ORCHESTRATION OF ULTRA-DENSE 5G NETWORKS

SAGECELL: Software-Defined Space-Air-Ground Integrated Moving Cells

Zhengyu Zhou, Junhao Feng, Chuntian Zhang, Zheng Chang, Yan Zhang, and Kazi Mohammed Saidul Huq

ABSTRACT

Ultra-dense networks (UDNs) provide an effective solution to accommodate the explosively growing data traffic of multimedia services and real-time applications. However, the densification of large numbers of static small cells faces many fundamental challenges, including deployment cost, energy consumption and control, and so on. This motivates us to develop software-defined space-air-ground integrated moving cells (SAGECELL), a programmable, scalable, and flexible framework to integrate space, air, and ground resources for matching dynamic traffic demands with network capacity supplies. First, we provide a comprehensive review of state-of-the-art literature. Then the conceptual architecture of SAGECELL is elaborated in detail, and the technological benefits are emphasized. Next, we present four typical application cases of SAGECELL. A case study is conducted based on real-world road topology to validate the efficiency and flexibility of SAGECELL.

Finally, we identify future research directions and challenges, and conclude this article.

INTRODUCTION

Driven by multimedia-rich mobile Internet services such as augmented reality (AR), video streaming, and online gaming, and the massive number of Internet of Things (IoT) connections, it is estimated that mobile data traffic will grow two times faster than fixed Internet traffic, and reach 48,270 petabytes per month by 2021 (i.e., 7-fold growth) [1, 2]. Such huge data traffic demands pose stringent requirements on the next-generation mobile infrastructure design, including extremely large capacity and dense connections, which cannot be met simply by physical layer solutions. To this end, ultra-dense networks (UDNs), in which a large number of small cells are deployed densely in the proximity of end users, have been proposed to accommodate the huge data traffic demands [3, 4]. However, the wide deployment of UDNs still faces several impediments. Physical infrastructures of UDNs are deployed redundantly to cope with the peak traffic demand, and the level of network densification cannot grow endlessly due to fundamental limitations such as high deployment, maintenance, and energy consumption costs [5]. The static UDN architecture provides little flexibility in adapting data traffic demands with fast temporal, spatial, and spectral variations [3], which cannot jeopardize quality of service (QoS) and quality of experience (QoE) guarantees in the domains of reliability and timeliness.

Therefore, it is envisioned that intelligent and effective approaches are urgently required to dynamically match supply and demand across time, space, and spectrum. Among numerous technologies, space-air-ground integrated moving cells, which consist of radio access infrastructures mounted on satellites, unmanned aerial vehicles (UAVs), and vehicles, have emerged as a promising solution to provide on-demand network capacity augmentation and deployment densification [7]. Instead of relying on a single technology, the advantages of spatial, aerial, and terrestrial paradigms are combined complementarily to meet the bursty traffic demands. The large array of vehicles equipped with high-speed radio access capabilities can be envisaged as supplementary communication, computing, and caching resources, and should be well leveraged to serve users who experience enormous latency when fetching data over the conventional (fixed) small cells. UAVs, which have unique characteristics such as fast deployment, easy programmability, reconfiguration, control flexibility, and scalability, can be deployed in a complementary way with vehicles to provide additional capacity in hotspots [6]. Satellite networks with superior broadcasting/multicasting capabilities and large-scale geographical coverage can be utilized to deliver similar contents to a large number of users, and provide network access for areas with inferior terrestrial connectivity.

Nevertheless, the successful implementation of moving cells from a space-air-ground integrated perspective remains ambiguous. The main research challenges are summarized as follows.

Network management and interoperability: In each network paradigm, there are already a massive number of devices that are developed based on customer proprietary protocols and specifications. It becomes extremely challenging to manage, configure, and control the space-air-ground integrated moving cells since a large number of dedicated gateways and interfaces are required for protocol conversion [7]. Furthermore, due to the heterogeneity across hardware, software, and interconnectivity, it is difficult to achieve reconfiguration with stringent timelines.

