A Comprehensive Simulation Platform for Space-Air-Ground Integrated Network

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Abstract

Space-air-ground integrated network (SAGIN) is envisioned as a promising solution to provide cost-effective, large-scale, and flexible wireless coverage and communication services. Since real-world deployment for testing of SAGIN is difficult and prohibitive, an efficient SAGIN simulation platform is requisite. In this article, we present our developed SAGIN simulation platform which supports various mobility traces and protocols of space, aerial, and terrestrial networks. Centralized and decentrallized controllers are implemented to optimize the network functions such as access control and resource orchestration. In addition, various interfaces extend the functionality of the platform to facilitate user-defined mobility traces and control algorithms. We also present a case study where highly mobile vehicular users dynamically choose different radio access networks according to their quality of service (QoS) requirements.

Introduction

Future communication networks are envisioned to enable a wide range of promising services and applications by providing ubiquitous connectivity, high data rate, low latency, and high reliability. The current terrestrial communication networks, such as WiFi, Long-Term Evolution (LTE), and the emerging fifth generation (5G) networks, offer high-capacity data pipes by employing state-of-the-art communication and networking technologies; they can be further enhanced not only to meet the increasing service demand, but also to improve cost effectiveness. One one hand, providing network coverage for rural mobile users and remote Internet of Things (IoT) devices by deploying LTE or 5G infrastructure may lead to severe cost inefficiency. For example, in the U.K., the total 5G cost including capital expenditure (CapEx) and operational expenditure (OpEx) will be only 21 percent to serve the 70.5 percent of the population in urban and suburban areas, but 79 percent to serve the 29.5 percent of the population in rural areas by 2030 [1]. One the other hand, even in the urban areas, tmobile data traffic can vary dramatically both in time and space, due to events such as sport games, and users mobility such as daily vehicle traffic variations. The fixed deployment of terrestrial communication networks is not flexible for on-demand services [2], [3].

Space-air-ground integrated network (SAGIN) is envisioned as a key solution to provide large-scale coverage and further improve the network performance [4], [5]. The SAGIN is composed of three network layers, i.e., the space layer, which includes communication satellites; the aerial layer, which includes aerial communication devices such as balloons and unmanned aerial vehicles (UAVs); and the ground layer, which includes the terrestrial communication networks and the users. With SAGIN, the high cost of 5G networks can be substantially reduced since the large rural areas can be effectively covered by the satellites. Normally, a low earth orbiting (LEO) satellite can cover up to 7.95 percent of the earth's area while a geostationary (GEO) satellite can cover nearly half of the Earth's surface area, providing access capability to rural users or widely deployed IoT devices. The space layer can be a promising candidate of emergency public services or network control. The spatiotemporally dynamic data traffic demands can be satisfied by flexibly scheduling UAVs to provide temporal coverage enhancement. In addition, reaping the flexibility and controlled mobility of UAVs, many network functions and applications can be enabled, such as edge computing, caching, and IoT services.

Motivated by the great potential, both academia and industry have paid increasing attention to the research and development of SAGIN. The industry has been deploying the space-and air-assisted communication networks, especially in recent years. Google's Loon and AT&T's Flying COW employ balloons and UAVs to provide high-speed wireless Internet access, while SpaceX is developing Starlink to build a low-cost and high-performance LEO satellite-based access network. Related research works in SAGIN have also flourished recently [6]. As an indispensable tool in both research and development of communication networks, the simulation platform plays a key role in analyzing and evaluating the network, especially in SAGIN, where real-world deployment and testing can be very expensive. Although

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some simulation software can work alone with satellite networks or terrestrial networks, a comprehensive SAGIN simulation platform, which addresses the challenge of integrating the space, aerial, and ground networks, is yet to be developed, which motivates our work.

In this article, we present a comprehensive SAGIN simulation platform and provide a case study on heterogeneous vehicular access control using the platform. Considering the complex network architecture, high mobility, and dynamic network conditions and demands of SAGIN, developing the simulation platform is a challenging task. The designed simulation platform can perform comprehensive and flexible SAGIN evaluation by implementing the following distinct features.

Integration: The space, aerial, and ground network and communication functions are supported simultaneously in the platform by integrating different simulation software. Specifically, we have first implement a LEO communication module in NS-3. Network node mobility, including the satellite orbits, UAV trajectories, and user movements, is implemented in order to capture the impacts of network dynamics on the network performance.

