TAKING DRONES TO THE NEXT LEVEL: Cooperative Distributed Unmanned-Aerial-Vehicular Networks for Small and Mini Drones

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***Abstract*—Unmanned Aerial Vehicles (UAV) have been widely used both in military and in civilian applications. However, the cooperation of small and mini drones in a network is capable of further improving both the performance and the coverage area of UAVs. Naturally, there are numerous new challenges to be solved before the wide-spread 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 as well. On the other hand, the stability control of the hierarchical UAV network guarantees the efficient collaboration of the drones. In this article, we commence with 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.**

***Index Terms*—Multi-UAV network system of small and mini drones, FANET network structure, distributed gateway selection algorithms, cloud-based stability control for collaboration and cooperation.**

I. Introduction

Unmanned Aerial Vehicles (UAV) 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, military surveillance and attack, etc [1].

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Based on their cruise duration and action radius, UAVs can be categorized into the following four kinds. The High-Altitude and Long-Endurance (HALE) UAVs are applied in high-altitude reconnaissance, interception or attack, as exemplified by the American Global Hawks and Predator UAVs, as well as by the Israeli Commando UAVs, etc. The medium-range UAVs having an action radius between $700 - 1000$ kilometers are primarily designed for moderate-range reconnaissance and combat effect assessment. The American Air Force D-21 UAVs and 350 UAVs both belong to typical medium-range representatives. Third, the low-cost, short-range small UAVs have an action radius of less than 350 kilometers and a take-off weight of less than 50 kilograms, such as the British Phoenix, French Marthe, Israeli Scout UAVs, etc. Their flight altitude is less than 3 kilometers and flight span is about 4 hours. Finally, in comparison to the small UAVs, the mini drones have a more limited cruising speed ranging from 10 to 30 kilometers per hour and a cruising duration of no less than 30 minutes. The weight of mini drones is usually lower than 1 kilogram. However, in the rest of this treatise, we will 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 full sophistication of their functionality can only be exploited with the aid of multi-UAV cooperation, networking, communication and coordinated control. Furthermore, the *ad hoc* networking, task assignment and dynamic negotiation amongst the cooperating drones is also beneficial in terms of extending the UAV functionalities and their coverage, as well as increasing their efficiency. Relying on the association of UAVs voluntarily joining in order 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 as well as the information processing unit.

However, the challenge is that the movement of UAVs leads to time-variant network topologies and hence to frequent link outages. Additionally, the agile flight states (yaw angle, pitch angle or roll angle) impose grave performance erosion as well as a substantial waste of communications resources and energy. These practical issues give us the motivation to conceive this article on the cooperation and collaboration of multi-UAV networks. This article commenced with a detailed survey of the multi-UAV networking technologies and the protocol architecture. Moreover, we investigated two critical issues of the cooperative distributed UAV networks, namely, distributed gateway selection algorithms as well as the stability control regimes. Specifically, acting as cluster heads, the gateways constitute the bottleneck and limit the network's reliable connectivity as well as 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 were introduced, complemented by a range of open challenges.

The remainder of the article is outlined as follows. The UAV networking technologies and protocol architectures are introduced in Section II. Distributed gateway selection designed for short-range small as well as mini UAVs and the associated critical research issues are discussed in Section III. In Section IV, the stability analysis of hierarchical UAV control systems, including their relay mechanism stability and networked control system stability is investigated, followed a range of open challenges and our conclusions in Section V and VI.

