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TAKING DRONES TO THE NEXT LEVEL

Cooperative Distributed Unmanned-Aerial-Vehicular Networks for Small and Mini Drones

Unmanned aerial vehicles (UAVs) have been widely used in both military and civilian applications. However, the cooperation of small and mini drones in a network is capable of further improving the performance and the coverage area of UAVs. There are numerous new challenges to be solved before the widespread introduction of multi-UAV-based heterogeneous flying ad hoc networks (FANET), including the formulation of a stable network structure. Meanwhile, an efficient gateway-selection algorithm and management mechanism is required. However, the stability control of the hierarchical UAV network guarantees the efficient collaboration of the drones. In this article, we begin by surveying the FANET structure and its protocol architecture. Then, a variety of distributed gateway-selection algorithms and cloud-based stability-control mechanisms are addressed, complemented by a range of open challenges.

Introduction

UAVs are equipped with radio-communication devices and rely on unmanned autonomous flight-control programs, which have been actively developed around the world. Given their low cost, flexible maneuvering capability, and unmanned operation, UAVs have been widely used in both civilian operations and military missions, including aerial mapping, disaster rescue, agricultural irrigation, and military surveillance and attack [1].

Based on their cruise duration and action radius, UAVs can be categorized into the following four types.

- The high-altitude and long-endurance UAVs are applied in high-altitude reconnaissance, interception, and attack, as exemplified by the American Global Hawks and Predator UAVs and by the Israeli Commando UAVs.
- The medium-range UAVs, having an action radius between 700 and 1,000 km, are primarily designed for moderate-range reconnaissance and combat-effect assessment. The American Air Force D-21 UAVs and 350 UAVs are both typical medium-range representatives.

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EVEN IF SOME UAV NODES ARE UNDER ATTACK, OTHERS CAN RECONSTRUCT THE NETWORK AND AUTOMATICALLY CHOOSE THE OPTIMAL ROUTE TO ACCOMPLISH THEIR MISSIONS.

- The low-cost, short-range small UAVs have an action radius of fewer than 350 km and a takeoff weight of less than 50 kg, such as the British Phoenix, French Marthe, and Israeli Scout UAVs; their flight altitude is fewer than 3 km, and flight span is about four hours.
- The mini drones have a more limited cruising speed, ranging from 10 to 30 km/h and a cruising duration of no fewer than 30 min. The weight of mini drones is usually lower than 1 km. However, in the rest of this article, we focus our attention on both the lower-cost and lower-velocity small or mini drones.

Although UAVs have indeed matured, the proliferation of small- or mini-drone application scenarios and the sophistication of their functionality can only be exploited with the aid of multi-UAV cooperation, networking, communication, and coordinated control. Furthermore, ad hoc networking, task assignment, and dynamic negotiation among cooperating drones are also beneficial in terms of extending the UAV functionalities and their coverage and increasing their efficiency. Relying on the association of UAVs voluntarily joining to meet their common goals through a jointly owned and democratically controlled unit, the concept of the cooperative multi-UAV system is proposed, which contains the sensor unit, the communication unit, and the information processing unit.

However, the challenge is that the movement of UAVs leads to time-variant network topologies and to frequent link outages. Additionally, the agile flight states (i.e., the yaw, pitch, or roll angles) impose grave performance erosion and are a substantial waste of communication resources and energy. These practical issues motivated us to conceive this article on the cooperation and collaboration of multi-UAV networks. This article begins with a detailed survey of the multi-UAV networking technologies and the protocol architecture. Moreover, we investigate two critical issues of the cooperative distributed UAV networks, namely, distributed gateway-selection algorithms and the stability-control regimes. Specifically, acting as cluster heads, the gateways constitute the bottleneck and limit the network's reliable connectivity and stability. Finally, as our original contributions, an efficient gateway-selection mechanism and a cloud-based stability-control regime for cooperative small- or mini-drone-based UAV networks are introduced, complemented by a range of open challenges.

The Network Architecture of UAVs

Given the recent progress in the field of embedded systems and the achievable scale of integration, it has become economically vital to produce low-cost small and mini drones. However, their low-load capacity and modest cruising capability limit the functionality of a single UAV. A single UAV acting in isolation usually communicates with the ground or with a relay station. Long-distance radio communication imposes a large propagation delay, high packet-loss ratio, and high power consumption. Moreover, if this single communication link is corrupted, the whole communication system becomes paralyzed. Therefore, it is beneficial to collaborate with multiple UAVs to create a network, which has a capacity beyond that of a single drone [2]. In this section, we mainly discuss the UAV networking technologies and relevant regulations.

