The Scanning the Literature column provides concise summaries of selected papers that have recently been published in the field of networking. Each summary describes the paper's main idea, methodology, and technical contributions. The purpose of the column is to bring the state of the art of networking research to readers of *IEEE Network*. Authors are also welcome to recommend their recently published work to the column, and papers with novel ideas, solid work, and significant contributions to the field are especially appreciated. Authors wishing to have their papers presented in the column should contact the Editor.

Xiaohua Tian, Shanghai Jiao Tong University (xtian@sjtu.edu.cn)

Space-air-ground integrated network (SAGIN) has emerged in recent years as a promising architecture to support seamless, high-rate, and reliable transmission with an extremely larger coverage, incorporating the merits of satellite systems, aerial networks, and terrestrial communications. While bringing great benefits for various practical applications, SAGIN is also facing many challenges due to its specific characteristics, such as heterogeneity, self-organization, and time-variability. This column focuses on recent research on the SAGIN, especially improvement on access control, fairness, throughput and outage performance and reduction on the cost of ground station communication infrastructure.

In the SAGIN, the unprecedented growth in data traffic might make the spectrum scarcity problem worse. With limited spectrum resources, data transmission in the SAGIN would be blocked due to transmission collision, leading to decreased transmission quality or even interrupted transmission. To tackle the enormous data traffic growth, C. Li *et al*. propose the dynamic spectrum access control (DSAC) protocol for SAGIN in the following paper.

## Throughput Analysis with Dynamic Spectrum Access Control in Space-Air-Ground Integrated Networks

C. Li, H. Wu, Z. Li, L. Guan, Y. Zhao, X. Shen, "Throughput Analysis with Dynamic Spectrum Access Control in Space-Air-Ground Integrated Networks", in *Proc. IEEE ICC' 21*, 2021.

Specifically, the proposed DSAC protocol uses sequences to represent the spectrum access decisions for authorized users at different time slots. Through iterative and orthogonal sequence transformation, the DSAC protocol can generate orthogonalized sequences to guarantee successful spectrum access for authorized users. In addition, the non-collision probability of the data packets accessing the shared spectrum under the guidance of the DSAC protocol is analyzed, based on which a closed-form expression of the system throughput is further derived. Simulation results are provided to validate the accuracy of the theoretical analysis and demonstrate that the proposed protocol is effective in access control and throughput improvement in the SAGIN when compared with the existing random access protocol.

SAGIN architecture gradually becomes a potential solution to support next generation networks. However, most existing works rely on computer simulations to investigate the performance of SAGIN, but hardly provide analytical results as a basis of the research. To address the challenge, J. Ye *et al*. introduce their insights of SAGIN from the perspective of cooperative communications and analyze the outage performance and approximate the outage probability in the following paper.

## Space-Air-Ground Integrated Networks: Outage Performance Analysis

J. Ye, S. Dang, B. Shihada, M.-S. Alouini, "Space-Air-Ground Integrated Networks: Outage Performance Analysis", *IEEE Trans. Wireless Commun.*, vol. 19, no. 12, pp. 7897-7912, 2020.

In essence, SAGIN is a cooperative relay network, in which high-altitude platforms (HAPs) and terrestrial base stations (BSs) serve as intermediates relaying signals between end device and satellite. In this article, the authors thereby view the SAGIN from the perspective of cooperative communications and introduce relay networking technologies to model and construct the framework of SAGIN. Meanwhile, they take the realistic propagation environment, HAP mobility and mathematical tractability into account and reconstruct the cooperative channel models for SAGIN, including the space-air, space-ground and air-ground links. Based on the constructed framework of SAGIN, they analyze the outage performance and approximate the outage probability as well as asymptotic outage probability in closed form. Numerical results generated by computer simulations verify their analysis and provide insight into the applicability of SAGIN. Although the relaying scenarios considered in this work are simplistic, the good tractability and expandability of the constructed framework provide a solid foundation for further research of advanced systems with complex configurations.

Wireless communication to the ground remains the key bottleneck in ensuring the success of the small satellite revolution, due to the cost and communication bottlenecks in communication with the satellite from the ground station, which means that very little useful data can be retrieved from small satellites. To address the issue, V. Singh *et al*. present a community-driven distributed reception paradigm for LEO satellite signals in the following paper.

## A Community-Driven Approach to Democratize Access to Satellite Ground Stations

V. Singh, A. Prabhakara, D. Zhang, O. Ya?an, S. Kumar, "A Community-driven Approach to Democratize Access to Satellite Ground Stations", in *Proc. 27th Annual International Conference on Mobile Computing and Networking (MobiCom '21)*, 2021.

Should you decide to launch a nano-satellite today in Low-Earth Orbit (LEO), the cost of renting ground station communication infrastructure is likely to significantly exceed your launch costs. While space launch costs have lowered significantly with innovative launch vehicles, private players, and smaller payloads, access to ground infrastructure remains a luxury. This is especially true for smaller LEO satellites that are only visible at any location for a few tens of minutes a day and whose signals are extremely weak, necessitating bulky and expensive ground station infrastructure. In this paper, the authors present a community-driven distributed reception paradigm for LEO satellite signals where signals received on many tiny handheld receivers (not necessarily deployed on rooftops but also indoors) are coherently combined to recover the desired signal. This is made possible by employing new synchronization and receiver orientation techniques that study satellite trajectories and leverage the presence of other ambient signals. They compare their results with a large commercial receiver deployed on a rooftop and show a 8 dB SNR increase both indoors and outdoors using 8 receivers, costing $38 per RF frontend.