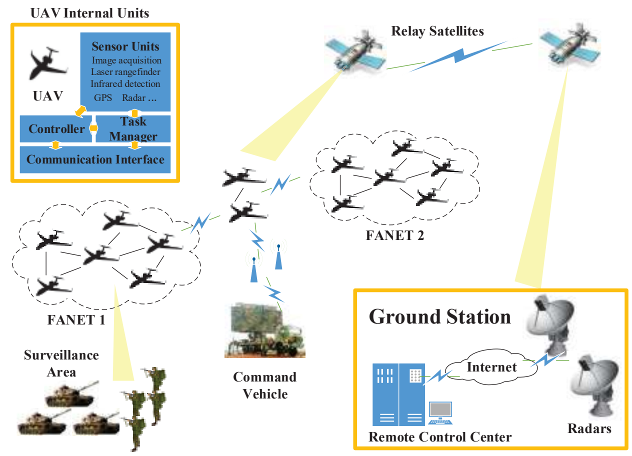


Fig. 1. Multi-UAV network architecture and necessary UAV internal units. Specifically, both the small and mini drones should be equipped with sensor units, control and management units, and communication units in order to fulfil certain tasks. Except for some essential sensors, such as the gyroscope, GPS, radar, etc. 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 802.11, IEEE 802.15, LTE, etc. in order to support different communication scenarios. [5].

II. 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 limits the functionality of a single UAV to a certain degree. 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 also high power consumption. Moreover, if this single communication link is corrupted, the whole communication system will become paralyzed. Therefore, it is beneficial to collaborate with multiple UAVs in order to create a network, which has a capacity way beyond that of a single drone [2]. In this section, we mainly discuss the UAV networking technologies as well as relevant regulations.

A. *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 Federal Aviation Administration (FAA) of America, 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 right of way to other aircrafts. The person manipulating the flight should hold a remote pilot certificate. Moreover, the maximum weight, altitude, speed, etc., are strictly regulated by a range of government rules.

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

B. *UAV Networks: Airborne Ad Hoc Networks*

In contrast to classic Mobile Ad Hoc Networks (MANET) and Vehicular Ad Hoc Networks (VANET), the mobility and nimble flight attitude of UAV systems have a grave 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, when for example cell-splitting occurs in the terrestrial vehicular subnetwork. The multi-UAV system was first proposed in [4] based on the concept of Flying Ad Hoc Network (FANET), where the network-centric methodology provided the UAVs with the ability to autonomously position themselves for ideal connectivity and to be able to cooperate with other UAVs for the sake of achieving the best effective coverage. Figure 1 illustrated a multi-UAV system, relying on ground stations, ground or airborne relay stations and remote network monitoring stations as backhauls.

The major advantages of the multi-UAV network over its single-UAV counterpart can be summarized in terms of the networking viewpoint as well as the system viewpoint [6] [7]. Specifically, from the networking viewpoint:

- **Improves the attainable transmission efficiency:** Their 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 will be 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 a high reliability and it can be constructed anytime and anywhere. Even if some UAV nodes are under attack, others can reconstruct the network and automatically choose the optimal routing to accomplish their missions. In other words, the *ad hoc* feature, distributed structure and node redundancy improve the system's survivability.
- **Self-organization and adaptive:** Multi-UAV networks relying on mesh networks for example, are capable of self-reorganization. This means that the multi-UAV network is resilient to node-failure, hence it is suitable for diverse circumstances.

By contrast, from a system-oriented viewpoint:

- **High energy efficiency:** The UAVs are smaller and less expensive in small and mini multi-UAV networks, which leads to a low energy consumption. Moreover, by operating in a coordinated manner, the system's power consumption can be reduced to the minimum by relying on their sleep mode as well as on sophisticated power allocation schemes.
- **Convenient scalability:** Considering the various mission requirements, the multi-UAV system is capable of changing the network architecture or adding more UAV nodes in order 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 employment of different sensors and diverse data delivery strategies result 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, power and bandwidth constraints, etc. On one hand, due to their highly dynamic topology and nimble flight attitude, how to design a beneficial multi-hop 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 hand-off methods relying on an expert system lend themselves to employment in multi-UAV networks.