Regulations of Small and Mini UAVs

The networking architectures and operations of multi-UAV networks should follow the regulation and supervision of different agencies or governments. According to the U.S. Federal Aviation Administration (FAA), the small or mini unmanned aircraft must indeed remain within visual line of sight (VLOS) of the remote pilot in command or visual observers. Moreover, small or mini drones are only allowed daylight operations and must yield the right of way to other aircrafts. The person manipulating the flight should hold a remote pilot certificate, and the maximum weight, altitude, and speed are strictly regulated by a range of government rules.

China's Civil Aviation Administration (CAA) stipulates certain illegal airspace for small and mini UAVs, such as civil airports, military bases, and crowded areas. In contrast to the VLOS-only flight authorized by the FAA, CAA allows beyond-VLOS flight of small or mini drones. However, these drones must be controlled by a remote pilot who can stop the flight in case of an emergency. Moreover, the CAA regulates the use of the UAV-cloud system. Meanwhile, the Japanese and European authorities have issued a series of regulations for small and mini UAVs.

UAV Networks: Airborne Ad Hoc Networks

In contrast to classic mobile ad hoc networks (MANETs) and vehicular ad hoc networks (VANETs), the mobility and nimble-flight attitude of UAV systems have a serious influence on their networking technologies. In [3], Zhou et al. proposed a two-layer aerial-ground cooperative networking architecture where multiple UAVs forming an aerial subnetwork assist the terrestrial vehicular subnetwork through UAV-to-UAV and UAV-to-ground communications. The UAVs act as intermediate relays due to their flexible mobility, such as when cell splitting occurs in the terrestrial vehicular subnetwork. The multi-UAV system was first proposed in [4] based on the concept of the FANET, where the network-centric methodology provided the UAVs with the ability to autonomously position themselves for ideal connectivity and cooperate with other UAVs for the sake of achieving the best coverage. Figure 1 illustrates a multi-UAV system that relies on ground stations, ground or airborne relay stations, and remote network monitoring stations as backhauls.

The major advantages of the multi-UAV network over the single-UAV network can be summarized in terms of the networking perspective and the system perspective [6], [7]. The networking perspective shows the following results:

- *Improves the attainable transmission efficiency*: The UAVs' information transmission capacity, processing rates, and response capability are improved. Multi-UAV systems extend the range of airborne surveillance. Meanwhile, when the relay link encounters interruptions, to ensure seamless unobstructed communication, the packets to be relayed are forwarded to other UAVs under the control of the ground station. Additionally, due to the coordination and collaboration among multiple drones, the multi-UAV network exhibits an improved information-preprocessing capability and transmission efficiency.
- *Increases survivability*: The multi-UAV network has high reliability and can be constructed anytime and anywhere. Even if some UAV nodes are under attack, others can reconstruct the network and automatically choose the optimal route to accomplish their missions. In other words, the ad hoc feature, distributed structure, and node redundancy improve the system's survivability.
- *Allows for self-organization and adaptivity*: Multi-UAV networks relying on mesh networks are capable of self-reorganization. This means that the multi-UAV network is resilient to node failure; hence, it is suitable for diverse circumstances.