Controllability: Network controllers are implemented in the simulation platform. Different from existing implementation of network controllers, which mainly work on the flow control in the Internet, the heterogeneous network controllers in SAGIN, deployed in both edge nodes and cloud servers, mainly focus on the radio access network, and deal with the network information collection and monitoring, mobility management, radio resource orchestration, and other types of network control in SAGIN;

Flexibility: We implement various interfaces to support the functionality of the simulation platform. We design interfaces to import the mobility traces in order to support different mobility simulation and software. In addition, we implement control interfaces, such that the network control functions can be customized to improve platform flexibility.

The article presents the design and implementation details of the SAGIN simulation platform, and validation of the platform through a case study. The simulation platform can be used by researchers and developers to evaluate new protocols and algorithms. Furthermore, new research and developments results will help to improve the SAGIN simulation platform.

Overview of Existing Methodology

In this section, we review the existing methodology in SAGIN simulation, including potential simulation tools and initiatives to simulate SAGINs.

Simulation Software

For our SAGIN simulation platform, various simulation tools can be leveraged to simulate node mobility and data communications. Table 1 lists a brief summary of some existing simulation tools. We provide some commonly used simulation tools, and discuss the features which make them suitable for SAGIN simulations.

VISSIM: VISSIM is a popular traffic simulation and analysis solution in transportation research. Leveraging its comprehensive characteristics of vehicle and driver behaviors, as well as the detail models of road links, junctions, road traffic light, pedestrians, etc., VISSIM is a powerful tool for the evaluation and analysis of urban and extra-urban transportation scenarios. VISSIM is fully controlled by GUI with all vehicles and road segments displayed in one scenario window, and the simulation scenario can be displayed through a 3D animation mode. It also contains a detailed world map that allows simulations to be based on real world scenarios. Furthermore, the customized trace file including all vehicles' mobility characteristics is supported.

STK: STK is a physics-based simulator for analyzing and simulating various assets in ground, sea, air, and space scenarios. Originally created to simulate earth-orbiting satellites, STK provides highly comprehensive parameters and data of existing LEO, Medium Earth Orbit (MEO), GEO, and High Earth Orbit (HEO) satellite systems. The movements and trajectories of HAPs and UAVs can be designed with corresponding aircraft models. STK uses GUI display with customizable maps and 3D animations. It also provides a scripting interface named Connect which connects STK to external platforms.

NS-3 and SNS-3: NS-3 is an open-source event-driven network simulator supporting simulations of wired and wireless communication networks. Many researchers use NS-3 to conduct simulations of Wi-Fi, LTE, and core networks. NS-3 provides highly customized classes for all types of simulations, especially for layers 1, 2 and 3 in the network protocol stack. As a free and powerful network simulator, NS-3 has attracted an enormous number of developers to contribute validated models and extensions for specific types of communications. For the satellite related simulations, we leverage the Satellite Network Simulator 3 (SNS-3) extension, which simulates a single multi-spot beam GEO satellite communication system which operates on Ka-band and consists

Tools	Characteristics/Focus (Current Version)	Links
MATLAB	Communications System Toolbox: Channel Modeling and RF Impairments, Simulate link-level models.	www.mathworks.com
STK	Four-dimensional Modeling and Simulation: Time-dynamic position/attitude of objects from land, sea, air, and space, orbit collision avoidance, and 3D viewing.	www.agi.com
NS-2	Discrete-event Network Simulator for Internet Systems: LTE, WIFI, routing, WAVE, TCP, UDP, mobility, energy monitor, TCP/IP protocols and modules.	www.isi.edu/nsnam/ns
NS-3		www.nsnam.org
VISSIM	Flexible Traffic Simulation Software: complex vehicle interactions, mobility, traffic planning.	www.ptvgroup.com
Omnet++	Discrete Event Simulator: extensible, modular, component-based C++ simulation library and framework.	www.omnetpp.org
Mininet	Instant Virtual Network: running real kernel, switch and application code, providing experiments with SDN systems.	mininet.org
QualNet	Network Simulator: A comprehensive environment for designing protocols, protocol models, network layer protocols.	web.scalable-networks.com

TABLE 1. A brief summary of existing simulation tools.

Considering distinct network characteristics and various protocols and mobility patterns of the space, aerial, and ground network segments, it is difficult to use one single simulation tool to simulate realistic SAG environments. Therefore, how to design a unified simulation platform for SAGINs is an important yet challenging issue.