Resource allocation: The space-air-ground integrated resources exhibit high heterogeneity
and dynamic availability. The non-uniformity of moving cell distributions leads to a geographical imbalance of resource availability. Hence, resources from different network paradigms should be combined and allocated intelligently in order to provide consistent connectivity and capacity enhancement, which relies on good exploration of physical infrastructure abstraction from multiple dimensions and scales.

**QoS guarantee:** Due to the diverse QoS requirements specified from different perspectives such as latency, peak rate, burst size, jitter, and packet arrival rate, a comprehensive architecture is lacking that can enforce the high-level QoS requirements through the intelligent interaction with heterogeneous underlying devices.

Addressing these challenges motivates us to develop software-defined space-air-ground integrated moving cells (SAGECELL), a programmable, scalable, and flexible framework for integrating space, air, and ground resources with UDNs. We begin with a literature review of state-of-the-art developments. Then the conceptual structure and unique advantages of SAGECELL are elaborated in detail. Next, we present four typical application scenarios of SAGECELL to validate its feasibility and capability of network capacity enhancement. Finally, we conclude this article and present future research directions and challenges.

## Related Works

In this section, we present a comprehensive review of UDNs, vehicle- or UAV-enabled moving cells, and space-air-ground integration, which is summarized in Table 1.

<table>
<thead>
<tr>
<th>Category</th>
<th>Literature</th>
<th>Feature</th>
<th>Merit</th>
<th>Limit</th>
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<tbody>
<tr>
<td>Static UDNs</td>
<td>• [8]</td>
<td>• Dense access infrastructures with fixed locations</td>
<td>• Improve spectral efficiency and energy efficiency</td>
<td>• The mobility of cells is ignored</td>
</tr>
<tr>
<td></td>
<td>• [9]</td>
<td>• Dense access infrastructure with fixed location</td>
<td>• Derive the optimal system parameters</td>
<td>• The space-air-ground integrated resources are neglected</td>
</tr>
<tr>
<td></td>
<td>• [10]</td>
<td>• Dense access infrastructure with fixed location</td>
<td>• Improve cell spectral efficiency</td>
<td>• The mobility of cells is ignored</td>
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<td></td>
<td></td>
<td>• UDNs with indoor and outdoor deployment</td>
<td>• The space-air-ground integrated resources are neglected</td>
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<tr>
<td>Vehicle or UAV enabled moving cells</td>
<td>• [11]</td>
<td>• UAV-assisted relay networks</td>
<td>• Effective capacity and coverage enhancement</td>
<td>• The space-air-ground integrated resources are neglected</td>
</tr>
<tr>
<td></td>
<td>• [12]</td>
<td>• Content delivery based on parked vehicles</td>
<td>• Enhance the transmission rate of parking area</td>
<td>• The space-air-ground integrated resources are neglected</td>
</tr>
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<td></td>
<td>• [13]</td>
<td>• Disaster-oriented vehicular resilient networks</td>
<td>• Maximize the total weight of conducted task</td>
<td>• The space-air-ground integrated resources are neglected</td>
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<td></td>
<td>• [14]</td>
<td>• UAV-assisted relay networks under emergency situations</td>
<td>• Enhance the achievable broadband throughput</td>
<td>• The space-air-ground integrated resources are neglected</td>
</tr>
<tr>
<td>Space-air-ground integration</td>
<td>• [7]</td>
<td>• Software defined space-air-ground integrated vehicular networks</td>
<td>• Effective mobility management</td>
<td>• The space-air integrated resources are only used for vehicular networks</td>
</tr>
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<td></td>
<td>• [15]</td>
<td>• Space-air-ground integrated big data collection</td>
<td>• Fine-grained vehicular resource allocation</td>
<td>• The space-air integrated resources are only used for vehicular networks</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Effective multi-dimensional data update</td>
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</table>

Table 1. A comprehensive summary of related works.

