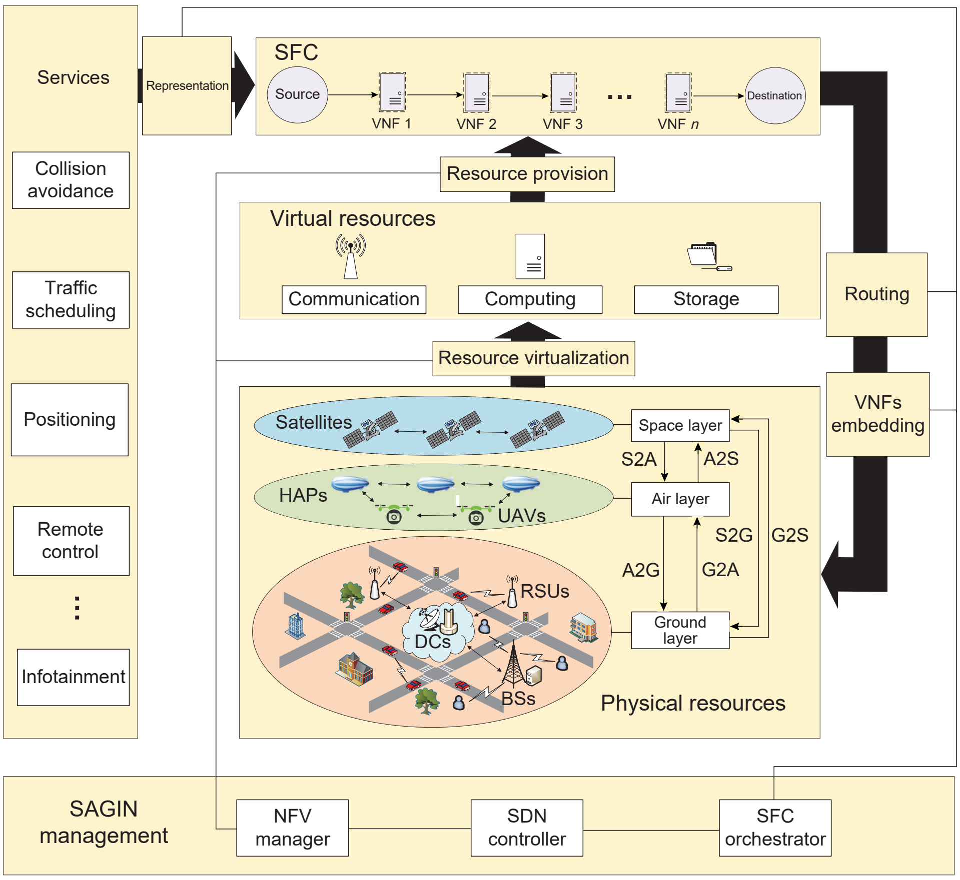


Fig. 1 SFC-based service management and reconfiguration framework for SAGiven.

in datacenters is investigated in Refs. [51, 52]. In Ref. [51], the SFC deployment problem is formulated as a mixed integer programming problem to maximize the reliability of network service under delay constraints. The proposed heuristic algorithm only takes end-to-end delay into account when designing the weight of communication links. The objective in Ref. [52] is to minimize the computing resource utilizations under time-varying workloads constraints, and a two-stage heuristic algorithm is proposed to solve the problem. Existing works mainly consider traditional wired or wireless networks to optimize resource utilizations under different QoS constraints. The limitations have two aspects: (1) physical network nodes have no differences; (2) the trade-off between communication and computing resources is handled, which is important in SAGiven. For example, in SAGiven, the service flow passing through the space/air network node can significantly reduce the transmission hops, which saves communication resources on the ground at the cost of high computing resource consumptions in the space/air.

We address the SFC deployment problem in SAGiven to optimize the resource management of heterogeneous network nodes and balance the resource consumptions of computations and communications[53, 54]. First of all, various types of network nodes need to be distinguished by the coverage and processing capabilities. The space/air nodes typically have full connections with ground nodes but lack computing resources. The ground nodes have limited coverage, but have cheap computing resources. Moreover, a specific VNF can be shared by multiple chains to save computing resource. However, the service flow may experience more hops to reach the VNF, which increases the communication resource consumptions. Thus, the level of function sharing should be identified to achieve the trade-off between communication and computation resources. Based on these considerations, we formulate the SFC deployment problem in SAGiven as an Integer Non-Linear Programming problem (INLP). Then, a heuristic algorithm with low complexity is proposed, and is shown to achieve near-optimal performance. The heuristic takes different features of aerial and ground nodes into considerations. Specifically, we allocate a higher priority to the ground nodes to make full use of its cheap computing resources. When the end-to-end delay can not be guaranteed or the communication links are saturated on the ground, the space/air nodes can be used to reduce the communication hops. The routing path is selected in a greedy manner, the weight design of which refers to the QoS requirements, the level of function sharing, and bandwidth capacity. We choose network nodes along the selected path according to available computing resources and the level of function sharing for VNF embedding. Furthermore, we propose a new metric, Aggregation Ratio (AR), to identify the the level of function sharing. The trade-off relationship between communication and computing resources is achieved via tuning AR. We find that when the bandwidth requirement of the service is small, at the cost of a small amount of communication resource consumptions, a large amount of computing resources can be saved by increasing AR. Reversely, when the bandwidth requirement of the service is large, a slight increase in the cost of computing resources can be exchanged for a large amount of communication resources by decreasing AR. Compared with independent networks, we verify that the SAGiven can significantly reduce the service blockage probability and save 12.5% to 45.1% of resources for implementing each service.

3.2 Bidirectional mission offloading

In SAGvien, the space/air networks have wide-range coverage, which can reduce the number of transmission hops as a relay node, thereby reducing the delay. However, their resources are constrained by the load of the aircrafts or satellites, which are very scarce. Reversely, the ground networks have rich resources and limited coverage. To make full use of the complementary advantages of different network segments in SAGvien, we propose the concept of bidirectional mission offloading, as shown in Fig. 2. The ground missions are defined as the missions originally carried out in ground networks, which are mainly communications that need to pass through the core networks with multiple hops. The space/air missions are defined as the missions originally carried out in space/air networks, which are mainly computations that require high-speed processing

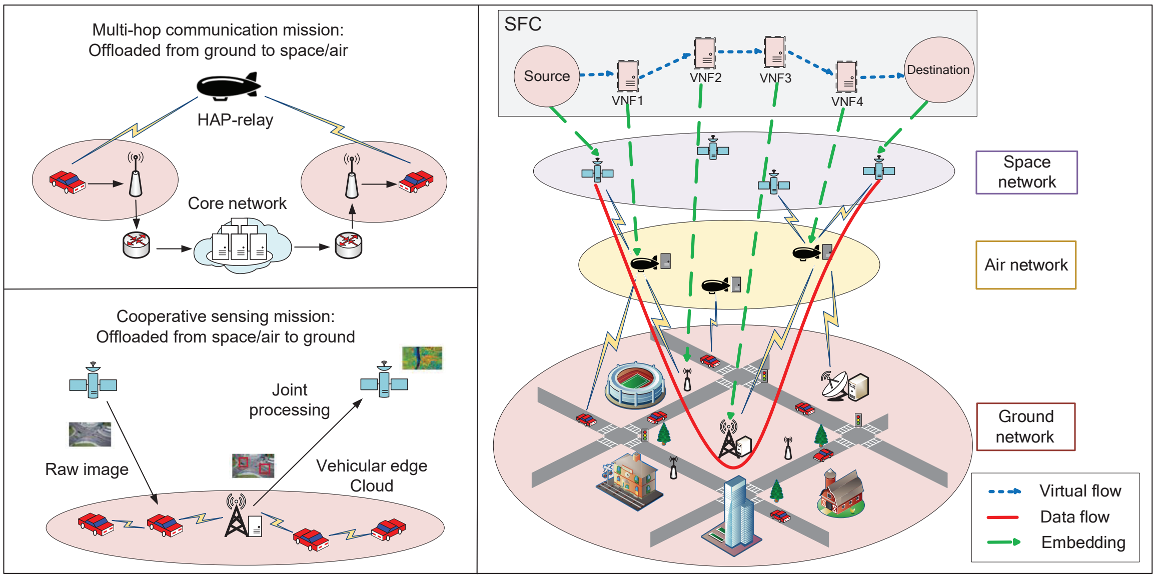


Fig. 2 Bidirectional mission offloading in SAGvien.

capabilities.

