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Airborne Communication Networks: A Survey

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***Abstract*—Owing to the explosive growth of requirements of rapid emergency communication response and accurate observation services, airborne communication networks (ACNs) have received much attention from both industry and academia. ACNs are subject to heterogeneous networks that are engineered to utilize satellites, high-altitude platforms (HAPs), and low-altitude platforms (LAPs) to build communication access platforms. Compared to terrestrial wireless networks, ACNs are characterized by frequently changed network topologies and more vulnerable communication connections. Furthermore, ACNs have the demand of the seamless integration of heterogeneous networks such that the network quality-of-service (QoS) can be improved. Thus, designing mechanisms and protocols for ACNs poses many challenges. To solve these challenges, extensive research has been conducted. The objective of this special issue is to disseminate the contributions in the field of ACNs. To present this special issue with the necessary background and offer an overall view on this field, three key areas of ACNs are covered. Specifically, this paper covers LAP-based communication networks, HAP-based communication networks, and integrated ACNs. For each area, this paper addresses the particular issues and reviews major mechanisms. This paper also points out future research directions and challenges.**

***Index Terms*—Airborne communication networks (ACNs), heterogeneous networks, low-altitude-platform-based communication networks, high-altitude-platform-based communication networks, integrated airborne communication networks.**

I. Introduction

RECENT advances in manufacturing, communications, sensors, electronics, and control technologies have witnessed an unprecedented application increase of airborne communication networks (ACNs) in the military, civil, and public fields, for example, emergency rescue and communications, navigation and positioning, monitoring and detection. ACNs are engineered to utilize various aircrafts, which are equipped with transceivers and sensors, to build communication access platforms. These aircrafts mainly include satellites, high-altitude platforms (HAPs) (e.g., airships and balloons), and low-altitude platforms (LAPs) (e.g., unmanned aerial vehicles, UAVs). Moreover, the utilization of both satellites and HAPs as new radio access platforms for the 5G wireless communication system has been considered by the 3GPP [1], while there is substantial interest in the research community towards the utilization of LAPs as radio access platforms as well in beyond-5G systems.

This paper is concerned with the design of ACNs. ACNs have many distinctive and even tricky characteristics including a high level of network heterogeneity, frequently changed network topologies, weakly connected communication links, complex radio frequency (RF) propagation model, and platform constraints (e.g., size, weight, and power (SWAP)). These characteristics make it difficult to apply standards, protocols, and design methodologies, which are exploited for terrestrial wireless networks, in the design of ACNs directly. Furthermore, the heterogeneity of both networks and platforms increases the design complexity of the integrated ACNs. Therefore, designing mechanisms and protocols for ACNs poses many challenges.

To address these challenges, extensive research has been conducted. This paper is aimed at the dissemination of contributions in the field of ACNs. This paper does not promote any specific architecture of ACNs; however, it shows one for illustration in Fig. 1. This architecture includes two components, non-terrestrial network (NTN) and terrestrial network (TN). This paper focuses on discussing the NTN that consists of three layers of ACNs, i.e., satellite layer, HAP layer, and LAP layer. Specifically, this paper covers three major areas of ACNs, namely: LAP-based communication networks, HAP-based communication networks, and integrated ACNs. The former two areas are the basic building blocks. By combining them with the satellite layer, an architecture of integrated ACNs is built. This paper briefly describes these three areas as follows:

- *LAP-based communication networks:* The LAP-based communication networks have received extensive attention from industry and academia. As emerging technologies, LAP networks have many distinctive characteristics such as frequently changed topologies, various topology structures, SWAP constraints, and three-dimensional (3-D) transmission nature. These characteristics lead to a different design approach for LAP networks in comparison to other wireless networks, for example, wireless cellular networks, mobile ad hoc networks (MANET), and vehicular ad hoc networks (VANET). This paper describes the design of LAP networks from three major perspectives including movement control, networking, and transmission.

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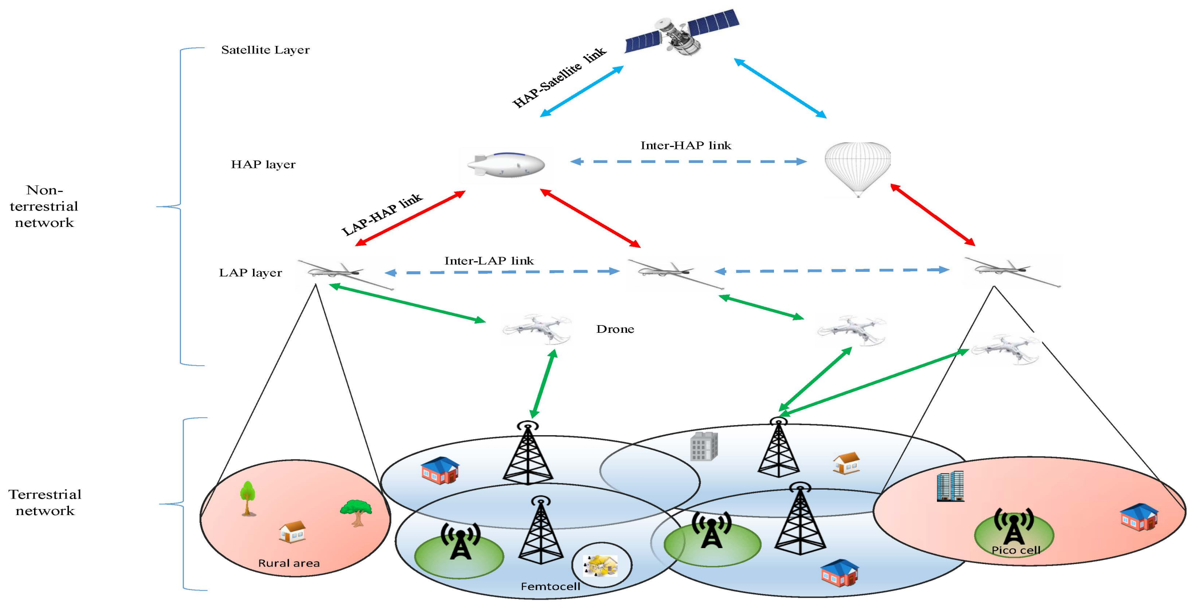

Fig. 1. An architecture of airborne communication networks.

- *Movement control:* To complete their missions, LAPs first need to be moved to the target areas by leveraging movement control mechanisms. Movement control mechanisms include single LAP path planning and multi-LAP cooperative movement control. Single LAP path planning mechanism is developed to compute a flight path for a single LAP to follow. It includes offline, online, and hybrid path planning. The multi-LAP cooperative movement control mechanism is responsible for the cooperative path planning and collision avoidance of multiple LAPs. It includes centralized control and decentralized cooperative control [2].
- *Networking:* Networking mechanisms play a key role in LAP-based communication networks after moving LAPs to target areas. The networking mechanisms can efficiently improve network resource utilization and quality-of-service (QoS) through identifying the optimal spatial locations of deployed LAPs. Moreover, networking mechanisms can adapt to configuration changes of LAP networks resulting from a mission update or changes in network topologies.
- *Transmission:* To enable the LAP-based communication networks to provide high-speed and reliable data transmission, the support from transmission mechanisms is crucial. To offer high-speed packet transmission, a number of mechanisms, including the spectrum efficiency improvement [3], frequency extension [4], and optimal LAP density [5], can be exploited. To improve the reliability of the end-to-end data transmission in highly dynamic networks, delay/disruption-tolerant network (DTN) routing protocols may be required [6]. The DTN routing protocols can be classified into three categories: deterministic, stochastic, and enhanced routing protocols.

- *HAP-based communication networks:* In contrast to LAPs, HAPs have a larger footprint and longer communication persistence. HAP-based communication networks also have a bright future in providing mobile communications and broadband wireless access services. HAP networks can be composed of various types of high-altitude airborne platforms and have many gratifying advantages. Meanwhile, the channel models of HAP-based communication networks should be investigated so that the networks can benefit the most.
- *Integrated airborne communication networks:* The integration concept is significant for ACNs. The integration cannot only complement pre-existing airborne communication infrastructures, but also improve services provided by ACNs. As a heterogeneous airborne network, the implementation of integrated ACNs requires the integration of protocol stacks and network topologies [7].

The remainder of this paper is devoted to the exposition of the above three major areas. Section II discusses mechanisms of LAP-based communication networks. Section III presents an overview of the characteristics and channel models of HAP-based communication networks. Section IV describes the integrated ACNs. Future research directions and challenges are highlighted in Section V, and a summary is provided in Section VI.

II. LAP-Based Communication Networks

Low altitude UAV is one of the most important and widely utilized LAPs. The latest investigation by the Federal Aviation Administration (FAA) indicates that there may be seven million UAVs flying in the United States in 2020 [8]. It is noteworthy that there are two types of UAVs, i.e., low-altitude UAV, and high-altitude UAV. This section focuses

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on the research of the low-altitude UAV. The high-altitude UAV will be presented in Section III. For the convenience of description, this paper will simplify the low-altitude UAV into UAV. Without special explanation, the following UAV refers to the low-altitude UAV. Moreover, the UAV and drone are interchangeable terms in this paper.

In the rest of this section, the characteristics, movement control, networking, and transmission mechanisms of UAV communication networks are provided.

A. Characteristics of UAV Communication Networks

For an emerging technology, it is crucial to characterize UAV networks to figure out their nature and constraints. This subsection will discuss the following issues: How many UAVs are suitable for UAV communication networks? How fast do topologies of UAV networks change? Do UAV networks require an external control? What types of network topology structures may be appropriate for UAV networks? What are the constraints of UAV networks? What type of transmission nature do UAV networks have?

1) Single-UAV or Multi-UAV Networks: Single-UAV networks (although it may be an exaggeration to refer to most of these as “networks”) have been widely utilized in military, civil, and public applications. Furthermore, in military applications, such as reconnaissance, surveillance, attack, and patrol, the usage of the single-UAV networks is almost thirty years old [6]. Even now, various types of the US single-UAV networks (e.g., Global Hawk and Predator) play a key role in fighting against terrorism, and other military tasks. Many single-UAV networks employ satellite communications (SATCOM) for the relay of multi-spectral surveillance products, sometimes employing double satellite hops. A single SATCOM hop (or double hops) provides command and control on the forward link while the surveillance products and UAV parameters (e.g., health, remaining fuel supply, position, and altitude) are simultaneously delivered on the return link. Single-UAV networks have a simple topology structure that consists of just one UAV and one/multiple ground nodes. Moreover, single-UAV networks are widely applied because they are simple from a communication topology perspective.