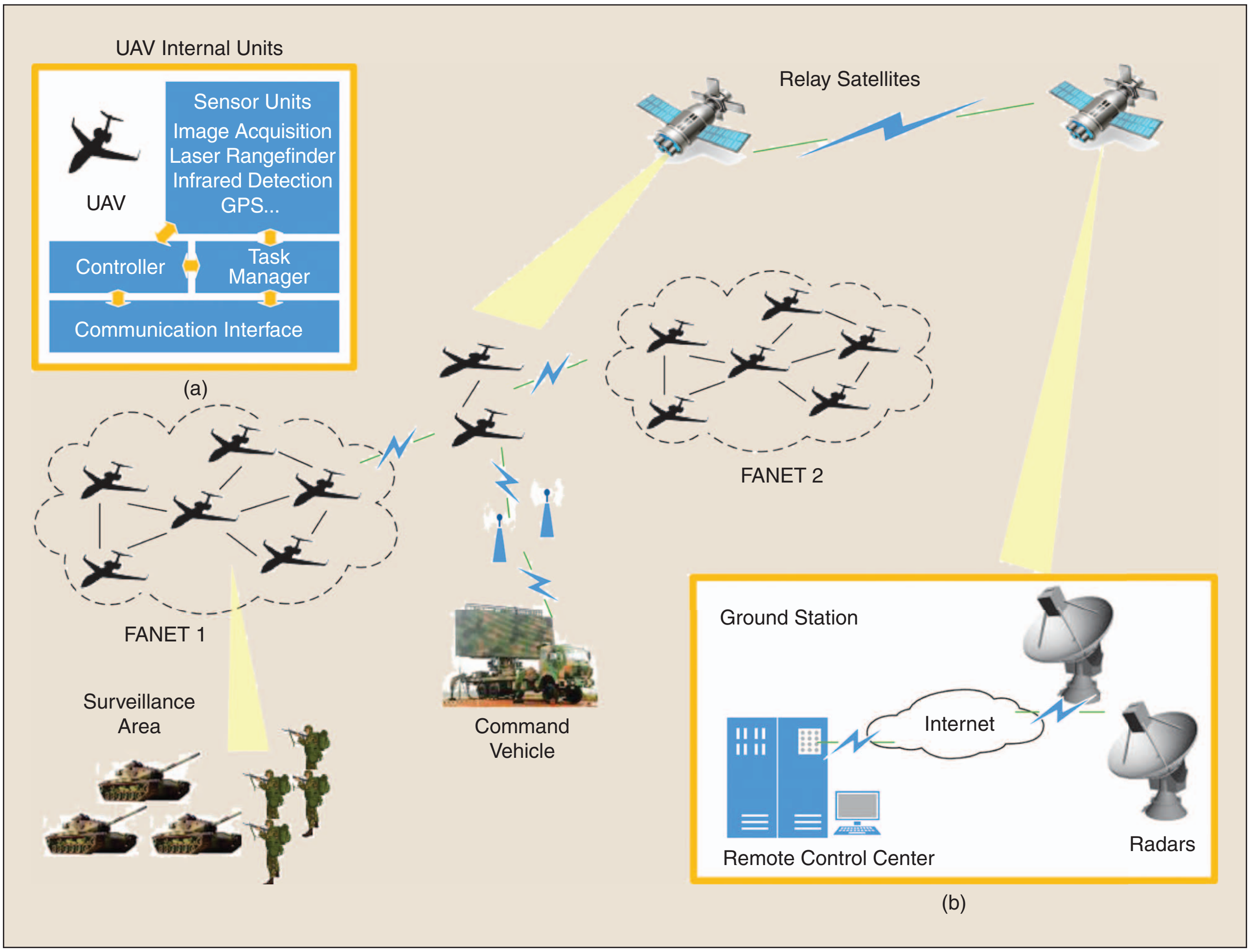

FIGURE 1 The multi-UAV network architecture and necessary UAV internal units. Specifically, both the small and mini drones should be equipped with (a) sensor units and control and management units, as well as with communication units to fulfill the tasks shown in (b). Except for some essential sensors, such as the gyroscope, global positioning system, and radar, the drones carry specific sensors depending on their particular missions. Moreover, the control and management units are responsible for the stable operation and the collaboration of each part. The communication units are composed of multiple modules configured by various protocols, such as IEEE Standards 802.11 and 802.15, [18], [19] and long-term evolution, to support different communication scenarios [5]. GPS: global positioning system.

In contrast, the system-oriented perspective shows the following results:

- *Provides high energy efficiency*: The UAVs are more compact and less expensive in small and mini multi-UAV networks, which leads to low energy consumption. Moreover, by operating in a coordinated manner, the system's power consumption can be reduced to a minimum by relying on sleep mode and on sophisticated power-allocation schemes.
- *Allows convenient scalability*: Considering the various mission requirements, the multi-UAV system is capable of changing the network architecture or adding more UAV nodes to achieve the required system capacity.
- *Enriches the applications*: The associated diversity-aided functions broaden the application-scope of the multi-UAV network. As a benefit of the UAV-to-ground station and UAV-to-UAV communication, the multi-UAV system improves the attainable load capacity and cruising capability. Moreover, the use of different sensors and diverse data-delivery strategies results in compelling value-added functions.

Although the multi-UAV network has some significant advantages over the single-UAV mechanism, the multi-UAV network has numerous challenges [8], such as intermittent links and power and bandwidth constraints. On the one hand, due to their highly dynamic topology and nimble-flight attitude, the method of designing beneficial multihop-routing schemes for UAV-to-UAV communication becomes an important issue. On the other hand, in the UAV-to-ground station communication associated with a relatively long distance, only delay-tolerant services can be supported. Secure transmission and protocol compatibility should also be carefully considered. As a result, powerful spread spectrum and smart antenna-aided soft handoff methods relying on an expert system can be used in multi-UAV networks.

Protocol Architectures for UAV Networks

Essentially, FANETs may be viewed as UAV-centric local area networks, where the communication protocols play an important role in guaranteeing seamless transmission. In this section, the FANET protocols and relevant open research issues are discussed. Given the plethora of beneficial applications of FANETs, such as information acquisition and data relaying, they can be viewed as a four-layer network relying on the physical player, datalink layer [or medium access control (MAC) layer], network layer, and transport layer, as listed in Table 1. There are two basic protocol architectures for ad hoc networks. One is based on the traditional TCP/IP, which is either the modification or extension of TCP/IP, while the other is based on the DTN paradigm. The DTN architecture was specifically designed for handling the long-delay links. Thanks to its long-term information storage and forwarding functions, the DTN protocol was first conceived for interplanetary networking but has also been invoked for satellite networks, MANETs, and FANETs. Some of the pertinent communication protocols are listed in Table 1 along with their brief description, and these protocols are readily applicable to FANETs from the multi-UAV system perspective.