The ground missions can be offloaded from ground to space/air on demand, which can reduce the communication delay with fewer hops. Moreover, vehicular communications with high mobility can be supported due to low handover frequencies in space/air networks. The space/air missions, such as intelligent sensing and information processing, can be offloaded from space/air to ground to make use of abundant ground resources. As the computation intensive on-board processing is offloaded, the power consumptions of space/air facilities are effectively reduced, thereby enhancing the system sustainability. Furthermore, the additional processing capability also brings opportunities to develop new space/air intelligent applications, such as autonomous flying.

In Ref. [55], we have verified the feasibility of bidirectional mission offloading in SFC-based network reconfiguration framework through a case study. We find that the sustainability of space/air nodes is notably increased by bidirectional mission offloading. We also demonstrate that the efficiency of resource utilization and the service reliability are substantially improved. In Ref. [56], we further investigate two important problems in bidirectional mission offloading:

(1) Radio resource allocation: How to allocate radio resources for the two types of missions?

(2) Offloading strategy: How many missions should be offloaded according to the network status?

We jointly optimize the radio resource allocation and offloading strategy and formulate a non-convex optimization problem. We first derive the closed-form expression of offloading strategy. Then, we prove that the optimal radio resource allocation locates at the boundary of feasible domain. Based on the analysis, we propose a heuristic algorithm to solve the joint optimization problem and it is shown to achieve near-optimal results. We find that the ground mission offloading is necessary when the ground network is congested, otherwise ground missions are offloaded only when the link capacity is larger than a threshold. The closed-form expression of the threshold is also derived. We also validate that bidirectional mission offloading can significantly reduce the end-to-end delay under different mission arrival rates.

4 Multi-dimensional and multi-scale context information sensing and integration

4.1 Integration of radar and communication systems

Autonomous vehicles are required to navigate efficiently and safely in a wide variety of complex environments. To meet these requirements, the self driving cars must be able to reliably sense and interact with their surroundings, which include the sensory information as well as data communication with neighbor vehicles, RSUs, and other numerous obstacles to avoid, all in real-time. Due to their similarity on the transmission and processing of electromagnetic signals, it is attractive to jointly design the radar and wireless communications as an integration system, i.e., the RadCom system. In addition to the LIDAR, camera, and other sensors, radar can provide the relative velocity of the target as well as the range. It will be helpful especially in complex driving environments, by which the target identification can be greatly enhanced.

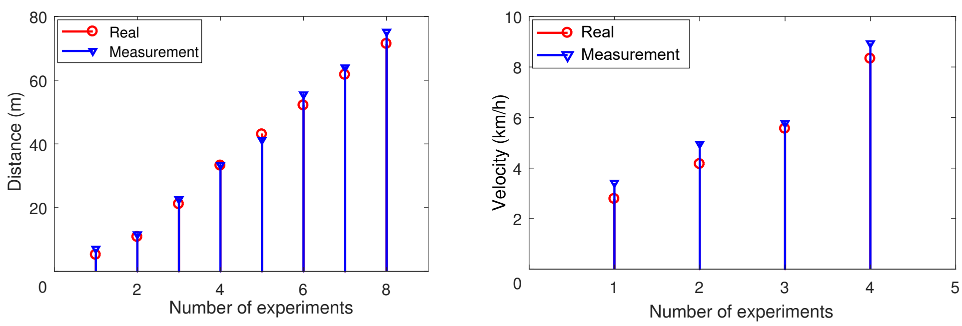
We implement an Orthogonal Frequency Division Multiplexing (OFDM) based RadCom system with the carrier frequency at 5.7 GHz, and 55 MHz bandwidth, using the USRP platform. In the proposed RadCom system, the information data are modulated on the OFDM radar waveform. Therefore, the dual function of RadCom can be fulfilled simultaneously on the same frequency band and on the cost of the communication data rate. As shown in Fig. 3, practical experiments are also carried out to detect a vehicle in a typical urban environment. Both range and velocity of the vehicle are evaluated, using the Time Of Arrival (TOA) estimation, and the low complexity Doppler processing algorithms. In Fig. 4, we can see that the proposed RadCom system can achieve sub-meter (actually within 50 cm) ranging accuracy, which is promising in autonomous driving.

4.2 UAV-aided high accuracy vehicular positioning

Location awareness is essential for those location-based services in vehicular networks. In order to improve the positioning accuracy, we introduce collaborative localization technologies for relative vehicular positioning in the space-air-ground integrated vehicular network. The space-based satellites and ground-based stations are used as anchors to provide the spatiotemporal reference. UAVs provide higher-precision relative positioning to support the ground vehicles after obtaining positioning from satellites and base stations, as shown in Fig. 5.

(1) Relative vehicle localization: First, we introduce the theory of relative localization. Most of the existing studies focus on the absolute localization performance

Fig. 3 Integration of radar and communication systems.



(a) Distance measurement (b) Velocity measurement

Fig. 4 Range and velocity estimations in practical RadCom systems.

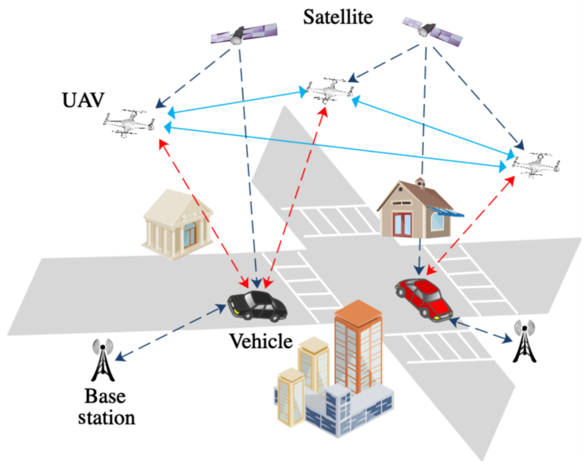


Fig. 5 An illustration of proposed relative vehicular positioning architecture in SAGiven.

of vehicles while the relative localization is not widely investigated. The relative relationships between vehicles are often more pertinent for cooperative tasks such as formation driving. Absolute position error refers to the distance between the estimated position and the real position. And relative position error refers to the error on the network geometry, i.e., it evaluates the "shape" of the network topology[57–59], as shown in Fig. 6.

In such a relative vehicular positioning scenario, we design centralized and distributed positioning algorithms. In the centralized case, we relax the non-convex problem of relative positioning into a classic Semi-Definite Programming (SDP) solution. In the distributed case, the distributed iterative gradient descent method is used to get the relative position of vehicles.

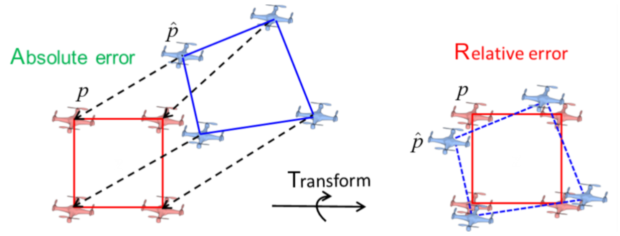


Fig. 6 An illustration of absolute and relative position errors (p: real position of UAV; $\hat{p}$: estimated position of UAV).

Additionally, we perform resource allocation with positioning performance as the optimization goal, and prove that the optimal allocation can be converted to an SDP problem. The simulation results show that the ground base station can greatly reduce the three-dimensional vehicular positioning error, especially to reduce positioning error in height, as shown in Fig. 7a.

Furthermore, resource allocation optimization can greatly reduce vehicular positioning errors as shown in Fig. 7b. For example, vehicular positioning error can be reduced by 2.3 times in the case of 5 UAVs. At the same time, we find that the network measurement under the optimal resource allocation solution presents an aggregated characteristic, i.e., only a small number of links in the network are needed.

In brief, the proposed relative vehicular positioning algorithm can meet sub-meter level positioning accuracy and the resource allocation scheme can greatly reduce the resource overhead, which can provide insights for accurate and real-time vehicular positioning system.