C. Protocol Architectures for UAV Networks

Essentially, FANETs may be viewed as UAV-Centric Local Area Networks (UCLAN), where the communication protocols play an important role in guaranteeing seamless transmission. In this subsection, the FANET protocols and relevant open research issues are discussed. Given the plethora of beneficial applications of FANETs, such as information acquisition, data relaying, etc., they can be viewed as a four-layer network relying on the physical player, data link layer (or MAC layer), network layer and transport layer, as listed in Table I. There are two basic protocol architectures for *ad hoc* networks. One is based on the traditional Transmission Control Protocol/Internet Protocol (TCP/IP), which is either the modification or extension of TCP/IP, while the other is based on the Delay and Disruption Tolerant Networking (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 (IPN), but has also been invoked for satellite networks, MANETs and FANETs. Some of the pertinent communication protocols are listed in Table I along with their brief description. These protocols are readily applicable to FANETs from the multi-UAV system viewpoint.

III. Distributed Gateway Selection for UAV Networks

As mentioned before, 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 will be generated in the line of duty. However, when designing and performing the communication mechanism of UAV systems, the constrains of the drones have to be taken into account:

- **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 and light weights, the energy capacity is quite limited, especially during the observation missions, which consume a lot of energy during storing and forwarding.

TABLE I
AN OVERVIEW OF PROTOCOL ARCHITECTURES FOR FANET

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.
Data link Layer	- A Token-based FANET MAC protocol, Y. Cai, 2012 - AMUAV (Adaptive MAC Scheme for UAVs), A. Alshbatat, 2010	- Using the full-duplex and multi-packet 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	- GPSR (Greedy Perimeter Stateless Routing), B. Karp, 2000 - TSODR (Time-Slotted On Demand Routing), J. Forsmann, 2007 - DOLSR (Directional Optimal Link State Routing), A. Alshbatat, 2010 - GPMOR (Geography Position Mobili -ty 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 multi-point 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 - LTP (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 intermitted interruption environment.

- **Storage Constraint:** The storage capacity of UAVs is also limited. UAVs have to store the acquired data before sending it 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 above, directional antennas have advantages over omni-directional antennas. However, the nimble flight attitudes of UAVs impose challenges on the antenna alignment.

Hence, if every single 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 to 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 for improving their connectivity and communications with ground-based wireless *ad hoc* networks [9] [10].

A. Gateway Selection Algorithms Based on MANET

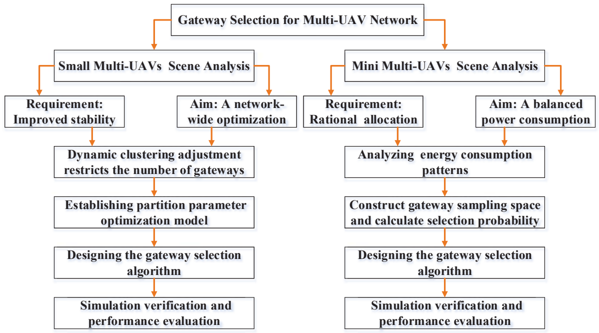
As discussed above, the careful choice of FANET gateways constitutes an important issue in heterogeneous network designs, which contributes to the construction of an integrated ground-air-space network. The study of FANET gateways has been mainly concentrated on the aspects of gateway selection, gateway advertisement messages and optimal gateway registration. However, the existing contributions regarding FANET gateway selection are essentially based on those of MANETs. Let us now consider the family of gateway selection algorithms, including cluster head selection and networks parameter optimization.