With the explosive growth of mobile data traffic, researchers have already focused on the UDN issues since physical layer technologies alone are insufficient to increase capacity by several orders of magnitude. In [8], Su et al. investigated the spectral efficiency and energy efficiency problems in UDNs, and proposed a network capacity enhancement approach by optimizing the frequency reuse factor. In [9], Stefanatos et al. explored the influence of several system parameters on the network properties with dense deployment, including a number of access points and bandwidth partitions. In [10], Yunas et al. evaluated the performance of UDNs while considering different deployment strategies from the perspectives of cell spectrum efficiency and network energy efficiency. It can be found that most of these works focus on conventional small cells with fixed locations, and have not considered the deployment of moving cells.

There are some other works that have shifted their focus to moving access points mounted on vehicles or UAVs. In [11], Sharma et al. studied UAV-assisted relay networks and proposed a neuron-based UAV assignment strategy to improve coverage and boost capacity. A content delivery framework based on parked vehicles was proposed in [12], where Stackelberg game was utilized to analyze the interactive relationships among parked vehicles, moving vehicles, and roadside units (RSUs). In [13], Li et al. designed a disaster-oriented vehicular resilient network that can cooperate without Internet connections, and proposed an online task scheduling algorithm. In [14], Athukoralage et al. utilized unmanned aerial base stations (UABSS) to assist the network under
emergency situations, and a game framework was designed to balance the load between UABSs and WiFi access points.

The above-mentioned works either deal with coverage problems in UAV-enabled relay networks or address resource allocation issues for vehicle-based small cells. A unified framework for space-air-ground integrated moving cells is lacking that comprehensively considers respective interoperability, reconfiguration, resource allocation, and QoS guarantee issues. In [15], Xiong et al. designed a computing platform for vehicular networks by exploring space-air-ground integrated big data. A space-air-ground integrated vehicular network architecture was proposed in [7] based on software-defined networking (SDN). However, these works mainly focus on vehicular networks, and the unique characteristics of space-air-ground integrated moving cells have been largely neglected.

Based on the above review, it motivates us to design a new framework (i.e., SAGECELL) to integrate space, air, and ground resources for matching dynamic data traffic demands with network capacity supplies.

**SAGECELL: SOFTWARE-DEFINED SPACE-AIR-GROUND INTEGRATED MOVING CELLS**

In this section, we elaborate the conceptual architecture of SAGECELL, and emphasize the corresponding technological benefits.

**Architecture Overview**

SAGECELL is developed based on the concept of SDN, which provides a unified platform for centralized network management and flexible resource allocation via the separation of control and data functions. Figure 1 shows the architecture of SAGECELL, which is based on the deep convergence of the infrastructure, control, and application layers. The infrastructure layer contains a great variety of programmable network equipment and elements from the space, air, and ground domains, including satellites, UAVs, vehicles, static macrocells and small cells, gateways, routers, and so on, which are essential for realizing data acquisition, storage, transmission, and analysis functionalities in UDNs. A hypervisor is placed between the infrastructure layer and the control layer to extract and virtualize the space-air-ground communication, computing, and storage resources, which are consolidated into a virtual resource pool.

In the control layer, SAGECELL adopts a hierarchical control architecture to handle network management and resource allocation with different scales. The lower-tier SDN controllers are connected with the space-air-ground integrated resources via the hypervisor. Since the hypervisor is transparent to the controllers, each controller can only see and manage its own virtual small cells. Hence, the data-control decoupling and the high-level abstraction allow vendor-independent management of the virtualized space-air-ground resources. A mobile virtual network operator (MVNO) or over-the-top (OTT) service provider can easily access a distinct virtual small cell and deploy its own applications under service level agreements (SLAs), which dramatically increase the utilization efficiency of densely deployed infrastructures. The upper-tier SDN controllers with
a global view of the status of the up-to-date network is in charge of lower-tier SDN controllers, and is responsible for the centralized management and coordination of heterogeneous resources from different network segments.