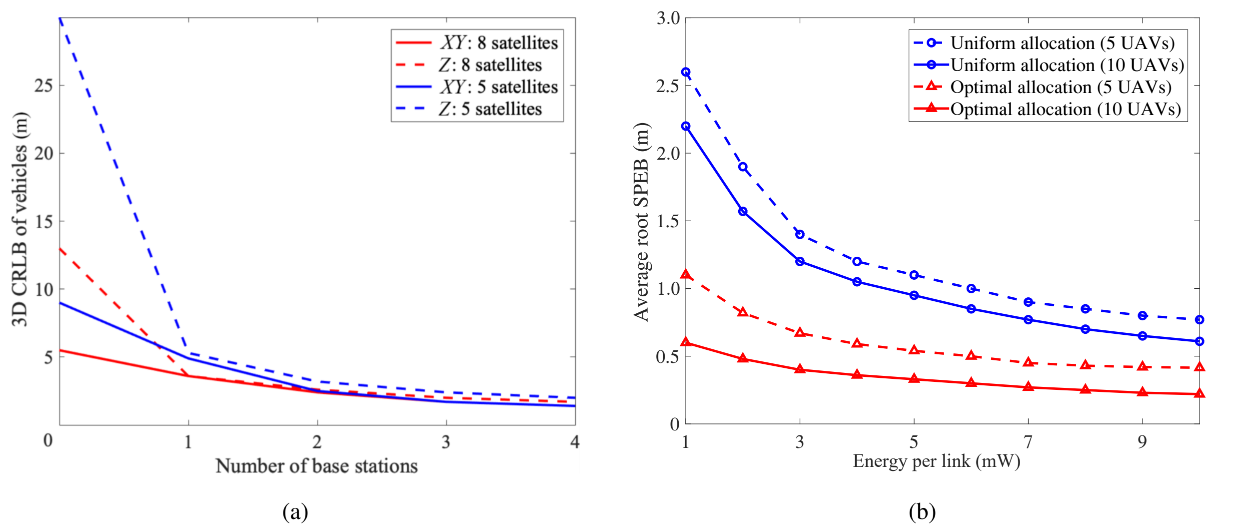


Fig. 7 (a) Three-dimensional Cramér-Rao Low Bound (CRLB) of vehicle positioning error with respect to the number of base stations. (b) Average root Squared Position Error Bound (SPEB) with respect to the energy of each link.

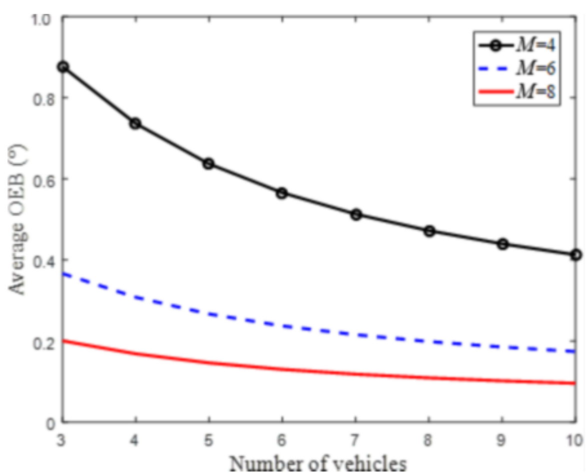
(2) Single-station positioning based on antenna arrays: As is known to all, cooperation through multi-base stations can improve positioning accuracy, but the conditions of multiple base stations may be difficult to meet in an urban environment, e.g., the base station may cause Non-Line-Of-Sight (NLOS) propagation due to occlusion. In this subsection, we propose a single-station positioning technology based on antenna arrays. The station is equipped with antenna arrays to measure azimuth, and vehicles fuse each other's position information through collaboration. The excellent performance of the proposed single-station positioning technology has been proved by simulation results, and some conclusions can be drawn as follows: Figure 8a proves that the accuracy of angle estimation increases with the number of collaborative vehicles; Fig. 8b shows that the positioning accuracy increases with the number of array elements, and the best performance is achieved when the array radius is half of the wavelength (the position results blur when the array radius is greater than half of the wavelength).

In general, the proposed scheme is able to grantee the positioning accuracy below the sub-meter level and the angle estimation accuracy below one degree, which enables the vehicles to maintain high-precision positioning capability even when multiple base stations are unavailable.

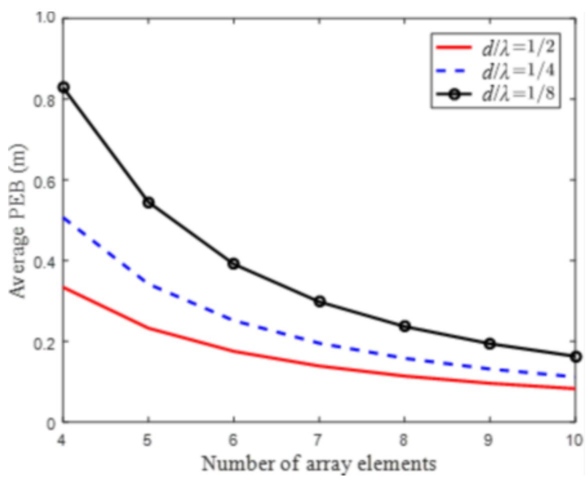
(3) Non-ideal factors affecting the positioning: During the positioning process, there will be many non-ideal factors affecting the positioning result. Nodes in the space-air-ground integrated vehicular network are not perfectly synchronized due to clock noise, which will cause the error of ranging measurement. NLOS is prone to occur on the ground due to block of the line-of-sight link, which will also have a crucial impact on high-precision vehicular positioning. We explore the impact of NLOS and clock noise in the proposed vehicular positioning network.

Our simulation results reveal that sub-meter positioning accuracy requires the clock noise of anchors at the nanosecond level. For example, the required standard deviation of clock noise is 5 ns in the simulation scenario when both satellites and base stations are utilized, as shown in Fig. 9a. Regarding the NLOS effects, the simulation in Fig. 9b shows that the space-air-ground integrated vehicular network can greatly reduce the error of positioning by mitigating the effect of NLOS, where P_1, P_2, and P_3 stand for the probability of NLOS links for satellites, base stations, and vehicles, respectively.

In short, NLOS and clock errors will adversely affect the positioning system. The possible solution is to increase the level of clock synchronization and the probability of LOS links in the integrated vehicular network.



(a)



(b)

Fig. 8 (a) Average Orientation Error Bound (OEB) with respect to the number of vehicles. *M* represents the number of antema elements. (b) Average Position Error Bound (PEB) with respect to the number of array elements. *d* represents the distance of antenna arrays and λ represents the wavelength of signal.

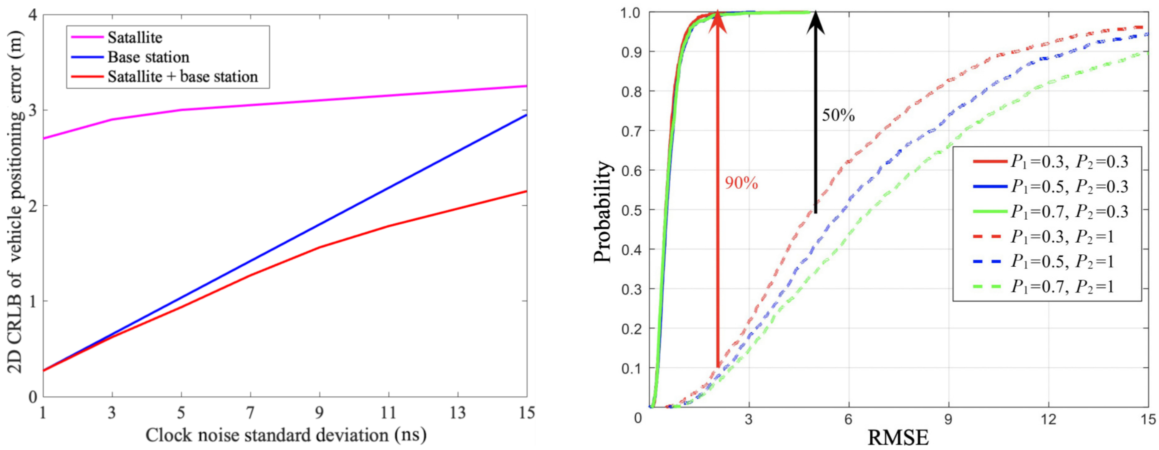


Fig. 9 (a) Two-dimensional CRLB of vehicle positioning error with respect to the clock noise standard deviation of anchors. (b) Failure probability of the network with respect to different NLOS probabilities. Here, RMSE represents root mean square error.

