UAV Communications for 5G and Beyond: Recent Advances and Future Trends

Bin Li, Zesong Fei, *Senior Member, IEEE*, and Yan Zhang, *Senior Member, IEEE*

***Abstract*—Providing ubiquitous connectivity to diverse device types is the key challenge for 5G and beyond 5G (B5G). Unmanned aerial vehicles (UAVs) are expected to be an important component of the upcoming wireless networks that can potentially facilitate wireless broadcast and support high rate transmissions. Compared to the communications with fixed infrastructure, UAV has salient attributes, such as flexible deployment, strong line-of-sight connection links, and additional design degrees of freedom with the controlled mobility. In this paper, a comprehensive survey on UAV communication toward 5G/B5G wireless networks is presented. We first briefly introduce essential background and the space–air–ground integrated networks, as well as discuss related research challenges faced by the emerging integrated network architecture. We then provide an exhaustive review of various 5G techniques based on UAV platforms, which we categorize by different domains, including physical layer, network layer, and joint communication, computing, and caching. In addition, a great number of open research problems are outlined and identified as possible future research directions.**

***Index Terms*—5G and beyond 5G (B5G), heterogeneous networks (HetNets), space–air–ground integrated networks, unmanned aerial vehicle (UAV) communications.**

NOMENCLATURE

2-D	Two-dimensional.
3-D	Three-dimensional.
4G	Fourth generation.
5G	Fifth generation.
B5G	Beyond fifth generation.
BS	Base station.
CR	Cognitive radio.
D2D	Device-to-device.
eMBB	Enhanced mobile broadband.
FANET	Flying ad-hoc network.
GCS	Ground control station.
HAP	High altitude platform.
HetNet	Heterogeneous network.
IoT	Internet of Things.
IoUAVs	Internet of UAVs.
LAP	Low altitude platform.
LoS	Line-of-sight.
MBS	Macro base station.
MEC	Mobile edge computing.
mMTC	Massive machine-type communications.
mmWave	Millimeter-wave.
NOMA	Nonorthogonal multiple access.
OMA	Orthogonal multiple access.
QoE	Quality of experience.
QoS	Quality of service.
RF	Radio frequency.
SBS	Small base station.
SDN	Software-defined networking.
SIC	Successive interference cancellation.
SWAP	Size, weight, and power.
UAV	Unmanned aerial vehicle.
URLLC	Ultrareliable low-latency communication.
WPCN	Wireless powered communication network.
WPT	Wireless power transfer.

Manuscript received July 15, 2018; revised October 21, 2018 and November 27, 2018; accepted November 30, 2018. Date of publication December 17, 2018; date of current version May 8, 2019. This work was supported in part by the National Natural Science Foundation of China under Grant 61871032, in part by the China National S&T Major Project under Grant 2017ZX03001017, in part by the 111 Project of China under Grant B14010, in part by the Projects 240079/F20 funded by the Research Council of Norway, in part by the European Union's Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Grant Agreement No. 824019, and in part by the Scholarship from China Scholarship Council under Grant [2017] 3019. *(Corresponding author: Zesong Fei.)*

B. Li is with the School of Information and Electronics, Beijing Institute of Technology, Beijing 100081, China, and also with the School of Computer and Software, Nanjing University of Information Science and Technology, Nanjing 210044, China (e-mail: libin_sun@bit.edu.cn).

Z. Fei is with the School of Information and Electronics, Beijing Institute of Technology, Beijing 100081, China (e-mail: feizesong@bit.edu.cn).

Y. Zhang is with the Department of Informatics, University of Oslo, 0316 Oslo, Norway, and also with the Simula Metropolitan Center for Digital Engineering, Fornebu, Norway (e-mail: yanzhang@ieee.org).

Digital Object Identifier 10.1109/JIOT.2018.2887086

I. INTRODUCTION

THE landscape of future 5G radio access networks is expected to seamlessly and ubiquitously connect everything, and support at least 1000fold traffic volumes, 100 billion connected wireless devices, and diversified requirements on reliability, latency, battery lifetime, etc., as opposed to current 4G cellular networks. Nowadays, the popularity of the IoT has triggered a surge in the number of mobile data traffic for upcoming 5G and B5G wireless networks. In accordance with the latest report [1], the global mobile traffic will reach 1 zettabyte/mo until 2028. This will lead the current infrastructure facing great capacity demands and also impose a heavy burden on the telecom operators in terms of increased capital investments and operational costs. Some early efforts have been dedicated to HetNets (i.e., deploy various small cells) to meet these growing demands [2].

However, in unexpected or emergency situations (such as disaster relief and service recovery), the deployment of terrestrial infrastructures is economically infeasible and challenging due to high operational expenditure as well as sophisticated and volatile environments. To handle this issue, intelligent heterogenous architecture by leveraging UAVs (or commonly known as drones) [3] has been considered to be a promising new paradigm to facilitate three central usage scenarios of future wireless networks, i.e., eMBB with bandwidth-consuming, URLLC, and mMTC. For instance, UAV may play a central role in providing network service recovery in a disaster-stricken region, enhancing public safety networks, or handling other emergency situations when URLLC is required. In particular, UAV-aided eMBB can be regarded as an important complement to the 5G cellular networks [4]. As a result, UAVs are identified as an important component of 5G/B5G wireless technologies.

Owing to the versatility and high mobility of UAVs, low-altitude UAVs are extensively used in diverse fields for different applications and purposes. On the standpoint of wireless communication aspects, UAVs can be employed as aerial communication platforms (e.g., flying BSs or mobile relays) by mounting communication transceivers to provide/enhance communication services to ground targets in high traffic demand and overloaded situations, which is commonly referred to as *UAV-assisted communications* [5]–[9]. On the other hand, UAVs can also be used as aerial nodes to enable a multitude of applications ranging from cargo delivery to surveillance, which is commonly referred to as *cellular-connected UAVs* [10], [11]. Most of the existing body of work, however, is restricted to UAVs in the role of assisting cellular communications. In most current contexts, UAVs are equipped with communication devices or dedicated sensors that can enable a myriad of applications, such as low altitude surveillance, post-disaster rescue, logistics application, and communication assistance. Furthermore, to support broadband wireless communications in a large geographical area, a swarm of UAVs forming FANETs [12], [13] and establishing connection links with the ground nodes, have been studied theoretically and validated through field experiments. As a desirable candidate to substitute or complement terrestrial cellular networks, UAV communications exhibit major attributes as follows [14].

1) *LoS Links:* UAVs without human pilots flying in the sky have a higher probability to connect ground users via LoS links, which facilitates highly reliable transmissions over long distances. In addition, UAVs can adjust their hovering locations to maintain the quality of links.
2) *Dynamic Deployment Ability:* Compared with stationary ground infrastructures, UAVs can be dynamically deployed according to real-time requirements, which is more robust against the environment changes. In addition, UAVs as aerial BSs do not require the site rental costs, thus removing the need for towers and cables.
3) *UAV-Based Swarm Networks:* A swarm of UAVs are capable of forming scalable multi-UAV networks and offering ubiquitous connectivity to ground users. Benefiting from its high flexibility and rapid provision features, the multi-UAV network is a feasible solution to recover and expand communication in fast and effective ways.

In fact, UAVs are distinguished according to the stringent constraint imposed by the SWAP, since the SWAP constraint directly impacts the maximum operational altitude, communication, coverage, computation, and endurance capabilities of each UAV. For instance, LAPs have low power and low capacity in terms of both payload and autonomy. By contrast, HAPs provide wider coverage and longer endurance [15]. As the altitude of UAV increases, the probability of having an LoS link for air-to-ground communication increases, mainly due to a higher probability of observing an unobstructed path. Meanwhile, the path loss is more severe due to the increased distance between the UAV and ground users. Thus, the two opposing aspects on the UAV's altitude need a fundamental tradeoff while guaranteeing the maximum cell coverage.

It is noteworthy that 5G/B5G wireless networks are expected to exhibit great heterogeneities in communication infrastructures and resources for connecting different devices and providing diverse services [16]. Researchers these days are focusing on ways to design heterogeneous infrastructures, such as densely deployed small cells; integrate heterogeneous communication networks, such as space-based, air-based, and ground-based [17]; employ multifarious 5G communication techniques [18], such as massive multiple-input multiple-output (MIMO), mmWave, NOMA transmission, D2D, CR, and so forth, to improve spectrum efficiency and energy efficiency. Regarding the UAV-assisted cellular networks, the operation cost (e.g., endurance time) is one of the most important factors. For this reason, energy harvesting can be a must-has core technology. In a meantime, UAVs can serve as edge network controllers to efficiently allocate computing and storage resources. Particularly, UAVs can either serve as edge computing platforms to offload the computing tasks from IoT devices, or cache popular contents to reduce the burden of backhaul networks [19].

A. Existing Surveys and Tutorials

A couple of surveys and tutorials related to UAV communications have been published over the past several years [12], [15], [20]–[27], including the characteristics and requirements of UAV networks, main communication issues, cyber-security, wireless charging techniques, and channel modeling for UAV communications, etc.

More specifically, Hayat *et al.* [12] have reviewed the civil applications of UAV networks from a communication perspective along with its characteristics. They also reported experimental results from many projects. A survey paper by Gupta *et al.* [20] elaborated many issues encountered in UAV communication networks to provide stable and reliable wireless transmission. Motlagh *et al.* [21] presented a comprehensive survey and highlighted the potentials for the delivery of low altitude UAV-based IoT services from the sky. The cybersecurity for UAVs was reviewed in [22], where actual and simulated attacks were discussed. Furthermore, Jiang and Han [23] surveyed the most representative routing protocols for UAVs and compared the performance of the existing major routing protocols. Another survey by Khawaja *et al.* [24] solely focused on the air-to-ground

TABLE I
EXISTING SURVEYS RELATING TO UAV COMMUNICATIONS

Publication	One-sentence summary
Hayat *et al.* [12]	A survey of the characteristics and requirements of UAV networks
Gupta *et al.* [20]	A survey on the main issues in UAV communications networks
Motlagh *et al.* [21]	A comprehensive survey on UAVs-based IoT services
Krishna *et al.* [22]	A review on cybersecurity for UAVs
Jiang *et al.* [23]	A survey of routing protocols for UAVs
Khawaja *et al.* [24]	An overview of air-to-ground propagation channel modeling
Khuwaja *et al.* [25]	A survey of the measurement methods proposed for UAV channel modeling
Lu *et al.* [26]	Review of wireless charging techniques for UAVs
Cao *et al.* [27]	Overview of airborne communication networks
Mozaffari *et al.* [15]	A comprehensive tutorial on the use of UAVs in wireless networks

propagation channel measurement and modeling. They also discussed various channel characterization efforts. While in [25], from a channel modeling viewpoint, Khuwaja *et al.* reported the extensive measurement methods for UAV channel modeling based on the LAPs and discussed various channel characteristics. Lu *et al.* [26] introduced various prevalent wireless charging techniques conceived for UAV mission time improvement. They provided a classification of wireless charging techniques, namely the family of nonelectromagnetic-based and the family of electromagnetic-based methods. Cao *et al.* [27] were concerned with the primary mechanisms and protocols for the design of airborne communication networks by considering the LAP-based communication networks, the HAP-based communication networks, and the integrated communication networks. Additionally, in a more recent study Mozaffari *et al.* [15] provided a holistic tutorial on UAV-enabled wireless networks and reviewed various analytical frameworks and mathematical tools conceived for solving fundamental open problems. The above-mentioned surveys related to UAV communications are outlined at a glance in Table I, which allows the readers to capture the main contributions of each of the existing surveys.

B. Paper Contributions and Organization

Although the aforementioned existing studies provided insights into several perspectives for UAV communication networks, it is worth reflecting upon the current achievements in order to shed light on the future research trends for 5G/B5G. Therefore, it is of great importance and necessity to provide an overview of the emerging studies related to the integration of 5G technologies with UAV communication networks. In this survey, we are intending to provide the reader with an emerging space–air–ground integrated network architecture and highlight a variety of open research challenges. Then, we present an exhaustive review of the up-to-date research progress of UAV communications integration with various 5G technologies at: 1) physical layer; 2) network layer; and 3) joint communication, computing, and caching. Finally, we identify possible future trends for UAV communications according to the latest developments.

The rest of this paper is outlined as follows. In Section II, we envision an overview of the space–air–ground integrated network and discuss the relevant challenges for the emerging architecture. In Section III, we provide a physical layer overview of the state-of-the-art studies dedicated to integrating UAV into 5G/B5G communications. In Section IV, we present a network layer overview of the existing studies dedicated to integrating UAV into 5G/B5G communications. In Section V, we review the existing contributions on joint communication, computing, and caching for UAV communications. Finally, in Section VI we describe a range of open problems to be tackled by future research, followed by our conclusions in Section VII. For the sake of explicit clarity, the organization of this paper is shown in Fig. 1.

II. B5G ARCHITECTURE: SPACE–AIR–GROUND INTEGRATED NETWORKS

In this section, we first present the space–air–ground integrated network architecture in upcoming 5G/B5G wireless communications, where a three-layer cooperative network is introduced and explained briefly. Then, we discuss the major challenges faced by the system design.

A. Space–Air–Ground Integrated Networks

To accommodate the diverse IoT services with different QoS requirements in various practical scenarios (e.g., urban, rural, and sparsely populated areas) [28], it is imperative to exploit specific advantages of each networking paradigm. For instance, densely deployed terrestrial networks in urban areas can support high data rate access, satellite communication systems can provide wide coverage and seamless connectivity to the most remote and sparsely populated areas, while UAV communications can assist the existing cellular communications for the rapid service recovery and offer

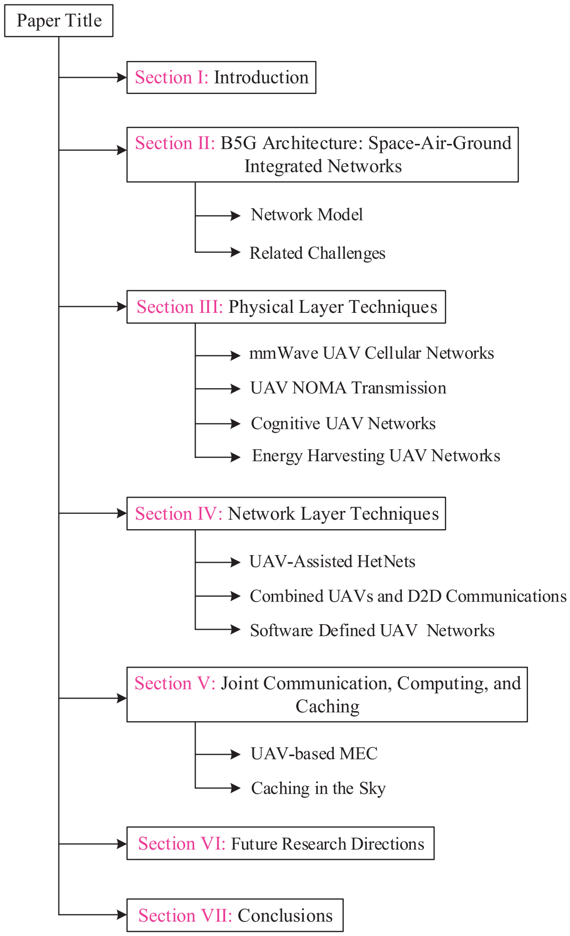

Fig. 1. Organization of this paper.

the traffic offloading of the extremely crowded areas in a cost-effective fashion [29]. At present, it is widely believed that the individually existing network cannot meet the need to process enormous volumes of data and execute substantial applications, such as IoT, cloud computing, and big data. Therefore, there is a growing demand among scientific communities to develop an integrated network architecture from the space-based network, air-based network, and ground-based network.