Category I : Cluster Head Selection Methods

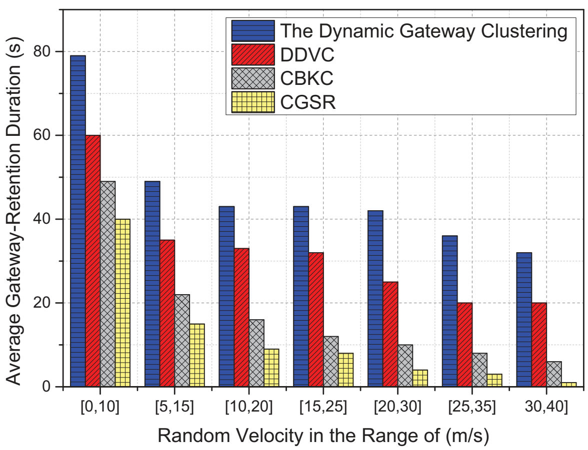
In [11], Leng *et al*. presented a K-hop Compound Metric Based Clustering (KCMBC) scheme, which used the relative node velocity and distance for selecting cluster heads as gateways. As an extension of the classic lowest ID algorithm and highest connectivity algorithm, the KCMBC scheme is capable of dynamically adjusting the period of announcing the relevant location information and reducing the redundant transmission overheads. Furthermore, a distance-based convergecast 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 medium access control 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 in order to forward the consolidated safety messages to the neighboring cluster heads. Both cluster head selection algorithms were capable of improving the attainable network performance in terms of scalability as well as stability and made 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 both 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 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 II.

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 by invoking network parameter optimization in a multi-hop mesh network. They conceived a mathematical programming



(a) The Design-Flow of Gateway Selection Algorithms



(b) Average Gateway-Retention Duration

Fig. 2. The Design-Flow of Gateway Selection Algorithms and Their Preformation for the Random Flight Mobility Model. (DDVC: Dubbed Doppler Value Clustering; CBKC: Connectivity Based K-hop Clustering; CGSR: Cluster-leader Gateway Switch Routing.)

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 for satisfying the Quality of Service (QoS) requirements. Similarly, in light of 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 II lists the pros and cons of some gateway selection algorithms based on parameter optimization.

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

In this subsection, we focus our attention on two distributed gateway selection algorithms conceived for both small and mini multi-UAV networks. At the time of writing, the cruising speed of small UAVs spans from 50 to 120 kilometers per hour, which is far faster than the traditional MANET nodes. Meanwhile, the 350-kilometer 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 has to 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. This is because the weight of mini drones is usually lighter than 1 kilogram, 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 kilometers per hour in order to guarantee a cruising duration of no less than 30 minutes. Briefly, given the above features, the mini multi-UAV network topology is relatively stable in comparison to the small multi-UAV network, but optimizing their energy consumption and extending the system's battery-recharge period remain important concerns in gateway selection.

According to the key issues mentioned above, we have conceived a range of gateway selection algorithms both for small and mini multi-UAV networks. Specifically, we analyzed the features of both the small as well as of mini multi-UAV networks and proposed a distributed gateway selection algorithm, based both 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 for example, the uplink/downlink asymmetry of the information flow of the different drones was analysed in a decentralized small multi-UAV network, and a beneficial network partitioning method was conceived for ameliorating the influence of the asymmetric uplink/downlink 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) shows the average gateway-retention duration, which is directly determined by both 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 5000m radius while utilizing the random flight mobility model. The performance comparisons were conducted between our scheme and the existing gateway selection algorithms of DDVC, CBKC, and CGSR. The results indicated that the proposed dynamic gateway clustering is capable of dramatically

TABLE II
GATEWAY SELECTION ALGORITHMS BASED ON MANETS

Category	Selection Algorithms	Pros and Cons
I	- CGSR (Cluster-leader Gateway Switch Routing), C. Chiang , 1997	- clusters unchanged, communication overheads reduced - heavy load is imposed on cluster heads, not scalable
I	- CBKC (Connectivity Based K-hop Clustering), 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 (Dubbed Doppler Value Clustering), E. Sakhaee, 2007	- for pseudo-linear MANET, high stability - not applicable for frequent change of direction and motion
I	- KCMBC (K-hop Compound Metric Based Clustering), S. Leng, 2009	- high scalability and stability, low overheads - poor performance for random movement and UL/DL asymmetry
II	- ITAP (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	- HLA (Heavy and Light Algorithm), Y. Bejerano, 2004	- minimizes the maximal relay load and the number of gateways - a brute force optimizer, power constraints
II	- GPTO (Gateway Placement for Throughput Optimization), F. Li, 2008	- maximizes the throughput, fine-grained interference model - fixed number of gateways, poor extensibility
II	- DYMO (Dynamic MANET On Demand), T. Matsuda, 2010	- gateway selection based on the type of data, routing optimization - poor performance in high-mobility network