5 Real-time, reliable, and secure communications

SAGiven provides bigger scope and more comprehensive context information for connected autonomous vehicles, which greatly makes autonomous driving close to high-level (L4 and L5). Real-time, reliable, and secure communications in V2X are specially requested by vehicular network applications. For example, high-level (L4 and L5) autonomous driving usually requires real-time status and context information sharing to enable cooperative vehicle maneuver, dense platooning, etc. The closed-loop communication latency, consisting of sensory data collection, information dissemination, data processing, and control decision, should be less than 10 ms, together with very low delay jitter, and higher than 99.999% reliability.

However, the complex cross-region and topological high dynamics of nodes in the SAGiven make it challenging to achieve real-time, reliable, and secure communications. Therefore, we need to explore the efficient interaction mechanism of context information in the SAGiven. As a result, there has been extensive activities developing technologies like URLLC in 5G and beyond. Some early evaluations report that 3GPP Release 15 has achieved user plane latency of 1 ms and control plane latency of less than 20 ms, and that wireless protocols designed specifically for factory automation, such as Wireless Interface for Sensors and Actuators (WISA), can achieve a closed-loop latency less than 10 ms. It should be noted that, however, these results are obtained in highly idealized scenarios. For example, the system is lightly loaded for 5G tests, and dedicated time/frequency resources are allocated to terminals in WISA assuming no system dynamics. Actually, URLLC reflects the long standing challenge of completely characterizing the non-asymptotic fundamental tradeoffs among delay, throughput, and error probability in wireless networks.

To this end, we propose an alternative perspective for URLLC to enable real-time communications for connected and automated vehicles. Here, connected and automated vehicles can be abstracted as Wireless Networked Control (WNC) systems, i.e., one or several controllers collect status information from distributed terminals through a wireless network, and then make control decisions based on the collected status information. For example, in automated platooning the lead vehicle collects status information from followers, and carries out the control decisions and sends to following vehicles. It is clear that the control performance is highly related to the distortion between the perceived and real status. The distortion stems from several aspects: limited sensing, communication, and control capabilities, etc. Besides the status distortion, the requirement for timely information also relies on the context in the system. Taking platooning as an example, when the vehicles are in high speed or the head car pulls off suddenly, more accurate information should be disseminated to the cars in the fleet in order to avoid collision. Therefore, to ensure the timeliness of information delivery and the effectiveness of control, status updates should adapt to the context of the system and the dynamics of the status. To this end, to measure the timeliness of status updates in remote control systems, we propose a new metric called the *Urgency of Information* (UoI) (previously the context-aware information lapse in Refs. [60, 61]), which is defined as the product of weight $\omega(t)$ and cost $\delta(Q(t))$:

$$F(t) = \omega(t)\delta(Q(t)) \tag{1}$$

where we denote the actual status of a continuous signal at time t by $x(t)$, the estimated status by $\hat{x}(t)$, and the estimation error at time t by $Q(t) = x(t) - \hat{x}(t)$. The performance degradation caused by status estimation distortion is denoted by $\delta(Q(t))$, where $\delta(\cdot)$ is a non-negative even function (e.g., norms, quadratic function). The time-varying context weight is denoted by $\omega(t)$. When the system is at a crucial situation, the corresponding context-aware weight $\omega(t)$ is large, and vice versa. There is a similar concept called the Age of Information (AoI) in Ref. [62]. However, AoI fails to measure the non-linear impact of the information freshness and also ignores the significance of the context information. Therefore, UoI is defined to capture the performance degradation caused by the non-linear and context-dependent effect of the information latency. Based on the new metric, we propose a transmission scheduling scheme to reduce the average UoI of a multi-access network for status updates. The decentralization of the scheduling policy is also proposed, which enables independent implementation at each terminal and reduces potential transmission collision by fine-tuned Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA). We have shown that using the proposed UoI has notable advantages in terms of remote control performance, via simulations for multiple Cartpoles and via real testbed for platooning toy cars, where the minimum inter-car distance can be notably reduced to guarantee safety compared with pure latency-aware status update schemes.

On the other hand, high mobility deteriorates the link quality of V2V and increases the collisions rate in contention-based random Media Access Control (MAC)-layer procedure, which produces more data packet retransmissions. The mobility also causes a low channel utilization, because vehicles are uneven distributed with variation of space time and the network topology changes frequently. In addition, the frequently changing topology makes the nodes need more time to update the state information of neighbor vehicle nodes in the network, which slows down the speed of vehicle access channel. Thus, the design of MAC-layer multiple access protocols becomes challenging.

The multiple access protocols in the V2X MAC layer have three categories: (1) Distributed control access. Nodes in the network randomly access the channel through contention. DSRC and random-access-based Time Division Multiple Access (TDMA) are such classical protocols. Generally speaking, by optimizing the backoff-based competitive transmission process and the related system parameters, the channel congestion can be greatly alleviated and the message collision can be effectively reduced[63, 64]. (2) Centralized control access. One way is to allocate the data transmission channel for vehicle nodes through the base station or roadside unit, so as to ensure the reliability of message transmission[65]. Another way is a cluster-based scheme, where the cluster is formed by the adjacent vehicles. The cluster-head as a control node can coordinate the channel allocation and improve the channel resource utilization[66]. At present, SDN technology develops rapidly. By introducing the SDN centralized controller into VANET, the flexibility of multiple access can be increased and the control plane latency can be reduced[67]. (3) Hybrid multiple access. LTE-V is the classical protocol that has both the distributed and centralized multiple access. In LTE-V, the centralized control model of base station to terminals and the decentralized direct connection mode of Device-to-Device (D2D) are combined. It is evolving to the 5G/B5G to support the differentiated demand of latency and reliability from various internet of vehicle applications[68].

In certain physical layer hardware environment, data transmission delay in network mainly depends on multiple access techniques in the MAC layer and routing mechanisms in the network layer. We study the distributed multi-channel MAC protocol and propose an adaptive MAC-layer frame structure scheme for different message types, such as safety and non-safety messages. It improves the channel utilization and reduces the MAC-layer latency[64].

Routing stability of nodes is weak due to the frequent change of vehicular network topology. The routing mechanism in V2X can be divided into three categories: (1) Position-based message propagation mechanism. The GPS is used to obtain the location information of nodes, and the forwarding path is selected according to the locations of destination node and neighbor nodes. A typical example is Greedy Perimeter Stateless Routing (GPSR) which was first proposed by Karp B and others in 2000. In the GPSR mechanism, the source node uses the location of the neighbor node to calculate the distance between the neighbor node and the destination node, and selects the next hop node based on the distance information[69]. (2) Topology-based message propagation mechanism. The link information is mainly used to select the message propagation path from the source node to the destination node, such as Destination-Sequenced Distance-Vector (DSDV)[70]. Optimized Link State Routing (OLSR)[71] is a typical topology-based routing protocol. (3) Broadcast-based message propagation mechanism. The easiest way to broadcast is flooding.

The combination of the space-air network and the VANET can greatly enhance the connectivity between mobile vehicles on the ground and improve the real-time and reliability of information transmission on V2X. A Drone Assisted Vehicular Network (DAVN) architecture that simultaneously integrates UAVs and infrastructure is proposed, in which the UAV acts as a relay to transmit emergency information of road conditions or delay-constraint data between the UAV and vehicles while vehicles outside the coverage of the RSU or in the coverage hole[72,73]. The reliability of UAVs as relay nodes is significant for message transmissions. Utilizing energy loss, interrupt probability, and bit error rate as reliability measures, the optimal deployment location of UAVs can be achieved by using the convex optimization methods[74,75].

In many existing routing schemes, the lack of maintenance scheme on easily broken routes increases the times of the route reestablish and the network latency. Therefore, we propose a preemptive local repair strategy, which reduces the probability of route interrupting due to the link broken and the delay of starting route discovery process after the route is broken. Because the SAGiven has an open wireless channel and a dynamic network topology, V2X routing is vulnerable to hostile interference and other malicious attacks. We propose a reinforcement learning-based UAV relay scheme against smart jamming attacks, which derives the Nash equilibrium of the UAV anti-jamming transmission game and uses the Policy Hill Climbing (PHC) algorithm to choose the UAV relay policy without knowing the specific UAV-ground channel model and attack model[76]. As illustrated in Fig. 10, OBU_i sends the sensing messages with a fix transmit power to the server via the RSU_1 or the UAV. The UAV relays the OBU messages with the power P_{U} to the RSU_2 that is too far away from the jammer and not easy to be attacked. The jammer applies smart radio devices to eavesdrop the control channel of the VANET and sends jamming signals with a smart jamming power y to block the transmission between the OBU and the RSU_1.