The overall architecture of the space–air–ground integrated network is presented in Fig. 2 to provide user devices with improved and flexible end to end services, which is categorized into three segments, i.e., space-based, air-based, and ground-based layers. Thereinto, UAVs are deployed to set up a multitier UAV network, as well as the radio access infrastructure, the mobile users and vehicles form the ground network. At the same time, SDN controllers [17] can be deployed to regulate the network behaviors and manage the network resources in an agile and flexible manner (in software) to facilitate the space–air–ground interworking. Considering different segments having distinct characteristics, such as communication standards and diverse network devices with various functions, the control and communication interfaces of SDN controllers for each segment should be dedicated to the corresponding segment.

Regarding the space-based network, it is composed of a number of satellites or constellations of different orbits [like geostationary earth orbit (35 786 km), low earth orbit (700–2000 km) and medium earth orbit (8000–20 000 km)], ground stations, and network operations control centers. Satellites in different orbits, types and properties can form a global space-based network through intersatellite links, which in turn utilize the multicast and broadcast techniques to improve the network capacity. Meanwhile, by establishing the satellite-to-UAV and satellite-to-ground links, the connections are created with their neighbor satellites and ground cellular networks. On the basis, the space-based network can provide global coverage on the earth with services for emergency rescue, navigation, earth observation, and communication/relaying. We can imagine that the future earth will be surrounded by large volumes of satellites. However, the data delivery between the satellites and the ground segment is affected by long transmission latencies in virtue of the large free-space path loss and tropospheric attenuation. It is compelling to use higher frequency band for providing low-latency and high-throughput services, such as C-band and Ka-band [30].

Satellite-to-UAV communication is a key component for building the integrated space–air–ground network. It is worth noting that the satellite-to-UAV channel mainly relies on the LoS link and also suffers from the rain attenuation significantly when using the Ka-band and above. In light of its applications and equipment, UAV can communicate with the satellites in different orbits during UAV navigation. Generally, geosynchronous satellite is used for satellite-to-UAV communication since its location relative to earth keeps invariant [31]. For UAV-to-satellite link, the premise of establishing a successful link is the alignment of the spatial beam from UAV to target satellite (i.e., the direction). Nevertheless, the continuous navigation of UAVs would result in the attitude variation all the time, which directly affects the spatial beam pointing for the UAV-to-satellite link. One typical scenario is UAV-assisted satellite communication, where UAV needs to constantly adjust its beam toward the target satellite to maintain the communication link [32].

In the air-based network, a wide variety of unmanned flying platforms, including UAVs, airships or balloons may be restricted to different operational altitudes due to the SWAP constraints. Generally, a UAV is equipped with transceivers to provide flexible Internet access for a group of ground users and a *drone-cell* is the corresponding coverage area. The size of drone-cell is dominated by UAV's altitude, location, transmission power, and the environment factors. Furthermore, a swarm of UAVs are connected by establishing the UAV-to-UAV links to provide services cooperatively. The multitier UAV network not only supports control messages exchanging among UAVs to avoid collisions and calculate flying paths, but also sends data to mobile devices accessing them. Specific UAVs are outfitted with heterogeneous radio interfaces, such as LTE or WiFi, to communicate with infrastructures or satellites, which establishes gateways between multitier UAV networks and other networks. The UAV can either use a sky-haul link to the satellites or connect to the ground system via a backhaul link [33].

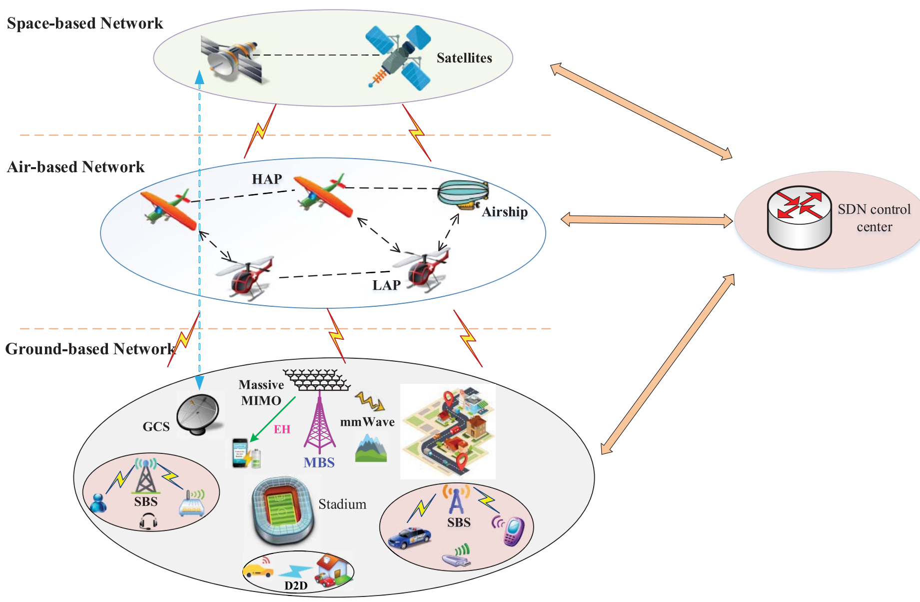

Fig. 2. Illustration of space–air–ground integrated networks. The conceptual communication architecture in UAV-aided networks is composed of three layers: the space layer for the satellite data links, the air layer for UAVs and LoS data links, and the ground layer for end user devices, GCS, and government/security center.

In the ground-based network, the heterogeneous radio access network comprising of macro cells and small cells serves the mobile users, such as mobile phones, self-driving cars, IoT devices, and so forth, which will create an coexistent system of disruptive technologies for 5G wireless networks. This covers all promising 5G cellular technologies, including mmWave frequency band, energy harvesting, NOMA transmission, and D2D communication, as shown in Fig. 2, and has become an important research topic recently. In addition, the exponentially increasing computing capability of mobile devices can be conceived for MEC, where UAVs can schedule the computing tasks while onboard computers fulfill these tasks. And along with this, popular contents can be cached at the UAVs or ground devices, and transmitted through the drone-cells or D2D communication between end devices. In particular, there are two kinds of transmission channels in the integration of air-based network and ground-based network: the LoS data link and the satellite data link. The LoS data link is used for direct transmission from the UAV to the GCS, in which light emissions travel in a straight line. In this kind of transmission, the waves may be easily absorbed by obstructions, so it is not suitable for the military fields.

In this paper, a general B5G integrated network architecture has been proposed. It describes the interconnectivity among the different emerging technologies. The concept of mmWave frequency band, energy harvesting, NOMA transmission, and D2D communication has also been incorporated in this proposed B5G network architecture. This proposed architecture also explains the roles of MEC and cache. In general, the proposed integrated network architecture may provide a good platform for future network standardization, which is expected to be reliable, real-time, efficient, and safety.

B. Potential Challenges

Although the importance of the space–air–ground integrated network in B5G wireless communications is increasingly growing, developing the integrated network is a challenging task [34] that includes air-to-ground channel modeling, optimal deployment, energy efficiency, path planning, resource management, network security, etc. In this section, we summarize in detail the key challenges faced by future space–air–ground integrated networks as follows.

1) Channel Modeling: Due to the distinctive channel characteristics of the air segment (such as 3-D space and time-variability), the UAV-to-ground channels are much more complex than current ground communication channels [35]. Also, the UAV-to-ground channels are more susceptible to blockage than the air-to-air communication links that experience dominant LoS. Therefore, the conventional models are often not well suited for characterizing UAV-to-ground channels. Given the heterogeneous environment, the UAV-to-ground channels are highly dependent on the altitude and type of the UAV, the elevation angle, and the type of the propagation environment. Clearly, accurate channel modeling link is of vital importance to evaluate the system performance properly. However, finding a generic channel model for UAV-to-ground communications in consideration of such factors is challenging, which needs comprehensive simulations and measurements in various environments. Currently, many channel measurement campaigns and modeling efforts have been made to characterize the UAV-to-ground channels [36]–[38].

2) Deployment: UAV-satellite communication is a key component for building the integrated space–air–ground network, the mobility of UAV and satellite complicates integrated network operation. On one hand, the characteristics of the air-to-ground channels need to be considered for optimal 3-D deployment of UAVs to decrease handover and avoid physical collisions. On the other hand, a satellite system is limited in power and bandwidth suffering from large transmission delay, and the satellite-to-ground channel fading at high frequencies (typically Ka-band) is much more severe, which seemingly blocks it from practical usage.

3) Path Planning: For an air-based network comprising the swarm of UAVs, each of which has a trajectory flying over the ground. In order to reduce the communication delay, a UAV needs to move close to the ground users. However, due to the need of keeping interconnection with its neighboring UAVs, it is not always possible for a given UAV to maintain a close link with the served users. As a consequence, if a swarm of UAVs are considered, finding an optimal flying trajectory for a UAV is an arduous task due to practical constraints. Thus, it is urgently needed to exploit a dynamic trajectory control method for UAVs to increase the probability of end-to-end link connections while maintaining sufficient coverage of the entire target area.

4) Operational Altitude: Due to SWAP constraints, different types of UAVs may be restricted to different operational altitudes. For instance, mobile devices in urban scenarios may require higher LoS connectivity, whereas mobile devices in suburban scenarios may need higher degree of path loss reduction. Note that the higher altitude of UAVs promotes higher LoS connectivity since reflection and shadowing are diminished, while lower altitude ensures reduction in path loss. By selecting different heights for multitier UAVs, an optimal tradeoff between LoS connectivity and path loss can be struck.

5) Interference Dynamics: In the constructed multitier HetNets, the ground cellular network and the air-to-ground channel suffer from high co-channel interference from the same and different segments, which will gradually render the current air interface obsolete. Furthermore, the UAV's mobility creates Doppler shift, which also causes severe intercarrier interference at high frequencies. Hence, in consideration of mobile characteristics, appropriate interference management in the integrated network becomes more challenging.

6) Limited Energy: Since UAVs mainly rely on rechargeable battery power, the cruising duration on UAVs is strongly affected by the energy consumption of UAVs which may depend on their mobility, transmission power, and circuit power consumption. This is a prime challenge that significantly limits their operation time. Naturally, it is crucial to prolong the service duration or even provide persistent service during the mission via advanced charging technologies.

7) Backhaul Cellular Communication: An important distinction between ground BSs and UAV-BSs is the fact that the backhaul network is characterized by heterogeneous links. Specifically, ground BSs are typically connected with the core network via wired links that have large bandwidth. By contrast, UAV-BSs connecting with the MBSs or the core network need high-capacity wireless backhaul links. Practically, the limited backhauls will become the bottleneck and affect the QoS of mobile users.

8) Network Security: As the integrated network creates a multitier topology where multiple nodes are deployed with dissimilar characteristics and the broadcasting nature of wireless LoS propagation, the integrated network is particularly vulnerable to malicious attacks. As a result, safeguard strategies or protocols are of paramount importance. Furthermore, the accurate positioning of the UAVs and the detection of unauthorized intrusion into the airspace is another open aspect. Besides, SDN controllers are mainly responsible for managing resources and controlling network operation, protecting the SDN controllers from different cyber attacks is still a challenge in integrated networks.

9) Real-Time Demand: Satellites for different tasks or services have different velocities and communication coverage, the data links between nodes may be frequent intermittence owing to the high bit error rate and transmission latency. Since the satellite data link adopts an onboard satellite transmission system to transmit remote data, a challenge is how to maximize the fast data acquisition ability and real-time exchange of information capability while transmitting data to the GCS.

In the next three sections, we provide an overview of the existing contributions related to UAV communications in the context of 5G/B5G wireless networks. We review these state-of-the-art studies mainly based on the current 5G technologies from physical layer, network layer, as well as joint communication, computing, and caching perspectives, which are intended to provide useful guidelines for researchers to understand the referenced literature.

III. PHYSICAL LAYER TECHNIQUES

Currently, a variety of works are mainly concerned with the UAV-assisted communication networks, especially in unexpected or temporary events [39]. Benefiting from the portable transceiver functionality and advanced signal processing techniques, the success of UAV communications can realize omnipresent coverage and support massive dynamic connections. Fig. 3 depicts the scenario of UAVs acting as flying BSs (i.e., UAV-BSs) where these UAVs are usually equipped with diverse payloads for receiving, processing, and transmitting signals, aiming to complement pre-existing cellular systems by providing additional capacity to hotspot areas during temporary events. This scenario has been considered as one of the five key scenarios faced by future cellular networks [40]. Also, UAVs can be used to reinforce the communication infrastructure in emergency and public safety situations during which the existing terrestrial network is damaged or not fully operational [41].

In order to improve the system performance of UAV communication in 5G networks, physical layer techniques are of much concern as they affect the applications of UAVs significantly. There are mainly five candidate key technologies at physical layer, namely mmWave communication, NOMA transmission, CR, and energy harvesting. In this section, we review the state-of-the-art works on mmWave UAV-assisted cellular networks, UAV NOMA transmission, cognitive UAV networks, and energy harvesting UAV networks.

A. mmWave UAV-Assisted Cellular Networks

It is crucial to note that UAVs may have to deal with different types of data, such as voice, video, and huge data files, which creates unprecedented challenges in terms of high

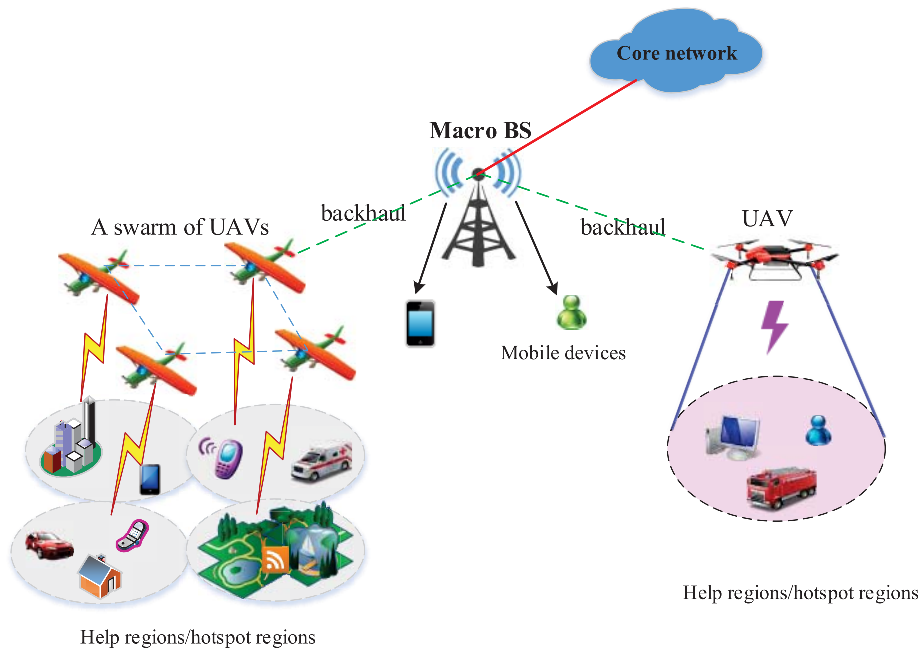

Fig. 3. Exemplary scenario of UAVs as aerial BSs serving a target area, where each UAV is equipped with wireless transceivers allowing them to communicate with ground users and also with other UAVs.

bandwidth requirements. This expected growth along with the spectrum crowding encourages the migration to new frequency allocations. In this context, mmWave communications [42] are emerging as a suitable candidate that can take advantage of a vast amount of unlicensed spectral resource at the mmWave frequency band (over 30–300 GHz) to deal with the high requirements for 5G wireless networks.