The application layer contains an array of UDN applications such as enhanced mobile broadband (eMBB), disaster and emergency management, Industry 4.0, and smart city. The application requests can be translated into explicit instructions and delivered to the respective controllers via the standard-based northbound interfaces (NBIs), which are further utilized as guidance to determine the operation of underlying moving cells. Hence, the underlying hardware/software heterogeneity and complexity are hidden from resource orchestration and service provision by the hypervisor. For instance, the specific functionalities of moving cells can be realized via software running on top of the virtualized space-air-ground integrated resources, rather than being constrained to a specific vehicle or UAV. The programmability and controllability allow network operators to swiftly tailor service provision in accordance with the dynamic resource availability. Furthermore, advanced network management functions such as traffic steering and mobility management can be incorporated to ensure reliable service delivery and differentiation.

**BENEFITS OF SAGECCELL**

**Fast Network Reconfigurability and Seamless Interoperability:** SAGECCELL allows fast network reconfigurability and seamless interoperability through advanced resource abstraction and control-data decoupling. The underlying infrastructures of spatial, aerial, and terrestrial network segments are virtualized into distinct slices, based on which the implementation of moving cells can be flexibly and efficiently operated independent of the physical network resources. Since the virtualization process is taken care by the hypervisor, the controllers can manage the respective virtual resources in a highly abstracted manner instead of directly interacting with underlying hardware/software heterogeneities. Hence, network structure reconfiguration can be performed flexibly, scalably, and swiftly via intelligent and automatic network resource decoupling and reassembling with much lower management complexity and operation latency. Furthermore, the uninterrupted control coverage required for synchronization, peer discovery, link establishment, resource allocation, and so on can be realized by exploring space and air integrated resources; for instance, the high altitude of space and air integrated resources enables coverage of larger-scale geographical areas, which can effectively eliminate unnecessary handovers, and provide seamless connectivity and reliable mobility management.

**Adaptive Resource Allocation and Network Control:** In SAGECCELL, the scale of abstraction and virtualization of the multi-segment space-air-ground resources can be adaptively adjusted from multi-dimensional attributes (i.e., node, link, and topology). The node-level resource abstraction involves communication, computation, and storage resources located on a specific UAV or vehicle such as memory, hard disk, number of antennas, RF chain, and CPU. The link-level resource abstraction depends on the resources available for data transmitting, receiving, and forwarding in a physical link, including bandwidth, power, buffer, queue, and so on. The types of link contain a great variety of forms, from single-segment ground-to-ground, space-to-space, air-to-air links, to inter-segment ground-to-air, space-to-air, and space-to-ground links. The degree of topology abstraction is determined by the virtualization of underlying node and link resources. The hierarchical control architecture enables coarse-grained and fine-grained resource allocation and virtual network control by the upper-tier controllers and lower-tier controllers, respectively. Specifically, the macro-scale management of UAV/vehicle dispatch, UAV/vehicle involvement ratio, trajectory, and inter-network resource coordination are controlled by the lower-tier controllers, while the upper-tier controller provides micro-scale control of power allocation, channel selection, user association, and relay selection based on instantaneous channel conditions and data traffic demands. For instance, considering a hotspot where the network is overwhelmed by a large number of connection requests, a group of UAVs can be immediately dispatched to improve connection quality and capacity. Hence, the level of network densification can be dynamically adjusted to balance network resources with connection demands.

**Differentiated QoS Provisioning:** In SAGECCELL, the space-air-ground resources are utilized in a complementary way to ensure various end-to-end QoS guarantees. For example, UAVs with line-of-sight (LoS) connectivity and large-scale coverage can also be used to reduce the outage...
Figure 3. The real-world road topology of Zhongguancun area.

of probability experienced by users in cell edges or to provide massive connectivity for ubiquitous IoT applications. Moreover, the utilization of vehicle-based moving cells can achieve quick network capacity augmentation in hotspot areas with high vehicle density and large data volume. First, vehicles that are proximate to pedestrians with flexible deployment and reconfigurability are conceived in a mutually beneficial way to enhance network access capacity. Second, the large volume of vehicles in hotspots can act as relays to provide multihop data delivery, which provides effective data offloading for heavy-load cells. In contrast, pedestrians who are only connected to static small cells and may suffer from inferior non-LoS (NLoS) channel conditions due to the surrounding blockages. Hence, SAGECELL is extremely beneficial to conventional UDNs from a QoS guarantee perspective. Furthermore, by combining multi-connectivity with virtual resource migration, an ongoing application session such as video streaming can be seamlessly migrated to a new cell with higher QoS provisioning capability, which is transparent to the end users without any disruption in service delivery.