As shown in Fig. 11, the SINR ρ_1 between the UAV and the OBU_i, the SINR ρ_2 between the RSU_1 and the OBU_i, the SINR ρ_3 between the RSU_2 and the UAV, and the Bit Error Rate (BER) of the OBU messages are used to formulate the system state s. The UAV chooses the relay policy x under the state

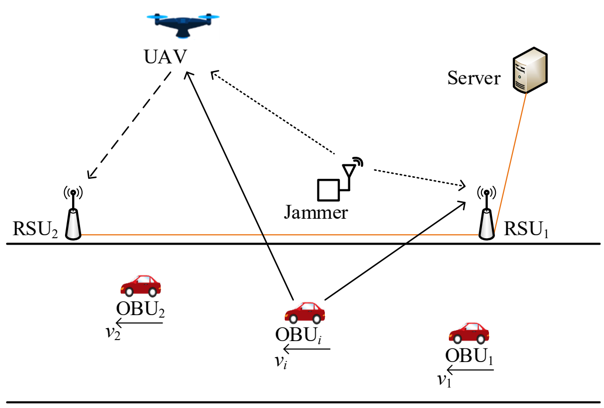


Fig. 10 Illustration of a UAV-aided VANET, in which the OBU moving with speed v sends a message to a server via the serving RSU_1 and the UAV.

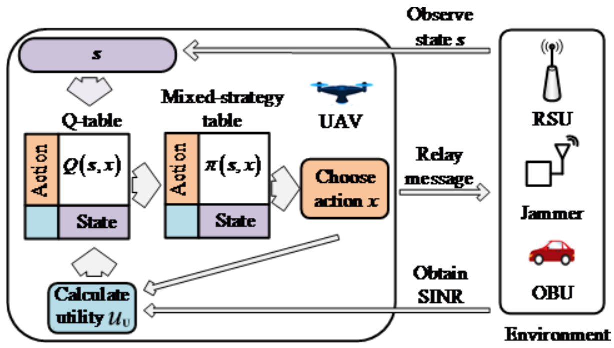


Fig. 11 Illustration of the Reinforcement Learning (RL) based UAV relay anti-jamming scheme.

s based on the policy distribution $\pi(s, x)$. The UAV uses the SINR of the received signals and the energy consumption to obtain the utility $u_{\rm U}$, updates the Q-value $Q(s, x)$ according to the Bellman equation, and then updates the policy distribution $\pi(s, x)$ based on the Q-value $Q(s, x)$. Simulation results show that the proposed scheme reduces the BER of the OBU messages compared with a standard Q-learning based relay scheme.

The SAGiven security mechanisms mainly include authentication, encryption, and physical layer security mechanisms[77]. The SAGiven uses an encryption mechanism to implement broadcast authentication, and uses key pairs to protect the exchange of data information between vehicles. Here, Ref. [78] proposed a VANET authentication scheme, which uses Revest-Shamir-Adleman (RSA) encryption technology to generate a pseudonym for each vehicle quickly. It uses online/offline signature technology based on elliptic curve cryptography identity authentication in vehicle-to-vehicle communication. Meanwhile, it is able to improve efficiency of identity authentication between the vehicle and the infrastructure such as roadside units. However, the encryption and authentication-based schemes have large calculation and storage overhead. The delay of authentication cannot meet the requirements of the SAGiven. In addition, malicious attacks can undermine key security by hijacking normal vehicle nodes[78]. In order to reduce communication and computational overhead, physical layer characteristics of signals such as the received signal strength are utilized to detect malicious nodes in the SAGiven[79].

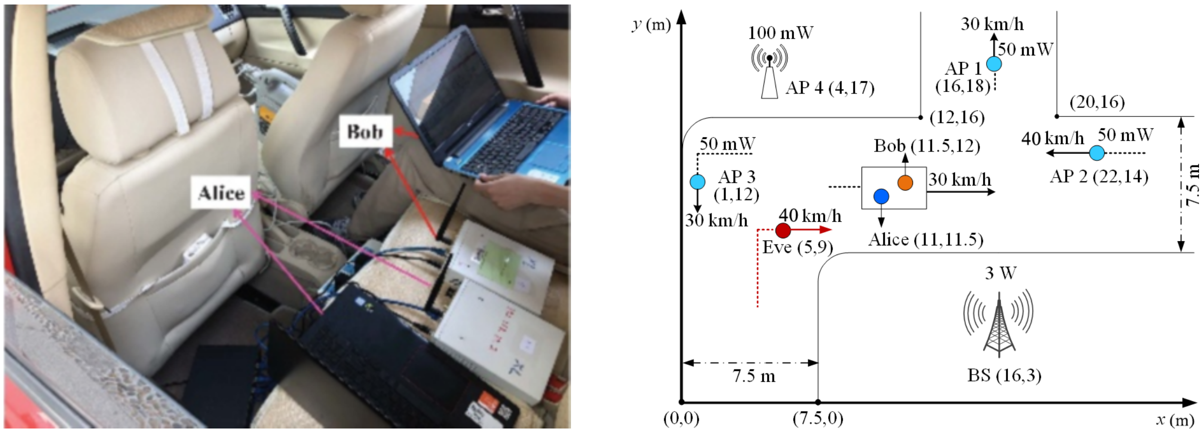
The security authentication based on physical layer characteristics of signals shows advantages[80,81]. On the one hand, it reduces the calculation and communication overhead of the authentication process without strong calculation capabilities. On the other hand, the uniqueness of the physical layer fingerprints effectively overcomes the problem of key leakage of the traditional upper layer encryption algorithm. Thus, we propose a metric deep learning algorithm for signal feature extraction and recognition in the physical layer of the air-ground node. The multi-target open class individual feature representation calculation model network, wireless Signal classification based on Triple Loss Network (SigTLNet), is established based on the triple metric loss function. By judging the characteristic distance of the signal, the legal and malicious nodes can be effectively identified, which solves the problem that a lot of storage space of sample data needed and the difficulty of the complete sample dataset collection in traditional identification methods.

We propose a Deep Reinforcement Learning based Physical-layer Authentication (DRLPA) scheme to resist rouge edge attacks in vehicular ad hoc networks, which exploits the channel states of the received signals and the shared ambient radio signals of the mobile device and its serving edge device during the same moving trace[82]. More specifically, the channel vector $\boldsymbol{H}$ and the physical-layer features of the ambient radio signals denoted by $\boldsymbol{F}$ consisting of the received signal strength indicator and the arrival interval are used to compare with the channel state record $\hat{\boldsymbol{H}}_A$ and the ambient feature record $\overline{\boldsymbol{F}}$ via a hypothesis test, and the test statistic denoted by $\varDelta$ is calculated by

$$\varDelta = \frac{\|\boldsymbol{H} - \hat{\boldsymbol{H}}_A\|^2}{\|\hat{\boldsymbol{H}}_A\|^2} + \frac{(x_0 - 1)\,\|\boldsymbol{F} - \overline{\boldsymbol{F}}\|^2}{\|\overline{\boldsymbol{F}}\|^2}.$$

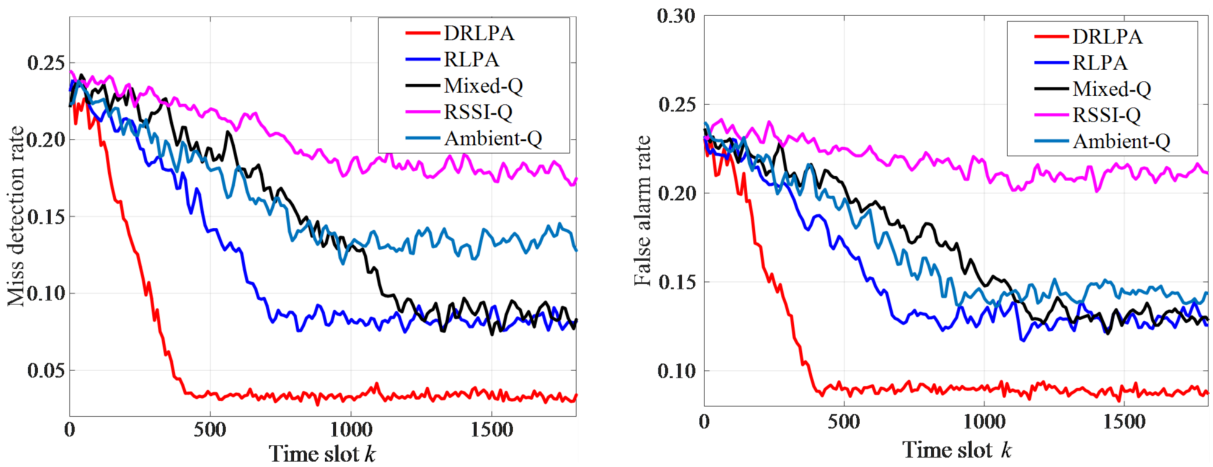
The mobile device applies a neural episodic control based deep reinforcement learning to choose the authentication mode x_0 and the test threshold x_1 to authenticate messages based on the calculated test statistic $\varDelta$. Specifically, the mobile device accepts the packet if $\varDelta < x_1$ and sends a spoofing alarm otherwise.