With the vision of providing wireless mobile access for UAV-assisted cellular networks in mmWave spectrum, an immediate concern is the extremely high propagation loss, since Friis' transmission law states that the free space omni-directional path loss grows with the square of the carrier frequency. Fortunately, the short wavelength of mmWave signals allows multiple antennas to be packed into a small UAV [43]. As a byproduct, beamforming technique can be exploited to construct a narrow directional beam and overcome the high path loss or additional losses caused by atmospheric absorption and scattering. The main difference between a mmWave UAV-assisted cellular network and a conventional mmWave cellular network with a fixed BS is that a UAV-BS may move around. Some of the existing challenges are intensified due to UAV's movement. For example, more efficient beamforming training and tracking are needed to account for UAV movement, and the channel Doppler effect needs extra consideration, while the UAV position and user discovery are intertwined. This problem has been invoked in recent years. Table II shows a summary of the major related works on mmWave UAV-assisted cellular networks.

Benefited by the abundant bandwidth and short wavelength, Xiao *et al.* [44] first introduced the concept of mmWave UAV cellular network along with its characteristics and pointed out possible solutions ahead. Specifically, they investigated a hierarchical beamforming codebook structure for fast beamforming training and tracking and explored the use of mmWave spatial-division multiple access for cellular network capacity improvement. Zhu *et al.* [45] examined the secrecy performance of a randomly deployed UAV-enabled mmWave communication network over Nakagami-m fading channels, where Matérn Hardcore point process was applied to maintain the minimum safety distance between the randomly deployed UAV-BSs. In order to bypass these obstacles brought by short wavelength as mentioned above, UAVs as mobile relays are widely needed in mmWave communications. For real applications, it is challenging to find the optimal relay location automatically. Aiming at this, Kong *et al.* [46] studied a novel UAV-relay method specialized for mmWave communications, where a UAV-relay was used to measure the real-time link qualities and the aerial location was designed properly. The numerical results demonstrated that UAV-relay was capable of providing more accuracy and efficiency solutions than the existing relay method. An efficient channel tracking method was proposed in [47] for a mmWave UAV MIMO communication system, where the communication and control system were jointly conceived, and the 3-D channel model was formulated as a function of the UAV movement state information and the channel gain information. Naqvi *et al.* [48] formulated a UAV-assisted multiband HetNet, including ground-based macro BS and dual-mode mmWave small BS, and they proposed a joint subcarrier and power allocation scheme to maximize the system energy efficiency. By taking into account the LoS blockage by human bodies, Gapeyenko *et al.* [49] studied the effective deployment of a mmWave-UAV-BS and derived the corresponding height and cell radius. In contrast, Khosravi *et al.* [50] evaluated the performance of utilizing small cell densification technique combined with UAV operating at mmWave frequent band, and

TABLE II
SUMMARY OF CONTRIBUTIONS TO MMWAVE UAV CELLULAR NETWORKS

Reference	**Objective**	**Mobility**	**Types of BSs**	**Number of UAVs**
Xiao *et al.* [44]	Beam tracking	Mobile	UAV-only	Single UAV
Zhu *et al.* [45]	Density optimization	Static	UAV-only	Multiple UAVs
Kong *et al.* [46]	Optimal relay location	Static	Hybrid (UAVs & ground BSs)	Single UAV
Zhao *et al.* [47]	Channel tracking	Mobile	UAV-only	Single UAV
Naqvi *et al.* [48]	Energy efficiency	Mobile	Hybrid (UAVs, MBS & SBSs)	Multiple UAVs
Gapeyenko *et al.* [49]	Optimized deployment	Static	UAV-only	Single UAV
Khosravi *et al.* [50]	Performance evaluation	Mobile	UAV-only	Two UAVs
Khawaja *et al.* [51]	Channel measurement	Mobile	UAV-only	Single UAV

the simulation results showed that this method is a promising solution for addressing the propagation limitations. To top it off, Khawaja *et al.* [51] carried out the propagation measurement for mmWave air-to-ground channels for UAV communications by using ray tracing simulations, four types of environments were analyzed, such as urban, suburban, rural, and over sea.

B. UAV NOMA Transmission

NOMA has recently drawn considerable attention as one of the key enabling technologies for 5G communication systems [52], reaping a high spectral efficiency via incorporating superposition coding at the transmitter with SIC at the receivers. Compared to OMA, NOMA serves a multitude of users with diversified traffic patterns in a nonorthogonal fashion by considering power domain for multiple access. This provides an effective pathway for UAVs to ensure the needs of massive ground users at different power levels. The basis of NOMA implementation relies on the difference of channel conditions among users. Until now, lots of works have contributed to the adoption of NOMA transmission for UAV-assisted communications, in which the UAV-BSs can serve multiple users that operate at the same time/frequency carrier, especially for emergency services with a larger number of users. A simple illustration of the NOMA transmissions in a UAV-based network is depicted in Fig. 4.

More specifically, for a two-user NOMA case, the work presented by Sohail and Leow [53] focused on finding the optimal altitude of a rotary-wing UAV-BS to maximize the fairness among users under individual user-rate constraint and the promised gains achievable by NOMA were exhibited over OMA. By extending [53], the authors further formulated the sum-rate problem as a function of power allocation and UAV altitude in [54] and a constrained coverage expansion methodology was proposed to find the optimal altitude. Sharma and Kim [55] adopted a fixed-wing UAV to serve two ground users using downlink NOMA transmission, in which the outage probability for both ground users was derived and

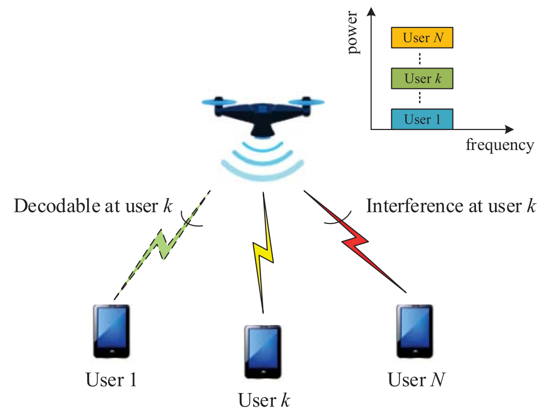

Fig. 4. Diagram for the considered UAV NOMA scenario. A UAV serves multiple ground users where the signals of users 1 to $k-1$ are cancelled at the kth user, while the signals of users $k+1$ to N are received as interference.

an effective transmission mode was selected to guarantee better outage probability for achieving user fairness. In addition, the NOMA transmission was also applied to the UAV-assisted relaying systems [56], where a novel optimal resource allocation algorithm was proposed to maximize the throughput of ground users and to extend the actual operation range of the UAV.

For a multiuser NOMA case, Rupasinghe *et al.* [57] introduced the NOMA transmission at UAV-BS operating on mmWave frequency in a large stadium, where multiple users were served simultaneously within the same beam and the optimal operational altitude as well as power allocation strategy were identified to enhance the outage sum-rate performance. With the mmWave-NOMA transmission at UAV-BS, tracking and feeding back full channel state information become cumbersome, thus the limited feedback schemes were tackled in [58] and [59] based on the availabilities of user distance information and user angle information for user ordering. The numerical results revealed that the proposed user angle-based feedback scheme was significantly superior to the proposed user distance-based feedback scheme. Nasir *et al.* [60] employed a single-antenna UAV-BS and

TABLE III
SUMMARY OF CONTRIBUTIONS TO UAV NOMA TRANSMISSION

Reference	Objective	Mobility	Types of BSs	Number of UAVs
Sohail *et al.* [53]	Power optimization	Static	UAV-only	Single UAV
Sohail *et al.* [54]	Joint power and altitude optimization	Static	UAV-only	Single UAV
Sharma *et al.* [55]	Performance analysis	Mobile	UAV-only	Single UAV
Baek *et al.* [56]	Power optimization	Mobile	UAV-only	Single UAV
Rupasinghe *et al.* [57]	Performance analysis	Static	UAV-only	Single UAV
Rupasinghe *et al.* [58]	Performance analysis	Static	UAV-only	Single UAV
Rupasinghe *et al.* [59]	Performance analysis	Static	UAV-only	Single UAV
Nasir *et al.* [60]	Max-min rate optimization	Static	UAV-only	Single UAV
Hou *et al.* [61]	Performance analysis	Static	UAV-only	Single UAV
Liu *et al.* [62]	Power allocation and trajectory design	Mobile	UAV-only	Single UAV
Pan *et al.* [63]	Theoretical-plus-experimental investigation	Mobile	UAV-only	Single UAV
Pan *et al.* [64]	Radio resource allocation	Mobile	Hybrid (UAVs & MBS)	Multiple UAV

NOMA technique to serve a large number of ground users, where the max-min rate optimization problem was formulated by jointly optimizing multiple parameters (i.e., the UAV's flying altitude, transmit antenna beamwidth, and the amount of power and bandwidth) and a path-following algorithm was developed to solve the nonconvex problem. As a further advance, Hou *et al.* [61] proposed an MIMO-NOMA aided UAV framework where a multiantenna UAV communicates with multiple users equipped with multiple antennas each. By adopting stochastic geometry, the locations of NOMA users were modeled as independent spatial random processes and the closed-form expressions for outage probability of paired NOMA users were derived. With this approach, the positions of UAVs and ground users were modeled in an NOMA-enabled UAV network by Liu *et al.* [62] and the system performance was evaluated. Also, they applied a machine learning framework to solve the dynamic placement and movement of UAVs in a 3-D space. Very recently, Pan *et al.* [63] developed a network-coded multiple access downlink scheme for UAV communications, which was more robust against varying downlink channel conditions by the experimental results, while a cooperative NOMA scheme was applied in a wireless backhaul network [64] where UAVs were used as flying SBSs to maximize the sum rate of all users, by jointly optimizing the UAVs' positions, the decoding order of the NOMA process and the transmit beamforming vectors. Finally, Table III portrays a summary of the existing major contributions to UAV NOMA transmission.

As discussed in the above-mentioned literature, it is evident that NOMA is flexible and efficient in multiplexing a number of end users to UAV communications. However, the successful operation of NOMA in UAV communications requires numerous associated challenges and constraints for the following reasons.

1) The distinct feature of NOMA with improved spectral efficiencies is that a sophisticated SIC technique at the receiver side is used.
2) SIC exclusively relies on the channel state information at both receivers and transmitters to determine the allocated power for each receiver and the decoding order, which needs to be estimated relatively accurately in a UAV communication network.
3) NOMA multiplexing multiple users in the power domain introduces interlayer interference, more efforts are needed to further eliminate the resulting interlayer interference in UAV communications with NOMA.
4) Considering the high mobility of UAVs in practice, the communication distance between the UAV and ground users would vary constantly based on the realtime requirements, thereby the SIC decoding order determined by the received signal strengthes of difference users varies with the locations of UAVs.

C. Cognitive UAV Networks

Nowadays, one crucial predicament faced by the UAV-enabled wireless networks is the shortage of radio spectrum. Many concerning reasons are listed as follows: 1) there is a dramatic growth and usage of new portable mobile devices on the ground (such as smartphones and tablets) and 2) different wireless networks (Bluetooth, WiFi, LTE, and cellular networks) coexist on the operating spectrum bands of UAVs. These lead to a very intense competition of spectrum usage and thus UAV communications will face the problem of spectrum scarcity [65], [66]. Therefore, it is necessary for UAV communications to obtain further spectrum access by dynamic utilization of the existing frequency bands.

TABLE IV
SUMMARY OF CONTRIBUTIONS TO COGNITIVE UAV NETWORKS

Reference	Objective	Mobility	Types of BSs	Number of UAVs
Huang *et al.* [68]	Joint trajectory and power optimization	Mobile	Hybrid (UAV & ground BSs)	Single UAV
Zhang *et al.* [69]	Optimal deployment	Static	Hybrid (UAVs & ground BSs)	Multiple UAVs
Sboui *et al.* [70]	Power optimization	Static	Hybrid (UAVs & ground BS)	Two UAVs

Thus far, many researchers and standardization groups have presented the incorporation of CR and UAV communication systems to increase the spectrum opportunities, which is referred to as *cognitive UAV communications* [67], [68]. This concept constitutes a promising network architecture that allows the coexistence of UAVs with terrestrial mobile devices operating in the same frequency band. In this case, the UAV-to-ground communications may cause severe interference to the existing terrestrial devices since UAVs usually have strong LoS links with ground users. Table IV shows a number of existing contributions to cognitive UAV networks at a glance.

Note that in the literature, there have been several works that studied the cognitive UAV communication system. For example, Huang *et al.* [68] jointly optimized the UAV's trajectory and transmit power allocation with the aim of achieving the maximum throughput of a cognitive UAV communication, while restricting the interference imposed at primary receivers below a tolerable level. Zhang and Zhang [69] presented an underlay spectrum sharing method between the drone-cells network and traditional ground cellular network under different scenarios, i.e., spectrum sharing of single tier drone-cells in 3-D network, and a spectrum sharing between the drone-cells network and the traditional 2-D cellular network. Using stochastic geometry theory, they derived the explicit expressions for the drone-cells coverage probability and achieved the optimal density of UAV-BSs for maximizing the throughput. Similarly, Sboui *et al.* [70] proposed to integrate an underlay CR into a UAV system where the UAV as a secondary transmitter opportunistically exploited and shared the primary spectrum for the UAV-to-ground transmission. The objective was to maximize the energy efficiency of the UAV unit, thereby ensuring effective and long-time operations of UAVs.

D. Energy Harvesting UAV Networks

Unlike traditional ground transceivers connected to external power supplies, UAV is powered by capacity-limited battery and thus the UAV-based communications are facing the limited energy availability for performing various operations like flight control, sensing/transmission of data, or running some applications. As is known to all, the finite on-board energy storage of typical UAVs (battery life is usually less than 30 min) restricts their operation time (i.e., flight time or hovering time) [71], and it is not always possible that the UAVs are required to return to the depot for battery charging frequently. Thus, this is critical but challenging to guarantee stable and sustainable communication services and will act as a performance bottleneck.

1) Energy Efficiency: For many UAV applications, energy consumption saving is of significant importance to prolong the lifetime of a UAV network. In recent years, many research endeavors have been conducted on the energy-aware UAV deployment and operation mechanisms. More explicitly, Li *et al.* [72] proposed an energy-efficient transmission scheduling scheme of UAVs in a cooperative relaying network such that the maximum energy consumption of all the UAVs was minimized, in which an applicable suboptimal solution was developed and the energy could be saved up to 50% via simulations. By exploiting the optimal transport theory, Mozaffari *et al.* [73] investigated the energy-efficient deployment of multiple UAV-BSs for minimizing the total required transmit power of UAVs under the rate requirements of the ground users. Zeng and Zhang [74] presented an energy-efficient UAV communication by optimizing UAV's trajectory with a fixed altitude, where the propulsion energy consumption of the fixed-wing UAV was taken into account and the theoretical model was derived. Ghazzai *et al.* [75] developed an energy-efficient optimization problem for a UAV communication by integrating CR technology to minimize the total energy consumption of UAV, including the flying and communication energies, where a joint algorithm inspired from the Weber formulation was proposed to optimize the transmit power level and the location of cognitive UAV. Liu *et al.* [76] proposed a framework that leveraged deep reinforcement learning to study the energy consumption used for UAV movements, while maintaining the fair communication coverage and the network connectivity. Ruan *et al.* [77] built a multi-UAV energy-efficient coverage deployment model, in which the proposed model was decomposed into two subproblems to reduce the complexity of strategy selection, i.e., coverage maximization and power minimization.