TABLE 1 *An overview of protocol architectures for FANETs.*

Layer	Protocol Related Study	Brief Descriptions
Physical layer	■ General link-outage model for FANET, I. Abualhaol, 2011 ■ FANET antenna structures and types, J. Choi, 2010	■ Rayleigh, Nakagami, and Weibull fading models were considered to study the outage of UAV-to-UAV and UAV-to-station channels. ■ Studied advantages of directional antennas over omnidirectional antennas and enhanced the network's latency.
Datalink layer	■ A token-based FANET MAC protocol, Y. Cai, 2012 ■ Adaptive MAC scheme for UAVs, A. Alshbatat, 2010	■ Using the full-duplex and multipacket reception radios, it regularly updated the channel state information to eliminate packet collision. ■ Sending control and data packages via different antennas substantially improved the throughput, delay, and bit error ratio.
Network layer	■ Greedy perimeter stateless routing, B. Karp, 2000 ■ Time-slotted on-demand routing, J. Forsmann, 2007 ■ Directional-optimal-link-state routing, A. Alshbatat, 2010 ■ Geography-position-mobility-oriented routing, L. Lin, 2012	■ A position-based routing, the greedy geographic forwarding-based routing can be used for densely deployed FANETs. ■ Used dedicated time slots to send data packets, saved bandwidths, mitigated packet collisions, and increased the transmission rate. ■ A proactive routing protocol minimized latency and reduced the multipoint relay nodes at a low overheads. ■ Predicted the movement of UAVs relying on a Gaussian–Markov mobility model; provided effective data forwarding.
Transport layer	■ SCPS-transport protocol CCSDS 714.0-B-2 ■ Licklider transmission protocol, S. Burleigh, 2008	■ Extension and modification of the TCP/IP for the high bit-error rate, long delay, and asymmetrical space environment. ■ Based on the DTN architecture, a good performance in the highly dynamic, long delay, and intermittent interruption environment.

TCP/IP: transmission control protocol/Internet protocol; DTN: delay and disruption tolerant networking. SCPS: space communications protocol standards; CCSDS: the Consultative Committee for Space Data Systems.

Distributed Gateway Selection for UAV Networks

As mentioned in the "The Network Architecture of UAVs" section, connecting small and mini UAVs via a communication network to construct multi-UAV networks improves their capability of carrying out complex tasks. According to the existing applications of multi-UAV network systems, there are four main communication requirements:

- sending back the sensed data
- receiving the control commands
- cooperating for the sake of trajectory planning
- carrying out dynamic task assignments.

A large number of inter-FANET communication and long-distance air-ground communication sessions are generated in the line of duty. However, when designing and performing the communication mechanism of UAV systems, the constraints of the drones need to be considered:

- *Speed constraint*: In highly mobile environments, the topology of FANETs changes more frequently than that of MANETs or VANETs, which results in a rapid variation of the node distances and link qualities. Moreover, dynamic link fluctuations may arise at any time.
- *Energy constraint*: The main power source of UAVs is their solar panel and built-in battery. Due to their small battery sizes, the energy capacity is quite limited, especially during observation missions, which consume a large amount of energy during storing and forwarding.
- *Storage constraint*: The storage capacity of UAVs is also limited. UAVs have to store the acquired data before sending them to the ground or to other relay stations. Therefore, this constraint limits the amount of data, which may be mitigated by a higher forwarding efficiency.
- *Angle constraint*: In consideration of the power constraint mentioned previously, directional antennas have advantages over omni-directional antennas. However, the nimble-flight attitudes of UAVs impose challenges on the antenna alignment.

Hence, if every drone is allowed to establish long-distance UAV-to-ground station communication, it leads to both low energy efficiency and high interference. Therefore, the number of remote connections should be meticulously controlled to mitigate interference and conserve resources. As a remedy, some superior drones should act as gateways so that other drones in the network can communicate with the command center through them, rather than establishing long-distance connections. Moreover, both the locations and movements of specific UAVs may be optimized to improve their connectivity and communications with ground-based wireless ad hoc networks [9], [10].

Gateway-Selection Algorithms Based on MANETs

As discussed in the "Distributed Gateway Selection for UAV Networks" section, the careful choice of the FANET gateways constitutes an important issue in heterogeneous network designs, which contributes to the construction of an integrated ground-air-space network. The study of FANET gateways has been mainly concentrated on the aspects of gateway selection, gateway advertisement messages, and optimal gateway registration. However, the existing contributions regarding FANET gateway selection are essentially based on those of MANETs.