Experiments are performed to evaluate the authentication performance in a VANET as shown in Fig. 12. Experimental results in Fig. 13 show that the proposed scheme exceeds the benchmark schemes.



(a) VANET authentication snapshot (b) Initial network topology

Fig. 12 Experimental settings in which the mobile device Bob and its serving edge Alice in vehicle resisted a rogue edge Eve outside the vehicle, and both Alice and Eve sent packets with Alice's identity.



(a) Miss detection rate (b) False alarm rate

Fig. 13 Authentication performance of the physical-layer authentication scheme against a smart rogue edge attacker.

For example, the proposed scheme decreases the miss detection rate by 79.4% and the false alarm rate by 52.3% compared with the mixed-Q scheme.

Furthermore, we also propose a cross-region identity management authentication algorithm based on hashchain, which is used to manage the identity switching when a mobile node enters across regions[83].

6 Holistic integration and demonstration of SAGiven

For SAGiven, a comprehensive simulation and demonstration platform which consists of holistic integration of space, aerial, and ground segments is crucial. In this section, we review related works on the simulations of SAGiven, and propose a comprehensive SAGiven simulation platform.

6.1 Overview of existing software packages

In SAGiven simulations, various simulation tools can be employed to simulate the node mobility and data communications. Some commonly used simulation tools are presented and discussed to show the features suitable for SAGiven simulations, including VisSim, Systems Tool Ki (STK), and Network Simulator 3 (NS-3).

(1) VisSim: VisSim is widely used as a road traffic simulation and analysis tool in transportation research. In SAGiven, user mobility is a very important component which needs to accurately reflect the real-world node mobility. VisSim is a powerful tool for the evaluation and analysis of urban transportation scenarios by leveraging the characteristics of vehicle and driver behaviors, in addition to the models of road links, junctions, road traffic light, pedestrians, and so forth. A Graphic User Interface (GUI) displaying all vehicles and road segments displayed in one scenario window controls VisSim, and a 3D animation mode can be utilized to display the simulation scenario. It also supports to import a detail world map which allows real-world scenario-based simulations.

(2) STK: STK is a physics-based simulator to analyze and simulate various assets in space, aerial, sea, and ground. STK is especially designed to simulate earth-orbiting satellites, which provides various parameters and data of existing LEO, MEO, GEO, and High Earth Orbit (HEO) satellite systems. In addition, the aerial platform, i.e., HAPs and UAVs, are also supported with corresponding aircraft models. Customizable maps and 3D animations are displayed by GUI, and STK also provides a scripting interface named *Connect* which extends STK to external platforms.

(3) NS-3 and Satellite Network Simulator 3 (SNS-3): NS-3 is an open-source network simulator supporting event-driven simulations of various communication networks, which is widely used in simulations of ad-hoc networks, Wi-Fi, LTE, and core networks. NS-3 provides highly customized modules for simulations of many communication protocols throughout the network protocol stack. An important feature of NS-3 is that enormous developers have contributed validated models and extensions for specific types of communications. For SAGiven, the satellite related simulations are indispensable. The SNS-3 is a satellite network extension to NS-3, which simulates a full interactive multi-spot beam satellite network with a geostationary satellite operated in Ka-band frequencies with 72 spot-beams. Based on SNS-3, various types of satellite communications, including GEO, MEO, and LEO, can be supported in NS-3.

6.2 Related works on the simulations of SAGiven

In SAGiven, simulation plays an important role in analyzing protocols and evaluating the system performance. However, most existing works only focus on part of SAGiven, i.e., either only one single network segment, or the integration of space-ground network or air-ground network. For terrestrial communications, such as Ad-hoc networks, WiFi networks, and cellular networks, there are extensive works on simulation by using MATLAB[84], NS-3[85], OPNET network simulation platform[86], and so forth. Aerial networks, e.g., Flying Ad-hoc Networks (FANETs), can enhance the capacity for covered areas as a complement of the ground communication systems. In Ref. [87], the application of UAVs on providing services for ground users in disaster areas was evaluated using MATLAB. In Ref. [72], drone-assisted vehicular networks were proposed to provide higher throughput and delay performance than the terrestrial vehicular networks, where the simulations were conducted by combining VisSim, MATLAB, and NS-2. Satellite communication is a potential solution to provide ubiquitous connectivity to rural, ocean, and many other areas where terrestrial communication is not available or cost-ineffective. Kawamoto et al.[88] proposed a new multi-layered satellite network to solve the traffic congestion problems, which is evaluated using NS-2. Jia et al.[89] exploited STK to evaluate the proposed satellite-assisted data offloading algorithm. Radio resource allocation in space-ground networks has also been investigated and simulated by using the LTE-Sim simulator[90].

Despite these works, comprehensive simulations of SAGiven are still at infant stage[91]. Considering the challenges such as distinctive network characteristics, various protocols, heterogeneous network architecture, and complex mobility patterns, it is difficult to use existing simulation tools to evaluate realistic SAGiven. Therefore, how to design a comprehensive simulation platform for SAGiven is an important yet challenging issue.

7 Design of SAGiven simulation platform

7.1 An overview of the platform

A comprehensive SAGiven simulation platform requires to be capable of simulating the existing and potential communication and networking protocols, algorithms, applications, and services. In this section, we present the design of a comprehensive SAGiven simulation platform, which could efficiently support the existing network protocols and is sufficiently flexible and scalable such that it could be easily extended to implement new communication protocols, algorithms, control schemes, and applications. The overview of the designed simulation platform is shown in Fig. 14. It is composed of three function layers, i.e., network infrastructure layer, network communication module layer, and application and control layer. Furthermore, the APIs are also designed, supporting the extension of the simulation platform with customized applications and control algorithms. The details of each layer are described in the sequel.

(1) Network infrastructure: The SAGiven infrastructure layer comprises the physical environment of the simulation platform, which includes the earth representation, communication infrastructure, digital map, and communication devices such as orbiting satellites, drones, ground vehicles, mobile phones, and IoT devices. This layer also maintains the position and mobility of network nodes, and generates the mobility traces. Unlike the terrestrial network, in SAGiven simulation platform the complex three-dimensional mobility is supported, including the orbiting of satellites, the flying trajectory of drones, and the movement of ground users. Note that besides generated by the simulation platform, the mobility traces data can also be imported from different sources, such as real-world mobility data or other mobility generation tools.

(2) Network modules: SAGiven is a holistic integrated network which simultaneously supports a variety of communication and networking protocols, such as satellite communication, aerial communications, LTE, WiFi, IoT (NB-IoT, LoRa), etc. To simulate the various protocols and provide sufficient flexibility, in the simulation platform, we employ the modular method