2) Energy Harvesting: In fact, the energy consumption of the battery-powered UAV is usually split into an energy consumed by the communication unit and the energy used for the hardware and mobility of UAVs. Hence, energy harvesting UAV is crucial to prolong its flight duration without adding significant mass or size of the fuel system. In recent applications, it is very advantageous to harvest energy from ambient sources for recharging UAV's battery, which is referred to as *wireless powered UAV networks*. A lot of related works have proceeded to improve the endurance of electrically powered UAVs. In particular, solar-powered UAV has received significant attention that harvests energy from solar and converts it to electrical energy via photovoltaic effect for realizing perpetual flight, the system model is shown in Fig. 5. As a matter of fact, the available solar energy depends on the geographic location,

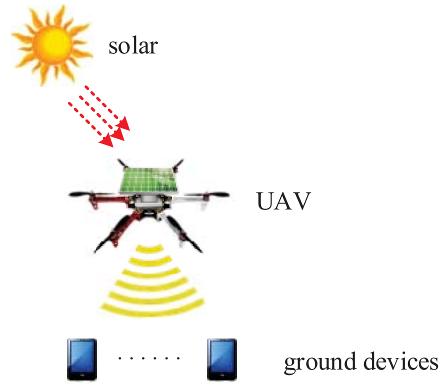

Fig. 5. Solar-powered UAV communication system, where the UAV is equipped with solar panels that can harvest energy from solar source.

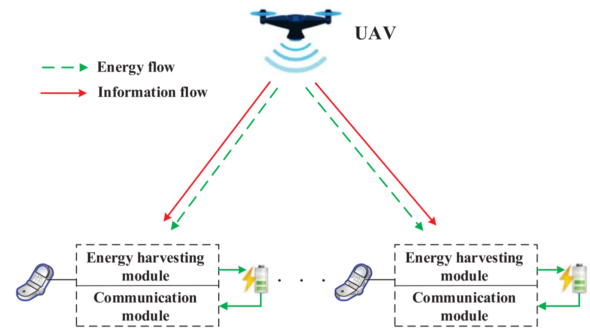

Fig. 6. Typical example of a UAV-enabled wireless powered network, where the UAV is able to transmit energy or simultaneously transmit data and energy to ground user devices via RF signals. The green color portion represents the energy flow and the red color portion represents the information flow.

altitude, the number of daylight hours and the day of the year. The solar-powered UAV prototypes have been developed by engineers in [78] and [79] and they revealed the possibility of continuous flight for 28 h. Wang and Shen [80] constructed the simulation model of solar cell for solar-powered UAV via MATLAB/Simulink software and the output characteristics of solar panels in three types of weather conditions (i.e., light rain, cloudy, and sunny days) were tested in Nanjing, China, the test site was the Nanjing University of Aeronautics and Astronautics. The experimental test results demonstrated that the output curve of a solar cell was mainly affected by the ambient temperature and light intensity. The Indian Institute of Technology Kanpur [81] carried out a day-only flight test of a solar UAV platform in April 2017, where the UAV took off at 9:30 A.M. successfully landed at 6:00 P.M. From the measurement results, one could observe that the generated power became less than the power required by the UAV system during around from 3:30 P.M. to 5:10 P.M. Meanwhile, the Aircraft Design Group of Cranfield University at U.K. [82] examined the impact of temperature and solar irradiance intensity on various solar module angles, the results showed that the optimum operating temperature for both nonlaminated and laminated solar modules was around 45 °C and the solar power rose almost linearly along the solar module tilt angle.

From the standpoint of academic research, Sun *et al.* [83] have invoked the resource allocation design for a solar-powered multicarrier UAV communication system for maximization of the system sum throughput, where a low-complexity joint 3-D position, power and subcarrier allocation algorithm was proposed to find out the suboptimal solution. Since the aerodynamic power consumption of realistic UAV systems depends on the flight velocity, the assumption of constant aerodynamic power consumption is not valid in practice. For this reason, Sun *et al.* [84] further studied a multicarrier solar-powered UAV communication system by jointly taking into account the solar energy harvesting, the aerodynamic power consumption, the dynamics of the on-board energy storage, and the QoS requirements of the ground users. The objective was to maximize the system sum throughput over a given time period. Simulation results showed that the UAV could harvest more solar energy when it was flying right above the clouds. Hua *et al.* [85] considered an energy-constrained UAV relaying scenario where the power splitting-based relaying protocol was adopted at a UAV for energy harvesting and information processing with the aim of maximizing the network throughput. In urban environment, Wu *et al.* [86] proposed a solar-powered UAV path planning framework that considered the obstacle condition and the shadow regions caused by high buildings. However, the solar energy for solar cell-based harvesting is often weather-dependent and unpredictable, thereby suffering from uncertainty caused by random energy arrivals. Most current works did not consider this practical environment. In this context, the work by Sowah *et al.* [87] presented a rotational energy harvester based on a brushless dc generator to harvest ambient energy for prolonging the indoor flight time of quadcopter, while a prototype of the rotational energy harvesting system was also implemented. Long *et al.* [71] proposed the architecture of energy neutral IoUAVs where recharging stations were used to energize the UAVs via WPT with RF signals, which significantly enabled the continuous operation lifetime. In UAV-assisted relaying systems, Yang *et al.* [88] analyzed the outage performance of UAV harvesting energy from the ground BS, where both shadowed-Rician fading and shadowed-Rayleigh fading were, respectively, considered.

On the other hand, mobile devices (such as low-lower sensors) usually are also energy-constrained and the useful lifetimes are limited by the battery capacity. Since UAVs have more energy available than mobile devices and the UAVs actually provide services to the ground devices, UAVs as aerial energy transmitters with additional flexibility are expected to provide ubiquitous wireless energy supply to massive low-power devices. This significantly improves the wireless charging efficiency compared to the conventional ground charging stations at fixed locations, which is referred to as *UAV-enabled wireless powered networks*. A detailed example of the energy harvesting from UAV is presented in Fig. 6, where the UAV comprises an energy transfer module for broadcasting RF energy to ground user devices. The idea has been conducted in recent years [89]–[93]. To be specific, Marano and Willett [89] looked into improving the sustainable operation of sensors during the sensing stage in the context of a wireless sensor

TABLE V
SUMMARY OF CONTRIBUTIONS TO ENERGY HARVESTING UAV NETWORKS

Reference	Objective	Mobility	Types of BSs	Number of UAVs
Sun *et al.* [83]	Joint optimizing position and power and subcarrier	Static	UAV-only	Single UAV
Sun *et al.* [84]	Joint optimizing 3D-trajectory and power and subcarrier	Mobile	UAV-only	Single UAV
Hua *et al.* [85]	Optimal location	Mobile	Hybrid (UAV & BS)	Single UAV
Wu *et al.* [86]	Path planning	Mobile	UAV	Single UAV
Sowah *et al.* [87]	Implementation viewpoint	Static	UAV-only	Single UAV
Long *et al.* [71]	Routing protocol	Mobile	Hybrid (UAVs & ground BSs)	Multi-tier UAVs
Yang *et al.* [88]	Outage Performance	Static	Hybrid (UAV & ground BS)	Single UAV
Marano *et al.* [89]	Energy allocation	Mobile	UAV-only	Single UAV
Wang *et al.* [90]	Power optimization and time allocation	Static	UAV-only	Single UAV
Xu *et al.* [91]	Trajectory optimization	Mobile	UAV-only	Single UAV
Xu *et al.* [92]	Trajectory optimization	Mobile	UAV-only	Single UAV
Nguyen *et al.* [93]	Optimal energy harvesting time and power control	Static	UAV-only	Single UAV
Park *et al.* [94]	Joint trajectory optimization and resource allocation	Mobile	UAV-only	Single UAV; Two UAVs
Xie *et al.* [95]	Joint trajectory optimization and resource allocation	Mobile	UAV-only	Single UAV

network via RF signal from a UAV. Wang *et al.* [90] proposed a joint time and power optimization algorithm for maximization of the average throughput, where UAV acted as a static energy source to power multiple D2D pairs and a harvest-transmit-store protocol was adopted. However, this paper did not take into account the mobility of UAV. By exploiting UAV's trajectory design, Xu *et al.* [91] presented the first work on characterizing the achievable energy region of ground users in a UAV-enabled two-user WPT system. Xu *et al.* [91] further considered the UAV-enabled multiuser WPT system in [92], where the problems of sum-energy maximization and min-energy maximization were, respectively, conceived by optimizing the UAV's trajectory subject to the practical speed constraint. Subsequently, Nguyen *et al.* [93] considered the energy efficiency problem in WPT-powered D2D communications with the help of UAV by jointly optimizing the energy harvesting time and power allocation, and then the performance of the UAV network was evaluated by embedded optimization module implemented in Python.

As a further development, Park *et al.* [94] have invoked a UAV-aided WPCN for maximization of the minimum user throughput by jointly optimizing the UAV's trajectory, uplink power control and time resource allocation, where both scenarios of integrated UAV and separated UAV WPCNs were, respectively, taken into consideration. Xie *et al.* [95] addressed a joint UAV trajectory and resource allocation optimization problem for the uplink throughput maximization in a UAV-enabled WPCN setup, while maintaining the UAV's maximum speed constraint and the users' energy neutrality constraints. Eventually, a summary of the existing works on energy harvesting UAV networks is shown in Table V.

IV. NETWORK LAYER TECHNIQUES

The next generation networks should intelligently and seamlessly integrate multiple nodes to form a multitier hierarchical architecture, including the drone-cell tiers for large radio coverage areas, the ground small cell tiers for small radio coverage areas, the user device tiers with D2D communications, and so forth. However, the integration of different tiers will result in new issues to the investigation of the network layer techniques. Therefore, specific strategies that coordinate the QoS of nodes are necessary. In this section, we review the state-of-the-art works on UAV-assisted HetNets, combined UAVs and D2D communications, and software defined UAV networks.

A. UAV-Assisted HetNets

With the forthcoming of 5G era, densely populated users are thirsty for broadband wireless communications and network operators are expected to support diverse services with high wireless data demands, such as multimedia streaming and video downloads. The unrelenting increment in mobile traffic volumes imposes an unacceptable burden on the operators in terms of increased capital expenditure and operating costs. An intuitive option to offload the cellular traffic is to deploy small cells (e.g., pico and femto cells). However, in unexpected or temporary events, the deployment of terrestrial infrastructures is challenging since the mobile environments are sophisticated, volatile, and heterogeneous. One potential solution resorts to the usability of drone-cells [15], which has been proved to be instrumental in supporting ground cellular networks in areas of erratic demand. The idea is to bring the ground users closer to the drone-cells in order to improve their QoS due to the short-range LoS connections from sky. Fig. 3 shows the typical UAV-assisted HetNet architecture with one MBS and multiple drone-cells.

At the same time, the mobility of drone-cells enables them to serve users with high mobility and data rate demand. In the open literature, two canonical lines of research can be identified involving *ground HetNets* and *aerial HetNets*. In the first line focusing on characterizing the ground HetNets, Li and Cai [96] introduced UAV-based floating relays to handle the increasing traffic volume due to the rapid development of mobile Internet, where UAVs were parked inside a small garage on the MBS and their batteries would be recharged when backing to the garage. The optimized bandwidth solution was proposed to enable heterogeneous deployment of UAV-based floating relay cells inside the macro cell and achieved dynamic and adaptive coverage. In a two-tier UAV-assisted HetNet, Kumbhar *et al.* [97] conceived the optimal deployment of UAVs and the interference coordination technique defined in LTE-Advanced was exploited to mitigate the intercell interference resulting from the HetNet. At the same time, the genetic algorithm was shown to be an effective method to maximize the spectral efficiency of the network. Merwaday *et al.* [98] aimed at exploring a large-scale disaster-affected environment consisting of MBSs and SBSs in which UAVs were designated for providing coverage and seamless broadband connectivity in desired regions. A genetic algorithm was proposed to optimize the positions of UAV-BSs with the goal of maximizing the network throughput.

As a further advance, the problem of user-demand-based UAV assignment in HetNets was investigated in [99], a neural-based cost function framework was formulated to strike the appropriate user demand areas and UAVs to enhance the network capacity. Zhang *et al.* [100] considered a heterogeneous cellular network comprising a set of UAVs as flying BSs and a set of ground BSs that provided an on-demand wireless service to a group of cellular users. They developed a novel machine learning framework to predict the cellular data traffic and formulated a power minimization problem for downlink communications and mobility to optimize the deployment of UAVs. Furthermore, the minimum delay scheme has been widely studied in UAV-assisted HetNets for improving QoS of mobile users. For example, in [101] the concept of entropy nets from the neural network was applied to minimize the overall network delay by optimizing the placement and distribution of cooperating UAVs in demand areas. Sun and Ansari [102] tried to balance the traffic loads between a UAV-BS and an MBS for achieving a minimum total average latency ratio among the MUs under the energy limitations of the UAV-BS. The optimization problem formulated comprised two steps, namely first determining the location of the UAV-BS and then optimizing the association coverage of the UAV-BS.

Another line of research has established that future aerial networks will be heterogeneous and comprise different types of UAVs, namely high-altitude long-range UAVs (less than 5 km), medium-altitude UAVs (between 5 and 10 km), and low-altitude short-range UAVs (greater than 10 km) [105]. The multitier aerial networks are much affected by the density of users and services and can be constructed by utilizing several UAV types, which is similar to terrestrial HetNets with macro-, small-, pico-cells, and relays. As an initial study, Mehta and Prasad [103] introduced the concept of aerial-HetNet to offload the data traffic from the congested ground BSs in hotspots, where a fleet of small UAVs were deployed as an ad-hoc network with variable operational altitudes in the air. The network performance improvement was also illustrated. To cater for the capacity and coverage enhancements of HetNets, an MBS-based decisive and cooperative problem was presented in [104] for the accurate mapping of the UAVs to the demand areas, where both single-layer model with multiple UAVs and multilayer model with multiple UAVs in each layer were, respectively, considered. An intelligent solution utilizing the priority-wise dominance and the entropy approaches was proposed for the accurate and efficient placement of the UAVs. Sekander *et al.* [13] concentrated on investigating the feasibility of multitier UAV network architecture over traditional single-tier UAV network in terms of spectral efficiency of downlink transmission, and identified the relevant challenges, such as energy consumption of drones, interference management, and so forth. The impact of different urban environments (including high-rise urban, suburban, and dense urban) on this multitier UAV network architecture was finally shown by numerical results. Finally, a brief summary of the above contributions is given in Table VI.

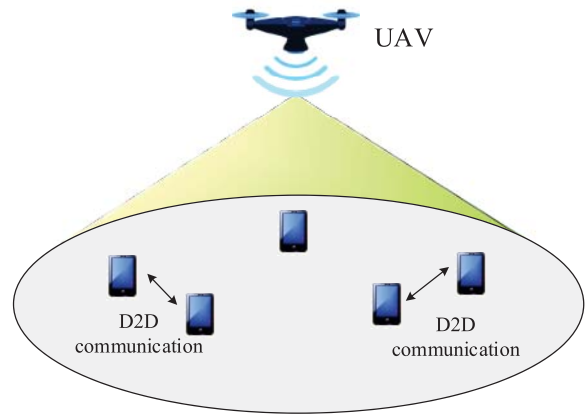

Fig. 7. D2D communications underlying UAV-supported cellular network.