SOME SUPERIOR DRONES SHOULD ACT AS GATEWAYS SO THAT OTHER DRONES IN THE NETWORK CAN COMMUNICATE WITH THE COMMAND CENTER THROUGH THEM.

Category I: Cluster-Head Selection Methods

In [11], Leng et al. presented a k-hop compound-metric-based clustering (KCMBC) scheme, which used the relative node velocity and distance for selecting cluster heads as gateways. As an extension of the classic lowest-identification algorithm and highest-connectivity algorithm, the KCMBC scheme is capable of dynamically adjusting the period of announcing the relevant location information and reducing the redundant transmission overheads. Furthermore, a distance-based converge-cast technique was employed for collecting memberships in a cluster, and the KCMBC scheme was capable of supporting all members in the vicinity of the coverage border. As a further development, Su and Zhang [12] proposed a cluster selection approach relying on a contention-free MAC scheme designed for VANETs. In their work, the elected cluster-head nodes acted as the coordinator to collect or deliver real-time safety messages within their cluster and forward the consolidated safety messages to the neighboring cluster heads. Both cluster-head selection algorithms improve the attainable network performance in terms of scalability and stability and make the network more efficient for data transmission in MANETs or VANETs. In this article, the cluster heads can be viewed as the gateways of the FANETs. However, FANETs are substantially different from MANETs and VANETs in terms of their velocity and energy capacity. If the mobile nodes frequently change their mobility patterns and more asymmetrical uplink/downlink (UL/DL) information is transmitted in the network, the performance of the gateway-selection schemes might be severely degraded. A range of gateway-selection algorithms based on clustering, along with their pros and cons, is listed in Table 2.

Category II: Network-Parameter Optimization Methods

A meritorious gateway-selection approach has a positive influence on the network's operation. Papadaki and Friderikos [13] deal with a range of gateway-selection issues

The proposed dynamic gateway clustering can dramatically enhance the average gateway-retention probability of each gateway.

by invoking network-parameter optimization in a multihop-mesh network, and they conceived a mathematical programing formulation for gateway selection. Moreover, their article proved that the shortest-path-based-cost matrix constitutes the optimal solution. In [14], Aoun et al. concentrated on network throughput maximization by utilizing different interference models. Furthermore, the maximal relaying load imposed on the nodes was also minimized. Additionally, they proposed a polynomial-time near-optimal algorithm, which recursively found minimum weighted dominating sets, aiming for appointing the minimum number of gateways and satisfying the quality of service requirements. Similarly, based on the highly mobile environment and limited storage capacity of the FANET, these optimal solutions might not be globally optimal. Furthermore, the associated mathematical search procedure was time consuming. Table 2 lists the pros and cons of some gateway-selection algorithms based on parameter optimization.

Distributed Gateway-Selection Algorithms for Small- and Mini-Drone Networks

In this section, we focus our attention on two distributed gateway-selection algorithms conceived for both small and mini multi-UAV networks. The cruising speed of small UAVs spans from 50 to 120 km/h, which is far faster than the traditional MANET nodes. Meanwhile, the 350-km cruising radius calls for long-distance microwave transmission, which is definitely a challenge, especially in battlefields or disaster scenes. Hence, the limited communication resources and the rapidly changing network topology become the dominant constraints imposed on gateway selection. Furthermore, as an air-ground communication bridge, gateways have numerous connections and a high traffic load. Hence, the stability of gateways directly affects the reliability of the entire multi-UAV network. Therefore, the gateway-selection scheme must carefully appoint the gateway drones based on the multi-UAV network topology of small UAVs. The mini multi-UAV systems impose different requirements and constraints on gateway selection than those of the small multi-UAV network, because the weight of mini drones is usually lighter than 1 km, which limits the volume of their power supply and memory. Owing to their small battery capacity and low-load-carrying capability, the mini UAVs are limited to a cruising speed ranging from 10 to 30 km/h to guarantee a cruising duration of no less than 30 min. Briefly, given the above features, the mini multi-UAV network topology is relatively stable in comparison to the small multi-UAV network topology, but optimizing their energy consumption and extending the system's battery-recharge period remain important concerns in the gateway selection.