Today, many public and civil missions (e.g., cargo delivery, oil field and high-tension line inspection, and search and rescue) may be completed more efficiently and successfully with multi-UAV networks. The capability of distributed processing of multi-UAV networks is one of the primary reasons for leveraging multi-UAV networks [9]. For example, in many applications such as real-time forest fire monitoring, multiple UAVs will work together cooperatively. Specifically, they will respectively search for some suspected targets and share information together through collaborative communications. Furthermore, a UAV equipped with a transceiver can act as an aerial base station to extend communication coverage and boost network capacity. Except for acting as mobile relays or flying base stations, UAVs can be utilized as mobile cloud and fog computing systems where a UAV-mounted cloud/fog provides low-latency-application offloading opportunities for mobile terminals [10], [11]. For example, mobile terminals can offload computationally heavy applications, such as augmented reality, and object detection and recognition, to the UAV-mounted cloud through uplink/downlink communications with the UAV. UAVs can also enable fog computing to deliver high-quality streaming to moving users through nearby wireless proxies and access points. Meanwhile, multi-UAV networks have the superiority in both survivability and reliability [12]. Despite being advantageous in many respects, multi-UAV networks increase complexities of UAV communication networks. For example, multi-UAV networks should have the ability of self-organization/self-healing. In multi-UAV networks, many UAVs may go out of service owing to a malfunction or battery drainage; in such situations, network topologies should be maintained autonomously to keep the reliable end-to-end communication and reduce the communication latency.

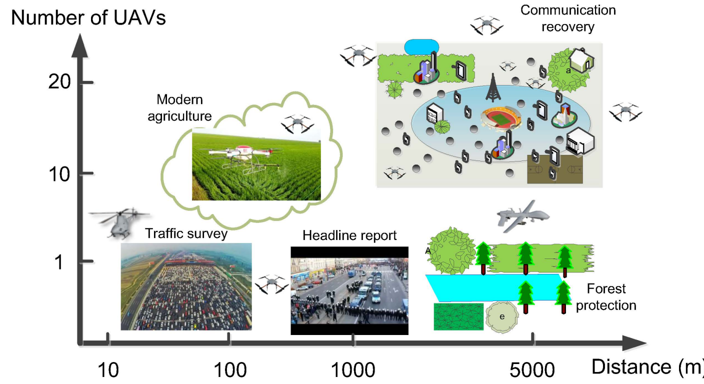

Fig. 2. Application areas over the number of UAVs vs. a range of distance.

In short, the number of UAVs may vary over a wide range of applications. Fig. 2 illustrates many UAV application areas over the number of UAVs vs. a range of distance.

2) Frequently Changed Topology: Node mobility may be one of the most apparent differences between UAV networks and other types of ad hoc networks such as VANET and MANET [13]. In UAV networks, the extent of mobility may be much higher than that in both VANET and MANET. Depending on applications, the speed of a UAV may be in the range of 0-460 km/h [6], [13]. Trajectories of UAV nodes may also be different. For example, UAV nodes fly in the sky, while MANET nodes move over a particular terrain, and VANET nodes move on roads. Therefore, topologies of UAV networks may change more frequently than those of both VANET and MANET. In addition to the mobility of UAV nodes, the failure of UAV nodes as well as the addition of new UAV nodes may also affect network topologies. In such case, old communication links are removed or new links are established, which may result in frequent update in the network topologies. Moreover, link outages due to airframe blockage and signal interference may further change the network topologies [14].

3) Topology Structure: The topology structure of UAV networks is still an understudied area. To ensure that there is a human intervention in case of an emergency, UAVs are obligated by the law to stay in the remote control range of a human [15]. In other words, although the device autonomy is the goal of UAV development, UAV networks must connect to a ground station. In single-UAV networks, there is an air-to-ground (AtG) link between the UAV and a ground station. Multi-UAV networks present a star/mesh topology structure [6]. In the case of star topology, all UAVs would directly connect to a ground node. The inter-UAVs communication would be realized through the ground node. It may incur high communication costs such as energy consumption and communication latency owing to the long AtG communication link. The long-distance communication is prone to disconnect owing to changes in weather conditions and blocking of terrains and buildings. Safety (e.g., the signal interception) is another primary concern in the long-distance communication [13]. Besides, for AtG links, the more expensive high bandwidth links may be required to guarantee the QoS of communications, which may increase the cost of UAVs.

In comparison with other possibilities, the meshed UAV structure is identified to offer the best option in terms of reliability, flexibility, and performance [16]. In meshed UAV networks, only a few UAVs connect to a ground station; most UAVs are interconnected and can directly exchange information through one or more air-to-air (AtA) link. In this way, the reliability of multi-UAV networks is improved. For example, if one UAV is disconnected to the ground station because of changes in weather conditions, it still can maintain the connectivity with the ground station through other ground-connected UAVs. Meanwhile, thanks to the connectivity of AtA links, the cost (e.g., energy consumption and transmission latency) of inter-UAVs communications may be reduced. The maintenance of the meshed UAV networks, however, may be more complicated due to the frequently changing network configurations. Furthermore, although the mesh structure is promising for multi-UAV networks, the impact of the nodes' mobility is a crucial issue with the challenge of UAV nodes spreading out to leave them sparsely connected [15].

4) Constraints of UAV Networks: All UAVs suffer from SWAP constraints, which would limit the endurance, computation, and communication capabilities of UAVs [13]. Compared with small UAVs, large UAVs may carry more powerful onboard sensors (e.g., transceiver, camera, optical pod, and distance detection sensor) owing to a large space and more mount points. Therefore, large UAVs may complete preset missions more accurately, quickly, and effectively. The acquisition and maintenance cost of a small UAV, however, is much lower than that of a large UAV [13]. For small UAVs, the energy constraint may be significant. This is due to the fact that the energy of a small UAV may support it to fly for only a few minutes, or at most a few tens of minutes. Furthermore, energy-drained UAVs may shorten the lifetime of a UAV network. Imagine a scenario where some UAVs would be out of services because of lack of energy. The absence of energy-exhausted UAVs may change network configurations. The changed configuration would force UAV networks to self-organize to maintain the network connectivity, which may exacerbate the drainage of the network energy. Therefore, the energy-aware UAV deployment and transmission mechanisms should be investigated to prolong the lifetime of UAV networks. The computing power is also a significant concern of a UAV. The size and weight constraints of a UAV significantly affect its computing power. Thanks to the payload miniaturization trend, more powerful computation payloads will likely be mounted on UAVs in the future [13].

5) 3-D Transmission Nature: As mentioned above, whatever their topology structures, UAV networks must connect to a ground station. Therefore, in UAV networks, there are both AtA and AtG links; that is to say, the signal transmission in UAV networks has the 3-D nature.

The systematic measurement and modeling of AtG links are still under-investigated. The type of the AtG channel model directly affects the network QoS and UAV deployment approach. It has been stated that the AtG channel model is related to underlying environment statistical parameters [17]. Furthermore, based on the environment, ground receivers can receive different types of signals such as line-of-sight (LoS) and strongly reflected non-line-of-sight (NLoS) signals and multiple reflected components which may cause multipath fading [18]. Each type has a specific occurrence probability that is a function of the environment parameters, density and height of buildings, and the elevation angle. The probability of having the multipath fading, however, is significantly lower than that of LoS and NLoS types [19].

In AtA channel, although some multipath components may be present due to ground and airframe reflections, the LoS signal component still dominates. The AtA link outage, however, may occur frequently due to the signal interference from neighbor UAV nodes, UAV maneuvering, airframe blockage, and antenna placement. Additionally, since the relative velocity between two UAVs may be high, the UAV receiver should compensate for the Doppler frequency offsets [20].

B. Movement Control

As mentioned above, UAVs have shown exciting and promising application prospects in public, civil, and military fields. To ensure that UAVs can safely and quickly arrive at target areas for executing missions autonomously (i.e., autonomous flight)[1], the careful design of movement control mechanisms would be crucial. For example, the latest movement control mechanism paves the way for the commercialization of the Google LOON Project [21]. The movement control refers to the moving of airborne communication platforms from a position A to a position B while avoiding collisions with obstacles (e.g., terrains, buildings) and other airborne platforms. It is noteworthy that the movement control can be designed independently of communications. In the design stage of the movement control, the onboard transceivers for networking and providing wireless access services do not need to be operational. Movement control mechanisms include single-UAV path planning and multi-UAV cooperative movement control.

1) Single-UAV Path Planning: The fundamental idea of the single-UAV path planning mechanism is to discretize the work space and express UAV dynamics by a discrete-time state space. The state vector in the state space may consist of the

[1]For UAVs, there are two levels of autonomy, i.e., remote control (or no autonomy) and autonomous flight. This paper focuses on the research of autonomous flight mechanisms.

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position and velocity in 3-D space, as well as the safety, and other costs of the UAV. The UAV path is then composed of a state sequence under multiple objectives and a limited set of constraints. Existing single UAV path planning mechanisms can be classified into three categories: offline, online, and hybrid path planning, which are presented as follows:

a. Offline path planning: Under the offline path planning, the UAV can fly autonomously, following the path pre-computed by a ground station. In other words, the UAV is not responsible for making decisions on its flight plan. Existing offline path planning methods follow two approaches: subpath-based and path-based approaches.

The subpath-based approach is based on the calculation of the optimal subpath. This approach is inspired by the fact that the subpath of the optimal path is optimal. Specifically, in this approach, the following formula is used to select the optimal UAV path from a starting point s to a destination point d [22]:

$$f(n) = g(n) + h(n) \tag{1}$$

where

$f(n)$ the estimated cost of the optimal path, which is constrained to go through the point n, from s to d;

$g(n)$ the actual cost of the subpath from s to n;

$h(n)$ the estimated cost of the subpath from n to d, which affects the efficiency of the subpath-based approach.

Under the subpath-based approach, the optimal path from s to d is composed of a sequence of discrete states with the minimum $f(n)$ [22].