USE CASES

SAGECELL can be widely applied to the real world and considered as one key enabler for fifth generation (5G) applications. Some promising application areas can be summarized as follows. In the four considered scenarios, satellites are utilized to provide consistent backhaul connectivity for moving vehicles or UAVs, which suffer from performance degradation caused by frequent handover in terrestrial networks. Particularly, in the case of disaster and emergency management, satellite networks help achieve ubiquitous coverage when terrestrial communication infrastructures are damaged. In these scenarios, the large transmission delay of satellites can be alleviated by exploiting LoS connectivity and emerging optical communication technologies. For example, an 8-beam free space optical link enables high-speed point-to-point connectivity with a peak rate of 1 Gb/s. Low-cost white LEDs can also be utilized to achieve data rate over 500 Mb/s.

eMBB: Through a software-defined architecture, SAGECELL is able to provide ubiquitous high-capacity connectivity to massive devices, which essentially breaks the bottleneck on the requirement of eMBB in 5G. By utilizing different resources over the space, time, and frequency domains, SAGECELL can deliver tremendous 3D immersive mobile multimedia services, such as augmented reality (AR) and virtual reality (VR), which require high capacity and ultra-low latency.

Disaster and emergency management: In addition, implementing SAGECELL can enhance public safety. Due to the inherent nature of SAGECELL, smarter disaster and emergency management can be achieved. The programmability of SAGECELL can provide adaptive network solutions to cope with any emergency. For instance, the involvement of vehicles, UAVs, and satellites can realize fast reactions to unexpected natural disasters, traffic accidents/incidents, and extreme weather conditions. When a traffic accident happens, vehicles can directly report to the nearby small cells or UAVs, and the dispatched/response UAVs can provide on-demand coverage and transfer the collected data to the management center in real time for further actions.

Industry 4.0: SAGECELL could not only improve the end-user service experience but also boost the evolution of industrial Internet via providing ultra-low latency and ultra-reliable connectivity to massive sensors and devices. For example, UAV-based power line inspection, which allows fast detection of a series of defects including line damage, cracking, galvanization loss, corrosion, and insulating breakage, is of significant importance for preventative maintenance in the smart grid industry. Another typical scenario is on-site manufacturing and logistics where reliable communication is required to realize factory automation and enable real-time monitoring of production lines. By deploying massive moving cells in the network, the controllers are able to seamlessly monitor the network, and intelligent decisions can be made autonomously based on the collected data. Densification of moving cells in various forms is able to extend the network coverage and reliability, and significantly reduce the traffic latency, which is vital for Industry 4.0.

Smart city: SAGECELL architecture has the potential to speed up the design of the smart city. The dense deployment of moving cells is able to provide ultra-reliable communications for massive IoT devices, which is the key solution to support reliable acquisition of city monitoring data including noise, air quality, temperature, traffic, and so on. The moving cells also bring powerful computing capabilities to network edges, where the response time of smart city applications can be dramatically reduced via proximate data processing and analysis. Moreover, higher-altitude moving cells, such as satellites and UAVs, can provide large-scale coverage compared to ground small cells, enabling cost-efficient urban traffic management and public transportation surveillance in the smart city.

CASE STUDY

In this section, we present a case study of eMBB to validate the performance of SAGECELL. We consider the scenario where a large number of indoor and outdoor users are involved in real-time applications such as AR/VR with large-volume multimedia streams. Both UAVs and vehicles are employed to augment the access capacity of
ground small cells, while satellites are utilized to provide backhaul connections for UAVs.