According to the key issues mentioned above, we conceived a range of gateway-selection algorithms for small

TABLE 2 ***The gateway-selection algorithms based on MANETS.***

Category	Selection Algorithms	Pros	Cons
I	CGSR, C. Chiang, 1997	■ clusters unchanged, communication overheads reduced	■ heavy load is imposed on cluster heads, not scalable
I	CBKC, G. Chen, 2002	■ large cluster size, improved scalability	■ low performance in heterogeneous and dynamic networks
I	Max-min heuristic algorithm, Amis A, 2000	■ improved scalability, fast convergence rate	■ node mobility is ignored, data packets are easy to lose
I	DDVC, E. Sakhaee, 2007	■ for pseudolinear MANET, high stability	■ not applicable for frequent change of direction and motion
I	KCMBC, S. Leng, 2009	■ high scalability and stability, low overheads	■ poor performance for random movement and UL/DL asymmetry
II	Internet transit access points, R. Chandra, 2004	■ minimizes the number of gateways, offers bandwidth guarantee	■ lacks constraints of other parameters, only a linear program
II	Heavy and light algorithm, Y. Bejerano, 2004	■ minimizes the maximal relay load and the number of gateways	■ a brute-force optimizer, power constraints
II	Gateway placement for throughput optimization, F. Li, 2008	■ maximizes the throughput, fine-grained interference model	■ fixed number of gateways, poor extensibility
II	Dynamic MANET on demand, T. Matsuda, 2010	■ gateway selection based on the type of data, routing optimization	■ poor performance in high-mobility network

CGSR: cluster-leader gateway-switch routing; CBKC: connectivity-based k-hop clustering; DDVC: dubbed-Doppler-value clustering.

and mini multi-UAV networks. Specifically, we analyzed the features of both the small and the mini multi-UAV networks and proposed a distributed gateway-selection algorithm based on dynamic partition adjustment and on a segmented equalization gateway-selection algorithm, with special attention to their energy consumption. Figure 2(a) portrays the design flow of the two different algorithms. Considering the small multi-UAV networks, the UL/DL asymmetry of the information flow of the different drones was analyzed in a decentralized small multi-UAV network, and a beneficial network partitioning method was conceived for ameliorating the influence of the asymmetric UL/DL load on the dynamic topology control. Moreover, based on this network partitioning model, a formal definition of stability was proposed with a focus on its effect on the network boundary stability. Finally, an optimization technique was conceived for equalizing the stability of different subareas.

Additionally, we proposed an adaptive gateway-selection algorithm based on dynamic-network partitioning for counteracting the time-variant evolution of the network topology. Our simulation results illustrated in Figure 2(b) show the average gateway-retention duration, which is directly determined by the link outages and energy outages in the small multi-UAV network. The simulations were conducted by generating 100 small UAV nodes randomly located within a circular region of 5,000-m radius while using the random flight-mobility model. The performance comparisons were conducted between our scheme and the existing gateway-selection algorithms of dubbed-Doppler-value clustering, connectivity-based k-hop clustering, and cluster-leader gateway-switch routing. The results indicated that the proposed dynamic gateway clustering can dramatically enhance the average gateway-retention probability of each gateway and that extremely agile reclustering and routing algorithms were required to manage the relatively short gateway-retention durations.

Cloud-Based Stability Control for Hierarchical UAV Networks

Numerous formal definitions of stability have been used in the literature, but in this article, we rely on the average gateway-retention duration as a quantitative measure of the network stability. Given their complex operating environment, the control of multi-UAV networks relies on internal functions and on the instructions received from the command center. Hence, the cooperation of small and mini UAVs having a low-load capacity and low-storage capability is intricately linked to the control center.

The small or mini multi-UAV network considered can be regarded as a networked control system supporting a range of sensors, actuators, and controllers that are interconnected by digital communication networks. The system's delay directly affects the stability of multi-UAV systems. Specifically, a large amount of data is collected by the sensors, such as video cameras. Given the rapid improvement of the video resolution, there is a danger of link congestion. Accordingly, the transmission latency increases and the system may become congested.

To avoid the potential congestion of critical nodes carrying a high throughput and having a limited processing capability in the network, cloud computing is proposed as a remedy. The cloud-computing system is capable of optimizing the resource configuration according to the user demands in the FANET considered. In [15], Misra