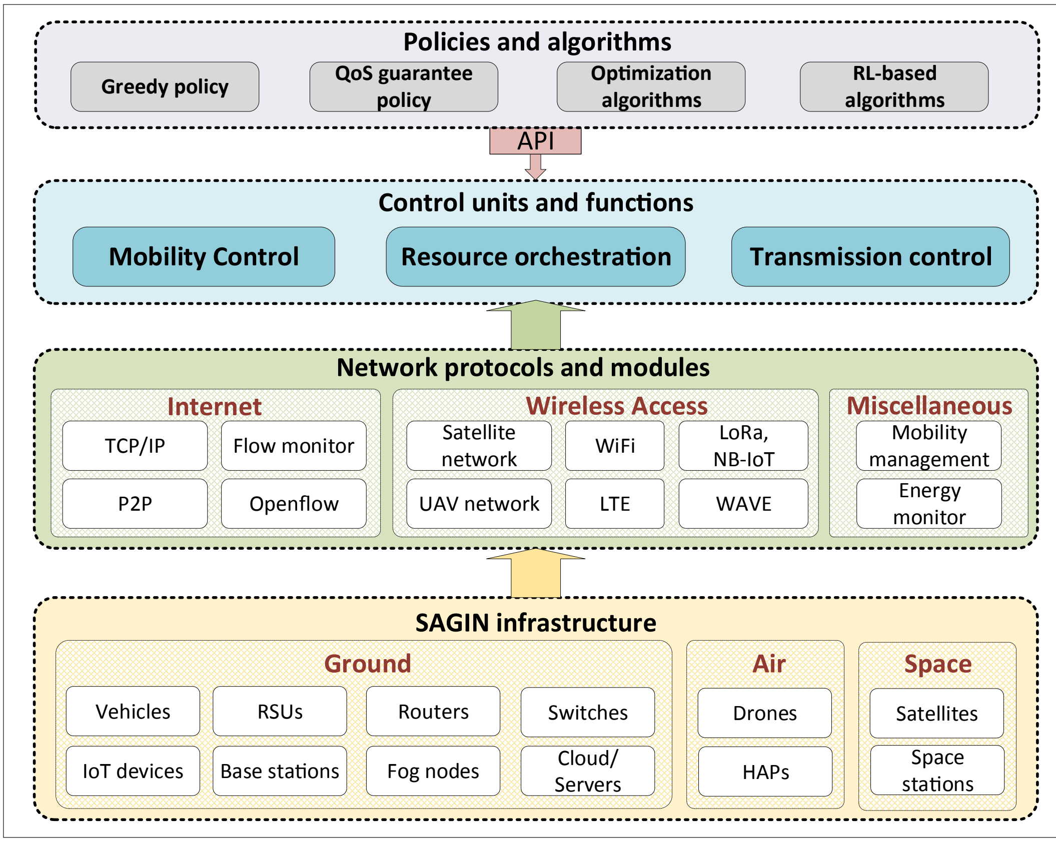


FIGURE 1. The architecture of SAGIN simulation platform.

of 72 spot-beams. A 500 MHz bandwidth is allocated to both uplink and downlink, respectively, for data transmissions.

Existing SAG Simulation

Simulation plays an important role in evaluating the communication performance of SAGINs in different scenarios under different assumptions. Until now, most existing works focus on evaluating either only one single network segment in space, air, or ground, or the integration of space-ground network or air-ground network. There exist extensive works evaluating the performance of terrestrial communications by using MATLAB/Simulink [7], Network Simulator NS.3 [8], OPNET network simulation platform [9], and so forth. Aerial networks can serve as a complement of the ground communication systems to enhance the capacity for covered areas. In [10], UAVs are exploited to provide services for ground users in disaster areas, which is evaluated using MATLAB. Drone-assisted vehicular networks can provide higher throughput and delay performance than the ground vehicular networks, and the simulations are conducted by combining VISSIM, MATLAB, and NS-2 [11]. Satellite communications can also complement the terrestrial communications and provide ubiquitous connectivity to rural, ocean, and mountain areas. To solve the traffic congestion problems, Kawamoto *et al.* propose a new multi-layered satellite network to minimize the packet delivery delay, and conduct simulations using NS-2 [12]. Jia *et al.* study satellite-assisted data offloading problems and use STK to obtain simulation results [13].

In spite of these works, unified simulations of SAGINs still remain limited. Considering distinct network characteristics and various protocols and mobility patterns of the space, aerial, and ground network segments, it is difficult to use one single simulation tool to simulate realistic SAG environments. Therefore, how to design a unified simulation platform for SAGINs is an important yet challenging issue.