B. Combined UAVs and D2D Communications

D2D communications as a new network architecture is becoming increasingly popular, which dramatically improves network capacity by offloading mobile traffic from BSs, when two neighboring nodes communicate with each other via D2D mode. In general, D2D communications are typically deployed using underlay transmission links which reuse existing licensed spectrum resources [106], while UAV can be a good candidate to promptly construct the D2D-enabled wireless network by introducing a new dimension, as shown in Fig. 7. In parallel, the working of UAVs alongside D2D communications over a shared spectrum band will also introduce important interference management challenges, thus the impact of UAV's mobility on D2D and network performance should be analyzed. Table VII shows a summary of the

TABLE VI
SUMMARY OF CONTRIBUTIONS TO UAV-ASSISTED HETNETS

Reference	**Objective**	**Mobility**	**Types of BSs**	**Number of UAVs**
Li *et al.* [96]	Optimized bandwidth	Static	Hybrid (UAVs & MBS)	Multiple UAVs
Kumbhar *et al.* [97]	Optimal placement	Static	Hybrid (UAVs & MBSs)	Multiple UAVs
Merwaday *et al.* [98]	Optimal location	Mobile	Hybrid (UAVs & MBSs)	Multiple UAVs
Sharma *et al.* [99]	Optimal placement	Static	Hybrid (UAVs & MBS)	Multiple UAVs
Zhang *et al.* [100]	Optimal placement	Mobile	Hybrid (UAVs & ground BSs)	Multiple UAVs
Sharma *et al.* [101]	Optimal placement	Static	Hybrid (UAVs & MBSs)	Multiple UAVs
Sun *et al.* [102]	Optimal placement	Static	Hybrid (UAV & MBS)	Single UAV
Mehta *et al.* [103]	Optimal placement	Static	Hybrid (UAVs & MBS)	Multiple UAVs
Sharma *et al.* [104]	Optimal placement	Static	Hybrid (UAVs & MBS)	Multiple UAVs
Sekander *et al.* [13]	Altitude optimization	Static	Hybrid (UAV & BSs)	Two-tier UAVs

TABLE VII
SUMMARY OF CONTRIBUTIONS TO COMBINED UAVS AND D2D COMMUNICATIONS

Reference	**Objective**	**Mobility**	**Types of BSs**	**Number of UAVs**
Mozaffari *et al.* [107]	Performance analysis	Static; Mobile	UAV-only	Single UAV
Tang *et al.* [108]	Channel Assignment	Mobile	UAV-only	Multiple UAVs
Guo *et al.* [109]	Altitude optimization	Static	UAV-only	Multiple UAVs
Christy *et al.* [110]	Trajectory optimization	Mobile	UAV-only	Single UAV
Wang *et al.* [111]	Spectrum sharing planning	Mobile	UAV-only	Single UAV
Xue *et al.* [112]	Social group utility maximization	Static	UAV-only	Single UAV

existing major contributions to combined UAVs and D2D communications.

To elaborate, Mozaffari *et al.* [107] conducted the first attempt on providing a comprehensive performance analysis to evaluate the coexistence of UAV and D2D in terms of different performance metrics, in which both key scenarios namely static UAV and mobile UAV were considered, respectively. Tang *et al.* [108] studied the assignment of the radio channels in a combined UAV and D2D-based network with the consideration of high mobility of UAV and D2D nodes, in which the UAVs could be used as both local content servers and aerial D2D nodes. Moreover, a distributed anti-coordination game algorithm was conceived for solving the channel assignment problem. In a multi-UAVs-enabled wireless network with D2D communications, Guo *et al.* [109] provided an analysis of the coverage probability of downlink users and D2D users and then optimized the altitude of UAVs to maximize the capacity of ground network. Christy *et al.* [110] examined the utilization of a UAV to discover potential D2D devices for establishing D2D transmissions as an emergency communication network. Through simulation results, the authors have shown that it can reduce the device energy consumption and increase the capacity of the network. The concept of full-duplex was introduced by Wang *et al.* [111] to UAV-assisted relaying systems with underlaid D2D communications, in which the transmit power and UAV's trajectory were jointly designed to achieve efficient spectrum sharing between aerial UAV and terrestrial D2D communications. Beyond that, the work in [112] proposed to apply multiple D2D peers to the UAV-supported social networking for the maximization of the sum social group utility, where both physical interference and social connections between users in the physical/social domain were considered.

C. *Software Defined UAV Networks*

Recent proposals for future wireless network architectures aim to create a flexible network with improved agility and resilience. SDN has been introduced in 2008 to program the network via a logically software-defined controller [113], which can decouple the control plane and data plane to facilitate network reconfiguration. This is conducive to manage the infrastructure and resources of wireless networks. Compared to traditional networking, SDN has better controllability and visibility for network components, which enables better management by using the common controller.

TABLE VIII
SUMMARY OF CONTRIBUTIONS TO SOFTWARE DEFINED UAV NETWORKS

Reference	Objective	Mobility	Types of BSs	Number of UAVs
Bor-Yaliniz *et al.* [34]	Optimal placement	Static	Hybrid (UAVs & ground BSs)	Multi-tier UAVs
Sharma *et al.* [114]	Fast handovers	Mobile	Hybrid (UAVs & ground BSs)	Multiple UAVs
Rahman *et al.* [115]	Optimal placement	Static	UAV-only	Multiple UAVs
Shukla *et al.* [116]	Computation offloading	Static	Hybrid (UAVs & ground BSs)	Multiple UAVs
Yang *et al.* [117]	Optimal density and location	Static	UAV-only	Multiple UAVs
Secinti *et al.* [118]	Multi-path routing	Static	UAV-only	Multi-tier UAVs
Secinti *et al.* [119]	Multi-path routing	Static	UAV-only	Multiple UAVs

In real-world applications of drone-cells, wireless networks must be configured efficiently for seamless integration/disintegration of UAVs, such as changing protocols and creating new paths. Based on the SDN architecture, UAVs can perform as SDN switches on data plane for collecting context information in a distributed way, while the ground BSs are controllers gathering data and making control decisions on network functions and resource allocation. Helped by SDN, network reconfiguration and resource allocation among a swarm of UAVs can be conducted in a more flexible way. Table VIII shows a summary of the existing major contributions to SDN with UAVs.

Pioneering work by Bor-Yaliniz and Yanikomeroglu [34] proposed a drone-cell management framework enabled by SDN and network functions virtualization technologies to assist a terrestrial HetNet. For an SDN-based UAV architecture, the proposed SDN variant in [114] provided handover facilities in the UAVs (i.e., as on-demand forwarding switches) that supported wireless networks with lower handover latency. Since SDN can enable a global view of network, ur Rahman *et al.* [115] considered the placement of the SDN controller in an SDN-based UAV network for providing better service, where an appearing tradeoff was achieved between the communication overhead and the end-to-end delay for sharing the control information between UAVs and SDN controller. Shukla *et al.* [116] studied the resource allocation of a multi-UAV network to minimize the operating delay and energy consumption by considering the edge servers and cloud servers. The network management between these units was enabled by SDN controller in an efficient manner such that the QoS demands of applications were ensured. Yang *et al.* [117] developed a proactive UAV-cell deployment framework to alleviate overload conditions caused by flash crowd traffic. Under this frame, the SDN technology was employed to seamlessly integrate and disintegrate drone-cells by reconfiguring the network. Similarly, Secinti *et al.* [118] carried out a study on a resilient multipath routing framework for a UAV-network, where the SDN controller was utilized to determine the preferred routes subjected to jamming. Also, Secinti *et al.* [119] further proposed an aerial network management protocol building on top of an SDN architecture, where each UAV became a software switch that performed control directives sent by a centralized controller. Finally, the multipath routing algorithm was proposed to reduce the average end-to-end outage rate.

V. JOINT COMMUNICATION, COMPUTING, AND CACHING

The 5G wireless network is envisaged to embed various resources to support massive traffic and various services. This will be characterized by the convergence of communications, computing, and caching capabilities [120]. As an essential component of IoT and future 5G networks, UAV cannot only act as an edge computing platform for providing flexible and resilient services to IoT devices with limited processing capabilities, but also act as a complementary method to cache some popular contents for reducing backhaul workload and transmission latency at peak time. The architecture of UAV-oriented communication, computing, and caching is shown in Fig. 8. In this section, we review recent works on UAV-based MEC and UAV-based cache, which may be applied in 5G/B5G communications.

A. UAV-Based MEC

Due to the limited battery and low computation capability, it is challenging for IoT devices to execute real-time applications. Fortunately, MEC has recently emerged as a paradigm to tackle this issue [121]. With the deployment of MEC server, mobile users can offload their computation tasks to the edge of network by empowering the cloud computing functionalities. It serves two important purposes.

1) Reduction in application latency (i.e., execution time), if a remote device has enormous computing resources.
2) Improving battery performance because application is being executed at a remote device.

In UAV-enabled networks, the resource-constrained mobile devices are able to offload their computation-intensive tasks to a flying UAV with high computing ability and flexible connectivity at the edge of network, thereby saving their energy and reducing traffic load at the fixed cloud servers. Therefore, the UAV equipped with an MEC server offers promising advantages compared to the conventional ground cellular network

TABLE IX
SUMMARY OF CONTRIBUTIONS TO UAV-BASED MEC

Reference	**Objective**	**Mobility**	**Types of BSs**	**Number of UAVs**
Jeong *et al.* [122]	Computation offloading	Mobile	UAV-only	Single UAV
Jeong *et al.* [123]	Computation offloading	Mobile	UAV-only	Single UAV
Tang *et al.* [124]	Computation offloading	Mobile	UAV-only	Multiple UAVs
Zhou *et al.* [125]	Computation offloading	Mobile	UAV-only	Single UAV
Jung *et al.* [126]	Computation offloading	Mobile	UAV-only	Single UAV
Motlagh *et al.* [127]	Computation offloading	Static	UAV-only	Single UAV
Hua *et al.* [128]	Computation offloading	Mobile	Hybrid (UAVs & ground BSs)	Multiple UAVs

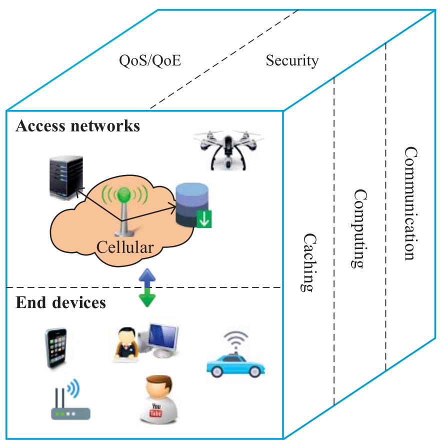

Fig. 8. Architecture of UAV-oriented communication, computing, and caching.

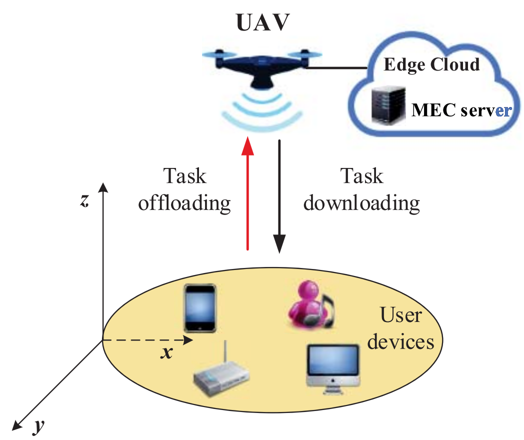

Fig. 9. Illustration of the UAV-mounted MEC system that provides application offloading opportunities to ground user devices.

with fixed BSs. The system model of UAV-mounted MEC is demonstrated in Fig. 9. In such a case, each mobile device needs to decide either local computing or edge computing. For the former, the mobile devices can locally execute their own tasks by the embedded micro-processor, this will occupy their local computation resources and consume large quantities of energy. For the latter, the mobile devices are allowed to offload their intensive computation tasks to the MEC server co-located in UAVs directly, and then the MEC server will execute the computation tasks on behalf of the mobile devices. Actually, each mobile device is associated with a nearby UAV node who currently has enough battery power and computing resources. Table IX shows a significant body of works on UAV-based MEC.

To expound a litter further, the idea of installing the MEC processor on a UAV was initially putted forth by Jeong *et al.* [122] that offered the computation offloading opportunities to mobile devices. In this paper, the authors considered a mobile device and a UAV with the aim of minimizing the energy consumption of mobile device by optimizing the bit allocation for uplink/downlink communication under the condition of a predetermined UAV's trajectory. After that, Jeong *et al.* [123] presented extension to the multiple mobile devices setting, the problem of optimizing the bit allocation and UAV's trajectory was tackled for minimizing the mobile energy consumption subject to the latency and UAV's energy budget constraints, where both OMA and NOMA schemes were considered, respectively. Tang *et al.* [124] discussed a highly dynamic social network supported by UAV-mounted cloudlets where UAVs were leveraged to quickly construct a meshed offloading backbone. With the deployed UAVs with high performance computing cloudlets, both computation and traffic load could be shared from central cloud to the edge of network, such that the computing burden of the cloud servers and the traffic load were reduced. Zhou *et al.* [125] concentrated their attention on the power minimization problem in a UAV-enabled MEC system by jointly optimizing the computation offloading and trajectory design. In this considered situation, UAV played dual-role namely, it not only performed the computation tasks offloaded from mobile devices, but also acted as a source transmitter to recharge the battery-powered devices.

On the other side, the on-board processor in a UAV may not have enough computing resources due to the small size of UAV. This puts a restraint on efficient execution of complex applications. The battery and computation performance of UAV can be virtually enhanced by leveraging computation

TABLE X
SUMMARY OF CONTRIBUTIONS TO CACHING IN THE SKY

Reference	**Objective**	**Mobility**	**Types of BSs**	**Number of UAVs**
Chen *et al.* [129]	UAV cache	Static	UAV-only	Multiple UAVs
Chen *et al.* [130]	UAV cache	Mobile	Hybrid (UAVs & remote radio heads)	Multiple UAVs
Xu *et al.* [131]	UAV cache	Mobile	UAV-only	Single UAV
Zhao *et al.* [132]	UAV cache	Static	Hybrid (UAVs & ground BSs)	Multiple UAVs
Fang *et al.* [133]	UAV cache	Mobile	UAV-only	Multiple UAVs

offloading to remote cloud server or nearby edge servers via MBS or SBSs. Therefore, a UAV node has an option to either process application using its own resources, or send its computation tasks to edge server or a remote cloud for processing according to applications' QoS requirements. When UAVs deal with high resolution images quickly, Jung *et al.* [126] addressed the problem of insufficient energy and computing resources via offloading the data processing to a GCS for prolonging UAV's flying time. After the GCS completed the image processing, the GCS returned the processed images to UAVs for the current operational mission. According to a use case of face recognition, Motlagh *et al.* [127] considered the offloading of video data processing from UAVs to an MEC node. Also, a testbed was developed from the viewpoint of a practical implementation to show the performance gains of the MEC-based offloading approach over the local processing of video data onboard UAVs in terms of energy consumption and processing time. Additionally, the problem of energy consumption for computation tasks offloading from multi-UAV to ground BS was pursued by Hua *et al.* [128], where four types of access schemes in the uplink transmission were proposed and compared.

B. Caching in the Sky

Wireless data traffic has been increasing dramatically in recent years due to the proliferation of new mobile devices and various mobile applications. The driving forces behind this traffic growth have fundamentally shifted from the steady increasing in demand for connection-centric communications (such as smart phones and text messages) to the explosion of content-centric communications (such as video streaming and popular music). Even though SBSs are densely deployed to accommodate the vast amount of traffic, a heavy burden will be imposed on the backhaul links. In fact, the backhaul network cannot deal with the explosive growth in mobile traffic. One promising method is to intelligently caching some popular contents at the network edge (i.e., UAVs, relays, or D2D devices), such that the demands from users for the same popular contents can be accommodated easily without duplicate transmissions via the backhaul links.

In general, mobile users are constantly moving, and thus a more flexible caching strategy is desired. UAV as a flying BS can dynamically cache the popular contents, track the mobility patterns of wireless devices and then effectively serve them. This not only significantly reduces the transmission latency, but also alleviates the traffic offloading on the backhaul especially during peak-load time. In UAV-assisted edge caching, the contents can be directly cached in the UAV-BSs and then distributed to users, or cached in the D2D devices and scheduled by the UAV-BSs [19]. For the former one, the contents can be cached at UAV-BSs during the off-peak times. For the latter one, mobile users can cache the contents requested, and distribute such contents among nearby users following the scheduling of ground BSs or UAV-BSs. Such edge caching strategies can enhance the QoE of users while reducing the needed backhaul link capacity. In this respect, a number of contributions on caching at UAV have been done, as shown in Table X.