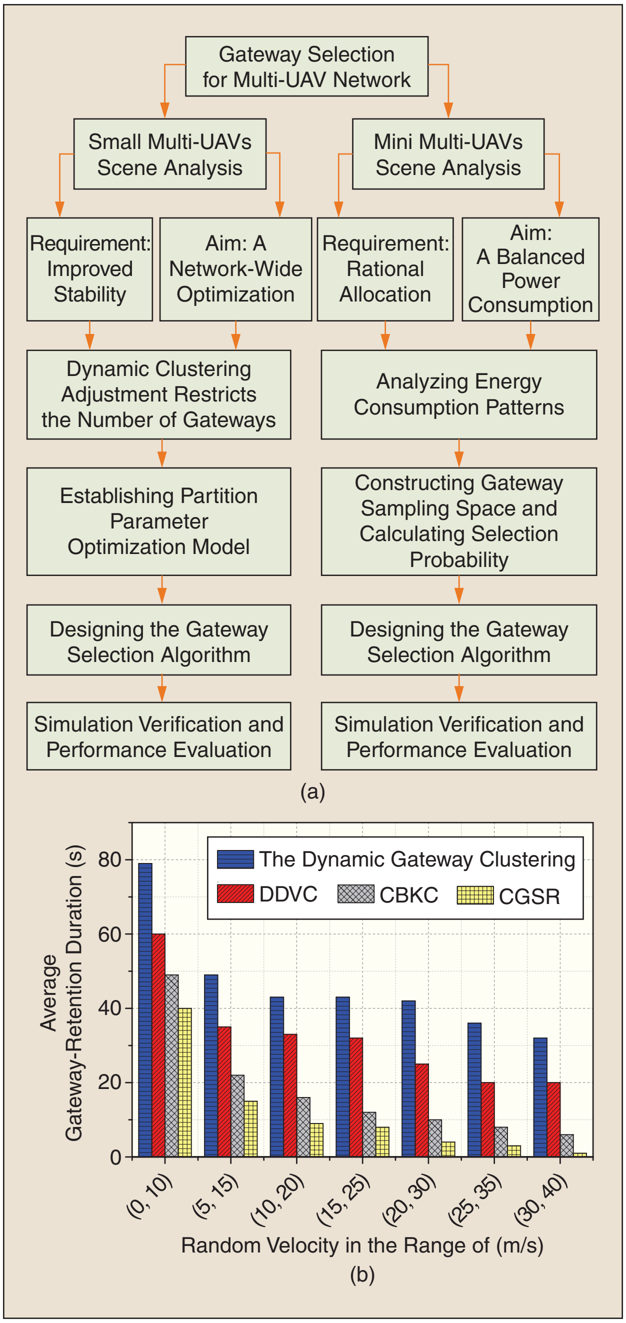

FIGURE 2 (a) The design-flow of gateway-selection algorithms and (b) their preformation for the random flight-mobility model.

CLOUD COMPUTING CAN IMPROVE THE LIMITED COMPUTATIONAL CAPABILITIES OF RESOURCE-CONSTRAINED MOBILE NODES AND ENHANCE THE SYSTEM'S STABILITY.

et al. addressed the problems of geographically nonuniform bandwidth demand by invoking a range of techniques developed for mobile-cloud computing. Specifically, due to the node mobility, bandwidth reallocation was used to satisfy a guaranteed quality of service. Moreover, they formulated the bandwidth redistribution as a utility-maximization problem. However, the cloud-service providers, rather than the mobile nodes, oversee the bandwidth reallocation mentioned earlier, and these functions are performed for only the gateways. Additionally, an energy-efficient and fault-tolerant mode was proposed by Chen et al. [16] to address the reliability and energy efficiency challenges in an integrated manner for data storage and processing based on mobile-cloud computing. They proposed a mathematical model for optimizing the energy consumption and meeting the outage specifications under the dynamic network topology of a mobile cloud. The previous algorithms demonstrated that cloud computing can improve the limited computational capabilities of resource-constrained mobile nodes and enhance the system's stability.

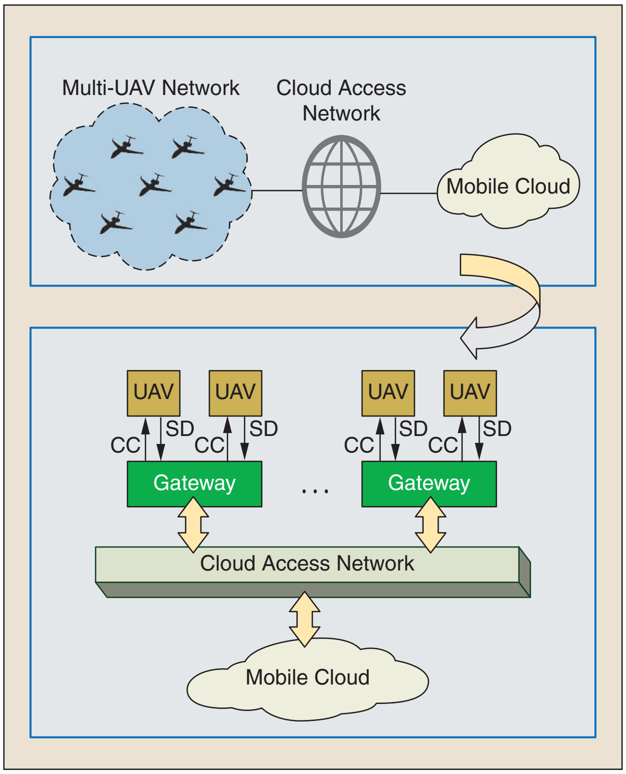

FIGURE 3 The Architecture of a multi-UAV network relying on a cloud-control system. CC: control command; SD: sensor data.