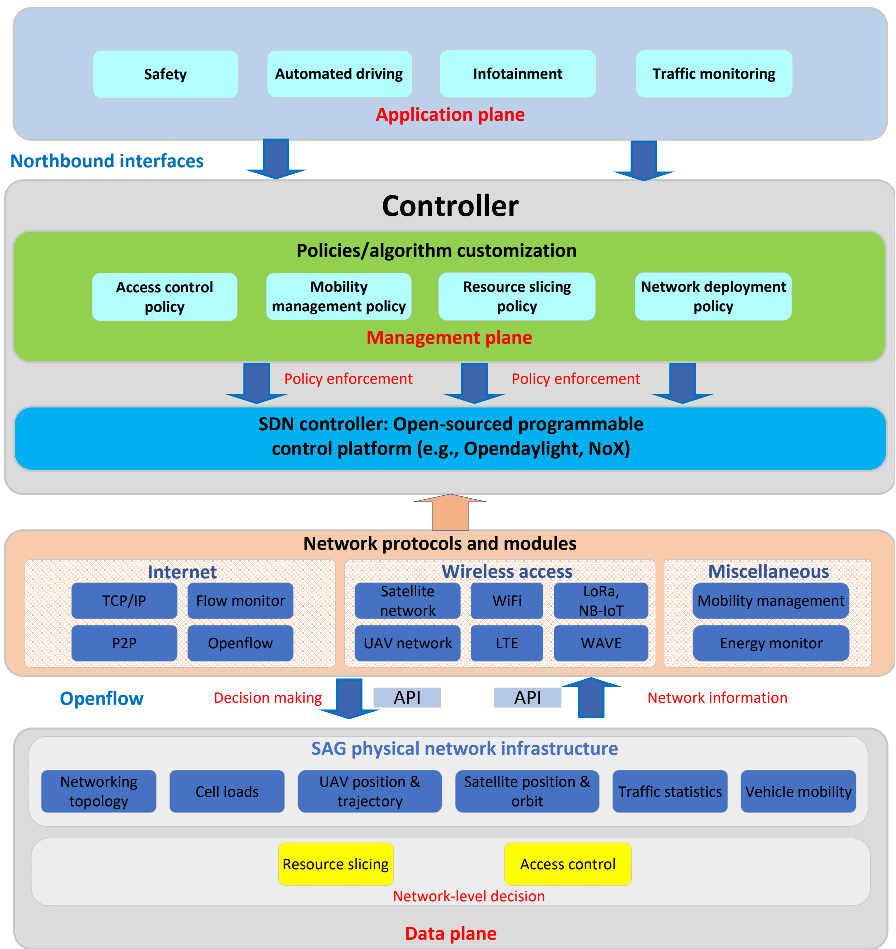


Fig. 14 Overview of SAGiven simulation platform. Here, API represents application programming interface.

in which each network protocol is implemented in a module. For instance, by using different network interface modules, network users can connect to different networks, such as satellite communication networks, UAV-based communication networks, and terrestrial networks. Two main advantages can be seen from the modularization design in the simulation platform. Firstly, the simulation scenario can be built by simply calling the modules without considering the couple between different network components. Secondly, it facilitates to modify the existing modules or add new modules, which extends the functionality of the simulation platform.

(3) Network control and application: Based on the functions provided by the SAGiven infrastructure layer and the network module layer, in the network control and application layer, varied network control algorithms and applications are deployed, the function of which is to set up the application behaviors and evaluate the network performance under specific network control algorithms. For example, in the space-air-ground three-dimensional network Resources Allocation (RA) problem, the conventional optimization-based allocation methods may not be sufficiently responsive to adapt to the dynamic SAGiven environment, and thus different RA methods can be implemented and evaluated in the platform. This layer also implements the APIs which allows specific user-customized control algorithms, applications, and network services.

7.2 Implementation details

In the following, the details of the SAGiven simulation platform are presented. The simulation platform integrates various simulation tools to realize the functions of every layer, such as SAGiven communication protocols, mobility generation and maintenance, network control, and result analysis and visualization. Figure 15 shows how to implement the simulation platform by integrating existing simulation tools. Since different simulation tools use different programming languages, network structures, and data formats, it is generally difficult to design the comprehensive simulation platform. In the proposed simulation platform, we employ NS-3 as the core simulator and design efficient parsers and interfaces to connect to other platform components for an integrated simulation.

(1) Scenario configuration: The simulation scenario configuration includes the determination of network components, network topology and node mobility, deployment of network services, etc. The simulation scenario configuration is supported by two functions, i.e., heterogeneous access and multi-domain integration, as shown in Fig. 15. Heterogeneous access is the capability of network nodes to select and access different network segments, which is realized by the communication modules in NS-3 and its extension.

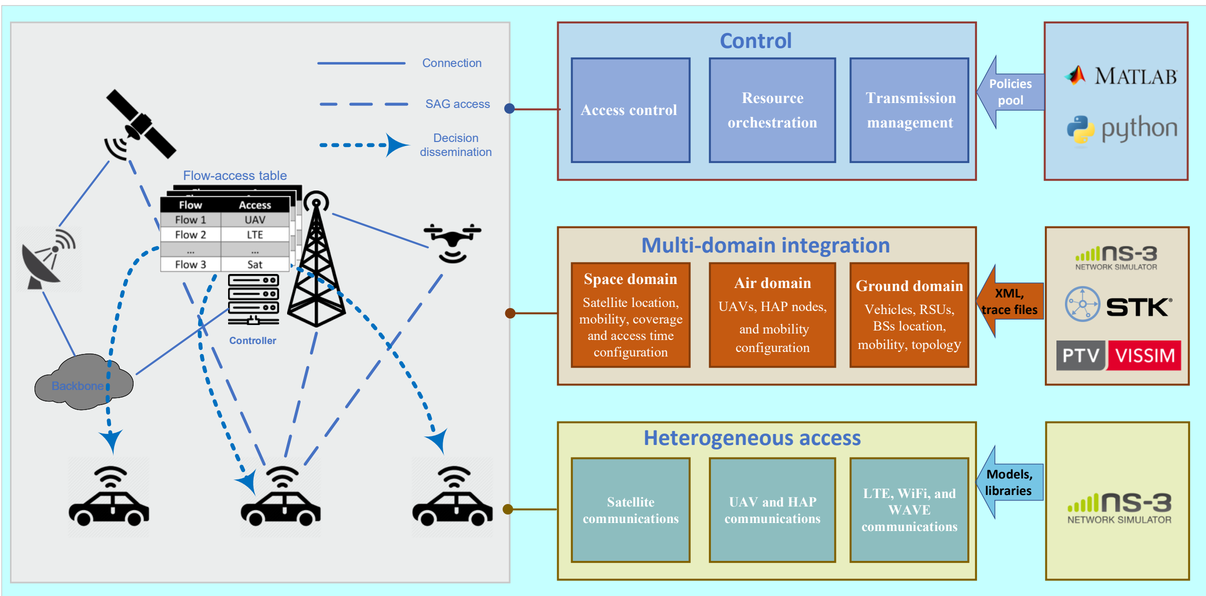


Fig. 15 Implementation of SAGiven simulation platform.

Some communication modules which are not available in NS-3, such as the UAV communication module and the satellite communication module, are customized for realistic simulations of SAGiven. Specifically, as SNS-3 is a highly specified extension for simulating the GEO satellite communication over the Europe region, we have modified the SNS-3 extension to support LEO satellite communications, named L-SNS-3 module, to adapt to the more promising LEO constellation communications.

(2) Network control: The network control layer has two main functions, i.e., controlling the network behavior and implementing the user-defined applications and control policies. In the following, these two functions and corresponding implementation details are described.

Network controllers are deployed in a hierarchical way, i.e., in the network edge (edge controller) and cloud (cloud controller). These network controllers collect real-time network information and control the network behaviors correspondingly in either centralized or decentralized way. Decentralized controllers, i.e., the edge controllers, are in charge of controlling the network edge, such as network access, user mobility, and cell power allocation, while the cloud/centralized controller coordinates among different edges controllers, such as the allocation of satellite resources and user handoff between neighboring edges. We implement P2P links from the controllers to different network components, which are with different delays and data rates to simulate different types of wireless/wired links. The network controllers collect the real-time information such as location, speed, channel conditions, and QoS requirements via these links, and the controllers make real-time decisions on network behaviors. In this way, the real network control process is simulated, including the round-trip delay of the information exchange and the delay for control decision making.

The network control layer also implements user interfaces for customized applications and control algorithms, which makes the simulation platform more extensible and flexible. For future potential research issues in the SAGiven, the proposed simulation platform allows the platform users to define customized simulation scenarios, communication protocols, and control policies. The extendibility stems from the ability to collect the real-time network information and disseminate the control messages. The user-defined RA algorithms, for instance, can respond to the collected network information and make RA decisions.

(3) Main simulation: We use NS-3 to perform the main simulation based on given simulation scenarios and the network control algorithms. We also implement the data parser and analytical tools. By monitoring the NS-3 logging output, we can debug the simulation programs and evaluate the simulation results.

8 Demonstration of SAGiven simulation platform

In this section, we present the demonstration of the SAGiven simulation platform, provide the simulation parameters, and give some typical simulation instances. We use a classic urban area, the region around University of Waterloo, Waterloo city in Ontario province, Canada as the basic simulation scenario, and employ VisSim to generate the mobility traces of 100 vehicular users. The SpaceX LEO constellation orbits are used for satellite orbiting simulation, and 3 UAVs are moving within the region along the predefined routes. The demonstration of the SAGiven simulation platform is shown in Fig. 16. Main simulation parameters can be seen in Table 2. In the following, some typical network applications and services in SAGiven are provided.