The path-based approach relies on the generation of complete paths. Specifically, it generates complete paths by using path generation models (e.g., waypoints-based [23], and fluid-based [24]) wherein the paths are considered as populations. Then, various intelligent optimization algorithms, such as genetic algorithm [25], particle swarm optimization algorithm [26], whale optimization algorithm [24], and their invariants [27], [28], are exploited to obtain the final path with the path cost being the fitness function.

Offline path planning approaches can perform well on developing plans for UAVs flying under a static environment. It may be inappropriate to utilize offline approaches to address the problem of the UAV path planning in a dynamic environment. This is because offline approaches require global and deterministic geographic information. In a dynamic environment, the unpredictable obstacles (e.g., birds, and other UAVs) and inclement weather conditions may result in the pre-computed path being outdated and dangerous. To mitigate the problem of the UAV path planning in a dynamic environment, online path planning approaches are required.

b. Online path planning: Unlike the offline path planning, a UAV will make self-decisions under the online path planning. In other words, the UAV is responsible for making decisions on its flight path using information collected from the environment (e.g., terrains, buildings, meteorology) via onboard sensors such as distance detection radars and global positioning system.

Most online path planning approaches share the idea of predicting trajectories of dynamic obstacles [29]. Specifically, in online approaches, a UAV first samples a point from 3-D UAV work space and then simulates a trajectory between the current position and the sample point by adopting some trajectory generation models (e.g., closed-loop prediction [30]). Meanwhile, the UAV will simulate trajectories of dynamic obstacles to identify potential collisions. Collision-free trajectories would be stored as candidate ones. After repeating this cycle for a fixed number of rounds, the shortest trajectory is selected for the UAV to follow. This above process is terminated when the UAV arrives at the destination [31].

c. Hybrid path planning: Under hybrid path planning approaches, both offline and online path planning approaches are involved. Specifically, the ground station is leveraged to compute the flight plan for the UAV offline. Subsequently, the UAV becomes responsible for partial and online updating of the pre-computed flight path. Examples of hybrid path planning approaches include the joint online and offline search path planning method [32] and the evolutionary-algorithm-based offline/online path planner [33].

2) Multi-UAV Cooperative Movement Control: Due to the increasing complexity of assigned missions and the limited capability of a single UAV, the multi-UAV systems are exploited to speed up the completion of missions. Before the deployment of multiple UAVs, however, cooperative path planning for collision-free operation should be addressed. Multi-UAV cooperative movement control approaches can help collaboratively optimize the UAV paths and to avoid UAV collisions. Existing multi-UAV cooperative movement control approaches follow two categories: centralized control and decentralized cooperative control [34].

a. Centralized control: In the centralized control approach, each UAV is driven along its pre-computed and time-dependent flight path, which is provided by a central unit. Meanwhile, under the centralized control approach, UAVs fly in a group [34].

Specifically, in the centralized control approach, a central unit is responsible for efficiently formulating and solving an optimization problem to generate a path for the UAV group under some objectives and constraints. For example, to ensure flight safety, the vertical distance f_v between the path and any face of obstacles should be greater than a certain threshold f_{th} [34]. Meanwhile, safe distances around the UAVs should be maintained.

b. Decentralized cooperative control: Under the decentralized cooperative control approach, each UAV runs its movement control approach. Thus, each UAV can autonomously react to behaviors of other UAVs and/or unforeseen events to arrive at a mutual destination safely. A typical decentralized cooperative control approach may consist of two steps [35]:

1) *Decentralized planning:* Each UAV independently plans its optimal path and notifies the optimal solution to the remaining UAVs.
2) *Cooperative optimization:* After receiving this helpful information (or by directly predicting paths of other UAVs according to their current flight status), each UAV formulates and solves a path optimization problem based on both individual and cooperative objectives and constraints.

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C. Networking

After moving UAVs to target areas by using movement control mechanisms, the efficient deployment of UAVs should be addressed next. In the design stage of networking mechanisms, the UAV onboard transceivers may be turned on and put into operation. Although the deployment of UAVs may be assisted by movement control mechanisms, it needs to satisfy the requirements of networking such as network capacity requirements and topology requirements. In other words, the design of the UAV deployment should consider the communication requirements of the networks. For example, the spatial locations of UAVs will affect the network topology. If communication requirements are ignored, UAVs may be deployed at either too high locations or too low locations resulting in the waste of network resources. Therefore, this subsection will discuss the UAV deployment problem.

Some expected and unanticipated factors such as UAV maneuvering, injection, failure, and environmental changes may result in the degradation of the performance of UAV networks. Therefore, UAV networks should be designed to adapt to changes in the network configuration. The equipped self-organization capability of UAV networks alleviates the impact of the above factors on the network performance. Furthermore, software-defined networking (SDN) technology can help build UAV networks with improved agility and resilience.

Next, survey of the related work on the UAV deployment problem, self-organization of UAV networks and SDN-enabled UAV networks will be presented.

1) UAV Deployment: UAV deployment can be explained as a dynamic process of determining the appropriate number of UAVs and their spatial locations according to communication requirements of networks. Typically, the UAV deployment problem is modeled as a mathematical optimization problem, and UAV networks can be efficiently deployed by solving this optimization problem.

There are two types of optimal deployment problems. The first type is to optimize the network revenue (e.g., coverage, achievable rates, and outage probability) due to UAV deployment under certain constraints such as UAV transmission power, UAV hovering time, and the number of UAVs. On the contrary, the second type is to minimize the cost (e.g., transmission power, UAV hovering time, UAV stop points, and the number of UAVs) of deploying UAVs while satisfying specific communication requirements, for example, QoS requirements. Existing UAV deployment mechanisms may be classified into two categories: two-dimensional (2-D) optimal deployment and 3-D optimal deployment [36], which are presented as follows:

a. 2-D optimal deployment: The 2-D optimal deployment problem investigates the optimal UAV placement problem in the horizontal space. Typically, the objective of the 2-D optimal deployment is to obtain the optimal horizontal location x_u and y_u of a UAV(s) under a given UAV altitude h. Existing 2-D optimal deployment approaches can be classified into two categories: mathematical-programming-based, and learning-based as described below.

The key idea of the mathematical-programming-based approach is to solve formulated UAV optimal deployment problems efficiently by exploiting mathematical optimization methods. For example, the authors in [37] divided the UAV deployment problem into two sub-problems since the locations of UAVs and their corresponding cell boundaries were mutually dependent, where the cell represented the coverage region of a UAV. The first sub-problem was responsible for optimizing cell partitions by assuming that locations of UAVs were fixed. Given cell partitions, the objective of the second sub-problem was to obtain the optimal UAV locations. By iteratively solving these two sub-problems, the optimal UAV horizontal locations were achieved. Furthermore, the authors in [38] formulated a joint UAV trajectory and power optimization problem as a mixed integer non-convex problem. An iteration optimization strategy is proposed to solve the challenging problem by exploiting block coordinate descent and successive convex optimization techniques. More work can be found in [39], [40] and references therein.

Under the learning-based approach, learning algorithms rather than mathematical programming algorithms are used to solve the UAV deployment problem. Existing learning algorithms follow two categories: clustering and reinforcement learning.

In the clustering-based approach, the clustering idea is investigated to solve the UAV deployment problem. Specifically, this approach considers the optimal deployment problem as a clustering problem where the set of users assigned to a UAV can be regarded as a cluster. Deploying a UAV at a cluster center can ensure that the UAV has the minimum sum of distances to all cluster members [41]. Besides, the authors in [42] proposed a joint clustering and parameter estimation algorithm to learn and reconstruct from small energy measurement samples an AtG radio map to predict a UAV position.

The reinforcement learning algorithm is based on the interaction with the environment in discrete time steps. Specifically, it may learn system states and exploit different actions to adjust locations of UAVs based on the states. After the learning step, each UAV may find a sub-optimal horizontal location to provide radio access services for users [43].

b. 3-D optimal deployment: In contrast to the 2-D optimal deployment problem, the 3-D optimal deployment problem discusses the optimal UAV placement problem in 3-D space. In this problem, the horizontal location and altitude of a UAV(s) may be jointly optimized. Because of the additional degree of freedom, the solution to the 3-D deployment problem becomes more difficult.

The dimension-reduction-based approach is one of the major approaches to solve the 3-D optimal deployment problem. The key idea of the dimension-reduction-based approach is to reduce the dimension of the optimization problem by fixing a decision variable. Typically, there are two ways of optimizing UAV spatial locations based on whether the UAV altitude and horizontal location problems can be separated or not.

- If the two problems can indeed be separated, the optimal UAV altitude is obtained first. Given this optimal altitude,

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the UAV horizontal location can be found by solving a 2-D optimal deployment problem [36], [44], [45].

- If the two problems can not be separated, the exhaustive search may be one possible approach. Under the exhaustive search approach, the UAV horizontal location is optimized first by assuming a fixed UAV altitude. Next, by traversing all altitude values and comparing revenues reaped from the correspondingly optimized horizontal locations, the optimal UAV altitude and horizontal location may be obtained.

2) Self-Organization Network Model: UAV networks are always under threats of some unanticipated situations. To ensure that UAV networks can continue to operate in such uncertain situations, the self-organization network model should be carefully developed [46].

The self-organization network model can be explained as a dynamic process where a network organizes itself without any external intervention [47]. The procedure of the self-organization network model is as follows [6]: when a UAV node fails or new UAV node joins, its neighbor(s) monitors the incoming and outgoing links. According to the measured link quality, the neighbor(s) adjusts physical layer parameters to match the appropriate physical layer options. For example, the neighbor(s) may regulate the angle of the airframe or onboard antennas and adjust the UAV altitude for better link quality. This process, however, may result in channel access competition and packets collision. The medium access control (MAC) layer may reasonably address the channel access problem and is responsible for establishing RF connections among the neighbor UAV nodes. It also notifies these connections and their current situations up to the network layer. Through referring to the information, the network layer autonomously updates network topologies by adding/removing UAV nodes and RF connections. Under the time-varying topology, the network layer may perform the end-to-end packet delivery through a store-carry-forward routing mechanism. Finally, the transport layer provides different reliability levels for different UAV application areas and executes a congestion control mechanism for the network load management.