More specifically, Chen *et al.* [129] presented an idea of locally caching the popular content at flying UAVs in an LTE unlicensed band system that allowed them to directly transmit data providing services for the ground users, where a dynamic resource allocation algorithm based on machine learning was proposed to autonomously learn and determine which content to cache and how to allocate the licensed and unlicensed bands. In [130], the problem of proactive deployment of cache-enabled UAVs in a cloud radio access network was explored to minimize the transmit power of the UAVs. In particular, a novel machine learning framework of conceptor-based echo state networks was proposed to effectively predict the content request distribution and mobility pattern of each user. Also, the optimal locations of UAVs and the contents to cache at UAVs were derived. Xu *et al.* [131] discussed a proactive caching scheme to prolong the UAV endurance where the UAV pro-actively delivered the files to a subset of selected ground nodes that cooperatively cached all the files. And then the files can be retrieved by each ground node either directly from its local cache or from its nearest neighbor via D2D communications. Simulation results showed the great potential of proactive caching in overcoming the limited endurance issue. In the meantime, Zhao *et al.* [132] examined the caching UAV-assisted secure transmission in a hyper-dense network where the video streaming was cached at both UAVs and SBSs simultaneously. The interference alignment was exploited to eliminate the interference between ground users, and the idle SBSs were further utilized to disrupt the potential eavesdropping by generating the jamming signals. Considering the practical influence of propagation groups (i.e., LoS and non-LoS), Fang *et al.* [133] designed a joint scheme of UAVs' caching contents and service locations in a multi-UAV-aided network with the aim of achieving the tradeoff between user's service probability and transmission overhead, where the formulated optimization problem was modeled as a UAV caching game and the optimal solution could be obtained.

VI. Future Research Directions

In spite of the potentials combining UAV with 5G techniques, the research on UAV-assisted wireless networks is still in its infant stage and many open issues are in need of further investigation. In this section, we shed light on the new opportunities in emerging network architecture and highlight interesting research topics for future directions.

A. Energy Charging Efficiency

Energy limitation is the bottleneck in any UAV communications scenario. As recent developments in battery technologies, such as enhanced lithium-ion batteries and hydrogen fuel cells, energy harvesting is used to extend the flight times by utilizing green energy sources (such as solar energy). However, the efficiency of energy harvesting is relatively lower due to longer distance and random energy arrivals. To enhance the charging efficiency, novel energy delivering technologies, such as energy beamforming through multiantenna techniques and distributed multipoint WPT are of great interest.

B. UAV-to-UAV and Satellite-to-UAV Communications

To provide communication service to ground wireless devices over a significantly wide area, a swarm of UAVs construct a multihop network to help the devices send and pick up packets, each of which has a trajectory. However, due to the high-speed mobility and the need to maintain the close communication links with ground users, the link connection with the neighboring UAVs is disconnected frequently. In this case, all the traditional routing protocols cannot work well in FANETs. Therefore, how to control the flight of the UAVs to realize a good service is a challenging direction. In addition, when multiple UAVs collaborate, collision avoidance also become a significant development for UAV safe operation. On the other hand, state-of-the-art satellite-to-UAV channel models lack detailed propagation effects. The exploitation of channel propagation models for satellite-to-UAV communications is still in its infancy and remains a topic for future research.

C. Interaction of Different Segments

For the integrated space–air–ground network, a major issue is how to take advantage of innovative techniques to ensure seamless integration among the space-based network, the air-based network and the ground cellular network. Thus, it is desirable to design some cooperative incentives between different segments and dedicated cross-layer protocol designs are needed to ensure link reliability. In such a complex network environment, it is also important to provide scalable and flexible interfaces for these segments to interact and cooperate for achieving attractive benefits, i.e., how to implement the seamless information exchange and data transmission among HetNets. For instance, the increasing variety of services may require UAVs to be the gateways between different networks, it is crucial in such a complex network to design interworking mechanisms for ensuring link reliability.

D. Synergy of UAVs and IoT Systems

The IoUAVs is a concept first introduced by Gharibi *et al.* [134], which argues the intersection of both existing IoT with UAVs in a dynamic integration. Due to the unique characteristics, such as fast deployment, easy programmability, fully controllable mobility, and scalability, IoUAVs are a promising solution to realize the framework of future IoT ecosystem where humans, UAVs, and IoT devices interact on a cooperative basis, which enable ubiquitous information sharing and fine-granularity coordination among a fleet of UAVs. In spite of the huge potential benefits of IoUAVs, the endurance and reliability performance is fundamentally limited by the maximum battery capacity, which is generally small due to practical SWAP constraints. On the other hand, additional energy consumption is required for IoUAVs to support mobility and avoid collision, which is usually several orders of magnitudes higher than the energy consumed for data delivery, and relies on trajectory variations in the timescale of seconds especially in industrial IoUAVs [135]. Therefore, how to achieve an energy-aware synergy between the angles of UAVs and IoT systems is nontrivial. Another worthwhile aspect is on how to exploit the synergy between UAV mobility and user mobility for improving the efficiency and increasing the profitability of wireless networks [136]. Besides, the synergy of IoT and UAVs remains largely an untapped field of future technology that has the potential to bring about drastic changes to how we live today.

E. Security and Privacy

The integrated network may face malicious attacks due to the open links and dynamic topologies that blanket out a mission-critical area by intentional jamming/disruption. In UAV-aided networks, the security is important since UAVs are always unattended, which leaves them easily captured or attacked. To avoid malicious modification, there is a need for a secure and lightweight mechanism to prevent attacks, such as eavesdropping, man-in-the-middle attack, and so on. Artificial intelligence solutions were proposed for addressing the security in cellular-connected UAV application use cases [137], while a zero-sum network interdiction game was advocated to capture the cyber-physical security threats in UAV delivery systems [138]. In the large coverage area of space–air–ground integrated networks, SDN controllers are responsible for managing resources and controlling network operation, it is urgent to protect the SDN controllers from different cyber-attacks where the adversaries are able to wiretap the data and control signals transmitted through the radio links of the UAV systems. The cyber-attacks to the UAV systems have been reported in [139] and the cyber-security is still a significant challenge to be overcome in the true utilization of UAVs. Therefore, designing timely strategies and counter-mechanisms are required to counteract malicious cyber-attacks.

F. Space–Air–Ground Integrated Vehicular Networks

Integrating space–air–ground communications into vehicular networks can provide high data rate for vehicular users in urban/suburban areas by ground network, ubiquitous connectivity between vehicles in rural and remote areas by satellite network, as well as coverage expansion of infrastructures and network information collection in poor or congested areas by UAVs [17]. For this reason, the work [14] proposed a UAV-assisted framework to integrate UAVs with ground vehicular networks for efficiently augmenting the system performance. In the ecosystem of space–air–ground communications, the high mobility of satellites and UAVs will change the propagation channel state all the time in terms of free space path loss and Doppler effect. To cope with the interworking issues between space–air–ground networks and vehicular networks, effectively designed network architecture is required. Going further, to support the data delivery with low latency and high reliability, a comprehensive control mechanism coordinating the spectrum allocation, link scheduling, and protocol design for the space–air–ground propagation channel needs to be further considered.

G. Integration of Networking, Computing, and Caching

Despite existing studies have been done on networking, computing, and caching in wireless networks separately, the joint consideration of the three advanced techniques should be carefully designed in a systematic way to meet the intrinsic requirements of next generation smart IoT, and even make a tradeoff between the operation costs (e.g., energy consumption) and performance benefits (e.g., decreasing latency). Huo *et al.* [140] developed an architecture for the integration of SDN, caching, and computing, and detailed the key components of data, control, and management planes. Later, He *et al.* [141] proposed a big data deep reinforcement learning approach to enable dynamic orchestration of networking, caching, and computing resources for improving the performance of applications in smart cities. Fully utilizing the networking, computing, and caching technologies can essentially complement the current development of IoT, however, new features also create unexpected problems that cannot be directly addressed through the traditional approaches designed for low-rate IoT systems. Thus, how to effectively integrate existing capabilities to address the fundamental problems in smart IoT remains a topic for future research.

H. Environment Uncertainty

Since future wireless networks can provide heterogenous communication, computation, and caching resources [142], it is of great importance to efficiently utilize these heterogenous resources to support different big data applications. Zhang *et al.* [143] focused their attention on the synergistic and complementary features of big data and 5G ecosystem that allowed service, content, and function providers to deploy their services/content/functions at the network edges, and the data network aided data acquisition and big data assisted edge content caching were provided. Since massive network data can be utilized to train prediction models to predict future network events, the proactive actions can be performed in advance to avoid network faults or service failures. For this purpose, accurate prediction, such as for spatial-temporal traffic distribution, service/content popularity, and user mobility, is required to facilitate optimal decision making and thus improves the overall network performance.

I. Other Interesting Topics

Apart from the above-discussed prospects, there are still many open issues related to the practicality of performing UAV communications. For instance, in certain application scenarios (such as in forests), there may exist obstacles and rich scatterers between the UAV and ground users, thus a more realistic air-to-ground channel model that incorporates temperature, wind, foliage, and urban environments is an interesting problem worth future research efforts. Furthermore, in UAV-enabled multiuser NOMA systems, it has been shown that the optimal user clustering and user-pairing algorithms are underexplored fields. Besides, new unmanned aircraft traffic management systems may be necessary to safely handle the high density of low altitude UAV traffic [144], which is responsible for the cooperative path planning and collision avoidance of multiple UAVs. The UAV-based antenna array system is another footprint for providing high data rate and low service time [145], since the number of antenna elements (i.e., the number of UAVs) is not limited by space constraints. To prevent privacy leakage of UAV communication and ensure the integrity of collected data from UAVs, blockchain technology (i.e., *aerial blockchain*) is expected to be a new paradigm to securely and adaptively maintain the privacy preferences during UAVs and GCS communication process.

VII. CONCLUSION

The number of mobile devices for IoT is growing rapidly, and there needs to be a high capacity and broadband connectivity communication system that can reliably support many IoT devices. To meet these requirements, the flying UAVs have attracted wide research interests recently. In this survey, we provided a brief understanding on UAV communications in 5G/B5G wireless networks. Particularly, we presented three major contributions: first, we have envisioned the space–air–ground integrated network for B5G communication systems. The related design challenges were discussed that can greatly help to better understand this newly introduced network architecture. Second, we have provided an overview of recent research activities on UAV communications combining the 5G techniques from the viewpoints of physical layer, network layer, and joint communication, computing and caching. In the end, we have unearthed several open research issues conceived for future research directions. This is a timely and essential topic with the hope that it can serve as a good starting point for the IoT applications of 5G/B5G.

REFERENCES

[1] F. Khan, “Multi-comm-core architecture for terabit-per-second wireless,” *IEEE Commun. Mag.*, vol. 54, no. 4, pp. 124–129, Apr. 2016.

[2] X. Zhang, Y. Zhang, R. Yu, W. Wang, and M. Guizani, “Enhancing spectral-energy efficiency for LTE-advanced heterogeneous networks: A users social pattern perspective,” *IEEE Wireless Commun.*, vol. 21, no. 2, pp. 10–17, Apr. 2014.

[3] Y. Zeng, R. Zhang, and T. J. Lim, “Wireless communications with unmanned aerial vehicles: Opportunities and challenges,” *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 36–42, May 2016.

[4] Y. Huo, X. Dong, T. Lu, W. Xu, and M. Yuen, “Distributed and multi-layer UAV network for the next-generation wireless communication,” *arXiv preprint arXiv:1805.01534*, 2018.

[5] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, “Wireless communication using unmanned aerial vehicles (UAVs): Optimal transport theory for hover time optimization,” *IEEE Trans. Wireless Commun.*, vol. 16, no. 12, pp. 8052–8066, Dec. 2017.

[6] Y. Zeng, R. Zhang, and T. J. Lim, “Throughput maximization for UAV-enabled mobile relaying systems,” *IEEE Trans. Commun.*, vol. 64, no. 12, pp. 4983–4996, Dec. 2016.

[7] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, “Mobile unmanned aerial vehicles (UAVs) for energy-efficient Internet of Things communications,” *IEEE Trans. Wireless Commun.*, vol. 16, no. 11, pp. 7574–7589, Nov. 2017.

[8] B. Li, Z. Fei, Y. Dai, and Y. Zhang, “Secrecy-optimized resource allocation for UAV-assisted relaying networks,” in *Proc. IEEE GLOBECOM*, Abu Dhabi, UAE, Dec. 2018, pp. 1–6.

[9] X. Qi *et al.*, “Secrecy energy efficiency performance in communication networks with mobile sinks,” *Phys. Commun.*, vol. 32, pp. 41–49, Feb. 2019.

[10] Y. Zeng, J. Lyu, and R. Zhang, “Cellular-connected UAV: Potentials, challenges and promising technologies,” *arXiv preprint arXiv:1804.02217*, 2018.

[11] M. Mozaffari, A. T. Z. Kasgari, W. Saad, M. Bennis, and M. Debbah, “Beyond 5G with UAVs: Foundations of a 3D wireless cellular network,” *IEEE Trans. Wireless Commun.*, to be published. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8533634

[12] S. Hayat, E. Yanmaz, and R. Muzaffar, “Survey on unmanned aerial vehicle networks for civil applications: A communications viewpoint,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 4, pp. 2624–2661, 4th Quart., 2016.

[13] S. Sekander, H. Tabassum, and E. Hossain, “Multi-tier drone architecture for 5G/B5G cellular networks: Challenges, trends, and prospects,” *IEEE Commun. Mag.*, vol. 56, no. 3, pp. 96–103, Mar. 2018.

[14] W. Shi *et al.*, “Drone assisted vehicular networks: Architecture, challenges and opportunities,” *IEEE Netw.*, vol. 32, no. 3, pp. 130–137, May/Jun. 2018.

[15] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, “A tutorial on UAVs for wireless networks: Applications, challenges, and open problems,” *arXiv preprint arXiv:1803.00680*, 2018.

[16] S. A. R. Naqvi, S. A. Hassan, H. Pervaiz, and Q. Ni, “Drone-aided communication as a key enabler for 5G and resilient public safety networks,” *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 36–42, Jan. 2018.

[17] N. Zhang *et al.*, “Software defined space-air-ground integrated vehicular networks: Challenges and solutions,” *IEEE Commun. Mag.*, vol. 55, no. 7, pp. 101–109, Jul. 2017.

[18] M. Agiwal, A. Roy, and N. Saxena, “Next generation 5G wireless networks: A comprehensive survey,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 3, pp. 1617–1655, 3rd Quart., 2016.

[19] N. Cheng *et al.*, “Air-ground integrated mobile edge networks: Architecture, challenges, and opportunities,” *IEEE Commun. Mag.*, vol. 56, no. 8, pp. 26–32, Aug. 2018.

[20] L. Gupta, R. Jain, and G. Vaszkun, “Survey of important issues in UAV communication networks,” *IEEE Commun. Surveys Tuts.*, vol. 18, no. 2, pp. 1123–1152, 2nd Quart., 2016.

[21] N. H. Motlagh, T. Taleb, and O. Arouk, “Low-altitude unmanned aerial vehicles-based Internet of Things services: Comprehensive survey and future perspectives,” *IEEE Internet Things J.*, vol. 3, no. 6, pp. 899–922, Dec. 2016.

[22] C. G. L. Krishna and R. R. Murphy, “A review on cybersecurity vulnerabilities for unmanned aerial vehicles,” in *Proc. IEEE Int. Symp. Safety Security Rescue Robot. (SSRR)*, Shanghai, China, 2017, pp. 194–199.