8.1 Deep learning-based radio access technology selection

In SAGiven, due to the existence of aerial and space network, generally the coverage is not a serious issue. However, different Radio Access Technologies (RATs) often have different characteristics and performance, and are suitable for different scenarios and service requirements. Therefore, in SAGiven, the RATs of users should be controlled to optimize the network performance. We propose a Deep Learning (DL)-based RAT selection scheme for SAGiven and evaluate its performance using the designed simulation platform. The main reason of using DL is that due to the ultra-high complexity of SAGiven, it is usually difficult to accurately model the system mathematically, yet the

Fig. 16 Demonstration of SAGiven simulation platform.

Table 2 SAGiven simulation platform parameters.

Layer	Parameter	Value
Simulation scenario	Number of vehicular users	100
	Number of UAVs	3
	Number of LTE BSs	1
	Number of satellites	39
	Simulation time (min)	10
	Data packet length (byte)	1024
	App data rate (Mbps)	8.192
UAV to ground communication	802.11 protocol	802.11 p
	Propagation model	Log distance
	Frequency (MHz)	5.9
	Bandwidth (MHz)	10
	Transmission power (dBm)	40
	Antenna gains (transmit & receive) (dB)	1
	Carrier sensing threshold (dBm)	–96
	Receiver noise figure (dB)	7
	DCF inter-frame space (DIFS) (µs)	58
	Short inter-frame space (SIFS) (µs)	32
	CWmin (time slot)	15
	CWmax (time slot)	1023
LTE to ground user communication	Propagation model	Log distance
	Frequency (MHz)	850
	Bandwidth (resource block)	25
	Transmission power (dBm)	30
	Antenna gains (transmit & receive) (dB)	0
	Receive threshold for PSS on RSRQ (dB)	–1000
	Receiver noise figure (dB)	9
Satellite to ground communication	Satellite type	LEO
	Orbit height (km)	717–787
	Frequency band	L-band

DL-based method can be used without accurate system model and achieve the optimal decision by learning the network samples. Specifically, the learning samples with labels could be obtained by collecting the samples in the simulation platform, and exhaustively searching the optimal decisions. Another obvious advantage of DL-based is that applying the learning model in the real network could be much faster than optimization-based methods since the DL forward-propagation could be calculated highly parallelized. The results are shown in Fig. 17. It can be seen that the DL-based method can achieve 16.4% throughput gain than LTE-preferred method (where LTE is selected if possible), and saves 92.4% processing time than exhaustive search method.

8.2 Spatial-aerial assisted computing offloading for IoT

Intensive computing tasks are specifically challenging for Internet of Things (IoT), since IoT devices are mostly with limited computing capability and energy. Although in urban areas such computing tasks can be offloaded to network edge, such as edge servers in cellular base station, it is not usually the case for remote IoT devices and services, where the terrestrial network coverage is not available. Therefore, SAGiven is a promising solution for remote IoT computing offloading, where the intensive computing tasks could be processed locally, offloaded to the UAVs, or to the cloud servers through the satellites. In Ref. [92], we proposed a deep reinforcement learning-based computing offloading scheme for IoT

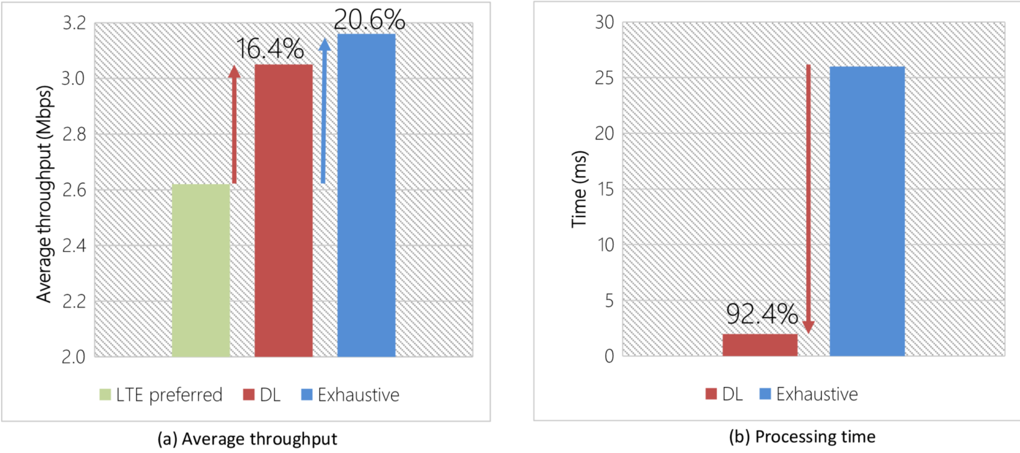


Fig. 17 RAT selection results.

in SAGiven, where the offloading decision making is formulated as a Markov decision process, with network dynamics considered. To handle the large action space and accelerate the learning process, we adopted the actor-critic learning method. The main result is shown in Fig. 18, where ω is the weight of total cost on the task delay. It can be seen that the proposed actor-critic deep reinforcement learning-based computing offloading method can achieve much better performance in terms of the total normalized cost.

8.3 Other simulation scenarios and applications

The designed SAGiven simulation platform can be easily extended and applied to many other potential network scenarios and applications. For example, in Ref. [93], we proposed and evaluated a multi-dimensional resource slicing scheme for vehicular network services.

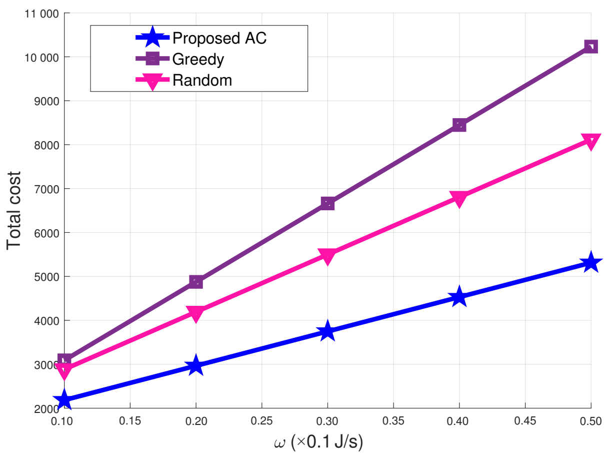


Fig. 18 Computing offloading results. Here, AC represents actor-critic.

The SAGiven resources are considered to provide differentiated service provisioning to different services, such as real-time high-definition map downloading, popular content downloading, streaming, etc. In Ref. [94], we proposed a 3D trajectory planning and scheduling for drone-assisted cellular network, and evaluated the performance in the simulation platform. It can be shown that with well planned drone trajectory, an average of 10 – 15 dB drone-to-user pathloss can be reduced, thus improving the network performance. SAGiven-related research is still in its infant stage, and many more potential research directions are explored. One core design idea of the simulation platform is to facilitate the flexibility and extendability, where the modules and interfaces naturally support various future SAGiven services and applications.

9 Conclusion

In this paper, an SAGiven has been proposed to support future connected and automated vehicles and intelligent transportation systems. In order to gracefully integrate the multi-dimensional and multi-scale context-information and network resources, an SFC-based network function virtualization and network resource reconfiguration technologies have been provided and, based on which, a Bi-directional Offloading (BDO) scheme has been further proposed to efficiently utilize the scare space and aerial network resources. For the localization of moving vehicles, a UAV-aided high accuracy positioning technology is then proposed, which can improve the positioning accuracy to sub-meter level without any infrastructure's help. To support ultra-reliable and low-latency communications among vehicles and/or between vehicles and SAGiven, a new performance metric named *Urgency of Information* has been proposed, which has been shown effective to capture the sensing-updating-controlling end-to-end latency rather than just transmission latency. For secure communication of context information, a reinforcement learning based UAV relay scheme has also been proposed, which can efficiently mitigate smart jamming attacks. Finally, a holistic integration and demonstration of the SAGiven on top of a generic simulation platform with real GEO/LEO/UAV and terrestrial network parameters is provided, by which most of the newly proposed schemes in this paper can be implemented and demonstrated. It is therefore concluded that the SAGiven can play a key role in future autonomous driving and Internet-of-Vehicles applications.

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