Existing self-organization network models can be classified into two categories: centralized and decentralized self-organization [46], which are presented as follows.

a. Centralized self-organization: Under the centralized self-organization model, there is an entity in the model that centrally coordinates all activities. The computational and communication overhead of the centralized self-organization approach is expensive due to the collection and dissemination of global information for coordination. Additionally, a failure of a single UAV node may trigger the reconfiguration of the whole UAV network [46].

b. Decentralized self-organization: Under the decentralized self-organization model, each entity makes self-decisions and takes actions according to nearby/local information, i.e., the direct interaction with neighbor UAV nodes [6]. In comparison with the centralized self-organization model, the decentralized self-organization model may be more robust to expected/unanticipated failures as a result of local activities [46]. Examples of local activities include “join a new UAV formation” and “forward packets to the nearest UAV”.

In summary, the purpose of the self-organization model is to alleviate the effect of uncertain failures on the performance of UAV networks and ensure the network operability. Moreover, the network self-organization generates computational overhead and requires high bandwidth [6]. Although challenges of the self-organization network model are significant, the advantages of this model make it an attractive research topic.

3) SDN-Enabled UAV Networks: SDN is an important technology for constructing flexible UAV networks with improved agility and resilience. It provides an opportunity to control UAV networks programmatically, making it easier to configure and manage UAV networks [48]. For instance, the SDN-enabled networks can implement and update both applications and services, such as energy-efficient networking, communication relays, and data mules, in software [49].

By enabling the following key points, SDN helps achieve the above promising goal [48], [49]: 1) Separate the network infrastructure into two distinct planes, i.e., data plane and control plane. The data plane is aimed at forwarding network packets, and the control plane is responsible for the routing process. 2) The control plane provides a global view (e.g., network states) of UAV networks; thus, global network optimization can be enabled. 3) External applications and services can interact with an SDN controller. The SDN controller derives a forwarding information base in software; 4) the SDN controller sends the forwarding information base to the data plane through a protocol (e.g., OpenFlow). OpenFlow protocol allows a finer control level and a faster introduction of new applications and services.

Recently, researchers have proposed many studies related to SDN-enabled UAV networks. For example, in [50], the authors demonstrated that SDN could be applied to heterogeneous networks with opportunistic connections. In this work, the SDN controller is used to mitigate the impact of mobility of UAVs on the network QoS by optimizing the network routing. The authors investigated the combination of SDN with DTN approaches in UAV relay networks and proposed an SDN-DTN network architecture in [48]. In this architecture, the DTN orchestrator can exchange information with the SDN controller. The DTN orchestrator can thus schedule data transmission efficiently among DTN nodes according to global network information provided by the SDN controller.

D. Transmission

In many scenarios, UAV communication networks require provision of high-speed communication services. For example, UAV networks are expected in many real-time applications (e.g., targets monitoring and tracking) where the high data transfer rate is required. Moreover, UAV communication networks have been regarded as promising proposals for the 5G system where the gigabits per second (Gb/s) data transfer rate is considered as one of the key performance indicators [51]. Therefore, this subsection discusses mechanisms of improving the capacity of UAV communication networks. The cooperative processing from multiple UAVs for network interference management will also be discussed.

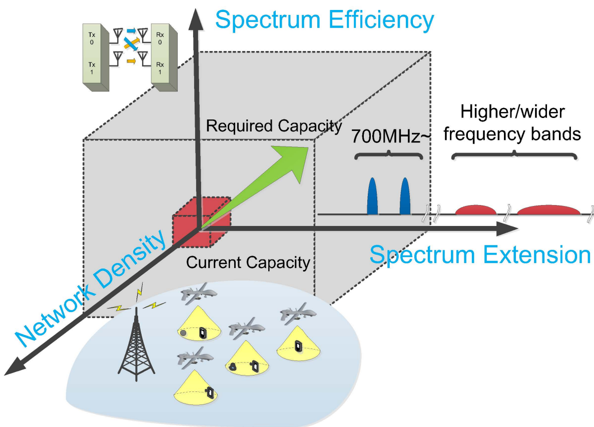

Fig. 3. Technical routes of improving the capacity of UAV networks.

On the other hand, a number of reliable transmission mechanisms should be developed for UAV communication networks. This is because UAV communication networks may be disconnected frequently, and instantaneous end-to-end paths may not be anticipated in such networks. Therefore, this paper will also survey protocols for the reliable end-to-end data transmission.

1) Network Capacity: Fig. 3 depicts three major ways to improve the capacity of UAV networks; namely, spectrum efficiency improvement, spectrum extension, and optimal UAV location and density [3]–[5] as discussed below.

a. Spectrum efficiency improvement: The spectrum efficiency (in bits per second per Hz) refers to the information rate that can be transmitted over a given bandwidth in communication networks. It reflects how efficiently a specific spectrum is used by the physical layer protocol, and sometimes by the MAC layer protocol [52]. High spectrum efficiency means that more information can be transmitted over the given bandwidth per unit of time. The multiple-input-multiple-output (MIMO) is one of the most popular techniques for improving the spectrum efficiency.

For MIMO communications, they can improve the spectrum efficiency by acquiring the spatial multiplexing gain. The spatial multiplexing is a transmission technique that can transmit separately encoded and independent information from each of multiple transmit antennas [53].

Recently, some results present significant potential for MIMO communications in UAV networks. It is, however, challenging to apply the MIMO to UAV communication networks. First, the lack of the abundant scattering in UAV networks considerably limits the spatial multiplexing gain. Second, the MIMO relies on accurate channel state information for increasing the spatial multiplexing gain. Channel state information is practically difficult to be obtained in UAV networks [3]. Third, MIMO requires more power during actual usage. Moreover, the increase of MIMO performance metric requires an accompanying increase in transmitted carrier power. There is thus a trade-off between the MIMO performance metric and the power consumption.

Despite the above challenges, there are a large number of studies investigating the use of MIMO techniques in UAV networks for both communications and location [3], [54]–[57]. For example, both multi-user MIMO and massive MIMO techniques are exploited to reap a high spatial multiplexing gain for UAV communications [3], [54]. Another effective way of obtaining a high spatial multiplexing gain is to resort to the careful design of the antenna separation on UAVs concerning both the carrier wavelength and the link distance [55]. The authors in [56] discussed how to obtain the multiplexing gain from the perspectives of using dual-polarized antennas and the selection of antenna separation in detail. Moreover, MIMO channel sounding was used to discriminate UAV positions [57].

Besides, the use of MIMO in the integration of UAV networks with other wireless systems has also been studied. For example, the authors in [58] used MIMO techniques to support communication in UAV-assisted sparse wireless sensor networks wherein UAVs were used to prolong the lifetime of sensor networks by keeping their connectivity.

b. Spectrum extension: The frequency allocated to all cellular networks today is below 3 GHz [59]. Extending the spectrum to the underutilized spectrum in very high frequencies, for example, millimeter-wave (mmWave) bands (between 30 and 300 GHz), is regarded as one of the most effective proposals for improving the transfer rate [60]. In such a case, the transfer rate in the order of multiple Gb/s may be achieved.

Because of the higher and wider frequency bands that are much wider than all cellular allocations today [61], the mmWave technique may have three major advantages and is thus suitable for UAV communications.

- *Higher bandwidth:* The mmWave may provide the promise of greater bandwidths combined with further gains via beamforming and spatial multiplexing from multi-element antenna arrays [62].
- *Higher transmitter/receiver (Tx/Rx) antenna gain:* The mmWave may also result in a higher signal-to-noise ratio and then a greater transfer rate. Wavelengths of mmWave signals locate between 1 and 10 mm. In this case, the separation between any two antennas locates between 0.5 and 5 mm; and thus the beam formed by two antennas is narrowed, and the energy of the beam is concentrated. Therefore, a receiver may have the opportunity to receive stronger data signals via an appropriate beamforming scheme [63]. Atmospheric attenuation, however, is a major factor throughout the frequency band and increases with frequency. Thus, the achieved higher antenna gain has to be weighed against the greater propagation losses at higher frequencies.
- *Tiny antennas:* Advances in low power complementary metal-oxide-semiconductor (CMOS) RF circuits and small mmWave wavelengths enable large numbers of tiny antennas to be placed in small dimensions [62]. Tiny antennas are especially suitable for a SWAP constrained UAV and may save space for deploying other advanced sensors and peripherals.

Despite the above advantages of mmWave communications, one of the key issues of applying the mmWave technique in UAV communications is to address the problem of Tx/Rx beam alignment for acquiring the Tx/Rx antenna gain. This is incurred by the high dynamic characteristic of UAVs [3].

One feasible way of solving the beam alignment problem is to leverage a beamforming training and tracking scheme [4]. This scheme is to find out the best pair of Tx/Rx beamforming codewords from all combinations of beam directions in the angle domain. The hierarchical beam search [4] is an efficient beamforming training and tracking approach. It needs not to test plenty of combinations of beam directions sequentially, which are incurred by the UAV mobility. Specifically, this approach first designs a multi-layer codebook. The codewords in each layer may collectively cover the entire search space in the angle domain. Next, it adopts a joint coarse and fine search scheme to find out the best pair of Tx/Rx beamforming codewords. In this way, the search complexity and the antenna training overhead are significantly reduced.

c. Optimal UAV density: The network capacity may also scale with the increase of the number of deployed UAVs (denoted by N). One of the key challenges of deploying multiple UAVs is interference management. Owing to the simultaneous data transmission of neighbor UAVs, more interference would be generated with the increase of N, which may result in a higher link outage probability. Therefore, it would be essential to identify the optimal N that maximizes the network capacity.

One popular approach is to leverage the stochastic geometry to analyze the performance of UAV networks [5]. In stochastic geometry, topologies of UAV networks are modeled as 3-D Poisson point processes. Specifically, in the problem of finding the optimal UAV density, the interference is implicitly associated with the density of UAVs. This is because the strength of interference depends on locations of UAVs that are correlated with the density of UAVs. Therefore, this approach distills the UAV density by computing the expectation of interference. As a result, the optimization problem concerning both density and interference is reduced to a density-related univariate problem wherein the optimal density of UAVs can be easily obtained.

2) Cooperative Interference Management: When network deployments become denser, interference may become a dominant performance degradation factor, regardless of underlining physical-layer technologies [64]. Cooperative processing from multiple UAVs is an efficient way of managing interference [65]. Existing cooperative interference management approaches follow two categories: centralized management and decentralized management [64], which are presented as the following.