Design of the SAGIN Simulation Platform

An Overview of the Platform

A SAGIN simulation platform should not only simulate the communication and networking protocols, but also support various existing and potential SAG applications and services. To this end, the simulation platform should efficiently support the existing network protocols, and is required to be flexible and scalable so that it should be easily extended to implement new communication protocols, algorithms, control schemes, and applications. Taking these requirements into consideration, we design the SAGIN simulation platform, an overview of which is shown in Fig. 2. The simulation platform is composed of three layers, i.e., the SAGIN infrastructure layer, the network module layer, and the application and control layer. Each layer has specific functionalities, and supports the upper layers. In addition, application programming interfaces (APIs) are designed for extending the simulation platform with specific applications and control algorithms. The details of each layer are described in the following.

SAGIN infrastructure: The SAGIN infrastructure layer builds the physical environment of the simulation platform. The physical environment includes the Earth representation, digital map,

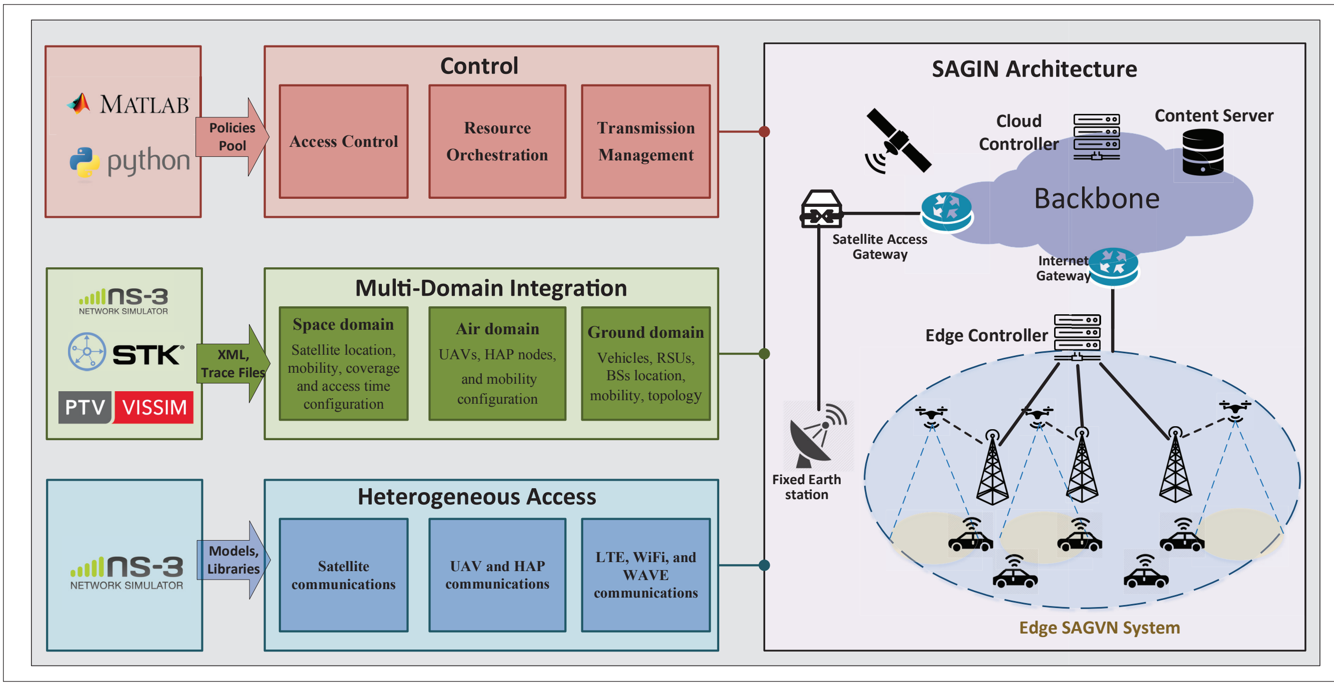


FIGURE 2. The implementation of SAGIN simulation platform.

communication infrastructure, and space, aerial, and ground devices such as satellites, UAVs, balloons, ground vehicles, user terminals, and IoT devices. The infrastructure layer also generates and maintains the position and mobility of network nodes. Unlike the ground network simulation, in the SAGIN simulation platform the three-dimensional position and mobility are supported, including the orbiting of satellites, the swarming and flying trajectory of UAVs, and the movement of ground users and vehicles. The mobility data can either be generated by the simulation platform or imported from different sources by users of the simulation platform.