Considering the UAVs' challenging operational environment and inevitable limitations, we proposed the UAV cloud-control system concept shown in Figure 3, which incorporated the computing capability of terrestrial clouds into UAV systems. First, we formulated the model of the link between the gateway UAVs and the rest of the UAVs as a relaying system communicating over time-varying wireless channels. The data relaying mechanism may rely on a slotted system where the slot length was equal to a single packet's transmission duration. The gateway scheduled the allocation of each slot for the drones it supported. Realistic imperfect-relaying service was considered, which had a certain successful-service probability as determined by the bandwidth and the buffer capacity of the gateway. Based on the successful-service probability, the stable region of the data relaying mechanism was derived. To briefly elaborate, the stable region represents the achievable data-acquisition rate; the queueing length of each UAV is always less than some finite threshold.

Second, we modeled the cloud-based multi-UAV system as an open Jackson network. Specifically, we divided the cloud-computing system into four parts. The input server represented the entry server of the cloud, and the data were forwarded to the processing server from the input server. The processing server handled the data and accessed the database server with a probability of δ, which provided access to any secondary memory supporting a specific service by the cloud architecture. Finally, the output server was responsible for transmitting the control commands over the cloud access network back to the gateway. Each of these four servers was modeled as M/M/1 queues, which formed a Jackson network. By analyzing each of the four queueing systems of this Jackson network, we calculated the distribution of the entire system's delay. Furthermore, since the gateway needed to switch its connection among its supported UAVs, a switched-control regime was proposed for modeling the UAV cloud-control system, which was capable of accommodating the different delays of the different UAVs.

Challenges and Open Issues

There are still numerous open challenges in the design of protocol architectures for FANETs. In contrast to the wired networks and MANETs, the FANETs' communications environments are characterized by high bit-error rates, long-packet latency, and frequent outages. Both civilian and military missions require high data rates, high capacity, and reliable microwave or free-space optical-communication technologies. We list promising research directions for future investigations as follows:

- *FANET protocol architecture*: Reliable, delay-tolerant network protocol architectures are required for

FANETs, which impose the minimum extra overhead. Furthermore, cross-layer operation-aided FANET protocols satisfying the associated challenging requirements necessitate further investigations.

- *Generalized gateway selection*: The efficient quantization of the receiver's perceived channel quality is required for beneficial gateway selection. Furthermore, efficient UAV clustering techniques have to be conceived for multitasking situations. Finally, meritorious gateway-selection algorithms have to be designed to satisfy the challenging mobility, energy, and storage constraints.
- *Stability control*: Maintaining system stability is of prime concern in system design. The collaboration and cooperation of multi-UAV networks requires stable system control, including the control principles, tactics, and algorithms. The accurate characterization of the stability domain of FANETs operating in multitasking environments requires future study.
- *Mobility modeling*: The foundation for accurately evaluating and designing FANETs is that of establishing more realistic mobility models for small and mini drones [17]. In comparison to the random flight movement, the mobility pattern of UAVs deployed in different missions should follow some clear rules. Therefore, it is essential to accurately capture the mobility statistics of FANETs.
- *Energy-efficient schemes*: Given the restrictions on the maximum weight of small and mini drones, which limits the volume and weight of their power supply and memory, using less energy to provide the same service in the FANETs becomes a critical issue. It is important to consider energy-efficient networking schemes when multiple small and mini drones cooperate with other UAVs or with terrestrial networks.
- *Privacy and safety*: As the small and mini UAV networks become an increasingly integral part of civil and military missions, questions regarding privacy and safety are on the rise. Naturally, their networking architectures and operations should obey the restriction and regulation of different agencies and should be under the supervision of the local government. Keeping private data safe, such as sensory data on the battlefield and personal information, is of critical concern.

Furthermore, the bandwidth allocation and resource distribution are all equally challenging but promising topics in FANETs. Apart from mobile-cloud computing, the benefits of other advanced networking technologies of the Internet or of MANETs and VANETs should be critically appraised and improved for FANETs in our further research.

Conclusions

The networked operation and communication of multiple UAVs has a vast array of compelling applications in both civilian and military missions. Hence, some of the key technologies of multi-UAV networks were discussed. We highlighted the advantages of constructing a multi-UAV network and a four-layer network structure. Furthermore, the pros and cons of the existing protocol architectures were investigated, followed by an overview of the associated gateway-selection issues. Specifically, we discussed a pair of distributed gateway-selection algorithms designed for small multi-UAV and mini multi-UAV networks, respectively. Finally, we studied the stability of networked multi-UAV systems and mentioned some possible research directions for future investigations. It is certainly a promising era for FANET research.

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