For the centralized management approach, a central entity is used to manage interference. Specifically, in this approach, instead of processing received data from terrestrial users locally, each UAV forwards the data to a central processor. The central processor adopts a zero-forcing beamforming method to eliminate the inter-user interference for each group of users [65].

For the decentralized management approach, interference is managed by local entities. Specifically, in this approach, locally cooperative entities adopt a coordinated beamforming technique to eliminate the intra-cluster and out-of-cluster interference for terrestrial users. The coordinated beamforming technique uses shared knowledge of channel states between entities in a cooperative cluster and their target users to separate different data streams without exchanging users' data. By only sharing channel state information, each entity therefore in the cooperative cluster may transmit independently [64].

3) Routing Protocols for Reliable Communications: Owing to the failure/replacement of UAVs, intermittent communication links and rapidly changed network topologies, the reliable end-to-end data transmission may be infeasible in UAV communication networks. The DTN routing protocol originating in interplanetary communications can be introduced in UAV networks to help improve the reliability of the end-to-end data transmission [7].

For the DTN routing protocol, the core mechanism is store-carry-forward, namely: if a packet cannot be routed to its destination, it will not be immediately dropped but will be stored and carried. Existing DTN routing protocols may be classified into three groups: deterministic, stochastic, and enhanced routing protocols.

a. Deterministic routing protocol: In the deterministic routing protocol, a node carrying packets may select a next hop node according to deterministic/known information (e.g., contact, queue, and traffic demand) [66], [67]. The deterministic routing protocol can be further classified into two categories: completely deterministic and semi-deterministic routing protocols [7], which are presented as the following:

In a completely deterministic routing protocol, future information such as the node movement and contact is completely known; and a node delivers packets to a next hop based on completely deterministic knowledge [68]. Specifically, each node maintains time-dependent topology snapshot sequences that record the changing process of the network topology. In this way, a deterministic temporal-spatial graph (including network nodes and all possible links) of UAV networks is obtained. In such a graph, each node has global knowledge of the availability and movement of the remaining nodes. Thus, a topology tree can be constructed by considering the source node as the root and adding child nodes and the corresponding time. Finally, the shortest end-to-end path can be reaped from the tree.

Compared with the completely deterministic routing protocol, the semi-deterministic routing protocol does not require complete knowledge. In this protocol, nodes may have simple mobility models and may appear in some known places with a high probability. The social-based routing protocol is a typical semi-deterministic routing protocol [7].

In a social-based routing protocol, a node utilizes one/multiple social characteristic (e.g., community, centrality, similarity, and friendship) of the social network to choose the next hop. For example, a social metric can take the following forms [69]:

$$SimBetUtil_n(d) = \alpha SimUtil_n(d) + (1-\alpha) BetUitl_n \quad (2)$$

$$SimUtil_n = \frac{Sim_n(d)}{Sim_n(d) + Sim_m(d)} \quad (3)$$

$$BetUtil_n = \frac{Bet_n}{Bet_n + Bet_m} \quad (4)$$

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In the above, n, m, and d denote the sending node, receiving node, and destination node, $Sim_n(d)$ represents the similarity (a measure of the number of common neighbors) of n and d, Bet_n denotes the estimated betweenness centrality of n, $SimUtil_n$ and $BetUtil_n$ represent the relative similarity utility and betweenness utility of node n, $SimBetUtil_n(d)$ represents the social metric and α is a weight coefficient.

Under the social-based routing protocol, (2) is used to determine the next hop for the node n. For a packet, if $SimBetUtil_m(d) > SimBetUtil_n(d)$, then the node n forwards the packet to the node m; otherwise, it continues to carry the packet [69].

b. Stochastic routing protocol: In the stochastic routing protocol, a sending node may select a next hop without any known information. Existing stochastic routing protocols may have two groups: broadcast-based and unicast-based routing protocols [70] as presented below.

Under the broadcast-based routing protocol, a sending node will indiscriminately forward data packets to every node within its transmission range. Specifically, in UAV networks, a source node may make many packets copies and broadcast these replicas to any node it encounters. Then these nodes forward replicas to other nodes when they are in contact. In this way, packets may be quickly distributed throughout the UAV networks [71]. The disadvantages of the broadcast-based routing protocol are [66]:

- *Contention:* It may create contention for buffer space and transmission time (or the channel resource).
- *Resource consumption:* It requires a large amount of buffer space, bandwidth, and power.

In the unicast-based routing protocol, instead of forwarding packets copies to each encountered node, a sending node will discriminately forward packets. Moreover, it will forward its piggybacked data to a winning node (e.g., the node closer to the destination one) it encounters. Specifically, a sending node will estimate probabilities of some nodes that eventually contact with the destination node of packets. These nodes include the sending node itself and its neighbor nodes. According to these contact probabilities, the sending node will decide whether to forward packets or carry-and-wait for a good opportunity [72].

c. Enhanced routing protocol: In UAV networks, packets may be lost/dropped owing to the buffer overflow or uncorrectable bit errors, which significantly degrades the network communication performance [70], [73]. The coding mechanism can be utilized to mitigate this problem effectively. Therefore, by combining the coding mechanism with the deterministic/stochastic protocol, the enhanced routing protocol can further enhance the reliability of communications and reduce the transmission delay.

In an enhanced routing protocol, a source node may send out a batch of coded messages to nodes it encounters. The coded message m is a linear combination of K source messages. Assuming that a forwarding node n_1 stores N coded messages (denoted by $m_1, m_2, \ldots, m_N$) when it encounters a node n_2. Node n_1 will transmit to node n_2 the L linearly re-encoded messages and the corresponding coding coefficients. Once receiving these re-encoded messages, n_2 either directly stores them or linearly combines them with messages that already exist in its buffer space. In this way, coded messages may be delivered and destined to the destination. The destination may wait until it receives enough coded messages to recovery K original messages. The decoding process can be successful only when K or more different coded messages are received [74].

In sum, the transmission is one of the crucial issues of designing UAV communication networks. A large amount of effort has been dedicated to this direction. So far, this paper has described transmission mechanisms from the perspectives of both the physical layer and the network layer. For more information on transmission mechanisms of UAV networks, please refer to [6], [13] and references therein. Furthermore, Table I summarizes main pros and cons of movement control, networking, and transmission related work of LAP networks.

III. HAP-Based Communication Networks

In addition to UAVs, HAPs are other important airborne platforms of ACNs. HAPs have a large footprint and long communication persistence. Furthermore, 3GPP has identified HAPs as new 5G radio access platforms [1]. This section will discuss the characteristics and channel models of HAP-based communication networks.

A. Characteristics of HAPs

Over the long history of the telecommunications industry, communications connectivity and services were mainly based on terrestrial networks or satellites. Despite the fact that the non-terrestrial networks (e.g., HAPs) can bring many benefits to the telecommunication industry, their use is still limited. Although several projects and studies considered the development of HAPs for telecommunication services in the 1990s and 2000s, they have not seen a widespread commercial deployment for reasons of safety, reliability, regulations, and cost. The recent investment in the HAPs industry by Google, through its LOON project, has brought back attention to HAPs, motivating both industry and academia to invest in and study HAP-based communications. While terrestrial and satellite systems are well-established technologies for delivering telecommunication services, they exhibit disadvantages and challenges which could be addressed by the use of HAPs. As an example, to provide a wide coverage area, a satellite or a large number of terrestrial base stations (BSs) along with a backhaul network may be needed. The high cost of infrastructure is a major concern with these. These expensive solutions could be replaced by a single HAP or a handful of HAPs [76].

Next, this paper will discuss the types, advantages, applications, and challenges of HAPs, respectively.

1) Types of HAPs: HAPs may be aircrafts, airships or balloons that operate at altitudes in the range of 17-22 km above the Earth's surface [76], [77]. This altitude range is chosen because of its low wind currents and low turbulence which reduce the energy needed to maintain the position of the HAP. Different categories of HAPs have been discussed throughout the history of HAPs as follows:

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TABLE I
SUMMARIZATION OF MAIN PROS AND CONS OF RELATED WORK OF LAP WORKS

Typical study	Pros	Cons
Offline path planning [22]	Obtain a globally optimal path	Unsuitable for dynamic scenes
Online path planning [31]	Suitable for dynamic scenes	Non-optimal path
Hybrid path planning [32]	High efficiency and suboptimal path	Unsuitable for 3-D UAV path planning
Centralize control [34]	Plan paths for multiple UAVs	One unit takes computationally heavy tasks
Decentralized control [35]	Plan paths for multiple UAVs in a decentralized way	Communication delay affects the performance of the planner
2-D optimal deployment [41]	Relieve the overload with a minimum number of UAVs	No discussion on a 3-D deployment
3-D optimal deployment [36]	Suboptimally deploy a UAV in 3-D space	Unsuitable for multiple UAVs
Decentralized self-organization [46]	Robust to failures owing to local activities	Weak mathematical modeling and reasoning [46]
SDN-enabled UAV networks [50]	Enable SDN in UAV networks	Combination of SDN with DTN approaches is deserved to be studied [50]
UAV MIMO communication [55]	Obtain a high spatial multiplexing gain	Good results within the Rayleigh distance [75]
UAV mmWave communication [4]	Reduce the beam-search complexity	Beam-alignment speed is still a concern
Optimal UAV density [5]	Optimal UAV density in 3-D space	No discussion on NLoS connections for AtG links
Decentralized management [64]	Eliminate interference among users	Great coordination overhead [64]
Deterministic routing [69]	Efficient prediction of contact probabilities between relays and the destination	Delivery performance vs. communication cost
Stochastic routing [71]	Simplest DTN dissemination protocol	Require many network resources
Enhanced routing [73]	Realize reliable end-to-end data transmission	Routing overhead may be a major concern

- **Balloons** are primarily designed to stay still in the air for a long period of time and can be lifted by using hydrogen, helium ammonia or methane [77]. The balloons are often huge, over 100 m, and capable of carrying payloads of 800 kg or more [78].
- **Airships** are huge aerial platforms with lengths of 100 m or more, and are mainly powered by solar panels mounted on the top surface of the airship [76]. In comparison to balloons, airships have station-keeping capability using electric motors and propellers.
- **High altitude unmanned aerial vehicles (HA-UAVs)** are aircrafts which cannot stay in the air unless they move. Therefore, they typically fly on a circular path. HA-UAVs that can fly at high altitudes for a long time are also known as high altitude long endurance platforms. They typically have a wide wingspan, are lightweight and are powered by solar cells or fuel. The key limitation of such HAPs is their typical low payload capacity and high operational cost.