Location information is another important aspect of many terrestrial applications as well as space applications including for satellites and the applications offered by them. With the rise in demand for small satellites over the past decade, the need for low-cost, low-energy space-borne GPS receivers is also increasing. However, building low-power GPS receivers still faces significant challenges, mainly due to the high speed of small satellites. To address the challenges, S. Narayana *et al*. introduce their design of a low-cost, low-power GPS receiver in the following paper.

## Hummingbird: Energy Efficient GPS Receiver for Small Satellites

S. Narayana, R. V. Prasad, V. Rao, L. Mottola, T. V. Prabhakar, "Hummingbird: Energy Efficient GPS Receiver for Small Satellites", in *Proc. 26th Annual International Conference on Mobile Computing and Networking (MobiCom '20)*, 2020.

Global Positioning System is a widely adopted localization technique. With the increasing demand for small satellites, the need for a low-power GPS for satellites is also increasing. To enable many state-of-the-art applications, the exact position of the satellites is necessary. However, building low-power GPS receivers which operate in low earth orbit pose significant challenges. This is mainly due to the high speed (~7.8 km/s) of small satellites. While duty-cycling the receiver is a possible solution, the high relative Doppler shift between the GPS satellites and the small satellite contributes to the increase in Time To First Fix (TTFF), thus increasing the energy consumption. Further, if the GPS receiver is tumbling along with the small satellite on which it is mounted, longer TTFF may lead to no GPS fix due to disorientation of the receiver antenna. In this paper, the authors elucidate the design of a low-cost, low-power GPS receiver for small satellite applications. They also propose an energy optimization algorithm called F3 to improve the TTFF which is the main contributor to the energy consumption during cold start. With simulations and in-orbit evaluation from a launched nanosatellite with their μGPS and high-end GPS simulators, they show that up to 96.16% of energy savings (consuming only ~1/25th energy compared to the state of the art) can be achieved using their algorithm without compromising much (~10 m) on the navigation accuracy. The TTFF achieved is at most 33s.

Unmanned aerial vehicle (UAV) assisted communications has drawn increasing attention from both academia and industry. However, the high mobility of UAV base stations (UAV-BSs) poses great challenge to full utilization of the advantages of UAV-BSs. Taking both ground users (GUs) and UAV-BSs into account, the objective of each GU is to maximize its own throughput, while the objective of UAV-BSs is to maximize the fair throughput which is jointly defined by the total throughput of the system and GU fairness. Therefore, to deal with the hybrid action space issue, R. Ding *et al*. propose a multi-agent deep reinforcement learning (MADRL) approach in the following paper.

## Air-Ground Coordination Communication by Multi-Agent Deep Reinforcement Learning

R. Ding, F. Gao, G. Yang, X. Shen, "Air-Ground Coordination Communication by Multi-Agent Deep Reinforcement Learning", in *Proc. IEEE ICC'21*, 2021.

In this paper, the authors investigate an air-ground coordination communication system where ground users (GUs) access suitable UAV base stations (UAV-BSs) to maximize their own throughput and UAV-BSs design their trajectories to maximize the total throughput and keep GU fairness. Note that the action space of GUs is discrete, and UAV-BSs' action space is continuous. To deal with the hybrid action space, they propose a multi-agent deep reinforcement learning (MADRL) approach, named AG-PMADDPG (air-ground probabilistic multi-agent deep deterministic policy gradient), where GUs transform the discrete actions to continuous action probabilities, and then sample actions according to the probabilities. The proposed method enables the users make decisions based on their local information, which is beneficial for user privacy. Simulation results demonstrate that AG-PMADDPG can outperform the benchmark algorithms in terms of fairness and throughput.

Since vehicular communications become prevailing in many cases, Space-Air-Ground integrated Vehicular Network (SAGVN) has also been proposed as a promising networking architecture. However, as different vehicular services share the underlying spectrum resource, the Quality of Service (QoS) of vehicular applications is difficult to guarantee since they have distinct traffic features and can affect each other significantly, especially when the network resource is insufficient. To address this problem, in the following paper F. Lyu *et al*. propose an online control framework to dynamically slice the SAG spectrum resource for isolated vehicular services provisioning.

## Service-Oriented Dynamic Resource Slicing and Optimization for Space-Air-Ground Integrated Vehicular Networks

F. Lyu, P. Yang, H. Wu, C. Zhou, J. Ren, Y. Zhang, X. Shen, "Service-Oriented Dynamic Resource Slicing and Optimization for Space-Air-Ground Integrated Vehicular Networks", *IEEE Trans. Intelligent Transportation Systems*, 2021.

In this paper, the authors study Space-Air-Ground integrated Vehicular Network (SAGVN), and propose an online control framework to dynamically slice the SAG spectrum resource for isolated vehicular services provisioning. In particular, at a given time slot, the system makes online decisions on the request admission and scheduling, UAV dispatching, and resource slicing for different services. To characterize the impact of those parameters, they construct a time-averaged queue stability criterion by taking queue backlogs of all services into consideration, and formulate a system revenue function which incorporates the time-averaged system throughput and UAV dispatching cost. The objective is to maximize the system revenue while stabilizing the time-averaged queue, which falls into the scope of Lyapunov optimization theory. By bounding the drift-plus-penalty, the original problem can be decoupled into four independent subproblems, each of which is readily solved. The merits of our control framework are three-fold: 1) the system is able to admit and process as many requests as possible (i.e., maximizing the time-averaged throughput); 2) the time-averaged UAV dispatching cost is minimized; and 3) service queues are stabilized in the long-term. Extensive simulations are carried out, and the results demonstrate that the control framework can effectively achieve the system revenue maximization and queueing stabilization. Moreover, it can balance the trade-off among system throughput, UAV dispatching cost, and queueing states via parameter tuning. Compared with the fixed slicing, their dynamic slicing can react to the vehicular environment rapidly and achieve an average 26% of throughput improvement.