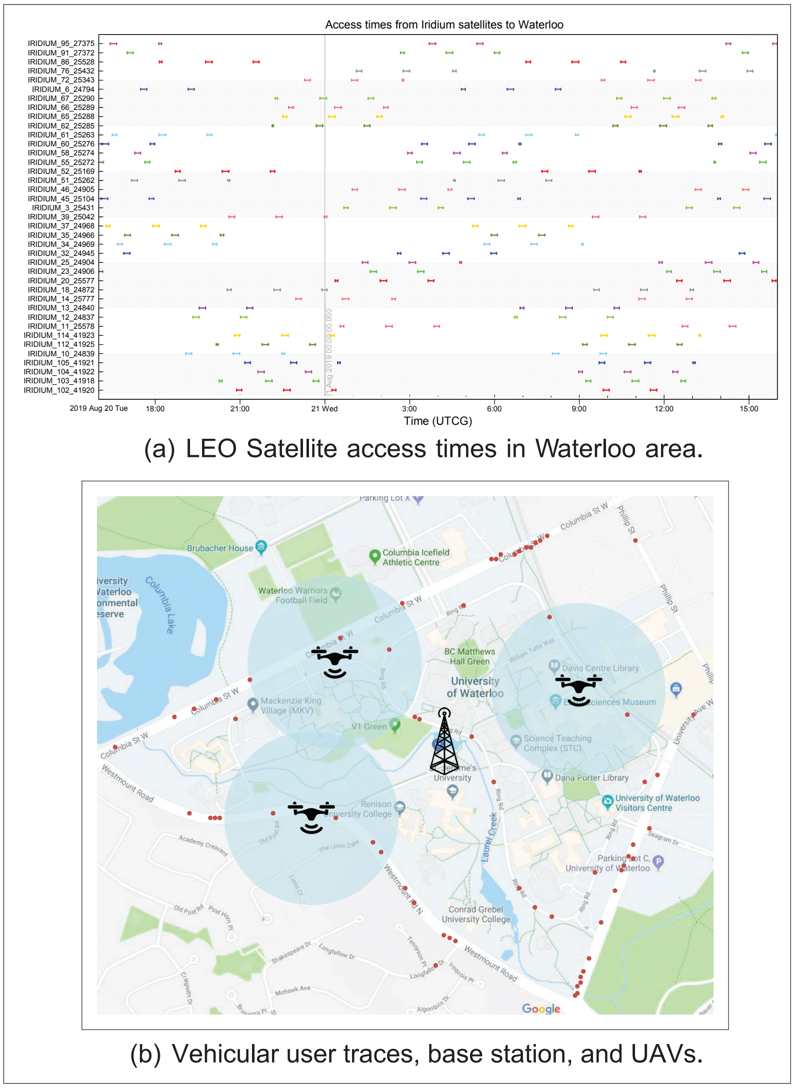
Network modules: The SAGIN simulation platform is to simulate a complex integrated network which supports a variety of communication and networking protocols, such as satellite communication, aerial communications, LTE, WiFi, IoT (NB-IoT, LoRa), etc. In the simulation platform, we incorporate such protocols in different modules in a way that each network protocol is implemented in a module. For instance, user devices are equipped with different communication modules as network interfaces to connect to different networks, such as a satellite communication module, UAV-based communication module, and terrestrial communication modules. It is noted that to support LEO satellite communication, we also implemented a LEO satellite communication module. There are two main advantages of network protocol modularization in the simulation platform. First, the simulation scenario can be built by simply calling the modules. For example, for the adaptive access control simulation, multiple access protocols are configured, such as the satellite and UAV communication, LTE, WiFi, and DSRC. Second, it is easy to modify the existing modules or add new modules to extend the functionality of the simulation platform.

Network control and application: In the network control and application layer, various control algorithms and SAGIN applications are deployed based on the functions provided by the SAGIN infrastructure layer and the network module layer. The function of this layer is to test the application behaviors and evaluate the network performance under specific network control algorithms. For example, the space-air-ground three-dimensional network resources should be efficiently allocated to improve the network performance. However, the optimization-based allocation methods may not be sufficiently fast to adapt to the dynamic SAGIN environment. Therefore, different resource allocation methods can be implemented in the complex SAGIN environment and evaluated in the platform. This layer also supports the APIs which allows specific user-defined control algorithms and applications to be evaluated in the simulation platform.

Implementation Details

Next, the details of the SAGIN simulation platform are presented. The simulation platform integrates different simulation tools to realize the functions of the platform, such as mobility generation and maintenance, network control, SAGIN communication protocols, and simulation result analysis and visualization. Fig. 3 shows the main functions supported in the SAGIN simulation platform and how to implement the simulation platform by integrating existing tools. It is generally difficult to design the unified simulation platform since different simulation tools use different programming languages, network structure, and data formats. Therefore, we employ NS-3 as the core simulator and design efficient parsers and interfaces to connect to other platform components for a unified simulation.