2) Advantages of HAPs: HAP-based communications have several advantages which are summarized as follows:

- *Wide area coverage*: The capability of HAPs to hover at high altitudes, allowing them to provide services for ground points over an extensive area, makes them more favorable in comparison to LAPs and terrestrial networks. A handful of HAPs could cover a whole country (e.g., Japan can be covered by 16 HAPs with an elevation angle of 10° while Greece can be covered by 8 HAPs) [78].
- *Favorable HAP-ground channel characteristics*: The under-utilized mmWave frequency spectrum is seen as a promising candidate for future wireless systems. The use of the mmWave spectrum, however, is challenging because it is sensitive to blockage and requires the LoS propagation between the transmitter and the receiver [79]. In terrestrial networks, this implies the need for densification of the access points. With the aid of HAPs, the LoS propagation is available most of the time which allows the realization of using mmWave and other point-to-point (PtP) communication technologies such as free space optics (FSO).
- *Rapid deployment* (compared to terrestrial networks and satellites): Emergency or disaster relief communications rely on rapid deployment of a wireless network. With their rapid deployment ability, HAPs can play a key role in emergency or disaster relief applications by restoring the telecommunication services in a matter of hours [80].
- *Quick response to temporal and spatial traffic demands*: HAPs are able to move and can accommodate temporal and spatial fluctuations in traffic demand. A large number of users demanding physical resources simultaneously from a BS may cause an interruption in the cellular service. Such a large traffic demand can be met by moving the HAPs above the heavy loaded terrestrial BSs.

3) Applications of HAPs: Owing to the above advantages, HAPs have exhibited promising results in many applications and services in civil, public, and military fields. The applications and services that can benefit from HAPs include telecommunications services, surveillance, remote sensing, pollution monitoring, traffic monitoring, and emergency services [81]. The emphasis in this subsection, however, is on the telecommunications services, including mobile services, broadband internet, and backhaul/fronthaul.

a. Mobile communications: Several projects and studies have addressed the feasibility of integrating HAPs into terrestrial wireless networks (e.g., GSM, UMTS or LTE). The Sky Station Project planned by Sky Station International intended to deploy 250 Geostationary 30-ton helium-filled dirigibles to provide internet access and video telephony for millions of

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users [81]. Utilizing HAPs as airborne BSs began with 2G cellular systems, in particular, GSM [82]. HAP-based BSs utilizing UMTS, HSPA, or in general WCDMA were also investigated in [83]–[88], and some studies even investigated the feasibility and performance of LTE-based HAPs [89]–[91].

b. Broadband wireless access: Several projects and studies investigated the feasibility of providing broadband internet from the sky for either access points or users. The European Union Framework Programme 6 project CAPANINA (2003-2006) aimed to provide low-cost, ubiquitous broadband wireless coverage for people in hard-to-reach areas or inside high-speed vehicles like trains [92]. The LOON project planned by Google aims to provide internet coverage for ground users in rural and remote geographical areas [21]. The LOON project utilizes a network of interconnected solar-powered balloons equipped with lightweight redesigned LTE-based BSs. The balloons act like airborne eNodeBs capable of providing 4G data connections to LTE phones or LTE-capable devices.

c. Vertical backhaul/fronthaul: It is acknowledged that ultra-dense deployment of small cells is a key enabler to allow the realization of 5G wireless networks. The key challenge for such a dense network, however, is how to backhaul/fronthaul a large number of small BSs, particularly in hard-to-reach areas where terrestrial infrastructure is not already available and is expensive to deploy. In such cases, HAPs are a promising technology to provide a vertical backhaul/fronthaul network [93]. The study in [93] was the first in the literature to propose a novel vertical backhaul/fronthaul network utilizing HAPs and FSO to connect the small cells to the core network. Besides, a hybrid FSO/mmWave or FSO/RF could be used to mitigate losses due to weather conditions. The key challenge reported by the study in [93] is the high operational cost of UAVs. However, balloons could be used instead of UAVs to reduce the system cost.

4) Challenges of HAPs: Despite the many benefits of HAPs, HAPs-based communication networks pose several challenges as summarized below:

- *Safety and regulations*: Commercial use of HAPs, including their usage for cellular services, requires the platforms to hover in civilian airspace. Current airspace regulations, however, do not allow unmanned HAPs to fly in civilian airspace for safety reasons. Two possible intermediate steps towards utilizing HAPs in civilian airspace are the use of manned HAPs and having a remote pilot on the ground [77]. The onboard pilot or remote pilot can control the HAP to ensure that it does not pose a risk to people on the ground.
- *Seamless integration with existing networks*: Despite the potential benefits of HAPs, they may only be seen as a complementary solution to terrestrial networks for reasons of reliability, safety, and cost [93]. To provide the seamless coverage or capacity enhancement, HAPs may need to be interconnected and connected to existing network entities to establish backhaul and communications links. Therefore, the integration of the infrastructure and services of HAPs and existing networks is needed.
- *Optimized telecommunications payload*: The payload carried by a HAP depends on the application. A HAP intended to deliver telecommunications services will be equipped with a telecommunication payload (e.g., a HAP-based BS will carry a BS that can deliver cellular services to ground users). The payload has a significant impact on the operation of the HAP. The use of a heavy payload implies more power consumed on the platform which results in a shorter mission time. Therefore, there is a need to optimize the payload design for HAPs.
- *Optimized signal processing and protocols*: Current telecommunications technologies, including physical layer functions like modulation and coding, protocols and handover mechanisms, are mainly designed for satellites and terrestrial applications. HAPs, however, exhibit different characteristics from satellites and terrestrial networks. A resource allocation scheduler implemented in eNodeB in LTE networks may not function well when implemented in a HAP-based eNodeB. This is because the characteristics of the HAP-ground channel is completely different from a terrestrial channel. Therefore, the physical layer functions and protocols should be optimized for use in HAPs.
- *Need for high-speed backhaul/fronthaul links*: One of the key benefits of HAPs is their large area coverage. The traffic that goes up must also go down to the ground. A HAP collecting traffic either from users (like airborne BS) or other access points (airborne hub) over a large area implies that high speed HAP-ground backhaul links are required. A single link or a single backhaul technology may not fulfill such a requirement. In such scenarios, multiple backhaul links and technologies such as PtP Microwave or FSO may be needed.

B. Channel Models of HAPs

Although the HAP channel model shows the 3-D transmission nature, it differs from the UAV channel model because of the unique stratospheric transmission environment. Further, the wireless channel in HAP-based communication networks exhibits different behavior from terrestrial channels. While terrestrial access points are mostly stationary, HAPs, in particular, HA-UAVs may need to move continuously during their missions. Thus, the transmitted signal may suffer from a severe Doppler shift even if the ground receiver is stationary. Besides, the continuous movement of the HAP may cause rapid fluctuations in the wireless channel. Therefore, an accurate channel modeling is of vital importance in HAP-based communications. Meanwhile, channel propagation model is one of the crucial issues of HAP-based communications. This paper focuses on the discussion of HAP channel models. Typically, two types of channels can be distinguished in HAP-based communications as summarized below:

1) HAP-Ground Channel: The International Telecommunication Union Radiocommunication Sector (ITU-R) allocated a number of frequency bands for HAP communications such as those in the Ka band (28-31 GHz and 47-48 GHz) and the L band (2 GHz) [77]. The HAP-ground wireless channel exhibits different characteristics in those bands. In contrast to the signals in the 2 GHz band, signals in the

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28-31 GHz and 47-48 GHz are sensitive to atmospheric conditions such as rain and suffer from high free space path loss [77]. Several channel models have been proposed and used for HAP-ground scenarios. The high likelihood of the presence of LoS transmission has led many researchers to use simplified free space path loss without considering multipath components, e.g., [85], [94], [95]. Other researchers proposed to use statistical channel models (e.g., the authors in [89], [96] used the frequency flat Rician channel model because of the presence of LoS component). It was, however, shown in [97] that such channel models might lead to overly optimistic results. The authors in [97], [98] derived theoretical small-scale models by extending the Rappaport-Liberti model which was proposed for terrestrial links. The authors in [97], [98] derived the power delay profile for the HAP-ground wireless channel from which small-scale statistical parameters, such as coherence bandwidth, were evaluated. The work in [99] used a Rician frequency selective channel to model the channel from a HAP to a high-speed train operating at a Ka band frequency in an urban environment. The work in [100] proposed an urban path loss model based on a ray tracing algorithm. A switched channel model based on a semi-Markovian process was proposed in [101]. The switched channel model assumes that the HAP-ground channel switches between two or three states defined as LoS, slight shadowing, and total obstruction.

2) Inter-HAP, HAP-LAP, HAP-satellite Channels: Integrating a HAP with existing networks requires the existence of high-speed links that connect the HAPs to other network entities such as satellites, LAPs or HAPs. In contrast to HAP-ground links, FSO, which relies on a laser to send high-speed data, is seen as a promising and efficient technology to establish space links[2] [102]. FSO is very sensitive to clouds and weather conditions such as the fog. Such conditions, however, do not exist for HAP-LAP links as HAPs are deployed above the clouds. With the aid of FSO technology, long-range communication links can be established. For example, the work in [103] designed an FSO system capable of delivering 384 Mbps with a bit-error ratio of 10^{-6} for two HAPs situated 500 km apart at an altitude of 20 km.

Accurate channel modeling for FSO links is of vital importance to estimate the system performance properly. While the optical signal propagates from the transmitter to the receiver, it is subject to losses such as turbulence, geometrical and pointing losses. Turbulence is a result of the random variation of the temperature, pressure, and humidity of the atmosphere and causes fluctuations in the received power known as scintillations [104]. Depending on the level of the turbulence, several statistical models have been used to model scintillations. For example, a lognormal model is used in low turbulence regime [105], and a Rayleigh model is used for a strong turbulence regime [106]. Geometrical loss occurs due to the spread of the optical signal over a large area which reduces the power collected by the receiver. The geometrical loss in dB is given by $L_{\text{geo}} = 10\log\left(\frac{\pi r^2}{\pi(\theta l/2)^2}\right)$, where r is the radius of the receiver's aperture, l is the length of the communication link, and θ is the divergence angle of the transmitter [93]. Generally, pointing loss is a critical issue in narrow beamwidth technologies such as FSO and mmWave. It occurs due to the misalignment between the transmitter and the receiver, which could result in a link failure or significant degradation in the system performance. Pointing loss is much more challenging in the case of moving HAPs or during high turbulence. Therefore, space FSO links are supported by tracking systems to ensure that a perfect alignment between the transmitter and the receiver exists. Besides, the recommendation [107] treats all the types of inter-altitude propagation paths mentioned above. The reader is recommended to refer to [107] and the additional recommendations therein for more information of the propagation paths for high altitude systems working at high frequencies. Furthermore, Table II summarizes main pros and cons of related work of HAP networks.