[23] J. Jiang and G. Han, “Routing protocols for unmanned aerial vehicles,” *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 58–63, Jan. 2018.

[24] W. Khawaja, I. Guvenc, D. Matolak, U.-C. Fiebig, and N. Schneckenberger, “A survey of air-to-ground propagation channel modeling for unmanned aerial vehicles,” *arXiv preprint arXiv:1801.01656*.

[25] A. A. Khuwaja, Y. Chen, N. Zhao, M.-S. Alouini, and P. Dobbins, “A survey of channel modeling for UAV communications,” *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2804–2821, 4th Quart., 2018.

[26] M. Lu, M. Bagheri, A. P. James, and T. Phung, “Wireless charging techniques for UAVs: A review, reconceptualization, and extension,” *IEEE Access*, vol. 6, pp. 29865–29884, 2018.

[27] X. Cao *et al.*, “Airborne communication networks: A survey,” *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 1907–1926, Sep. 2018.

[28] Y. Zhang *et al.*, “Home M2M networks: Architectures, standards, and QoS improvement,” *IEEE Commun. Mag.*, vol. 49, no. 4, pp. 44–52, Apr. 2011.

[29] X. Liu, M. Qiu, X. Wang, W. Liu, and K. Cai, “Energy efficiency optimization for communication of air-based information network with guaranteed timing constraints,” *J. Signal Process. Syst.*, vol. 86, nos. 2–3, pp. 299–312, Mar. 2017.

[30] J. Liu, Y. Shi, Z. M. Fadlullah, and N. Kato, “Space-air-ground integrated network: A survey,” *IEEE Commun. Surveys Tuts.*, vol. 20, no. 4, pp. 2714–2741, 4th Quart., 2018.

[31] J. Zhao *et al.*, “Beam tracking for UAV mounted SatCom on-the-move with massive antenna array,” *IEEE J. Sel. Areas Commun.*, vol. 36, no. 2, pp. 363–375, Feb. 2018.

[32] J. Zhao *et al.*, “Integrating communications and control for UAV systems: Opportunities and challenges,” *IEEE Access*, vol. 6, pp. 67519–67527, 2018.

[33] M. Alzenad, M. Z. Shakir, H. Yanikomeroglu, and M.-S. Alouini, “FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks,” *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 218–224, Jan. 2018.

[34] I. Bor-Yaliniz and H. Yanikomeroglu, “The new frontier in RAN heterogeneity: Multi-tier drone-cells,” *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 48–55, Nov. 2016.

[35] I. Bor-Yaliniz, S. S. Szyszkowicz, and H. Yanikomeroglu, “Environment-aware drone-base-station placements in modern metropolitans,” *IEEE Wireless Commun. Lett.*, vol. 7, no. 3, pp. 372–375, Jun. 2018.

[36] R. I. Bor-Yaliniz, A. El-Keyi, and H. Yanikomeroglu, “Efficient 3-D placement of an aerial base station in next generation cellular networks,” in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1–5.

[37] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, “Efficient deployment of multiple unmanned aerial vehicles for optimal wireless coverage,” *IEEE Commun. Lett.*, vol. 20, no. 8, pp. 1647–1650, Aug. 2016.

[38] X. Ye *et al.*, “Air-to-ground big-data-assisted channel modeling based on passive sounding in LTE networks,” in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Singapore, Dec. 2017, pp. 1–6.

[39] X. Zhou, J. Guo, S. Durrani, and H. Yanikomeroglu, “Uplink coverage performance of an underlay drone cell for temporary events,” in *Proc. IEEE Int. Conf. Commun. Workshops (ICCW)*, Kansas City, MO, USA, May 2018, pp. 1–6.

[40] A. Osseiran *et al.*, “Scenarios for 5G mobile and wireless communications: The vision of the METIS project,” *IEEE Commun. Mag.*, vol. 52, no. 5, pp. 26–35, May 2014.

[41] F. Lagum, I. Bor-Yaliniz, and H. Yanikomeroglu, “Strategic densification with UAV-BSs in cellular networks,” *IEEE Wireless Commun. Lett.*, vol. 7, no. 3, pp. 384–387, Jun. 2018.

[42] T. S. Rappaport *et al.*, “Millimeter wave mobile communications for 5G cellular: It will work!” *IEEE Access*, vol. 1, pp. 335–349, 2013.

[43] Z. Pi and F. Khan, “An introduction to millimeter-wave mobile broadband systems,” *IEEE Commun. Mag.*, vol. 49, no. 6, pp. 101–107, Jun. 2011.

[44] Z. Xiao, P. Xia, and X.-G. Xia, “Enabling UAV cellular with millimeter-wave communication: Potentials and approaches,” *IEEE Commun. Mag.*, vol. 54, no. 5, pp. 66–73, May 2016.

[45] Y. Zhu, G. Zheng, and M. Fitch, “Secrecy rate analysis of UAV-enabled mmWave networks using Matérn hardcore point processes,” *IEEE J. Sel. Areas Commun.*, vol. 36, no. 7, pp. 1397–1409, Jul. 2018.

[46] L. Kong *et al.*, “Autonomous relay for millimeter-wave wireless communications,” *IEEE J. Sel. Areas Commun.*, vol. 35, no. 9, pp. 2127–2136, Sep. 2017.

[47] J. Zhao, F. Gao, L. Kuang, Q. Wu, and W. Jia, “Channel tracking with flight control system for UAV mmWave MIMO communications,” *IEEE Commun. Lett.*, vol. 22, no. 6, pp. 1224–1227, Jun. 2018.

[48] S. Naqvi *et al.*, "Energy efficiency analysis of UAV-assisted mmWave HetNets," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kansas City, MO, USA, 2018, pp. 1–6.
[49] M. Gapeyenko, H. Y. I. Bor-Yaliniz, S. Andreev, and Y. Koucheryavy, "Effects of blockage in deploying mmWave drone base stations for beyond-5G networks," in *Proc. IEEE Int. Conf. Commun. Workshops (ICCW)*, Kansas City, MO, USA, May 2018, pp. 1–6.
[50] Z. Khosravi, M. Gerasimenko, S. Andreev, and Y. Koucheryavy, "Performance evaluation of UAV-assisted mmWave operation in mobility-enabled urban deployments," in *Proc. IEEE 41st Int. Conf. Telecommun. Signal Process. (TSP)*, Athens, Greece, 2018, pp. 1–5.
[51] W. Khawaja, O. Ozdemir, and I. Guvenc, "UAV air-to-ground channel characterization for mmWave system," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Toronto, ON, Canada, 2017, pp. 1–5.
[52] Z. Ding *et al.*, "A survey on non-orthogonal multiple access for 5G networks: Research challenges and future trends," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 10, pp. 2181–2195, Oct. 2017.
[53] M. F. Sohail and C. Y. Leow, "Maximized fairness for NOMA based drone communication system," in *Proc. IEEE 13th Malaysia Int. Conf. Commun. (MICC)*, Johor Bahru, Malaysia, 2017, pp. 119–123.
[54] M. F. Sohail, C. Y. Leow, and S. Won, "Non-orthogonal multiple access for unmanned aerial vehicle assisted communication," *IEEE Access*, vol. 6, pp. 22716–22727, 2018.
[55] P. K. Sharma and D. I. Kim, "UAV-enabled downlink wireless system with non-orthogonal multiple access," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Singapore, 2017, pp. 1–6.
[56] J. Baek, S. I. Han, and Y. Han, "Optimal resource allocation for non-orthogonal transmission in UAV relay systems," *IEEE Wireless Commun. Lett.*, vol. 7, no. 3, pp. 356–359, Jun. 2018.
[57] N. Rupasinghe, Y. Yapici, I. Guvenc, and Y. Kakishima, "Non-orthogonal multiple access for mmWave drones with multi-antenna transmission," in *Proc. IEEE 51st Asilomar Conf. Signals Syst. Comput.*, Pacific Grove, CA, USA, 2017, pp. 958–963.
[58] N. Rupasinghe, Y. Yapici, and I. Guvenc, "Non-orthogonal multiple access for mmWave drone networks with limited feedback," *IEEE Trans. Commun.*, to be published. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8449221
[59] N. Rupasinghe, Y. Yapici, I. Guvenc, and Y. Kakishima, "Comparison of limited feedback schemes for NOMA transmission in mmWave drone networks," in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Kalamata, Greece, Jun. 2018, pp. 1–5.
[60] A. A. Nasir, H. D. Tuan, T. Q. Duong, and H. V. Poor, "UAV-enabled communication using NOMA," *arXiv preprint arXiv:1806.03604*, 2018.
[61] T. Hou, Y. Liu, Z. Song, X. Sun, and Y. Chen, "Multiple antenna aided NOMA in UAV networks: A stochastic geometry approach," *IEEE Trans. Commun.*, to be published. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8488592
[62] Y. Liu *et al.*, "UAV communications based on non-orthogonal multiple access," *arXiv preprint arXiv:1809.05767*, 2018.
[63] H. Pan, S. C. Liew, J. Liang, Y. Shao, and L. Lu, "Network-coded multiple access on unmanned aerial vehicle," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 2071–2086, Sep. 2018.
[64] T. M. Nguyen, W. Ajib, and C. Assi, "A novel cooperative NOMA for designing UAV-assisted wireless backhaul networks," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 11, pp. 2497–2507, Nov. 2018.
[65] Y. Saleem, M. H. Rehmani, and S. Zeadally, "Integration of cognitive radio technology with unmanned aerial vehicles: Issues, opportunities, and future research challenges," *J. Netw. Comput. Appl.*, vol. 50, pp. 15–31, Apr. 2015.
[66] Y. Liu, S. Xie, R. Yu, Y. Zhang, and C. Yuen, "An efficient MAC protocol with selective grouping and cooperative sensing in cognitive radio networks," *IEEE Trans. Veh. Technol.*, vol. 62, no. 8, pp. 3928–3941, Oct. 2013.
[67] G. Ding *et al.*, "An amateur drone surveillance system based on the cognitive Internet of Things," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 29–35, Jan. 2018.
[68] Y. Huang, J. Xu, L. Qiu, and R. Zhang, "Cognitive UAV communication via joint trajectory and power control," in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Kalamata, Greece, Jun. 2018, pp. 1–5.
[69] C. Zhang and W. Zhang, "Spectrum sharing for drone networks," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 1, pp. 136–144, Jan. 2017.
[70] L. Sboui, H. Ghazzai, Z. Rezki, and M.-S. Alouini, "Energy-efficient power allocation for UAV cognitive radio systems," in *Proc. IEEE 86th Veh. Technol. Conf. (VTC-Fall)*, Toronto, ON, Canada, 2017, pp. 1–5.
[71] T. Long, M. Ozger, O. Cetinkaya, and O. B. Akan, "Energy neutral Internet of drones," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 22–28, Jan. 2018.
[72] K. Li *et al.*, "Energy-efficient cooperative relaying for unmanned aerial vehicles," *IEEE Trans. Mobile Comput.*, vol. 15, no. 6, pp. 1377–1386, Jun. 2016.
[73] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Optimal transport theory for power-efficient deployment of unmanned aerial vehicles," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Kuala Lumpur, Malaysia, May 2016, pp. 1–6.
[74] Y. Zeng and R. Zhang, "Energy-efficient UAV communication with trajectory optimization," *IEEE Trans. Wireless Commun.*, vol. 16, no. 6, pp. 3747–3760, Jun. 2017.
[75] H. Ghazzai, M. B. Ghorbel, A. Kadri, M. J. Hossain, and H. Menouar, "Energy-efficient management of unmanned aerial vehicles for underlay cognitive radio systems," *IEEE Trans. Green Commun. Netw.*, vol. 1, no. 4, pp. 434–443, Dec. 2017.
[76] C. H. Liu, Z. Chen, J. Tang, J. Xu, and C. Piao, "Energy-efficient UAV control for effective and fair communication coverage: A deep reinforcement learning approach," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 2059–2070, Sep. 2018.
[77] L. Ruan *et al.*, "Energy-efficient multi-UAV coverage deployment in UAV networks: A game-theoretic framework," *China Commun.*, vol. 15, no. 10, pp. 194–209, Oct. 2018.
[78] S. Morton, R. D. Sa, and N. Papanikolopoulos, "Solar powered UAV: Design and experiments," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst. (IROS)*, Hamburg, Germany, Sep. 2015, pp. 2460–2466.
[79] P. Oettershagen *et al.*, "Perpetual flight with a small solar-powered UAV: Flight results, performance analysis and model validation," in *Proc. IEEE Aerosp. Conf.*, Mar. 2016, pp. 1–8.
[80] H. Wang and J. Shen, "Analysis of the characteristics of solar cell array based on MATLAB/Simulink in solar unmanned aerial vehicle," *IEEE Access*, vol. 6, pp. 21195–21201, 2018.
[81] V. S. Dwivedi, J. Patrikar, A. Addamane, and A. K. Ghosh, "MARAAL: A low altitude long endurance solar powered UAV for surveillance and mapping applications," in *Proc. IEEE 23rd Int. Conf. Methods Models Autom. Robot. (MMAR)*, Miedzyzdroje, Poland, Aug. 2018, pp. 449–454.
[82] P. Rajendran and H. Smith, "Experimental study of solar module & maximum power point tracking system under controlled temperature conditions," *Int. J. Adv. Sci. Eng. Inf. Technol.*, vol. 8, no. 4, pp. 1147–1153, 2018.
[83] Y. Sun, D. W. K. Ng, D. Xu, L. Dai, and R. Schober, "Resource allocation for solar powered UAV communication systems," in *Proc. IEEE 19th Int. Workshop Signal Process. Adv. Wireless Commun. (SPAWC)*, Kalamata, Greece, Jun. 2018, pp. 1–5.
[84] Y. Sun *et al.*, "Optimal 3D-trajectory design and resource allocation for solar-powered UAV communication systems," *arXiv preprint arXiv:1808.00101*, 2018.
[85] M. Hua, C. Li, Y. Huang, and L. Yang, "Throughput maximization for UAV-enabled wireless power transfer in relaying system," in *Proc. IEEE Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Nanjing, China, 2017, pp. 1–5.
[86] J. Wu *et al.*, "Path planning for solar-powered UAV in urban environment," *Neurocomputing*, vol. 275, no. 31, pp. 2055–2065, Jan. 2018.
[87] R. A. Sowah, M. A. Acquah, A. R. Ofoli, G. A. Mills, and K. M. Koumadi, "Rotational energy harvesting to prolong flight duration of quadcopters," *IEEE Trans. Ind. Appl.*, vol. 53, no. 5, pp. 4965–4972, Sep./Oct. 2017.
[88] L. Yang, J. Chen, M. O. Hasna, and H.-C. Yang, "Outage performance of UAV-assisted relaying systems with RF energy harvesting," *IEEE Commun. Lett.*, vol. 22, no. 12, pp. 2471–2474, Dec. 2018.
[89] S. Marano and P. K. Willett, "Resource allocation in energy-harvesting sensor networks," *IEEE Trans. Signal Inf. Process. Netw.*, vol. 4, no. 3, pp. 585–598, Sep. 2018.
[90] H. Wang *et al.*, "Resource allocation for energy harvesting-powered D2D communication underlaying UAV-assisted networks," *IEEE Trans. Green Commun. Netw.*, vol. 2, no. 1, pp. 14–24, Mar. 2018.
[91] J. Xu, Y. Zeng, and R. Zhang, "UAV-enabled wireless power transfer: Trajectory design and energy region characterization," in *Proc. IEEE Globecom Workshops (GC Wkshps)*, Singapore, 2017, pp. 1–7.
[92] J. Xu, Y. Zeng, and R. Zhang, "UAV-enabled wireless power transfer: Trajectory design and energy optimization," *IEEE Trans. Wireless Commun.*, vol. 17, no. 8, pp. 5092–5106, Aug. 2018.