Simulation scenario: The simulation scenario includes the configuration of network components, determination of network topology and node mobility, deployment of network services, etc. As shown in Fig. 3, the simulation scenario is



(a) LEO Satellite access times in Waterloo area.

(b) Vehicular user traces, base station, and UAVs.

FIGURE 3. The simulation scenario in the case study.

supported by two functions, i.e., heterogeneous access and multi-domain integration. Heterogeneous access is realized by the communication modules in NS-3 and its extension, as discussed previously. Some communication modules are existing modules in NS-3, such as the LTE communication module and the P2P communication module, while other modules like the UAV communication module and the satellite communication module are customized for more realistic simulations of the SAGIN. The customization includes creating new self-defined functions (e.g. functions calculating the UAV-to-ground large scale pathloss), and modifying source codes of existing modules. Specifically, we have modified the SNS-3 extension to support LEO satellite communications, named the L-SNS-3 module. According to our knowledge, it is the first LEO satellite communication module in NS-3. As SNS-3 is a highly specified extension for simulating the GEO satellite communication over the European region, to adapt to LEO scenarios, we make a larger number of customizations on the source code of SNS-3, which can be summarized into three aspects. First, the static GEO mobility modules are replaced by our self-defined LEO mobility modules which read multiple LEO traces from STK through the designed interface. In addition, the LEO coordinates keep updating in the simulation. Second, the beam and antenna modules are revised according to LEO specified parameters. Third, since the LEO system can provide multiple LEOs over one region sometimes, the self-defined LEO selection function is designed to expose an interface for potential LEO selection schemes. Through these revisions, the designed L-SNS-3 module can well support the LEO satellite orbit and movements, as well as the satellite-ground communications.

Those modules can be called in the simulation script, e.g., "ns3::lte-Helper" and "ns3::epc-Helper" to configure the physical layer, MAC layer and network layer of the LTE access network and LTE core network, respectively. Multi-domain integration is achieved by integrating the mobility of the space, aerial, and ground network segments through mobility generation tools or mobility datasets. Specifically, we employ VISSIM to generate the vehicle mobility traces and STK[1] to generate satellite orbiting movements, and design a parser to transform the generated files to mobility files which can be recognized and imported by NS-3. In fact, any other files can be imported to NS-3 as long as they are transformed to the NS-3 mobility file format. The network protocols used in the simulation can be configured by calling the network modules in the simulation scripts.

Centralized and decentralized control: The network control layer plays two important roles, i.e., controlling the behaviors of the network and implementing the user-defined applications and control policies. In the following, the two functions and corresponding implementation details are explained.

First, we deploy network controllers in the network edge and cloud. These network controllers monitor the network by collecting real-time network information and control the network behaviors based on the information in both a centralized and decentralized way. The edge controllers are in charge of controlling the network edge, while the cloud controller coordinates among different edges controllers, such as the allocation of satellite resources and handoff between neighbor edges. We implement P2P links from the controllers to different network components, such as the satellite ground station and base stations. These links are with different delays and data rates to simulate different types of links. The network users report the real-time information such as location, speed, channel conditions, and QoS requirements to the controllers via the links, and the controllers make the real-time decisions on the behaviors of the network. In this way, the real control process, including the round-trip delay of the control information and the delay for control decision making, is simulated.

Second, the control layer also implements user interfaces to realize customized applications and control algorithms. There would be a variety of research issues in the SAGIN, and the platform allows the platform users to define customized simulation scenarios, subjects, and algorithms. The extendibility stems from the ability of the controller to collect the real-time network information and to disseminate the control messages. The user-defined resource allocation algorithm, for

[1] Currently, we use the free license to generate the satellite orbiting traces.

instance, can thus optimally allocate the network resources according to the designed goals and the network information.

Core simulation: Based on the simulation scenario and the network control algorithms, the simulation process is conducted using NS-3. The NS-3 logging output can monitor or debug the simulation programs. Since the target of the simulation platform is to evaluate the performance of the designed SAGIN communication protocols and control algorithms, we also implement the data parser and analytical tools to study the NS-3 simulation output data.