[2]For simplicity, this paper uses space links to refer to inter-HAP, HAP-LAP and HAP-satellite links

Traffic may become highly unpredictable in time and space which results in low traffic periods and high traffic periods in future wireless networks [108]. Under such situations, HAPs may be incompetent with regards to the speed of the deployment and service recovery. UAVs have the superiority in quick deployment and service response. Further, UAVs have preferable link budget and low maintenance cost. Therefore, owing to the consideration of the coverage, reliability, safety, and cost of networks, our vision for future ACNs is an integrated one that involves both UAV and HAP infrastructures.

IV. Integrated Airborne Communication Networks

The integration concept is significant for ACNs. The integration of ACNs cannot only complement pre-existing airborne communication infrastructures but also improve the QoS provided by ACNs. Table III depicts the communication performance comparisons of three types of airborne communication platforms: satellite, HAP, and LAP.

The rest of this section is organized as follows: Section IV-A describes an architecture of integrated ACNs. Section IV-B presents a proposal of implementing integrated UAV and satellite networks that may shed light on the design and implementation of ACNs.

A. Architecture of integrated airborne communication networks

ACNs consist of three network components: UAV networks, HAP networks, and satellite networks. These networks, however, can work in conjunction with terrestrial networks. This advancement could also be realized in future communications since terrestrial networks have been the primary solution for providing wireless connectivity. Therefore, in most cases, satellite, HAP, UAV, and terrestrial networks may together build flexible and synergically integrated ACNs.

Fig. 1 depicts a network architecture of integrated ACNs. It consists of layers of access points deployed either on the ground, referred to as the TN, or in the sky, referred to as the NTN. The TN is a typical heterogeneous terrestrial network comprised of fixed access points with different transmitting powers and coverage areas referred to as macro-, micro-, pico-

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TABLE II
SUMMARIZATION OF MAIN PROS AND CONS OF RELATED WORK OF HAP WORKS

Typical study	Pros	Cons
Airborne UMTS-BS [83]	Integrated HAP-Terrestrial UMTS Network	No frequency reuse & unlimited backhaul
HAP deployment [85]	Examine a wide range of parameters (e.g., height, transmit power, and array structure)	Only applicable to a stand-alone HAP
HAP-based IMT-2000 system [86]	Successful HAP-based IMT-2000 service	Tested BS is located on the ground
HAP-based WCDMA system [88]	Multiple HAPs system	No discussion on the downlink
HAP deployment [91]	Restore 92% of original throughput	Severe interference on terrestrial links
Vertical backhaul/fronthaul [93]	Integrated FSO-HAP backhaul network	High operational costs & poor performance in bad weather conditions
Co-channel interference prediction [94]	Efficient cochannel interference prediction	Severe interference on cell-edge users
Capacity enhancement [95]	Applicable to multiple HAPs scenarios	Need a perfect HAP station-keeping & no underlay TN
Airborne eNodeB [96]	Examine a wide range of parameters (e.g., elevation angle, bandwidth, and modulation)	No discussion on the downlink
HAP-Ground channel model [97]	Incorporated multipath fading	Inapplicable to moving or unstable HAPs
Path loss estimation [100]	Incorporate environment parameters (e.g., building height and street size)	No frequency reuse (interference-free)
Switched channel model [101]	Incorporate Los, slight shadowing, and total obstruction conditions	Doppler effect is still a concern
Interplatform FSO link [103]	Complete system design to achieve 384 Mbps for HAPs 500 km apart	Doppler effect & atmospheric losses are not considered

TABLE III
COMMUNICATION PERFORMANCE COMPARISONS OF THE SATELLITE, HAP, AND LAP

Performance	Satellite	HAP	LAP
Footprint	superiority	large	small
Overflight	superiority	restricted	restricted
Vulnerability to natural disasters	reduced	reduced	reduced
Responsiveness and flexibility	slow	medium	rapid
Communication persistence	long	long	short
Propagation delay	long	short	short
Broadcast/ multicast	capable	capable	capable
Cost	high	medium	low

or femtocells. Similarly, the NTN consists of different access points flying at different altitudes, ranging from low altitudes (e.g., tens of meters) to very high altitudes comparable to satellite altitudes. Based on the deployment altitude, the access points of the NTN can be classified as LAPs, HAPs or satellites.

LAPs layer: A LAP may be a UAV capable of flying at low altitudes (e.g., a few hundreds of meters) for a sufficient endurance for completing a mission. Different applications can be realized by such platforms. For instance, a LAP can be utilized as a flying BS, commonly known as a UAV-BS, where a BS is mounted on a LAP [44]. Such on-demand LAPs can be beneficial in several scenarios, such as offloading traffic from a congested BS or during a temporary event such as a sports event [44], [49]. With the aid of such UAV-BSs, the urgent need for the cellular coverage or capacity enhancements can be quickly met. Besides, LAPs can be used to provide services to access points. For example, a backhaul/fronthaul hub could be mounted on a LAP forming an airborne backhaul/fronthaul hub that can collect backhaul/fronthaul traffic from terrestrial BSs and forward the aggregated traffic back to a ground gateway if an AtG link is available. Otherwise, the traffic could be forwarded to a HAP or a satellite.

HAPs layer: The HAPs layer consists of HAPs positioned at altitudes between 17-22 km. Flying at such high altitudes makes HAPs ideal for large-area coverage. Besides, HAPs can enjoy favorable channel conditions due to the high likelihood of having LoS connections with ground points and LAPs. The atmospheric losses for HAP-to-HAP propagation paths are also less than those for LAP-to-LAP paths [107]. Therefore, HAPs can be utilized as airborne BSs capable of providing cellular services to areas larger than those served by LAPs. There is also an opportunity for the HAPs to act as airborne backhaul/fronthaul hubs. Supported by the fact that there are no obstacles between the HAPs and other NTN access points, the HAPs can provide high-speed PtP backhaul/fronthaul links. A single HAP can aggregate traffic from multiple LAP-, or tower-based BSs and forward the aggregated traffic back to a ground gateway or a satellite. PtP links can rely on the microwave or FSO to deliver the backhaul/fronthaul traffic at high speeds.

Over its long history, wireless networks have been primarily developed and built for terrestrial users. With new applications and use cases, however, users could also be located in the sky, such as the emerging application known as *delivery-drone* [109]. Delivery drones are UAVs intended to deliver goods such as mail, food or parcels. Here, a key question that needs to be addressed to realize the drone-based delivery market is how to control the delivery-drones, especially in remote areas where terrestrial infrastructure is not available. Such drones should be integrated properly within the underlying system to ensure a successful and seamless operation. The NTN access points such as LAPs, HAPs or even satellites could play a key role in such scenarios where terrestrial infrastructure is not adequate to provide a seamless operation. Therefore, our vision of future wireless networks is that services will be delivered to both terrestrial users (TUs) and non-terrestrial users (NTUs).

Satellites layer: Satellites have been introduced in the telecommunications industry since the mid-1960s. Depending on their altitude, satellites can be classified as low earth orbit (700-2000 km), medium earth orbit (8000-20000 km), geostationary earth orbit (35786 km), and high earth orbit (up to 42000 km) [110]. In addition to the existing services provided by satellites, other services can be realized by using satellites in the envisioned future wireless network. Satellites can provide backhaul/fronthaul connectivity to both HAPs and LAPs. PtP high-speed links utilizing FSO technology can be established[3]. It is, however, worth mentioning that such a solution may not be appropriate in some applications. A very long distance that separates satellites from LAPs or HAPs results in a considerable delay which is not suitable for delay-sensitive applications.

B. Implementation of Integrated Airborne Communication Networks

Although the application of integrated ACNs is promising, the design of such type of network is challenging mainly because of the high network heterogeneity. This paper next presents a technical proposal for implementing the integration of satellite and UAV communication networks.

1) Key Issues: To propose an implementation scheme of integrated networks, some key issues should be first refined. The key issues of implementing integrated satellite and UAV networks include [7]:

- *Universal protocol stacks*: Existing DTN routing protocols have been separately designed for satellite and UAV networks. It is evident that satellite and UAV networks are heterogeneous for such reasons as different network topology features, capacity constraints, and transmission latencies. In heterogeneous networks, current works on the design of routing protocols are mainly based on a hierarchical idea; and different networks have diverse routing strategies. For integrated networks, non-unified and uncooperative protocol stacks may increase the network complexity and result in the waste of network resources. Therefore, universal protocol stacks may be necessary for the uniform placement and centralized management of ACNs.
- *Integrated topology*: Owing to the fixed satellite trajectories, existing works transform the dynamic topology of satellite networks into a static temporal-spatial graph, which is taken as a sequence of topology snapshots.

[3]Such FSO products, which are designed for connecting flying platforms with satellites, are already available. Refer to https://mynaric.com/ for more information.

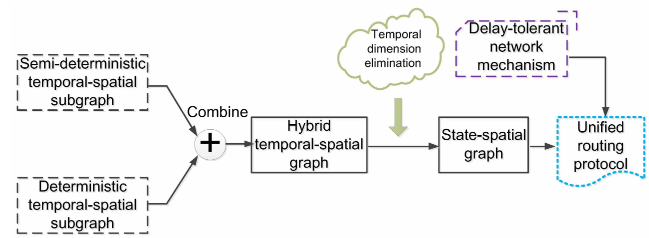

Fig. 4. A framework of the unified routing protocol for integrated satellite and UAV networks.

For UAV networks, however, a static temporal-spatial graph may be impossible because of the non-deterministic UAV flight trajectory. Most existing topology graphs are aimed at modeling a single deterministic network. How to construct an integrated topology consisting of both static and non-deterministic temporal-spatial graphs may be an open and promising issue.