[93] M.-N. Nguyen, L. D. Nguyen, T. Q. Duong, and H. D. Tuan, "Real-time optimal resource allocation for embedded UAV communication systems," *IEEE Wireless Commun. Lett.*, to be published. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8457275

[94] J. Park, H. Lee, S. Eom, and I. Lee, "Minimum throughput maximization in UAV-aided wireless powered communication networks," *arXiv preprint arXiv:1801.02781*, 2018.

[95] L. Xie, J. Xu, and R. Zhang, "Throughput maximization for UAV-enabled wireless powered communication networks," in *Proc. IEEE 87th Veh. Technol. Conf. (VTC Spring)*, Porto, Portugal, Jun. 2018, pp. 1–7.

[96] Y. Li and L. Cai, "UAV-assisted dynamic coverage in a heterogeneous cellular system," *IEEE Netw.*, vol. 31, no. 4, pp. 56–61, Jul./Aug. 2017.

[97] A. Kumbhar, I. Güvenç, S. Singh, and A. Tuncer, "Exploiting LTE-advanced HetNets and FeICIC for UAV-assisted public safety communications," *IEEE Access*, vol. 6, pp. 783–796, 2018.

[98] A. Merwaday, A. Tuncer, A. Kumbhar, and I. Guvenc, "Improved throughput coverage in natural disasters: Unmanned aerial base stations for public-safety communications," *IEEE Veh. Technol. Mag.*, vol. 11, no. 4, pp. 53–60, Dec. 2016.

[99] V. Sharma, M. Bennis, and R. Kumar, "UAV-assisted heterogeneous networks for capacity enhancement," *IEEE Commun. Lett.*, vol. 20, no. 6, pp. 1207–1210, Jun. 2016.

[100] Q. Zhang, M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Machine learning for predictive on-demand deployment of UAVs for wireless communications," *arXiv preprint arXiv:1805.00061*, 2018.

[101] V. Sharma, R. Sabatini, and S. Ramasamy, "UAVs assisted delay optimization in heterogeneous wireless networks," *IEEE Commun. Lett.*, vol. 20, no. 12, pp. 2526–2529, Dec. 2016.

[102] X. Sun and N. Ansari, "Latency aware drone base station placement in heterogeneous networks," in *Proc. IEEE GLOBECOM*, Singapore, Dec. 2017, pp. 1–6.

[103] P. L. Mehta and R. Prasad, "Aerial-heterogeneous network: A case study analysis on the network performance under heavy user accumulations," *Wireless Pers. Commun.*, vol. 96, no. 3, pp. 3765–3784, Oct. 2017.

[104] V. Sharma, K. Srinivasan, H.-C. Chao, K.-L. Hua, and W.-H. Cheng, "Intelligent deployment of UAVs in 5G heterogeneous communication environment for improved coverage," *J. Netw. Comput. Appl.*, vol. 85, pp. 94–105, May 2017.

[105] S. A. W. Shah, T. Khattab, M. Z. Shakir, and M. O. Hasna, "A distributed approach for networked flying platform association with small cells in 5G+ networks," in *Proc. IEEE GLOBECOM*, Singapore, 2017, pp. 1–7.

[106] F. Jameel, Z. Hamid, F. Jabeen, S. Zeadally, and M. A. Javed, "A survey of device-to-device communications: Research issues and challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 3, pp. 2133–2168, 3rd Quart., 2018.

[107] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Unmanned aerial vehicle with underlaid device-to-device communications: Performance and tradeoffs," *IEEE Trans. Wireless Commun.*, vol. 15, no. 6, pp. 3949–3963, Jun. 2016.

[108] F. Tang, Z. M. Fadlullah, N. Kato, F. Ono, and R. Miura, "AC-POCA: Anticoordination game based partially overlapping channels assignment in combined UAV and D2D-based networks," *IEEE Trans. Veh. Technol.*, vol. 67, no. 2, pp. 1672–1683, Feb. 2018.

[109] Z. Guo, Z. Wei, Z. Feng, and N. Fan, "Coverage probability of multiple UAVs supported ground network," *Electron. Lett.*, vol. 53, no. 13, pp. 885–887, Jun. 2017.

[110] E. Christy *et al.*, "Optimum UAV flying path for device-to-device communications in disaster area," in *Proc. IEEE Int. Conf. Signals Syst. (ICSigSys)*, 2017, pp. 318–322.

[111] H. Wang *et al.*, "Spectrum sharing planning for full-duplex UAV relaying systems with underlaid D2D communications," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 9, pp. 1986–1999, Sep. 2018.

[112] Z. Xue *et al.*, "Device-to-device communications underlying UAV-supported social networking," *IEEE Access*, vol. 6, pp. 34488–34502, 2018.

[113] S. Bera, S. Misra, and A. V. Vasilakos, "Software-defined networking for Internet of Things: A survey," *IEEE Internet Things J.*, vol. 4, no. 6, pp. 1994–2008, Dec. 2017.

[114] V. Sharma, F. Song, I. You, and H.-C. Chao, "Efficient management and fast handovers in software defined wireless networks using UAVs," *IEEE Netw.*, vol. 31, no. 6, pp. 78–85, Nov./Dec. 2017.

[115] S. ur Rahman, G.-H. Kim, Y.-Z. Cho, and A. Khan, "Deployment of an SDN-based UAV network: Controller placement and tradeoff between control overhead and delay," in *Proc. IEEE Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Jeju, South Korea, 2017, pp. 1290–1292.

[116] R. M. Shukla, S. Sengupta, and A. N. Patra, "Software-defined network based resource allocation in distributed servers for unmanned aerial vehicles," in *Proc. IEEE 8th Annu. Comput. Commun. Workshop Conf. (CCWC)*, Las Vegas, USA, USA, 2018, pp. 796–802.

[117] P. Yang *et al.*, "Proactive drone-cell deployment: Overload relief for a cellular network under flash crowd traffic," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 10, pp. 2877–2892, Oct. 2017.

[118] G. Secinti, P. B. Darian, B. Canberk, and K. R. Chowdhury, "Resilient end-to-end connectivity for software defined unmanned aerial vehicular networks," in *Proc. IEEE 28th Annu. Int. Symp. Pers. Indoor Mobile Radio Commun. (PIMRC)*, Montreal, QC, Canada, 2017, pp. 1–5.

[119] G. Secinti, P. B. Darian, B. Canberk, and K. R. Chowdhury, "SDNs in the sky: Robust end-to-end connectivity for aerial vehicular networks," *IEEE Commun. Mag.*, vol. 56, no. 1, pp. 16–21, Jan. 2018.

[120] C. Wang, Y. He, F. R. Yu, Q. Chen, and L. Tang, "Integration of networking, caching, and computing in wireless systems: A survey, some research issues, and challenges," *IEEE Commun. Surveys Tuts.*, vol. 20, no. 1, pp. 7–28, 1st Quart., 2018.

[121] N. Abbas, Y. Zhang, A. Taherkordi, and T. Skeie, "Mobile edge computing: A survey," *IEEE Internet Things J.*, vol. 5, no. 1, pp. 450–465, Feb. 2018.

[122] S. Jeong, O. Simeone, and J. Kang, "Mobile cloud computing with a UAV-mounted cloudlet: Optimal bit allocation for communication and computation," *IET Commun.*, vol. 11, no. 7, pp. 969–974, May 2017.

[123] S. Jeong, O. Simeone, and J. Kang, "Mobile edge computing via a UAV-mounted cloudlet: Optimization of bit allocation and path planning," *IEEE Trans. Veh. Technol.*, vol. 67, no. 3, pp. 2049–2063, Mar. 2018.

[124] F. Tang *et al.*, "On a novel adaptive UAV-mounted cloudlet-aided recommendation system for LBSNs," *IEEE Trans. Emerg. Topics Comput.*, to be published. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8254367

[125] F. Zhou, Y. Wu, H. Sun, and Z. Chu, "UAV-enabled mobile edge computing: Offloading optimization and trajectory design," in *Proc. IEEE ICC*, Kansas City, MO, USA, Feb. 2018, pp. 1–6.

[126] W.-S. Jung, J. Yim, Y.-B. Ko, and S. Singh, "ACODS: Adaptive computation offloading for drone surveillance system," in *Proc. IEEE 16th Annu. Mediterr. Ad Hoc Netw. Workshop (Med-Hoc-Net)*, Budva, Montenegro, 2017, pp. 1–6.

[127] N. H. Motlagh, M. Bagaa, and T. Taleb, "UAV-based IoT platform: A crowd surveillance use case," *IEEE Commun. Mag.*, vol. 55, no. 2, pp. 128–134, Feb. 2017.

[128] M. Hua *et al.*, "Energy optimization for cellular-connected multi-UAV mobile edge computing systems with multi-access schemes," *arXiv preprint arXiv:1806.11250*, 2018.

[129] M. Chen, W. Saad, and C. Yin, "Liquid state machine learning for resource allocation in a network of cache-enabled LTE-U UAVs," in *Proc. IEEE GLOBECOM*, Singapore, Dec. 2017, pp. 1–6.

[130] M. Chen *et al.*, "Caching in the sky: Proactive deployment of cache-enabled unmanned aerial vehicles for optimized quality-of-experience," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 5, pp. 1046–1061, May 2017.

[131] X. Xu, Y. Zeng, Y. L. Guan, and R. Zhang, "Overcoming endurance issue: UAV-enabled communications with proactive caching," *IEEE J. Sel. Areas Commun.*, vol. 36, no. 7, pp. 1231–1244, Jun. 2018.

[132] N. Zhao *et al.*, "Caching UAV assisted secure transmission in hyper-dense networks based on interference alignment," *IEEE Trans. Commun.*, vol. 66, no. 5, pp. 2281–2294, May 2018.

[133] T. Fang *et al.*, "Context-aware caching distribution and UAV deployment: A game-theoretic approach," *Appl. Sci.*, vol. 8, no. 10, pp. 1–15, Oct. 2018, doi: 10.20944/preprints201809.0170.v1.

[134] M. Gharibi, R. Boutaba, and S. L. Waslander, "Internet of drones," *IEEE Access*, vol. 4, pp. 1148–1162, 2016.

[135] Z. Zhou *et al.*, "Energy-efficient industrial Internet of UAVs for power line inspection in smart grid," *IEEE Trans. Ind. Informat.*, vol. 14, no. 6, pp. 2705–2714, Jun. 2018.

[136] I. Bor-Yaliniz, A. El-Keyi, and H. Yanikomeroglu, "Spatial configuration of agile wireless networks with drone-BSs and user-in-the-loop," *IEEE Trans. Wireless Commun.*, to be published. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8506622

[137] U. Challita, A. Ferdowsi, M. Chen, and W. Saad, "Artificial intelligence for wireless connectivity and security of cellular-connected UAVs," *arXiv preprint arXiv:1804.05348*, 2018.

[138] A. Sanjab, W. Saad, and T. Başar, "Prospect theory for enhanced cyber-physical security of drone delivery systems: A network interdiction game," in *Proc. IEEE Int. Conf. Commun. (ICC)*, Paris, France, May 2017, pp. 1–6.
[139] A. Y. Javaid, W. Sun, V. K. Devabhaktuni, and M. Alam, "Cyber security threat analysis and modeling of an unmanned aerial vehicle system," in *Proc. IEEE Conf. Technol. Homeland Security (HST)*, Waltham, MA, USA, 2012, pp. 585–590.
[140] R. Huo *et al.*, "Software defined networking, caching, and computing for green wireless networks," *IEEE Commun. Mag.*, vol. 54, no. 11, pp. 185–193, Nov. 2016.
[141] Y. He, F. R. Yu, N. Zhao, V. C. M. Leung, and H. Yin, "Software-defined networks with mobile edge computing and caching for smart cities: A big data deep reinforcement learning approach," *IEEE Commun. Mag.*, vol. 55, no. 12, pp. 31–37, Dec. 2017.
[142] E. K. Markakis, K. Karras, A. Sideris, G. Alexiou, and E. Pallis, "Computing, caching, and communication at the edge: The cornerstone for building a versatile 5G ecosystem," *IEEE Commun. Mag.*, vol. 55, no. 11, pp. 152–157, Nov. 2017.
[143] N. Zhang *et al.*, "Synergy of big data and 5G wireless networks: Opportunities, approaches, and challenges," *IEEE Wireless Commun.*, vol. 25, no. 1, pp. 12–18, Feb. 2018.
[144] G. Yang *et al.*, "A telecom perspective on the Internet of drones: From LTE-advanced to 5G," *arXiv preprint arXiv:1803.11048*, 2018.
[145] M. Mozaffari, W. Saad, M. Bennis, and M. Debbah, "Communications and control for wireless drone-based antenna array," *IEEE Trans. Commun.*, to be published. [Online]. Available: https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=8469055

Bin Li received the M.S. degree in communication and information systems from the Guilin University of Electronic Technology, Guilin, China, in 2013. He is currently pursuing the Ph.D. degree at the School of Information and Electronics, Beijing Institute of Technology, Beijing, China.

From 2013 to 2014, he was a Research Assistant with the Department of Electronic and Information Engineering, Hong Kong Polytechnic University, Hong Kong. From 2017 to 2018, he was a Visiting Student with the Department of Informatics, University of Oslo, Oslo, Norway. In 2019, he will be an Associate Professor with the School of Computer and Software, Nanjing University of Information Science and Technology, Nanjing, China. His current research interests include physical-layer security, wireless cooperative networks, and unmanned aerial vehicle communications.

Zesong Fei (M'07–SM'16) received the Ph.D. degree in electronic engineering from the Beijing Institute of Technology (BIT), Beijing, China, in 2004.

He is currently a Professor with the Research Institute of Communication Technology, BIT, where he is involved in the design of the next generation high-speed wireless communication. He is the Chief Investigator of the National Natural Science Foundation of China. He has authored or co-authored over 50 papers in the IEEE journals. His current research interests include wireless communications and multimedia signal processing.

Dr. Fei serves as a Lead Guest Editor for *Wireless Communications*, *Mobile Computing* and *China Communications*, Special Issue on Error Control Coding. He is a Senior Member of the Chinese Institute of Electronics and China Institute of Communications.

Yan Zhang (M'05–SM'10) received the Ph.D. degree from the School of Electrical and Electronics Engineering, Nanyang Technological University, Singapore.

He is a Full Professor with the Department of Informatics, University of Oslo, Oslo, Norway. His current research interests include next-generation wireless networks leading to 5G Beyond, and green and secure cyber-physical systems (e.g., smart grid, healthcare, and transport).

Dr. Zhang was a recipient of the Highly Cited Researcher Award (Web of Science top 1% most cited) by Clarivate Analytics. He is an Associate Technical Editor of *IEEE Communications Magazine*, an Editor of *IEEE Network Magazine*, the IEEE TRANSACTIONS ON GREEN COMMUNICATIONS AND NETWORKING, IEEE COMMUNICATIONS SURVEYS AND TUTORIALS, the IEEE INTERNET OF THINGS JOURNAL, and *IEEE Vehicular Technology Magazine*, and an Associate Editor of IEEE ACCESS. He is an IEEE Vehicular Technology Society (VTS) Distinguished Lecturer. He has served in chair positions for a number of conferences, including IEEE GLOBECOM 2017, IEEE VTC-Spring 2017, IEEE PIMRC 2016, IEEE CloudCom 2016, IEEE ICCC 2016, IEEE CCNC 2016, IEEE SmartGridComm 2015, and IEEE CloudCom 2015. He serves as a TPC member for numerous international conference, including IEEE INFOCOM, IEEE ICC, IEEE GLOBECOM, and IEEE WCNC. He is also a Senior Member of IEEE ComSoc, IEEE CS, IEEE PES, and IEEE VTS, and a Fellow of the IET.