Case Study

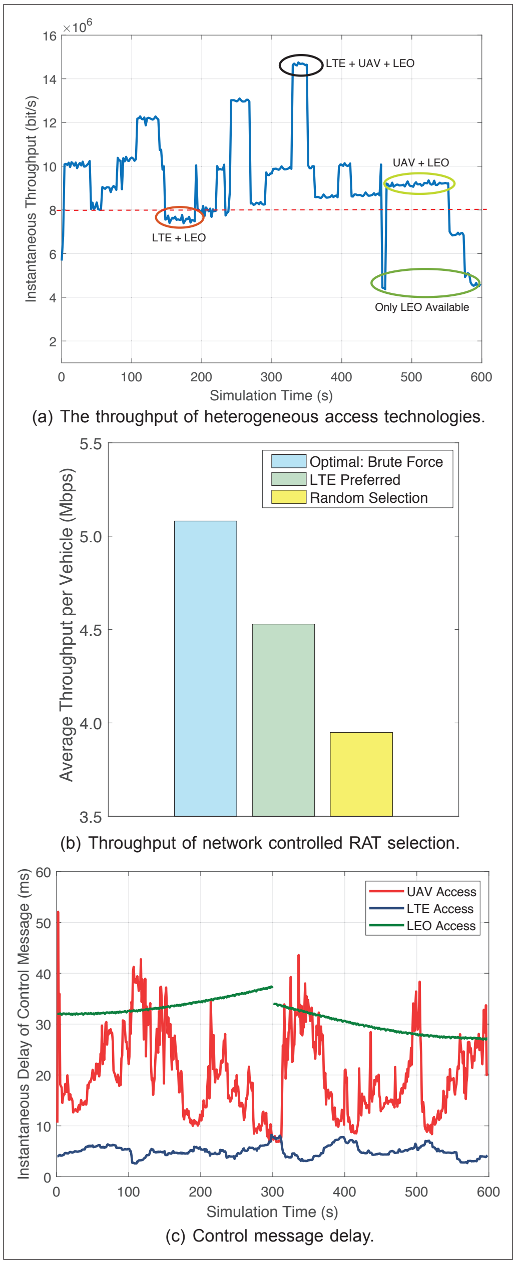
In this section, we study a specific case in vehicular communications, i.e., radio access technology (RAT) selection and control, to show the functions of the SAGIN simulation platform. Fig. 4 shows the simulation scenario, where the area around the campus of the University of Waterloo is considered. Each vehicle is equipped with three different network interfaces: LTE, DSRC and UT, to connect to network access points, i.e., the base stations, UAVs, and satellites, respectively. We use the Iridium satellite constellation for LEO satellite communications. Table 2 lists the configuration of the main simulation parameters in this case study. By loading the realistic map of the simulation scenario into VISSIM, we can configure the roads, intersections, traffic signals, vehicle types and attributes, and driver behaviors in the VISSIM to generate the realistic vehicle mobility trace for the simulation scenario.

An LTE base station is deployed at the center of the considered area. We purposely set the trajectories of UAVs in order that each UAV covers a portion of the area. The locations and mobility of UAVs can be directly set in the simulation script.

A network controller is deployed at the network edge to control the actions of all network components in the SAGIN. In the simulation script, the controller is connected to the satellite gateway station and the base stations through P2P links with average delay of 50ms and 10ms. The vehicles report the real-time network information via different links to the controller according to the location and network coverage. Then, the control algorithms run in the controller can use the information to make decision and disseminate them back through the links. Based on the SAGIN simulation scenario, we conduct a preliminary study of two network functions and analyze their performance: (i) three-dimensional heterogeneous RAT selection and (ii) network controlled throughput-maximization RAT selection.

Three-Dimensional Heterogeneous RAT Selection

In SAGIN, multiple RATs can be adopted for different vehicle users with various service requirements. Therefore, optimal access control is one of the key research issues to improve the network performance. Our SAGIN simulation platform can simulate three-dimensional (ground, air, and space) heterogeneous network access and support different access policies. Therefore, the users can customize their own access control design and analyze the design efficiency. Individual RAT access may not be sufficient for certain applications to meet their QoS requirements. Therefore, we implement a multi-path transmission protocol which allows a vehicle user to employ multiple RATs simultaneously. The controller selects a combination of a least number of RATs which can guarantee the QoS requirement for each vehicle (which is set to 8 Mbps). The simulation result is shown in Fig. 4a. It can be seen that by simultaneously using different RATs, the QoS requirement of 8 Mbps throughput can be achieved most of the time, which demonstrates the benefits of SAGIN.



(a) The throughput of heterogeneous access technologies.
(b) Throughput of network controlled RAT selection.
(c) Control message delay.

FIGURE 4. Simulation results.