2) Unified Routing Protocol for Integrated Satellite and UAV Networks: The authors in [7] mitigated the above issues by exploiting the concept of a temporal-spatial graph and proposed a unified routing protocol for integrated satellite and UAV networks. The temporal-spatial graph of a communication network reflects a time-evolving network topology. It consists of a sequence of network snapshots.

Fig. 4 shows a framework of the unified routing protocol for integrated satellite and UAV networks. In Fig. 4, the orbits of satellites are determined, and the spatial locations of satellites can be accurately achieved. Therefore, a completely deterministic temporal-spatial subgraph can be constructed for satellite networks. Under UAV networks, each UAV may have its non-deterministic flight plan owing to the random deviation caused by unanticipated obstacles or severe weather conditions. This means that future trajectories and spatial locations of UAVs cannot be accurately obtained. Therefore, a contact prediction model (e.g., discrete time homogeneous semi-Markov model) is used to predict the contact probability and contact time between two UAVs. According to these contact prediction results, a semi-deterministic temporal-spatial subgraph for UAV networks is generated. In this subgraph, each UAV has sufficient topology information to identify an appropriate packet transmission route such that the packet delivery ratio is increased and the end-to-end transmission latency is decreased. Further, by combining these two temporal-spatial subgraphs, a hybrid temporal-spatial graph of integrated satellite and UAV networks can be achieved. Owing to SWAP limitations, the information exchange between UAV networks and satellite networks in this hybrid graph can be realized through multiple UAV gateway nodes. Meanwhile, the graph edge can be characterized by both contact time and contact probability between a node pair. By removing the temporal dimension from graph edges, the hybrid temporal-spatial graph is further transformed into a state-spatial graph. Under such a graph, a unified routing protocol is developed by introducing the DTN mechanism [7].

V. Future Directions and Challenges

To provide more insights on the design of ACNs, this paper next points out future directions and challenges:

- *Movement control:* UAV path planning problem is subject to various constraints such as energy consumption, collision avoidance, trajectory cost, communication cost, flightable cost, and mission cost. When used to solve the UAV path planning problem, mathematical optimization theory may have the combination blast problem because of the dramatic growth of variable dimensions. Future research may resort to nature-inspired intelligent optimization algorithms since they can avoid the combination blast problem. The design of nature-inspired swarm intelligence models for the cooperative mission execution (e.g., targets monitoring and tracking) of multiple UAVs may also be an interesting research topic. Additionally, the movement control of UAVs based on emerging machine/deep learning techniques may become a major research topic shortly. The machine-learning based movement control approach of the Google LOON Project may be an excellent explanation.
- *Networking:* The 5G and beyond-5G systems require high agility and resilience and the ability to offer ubiquitous coverage. Because of the capability of flexible deployment and rapid service recovery, UAVs have been considered an important complement to 5G and beyond-5G infrastructures. There is, however, a gap between the utilization of UAVs and the ubiquitous coverage, and most existing works focus on the performance analysis of UAV networks. To bridge this gap, the proactive deployment of UAVs wherein the traffic pattern (e.g., traffic volatility and users' mobility) prediction plays a crucial role should be exploited. Software-defined networking (SDN) and network function virtualization (NFV) have been extensively researched in terrestrial cellular networks to improve the utilization efficiency of network resources [111]. The exploitation of them in UAV networks, however, is still in its infancy and remains a topic for future research. In case of UAV failures and the subsequent application interruption, the NFV technique may be investigated to recover the application. Through programming the hardware, NFV allows for using general UAVs instead of specific UAVs to perform particular network functions such as network gateways. By sharing available network resources, network costs can also be reduced, and the utilization efficiency of resources may be improved. On the other hand, owing to frequent changes of the network configuration, UAV networks should be self-healing/self-organized to be more fault tolerant [6]. SDN may be utilized to control and update the network configuration flexibly (e.g., add/remove paths, update protocols) in software [49]. This flexible control method enhances the ability of the network fault tolerance.
- *Transmission:* The application of the mmWave communication technique in UAV communication networks has a bright prospect. Many challenges, however, need to be addressed for UAV mmWave communication networks including [4]: 1) because of the UAV mobility, more efficient beamforming training and tracking mechanisms are required for the Tx/Rx antenna beam alignment. The compensation for Doppler frequency offsets at the Rx terminal also requires the extra consideration; 2) high directional UAV mmWave communication offers the opportunity for multiple users to access in the spatial domain simultaneously. In such a high directional communication network, UAVs in different directions may be well separated by different spatial beams. How to cluster mobile UAVs so that inter-cluster UAVs may simultaneously access without interfering with each other requires more researched. Except for mmWave communication techniques, as an emerging technique, non-orthogonal multiple access (NOMA) can also be exploited to improve the spectrum efficiency of communication networks significantly [112]. Since NOMA uses the power domain for the multiple access while mmWave provides the multiple access in the spatial domain, the investigation of the coexistence between NOMA and mmWave in UAV communication networks to improve the network capacity further may be a hot research topic. Similarly, the UAV pairing/clustering in mmWave NOMA communication networks is a key issue needed to be addressed effectively. 3) Some topics remain to be researched to maximize the benefit from coordinated beamforming in UAV networks: a) the design of dynamic and scalable UAV clustering methods. By minimizing the out-of-cluster interference, clustering methods can be combined with coordinated beamforming schemes to improve the network performance further [113]; b) the investigation of techniques for the low-overhead information exchange among cooperative UAVs [114]; c) the investigation of the combination of cooperative schemes with advanced communication technologies (e.g., NOMA and massive MIMO) in UAV networks [64].
- *Integrated network design:* Satellites, HAPs, LAPs, and terrestrial infrastructures have advantages and disadvantages concerning such aspects as cost, persistence, responsiveness, vulnerability, footprint, and overflight. Therefore, the design of integrated networks consisting of many of these infrastructures to achieve rapid mission-response and provide accurate, reliable, and continuous service coverage may be a hot research topic. For such an integrated network, future research topics may include: 1) how to design efficient and fault-tolerant dynamic networking mechanisms for multi-layer and heterogeneous networks (e.g., efficiently control the seamless integration/disintegration of various airborne platforms); 2) how to implement the on-demand maintenance of the service coverage provided by the networks; 3) how to design reliable transmission protocols for networks of high dynamic and weak connection characteristics; 4) how to implement the seamless information exchange and data transmission among heterogeneous networks; 5) how to design network operation control mechanisms under both multi-association and strong constraint conditions. The multi-association constraint indicates that platforms

are associated with service capabilities, flight paths, and operation strategies. The strong constraint represents that control strategies are subject to strong safety constraints such as meteorology, trajectory conflicts, and terrains.

- *Practical considerations:* Some practical considerations, such as expense and platform safety, should be taken into account when designing and deploying ACNs. Maintaining and keeping airborne platforms aloft may be expensive. Owing to potential physical and electronic attacks, the protection of airborne platforms for safety purpose should be considered. Meanwhile, ACNs need to adapt to the change of complex environment (e.g., battlefield environment) to provide reliable and effective area coverage services (e.g., monitoring and surveillance) or communication coverage services (e.g., airborne relays/base stations). Furthermore, ACNs should not be designed as isolated networks, and the integration of ACNs with existing infrastructures may be desired to achieve information sharing.
- *Knowledge-centric-networking (KCN) [115] based airborne communication networks:* The design of the KCN-based airborne communication networks may also be an interesting and promising research topic. KCN leverages machine/deep learning techniques to derive an in-network solution, which creates a little valuable knowledge from a large amount of raw data and then directly transmits and shares situation to satisfy requests of end users. Under the ACNs, this abstract knowledge is concretized into physically meaningful situations such as the movement of airborne platforms and traffic pattern. Therefore, the KCN can also be referred to as the situation-centric-networking (SCN) in ACNs. The SCN may create situations for the efficient design of ACNs and enhance the intelligence and interactivity of ACNs. For example, SCN may announce the risk-situation alert (e.g., potential collision-risks of airborne platforms) for the safe movement control of ACNs. It can yield the topology-situation to guide the traffic transmission efficiently such that the end-to-end data transmission is enhanced and the transmission latency is reduced. It may also provide traffic-situation (e.g., traffic distribution, type, and volatility) for the intelligent networking and reconfiguration of ACNs. Future research topics on the SCN-based ACNs include: 1) how to collect big raw data and process onboard for the model training and situation extraction; 2) how to conduct the collaborative situation awareness and situation sharing among airborne platforms; 3) how to implement the mergence/integration of heterogeneous situation information (e.g., the topology integration of heterogeneous networks); 4) how to represent situations for the efficient storage, transmission, and sharing; 5) how to design learning-based network optimization algorithms for the efficient and economical network resource allocation and utilization.

VI. Conclusion

Owing to the capability of providing rapid emergency response and accurate observation services, airborne communication networks (ACNs) have been widely applied in the military, civil, and public fields. Furthermore, ACNs are expected to become an essential component of future wireless communication networks. The specific characteristics such as high dynamic network topologies, high network heterogeneity and weak communication connections of ACNs pose many challenges to the design of ACNs. This paper had surveyed primary mechanisms and protocols for the design of ACNs concerning three key areas, that is, low-altitude-platform-based communication networks, high-altitude-platform-based communication networks, and integrated ACNs. This paper was aimed at offering the reader a perspective on general procedures of designing ACNs rather than providing an exhaustive review of existing mechanisms and protocols.

Moreover, this paper would like to emphasize that these three areas are building blocks for the architecture of ACNs. This architecture fastens together with a broad range of technologies from control, networking, and transmission. A comprehensive understanding of the whole architecture is necessary for exploiting techniques suitable for ACNs. Besides, in-depth knowledge of technologies of control, networking, and transmission helps design scalable, practical, and fault-tolerant ACNs.

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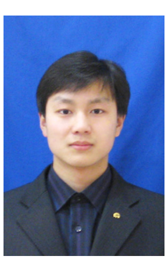

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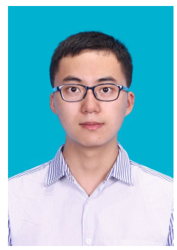

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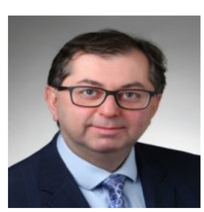

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