**Experimental Setup**

As a representative example of business districts, the evaluation is performed based on the real-world road topologies of the Zhongguancun area in Beijing, China, which is known as the Chinese version of Silicon Valley and is the birthplace of many famous Chinese Internet companies such as the Stone Group, Founder Group, and Lenovo Group. This area features wide avenues, narrow sidewalks, as well as large pedestrian zones. An aerial view of the Zhongguancun area is shown in Fig. 3 (obtained from Google Map).

We employ single-user multiple output (SUMO) to generate vehicle traffic, in which each vehicle is modeled as an independent ingredient, and the critical mobility characteristics such as takeover, speed, acceleration, deceleration, and heading direction are controlled separately. Generated vehicles and UAVs are marked as small yellow triangles and diamonds, respectively, in Fig. 3. Furthermore, critical simulation parameters and characteristics including vehicular velocity, departure time, and vehicle coordinates can be exported to Matlab for link-level simulations via predefined standard interfaces. The flying trajectory of UAVs is based on [11], while low Earth orbit (LEO) satellites with multiple beams and a spinning period of 7200 s are considered [7]. The multimedia streams generated by AR gadgets are modeled as a 2K video with 30 frames/s, which requires an instantaneous transmission rate of 16 Mb/s.

**Numerical Results**

Figure 4 shows the impact of moving cell involvement factor on normalized network throughput. The involvement factor represents the percentage of available moving cells. As observed in the simulation results, SAGECELL outperforms the vehicle and UAV assisted network by 28.2 percent due to the LoS connectivity and wide-area coverage provided by satellites. Specifically, satellites provide consistent backhaul connectivity for moving vehicles or UAVs, which suffer from performance degradation caused by frequent handover in terrestrial networks. It is also noted that the vehicle and UAV assisted network outperforms the vehicle assisted network. The reason is two-fold: first, the outage probability of cell edge users can be effectively reduced by UAVs with LoS connections and wide-area coverage; second, compared to UAVs, the coverage of vehicles is limited by numerous factors including vehicle density, user location, moving speed, road topology, and so on. For example, a user may experience service degradation when the associated vehicle moves away and there are no alternate vehicles nearby. SAGECELL outperforms the baseline system by 212.5 percent when the involvement factor is around 0.6 because the LoS communication links with good channel conditions enabled by UAVs or vehicles provide effective countermeasures to relieve the negative impacts of path loss and multi-path fading. As the involvement factor exceeds 0.6, the unit increment of the network throughput becomes saturated due to the limited backhaul capacity and network access capacity of moving cells. That is, there are not enough spectrum resources to accommodate additional users, as well as to relay data from moving cells to core networks.

Figure 4 shows the service success probability for a new request vs. normalized active loads. A new request can be successfully admitted only if there are available resources, and will be rejected otherwise. Simulation results show that service success probability drops dramatically as the active loads increase. The reason is that additional resources to admit new requests when the network is overloaded are lacking. We found that the maximum amount of active loads is pushed rightward by increasing the involvement factor, which means that service success probability can be significantly improved by incorporating more moving cells into the network. The reason behind this is that moving cells with LoS connectivity and large-scale coverage can effectively enhance QoS performance of cell edge users and provide more

![Figure 4. Performance of SAGECELL network architecture: a) normalized throughput vs. moving cell involvement factor; b) service success probability for a new request vs. normalized active loads.](image)
It appears that the realization of SAGECELL heavily relies on the ultra-dense deployment of moving cells and the participation of different types of network elements. However, it is unlikely that one operator or party can own all these resources. Therefore, efficient resource sharing among multiple parties will be a key enabler for SAGECELL.

CHALLENGES AND RESEARCH DIRECTIONS

Although the concept and architecture can bring tremendous benefits for the evaluation of the wireless networks, there are several challenges.