Network Controlled Throughput-Maximized RAT Selection

In this section, the network controlled RAT selection to maximize the total network throughput is simulated. In the simulation, a network controller collects the network information, makes access decisions, and disseminates the decisions to end

Optimal access control is one of the key research issues to improve the network performance. Our SAGIN simulation platform can simulate three-dimensional (ground, air, and space) heterogeneous network access and support different access policies. Therefore, the users can customize their own access control design and analyze the design efficiency.

To evaluate the performance of an SDN/NFV-enabled SAGIN, some open-source frameworks and protocols can be implemented in the simulation platform. However, there exist some challenging issues. For example, network slicing requires resource isolation, while in the SAGIN simulation platform, implementing the isolation of multi-dimensional resources involves modifications on basic NS-3 function module.

users. The results are shown in Fig. 4b and Fig. 4c. The average throughput of vehicular users is shown in Fig. 4. It can be seen that the network control RAT selection scheme outperforms the 'LTE-preferred' method in which LTE is selected when available and the 'Random' method since it has a global view of the network and can make centralized decisions. However, the network information collection and control message dissemination brings additional delay, which is shown in Fig. 4c. It is noted that for LEO access, the delay varies slightly which mainly stems from the LEO-user distance changes when the satellite moves.

Parameters	Numerical values
Simulation scenario	
Number of vehicle nodes	99
Number of UAVs	3
Number of LTE BSes	1
Number of satellite	39
Simulation time	10 min
App packet length	1024 bytes
App data rate	8.192 Mb/s
UAV to vehicle communication	
802.11 protocol	802.11p
Propagation model	Log distance
Frequency	5.9 GHz
Bandwidth	10 MHz
Transmission power	40 dBm
Antenna gains (transmit & receive)	1 dB
Carrier sensing threshold	–96 dBm
Receiver noise figure	7 dB
DCF inter-frame space (DIFS)	58 μs
Short inter-frame space (SIFS)	32 μs
CWmin	15 time slots
CWmax	1023 time slots
LTE to vehicle communication	
Propagation model	Log distance
Frequency	850 MHz
Bandwidth	25 resource blocks
Transmission power	30 dBm
Antenna gains (transmit & receive)	0 dB
Receive threshold for PSS on RSRQ	–1000 dB
Receiver noise figure	9 dB
Satellite to vehicle communication	
Satellite type	LEO
Orbit height	717–787 km
Frequency band	L-band

TABLE 2. Simulation parameters.

Future Research and Development

In this article, we have presented a SAGIN simulation platform which integrates multiple network protocols, node mobility, and control algorithms. However, research on SAGINs is still in its infancy, and thus the SAGIN simulation platform requires further improvement to simulate the emerging SAGIN architecture, protocols, and applications. In this section, we discuss several topics for future research and development in the SAGIN simulation platform.

Software-defined networking (SDN) and network function virtualization (NFV) technologies have significantly changed the communication network architecture, from purpose-built to commodity hardware, and from rigid to flexible and programmable functionality. The flexibility and scalability brought by SDN/NFV technologies are especially beneficial to SAGINs due to the heterogeneous network architecture, multi-dimensional resources, and strict service requirements [14]. However, due to the high complexity of SAGINs, it can be inefficient to use only one central controller which may cause overloaded control signaling and delayed responses to network events. Therefore, how to deploy the SDN controllers in SAGINs and coordinate the actions among the controllers requires careful investigation. To evaluate the performance of an SDN/NFV-enabled SAGIN, some open-source frameworks and protocols can be implemented in the simulation platform, such as OpenFlow, OpenStack, Opendaylight, Ryu control framework, etc. However, there exist some challenging issues. For example, network slicing requires resource isolation, while in the SAGIN simulation platform, implementing the isolation of multi-dimensional resources involves modifications on basic NS-3 function modules, which requires further study.

Cloud/edge computing can be incorporated in the SAGINs to meet the varying requirements of a myriad of services and applications. With the enhanced coverage and network flexibility provided by satellites and UAVs, SAGINs are capable of offering cloud services, computation offloading, and edge caching, to remote areas and highly demanding areas. In the simulation platform, implementing cloud/edge technologies poses technical challenges, such as modelling and simulation of cloud data centers and distributed edge servers, virtualizing server hosts and resources, supporting dynamic simulation elements (satellites, UAVs, and mobile users) and user-defined policies, and so forth.

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In the simulation platform, implementing cloud/edge technologies poses technical challenges, such as modelling and simulation of cloud data centers and distributed edge servers, virtualizing server hosts and resources, supporting dynamic simulation elements (satellites, UAVs, and mobile users) and user-defined policies, and so forth.