Physical layer issues: The challenges in the physical layer refer to the problems of data acquisition, transmission, and processing in SAGECELL. The mobility and ultra-dense nature make the interference coordination and mitigation more significant and difficult. Furthermore, SAGECELL requires novel wireless backhaul techniques. However, because the cellular spectrum is rather limited and the investigation of the higher frequency bands, such as millimeter-wave (mmWave), as the backhaul is not yet sophisticated, backhaul problems are envisioned as one of the major issues in the proposed structure. Some other issues (e.g., the utilization of unlicensed bands, carrier aggregation, and inter-cell cooperation) are also of profound importance for SAGECELL when the cell coverage is small and moving, and the traffic varies significantly.

Integrity: SAGECELL consists of multiple tiers and different network types. The convergence of heterogeneous networks operated by different entities becomes a vital issue. Although the software-defined architecture is explored to enable unified control in SAGECELL, it is still not easy to achieve seamless convergence of multiple radio access technologies and network types. Instead, at the current stage, different elements in SAGECELL have their own networks, that is, UAV networks, vehicular networks, and satellite communications. Hence, many issues regarding the design of protocols and utilizing satellite communication for civil ground networking remain unsolved and require long-term research work.

Security: SAGECELL contains both distributed cells with different velocities and coverage, and centralized SDN controllers. Therefore, security poses significant challenges as both the moving cells and controllers face different types of cyber-attacks, and it is very difficult to find a one-size-fits-all solution. Moreover, different categories of services offered by satellites, UAV networks, and vehicular networks have different security criteria in terms of privacy, confidentiality, and authentication, which translates into various security enforcement mechanisms across different layers. To better protect SAGECELL, the security aspect should be carefully treated.

Network virtualization and slicing: Network functions virtualization is employed to create virtual cells in SAGECELL. Good control plane performance with low latency is profoundly important for the development of the proposed architecture. Moreover, the created virtual networks should be stable enough to eliminate the adverse effects caused by the time-varying nature of physical networks. In addition, how to isolate the moving cells across different types, slice them into different virtual resources, and customize the network needs intensive investigation.

Non-technique issues: It appears that the realization of SAGECELL heavily relies on the ultra-dense deployment of moving cells and the participation of different types of network elements. However, it is unlikely that one operator or party can own all these resources. Therefore, efficient resource sharing among multiple parties will be a key enabler for SAGECELL. Intuitively, through the resource virtualization and sharing in SAGECELL, any consumer is both a supplier and a consumer of the resources exchanged via the network. Therefore, the research challenges, in turn, are to find proper incentive schemes for multiple parties (e.g., access networks, satellites, UAVs, and vehicles) to share their resources efficiently and effectively.

Energy efficiency issues: The endurance and reliability of UAVs are impeded by limited battery capacity. For instance, the maximum flight duration of a small-type UAV is only around 30 min. As a result, this characteristic of UAVs would have a severe influence in the following aspects when they are employed as moving cells: first, users will suffer from intermittent connection and service interruption due to battery drainage; second, new UAVs should be dispatched to replace those UAVs that are running out of battery, which raises the cost of service provisioning and network maintenance. Therefore, how to improve the energy efficiency of UAVs is critical to guarantee seamless coverage in SAGECELL, which remains an open issue.

CONCLUSION

In this article, we have proposed a programmable, scalable, and flexible framework, SAGECELL, to combine space, air, and ground resources in a complementary fashion for matching dynamic varying traffic demands with limited network capacity supplies. We have presented a comprehensive review of state-of-the-art developments, and elaborated the conceptual architecture and potential use cases of SAGECELL in details. A real-world road-topology-based case study was conducted to demonstrate its capacity augmentation capability. Numerical results show that SAGECELL is able to achieve a 212.5 percent capacity improvement with an involvement factor of 0.6 compared to the baseline system.

ACKNOWLEDGMENTS

This work was partially supported by the Beijing Natural Science Foundation under Grant Number 4174104, the Beijing Outstanding Young Talent under Grant Number 2016000020124G081, the National Natural Science Foundation of China under Grant Number 61601181, and the Fundamental Research Funds for the Central Universities under Grant Number 2017MS13.

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