enhancing the average gateway-retention probability of each gateway. Extremely agile reclustering and routing algorithms were required for coping with the relatively short gateway-retention durations.

IV. CLOUD-BASED STABILITY CONTROL FOR HIERARCHICAL UAV NETWORKS

Numerous formal definitions of 'stability' have been used in the literature, but in this treatise 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 both on internal functions as well as 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 (NCS) supporting a range of sensors, actuators and controllers, which 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, etc. 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.

In order 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 *et al*. addressed the problems of geographically non-uniform bandwidth demand by invoking a range of techniques developed for mobile cloud computing. Specifically, due to the node mobility, bandwidth reallocation was used for satisfying a guaranteed quality-of-service. Moreover, they formulated the bandwidth redistribution as a utility maximization problem. However, it should be noted that the cloud service providers, rather than the mobile nodes, are in charge of the bandwidth reallocation mentioned above, and these functions are performed for the gateways only. Additionally, an energy-efficient and fault-tolerant mode was proposed by Chen *et al*. [16] in order to address the reliability and energy efficiency challenges in an integrated manner for both data storage and processing based on mobile cloud computing. They proposed a mathematical model both for optimizing the energy consumption as well as for meeting the outage specifications under the dynamic network topology of a mobile cloud. The above algorithms demonstrated that

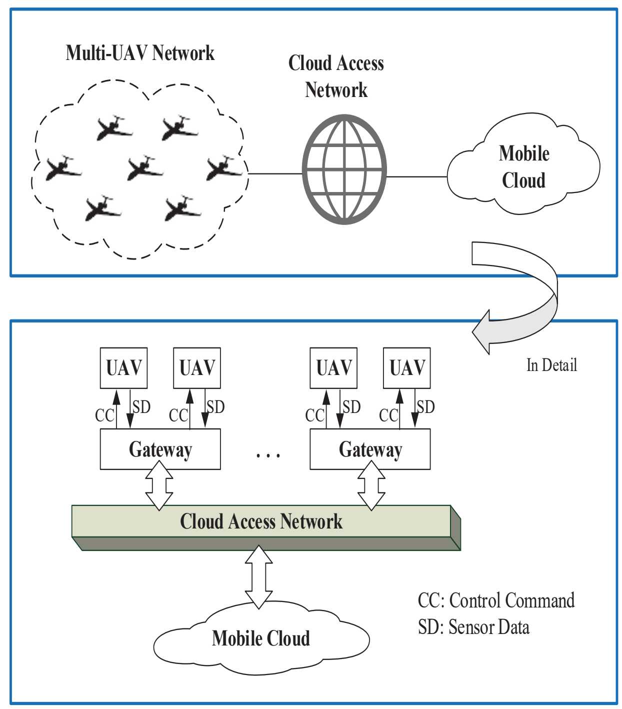


Fig. 3. The Architecture of a Multi-UAV Network Relying on a Cloud Control System.

cloud computing is indeed capable of improving the limited computational capabilities of resource-constrained mobile nodes and hence it enhanced the system's stability.

Bearing in mind the UAVs' challenging operational environment and inevitable limitations, we proposed the UAV cloud control system concept of Figure 3, which incorporated the computing capability of the 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 specific 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 elaborate briefly, the stable region represents the achievable data acquisition rate within which the queueing length of each UAV is always less than some finite threshold. Secondly, 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 then 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 during 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 has 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.

V. 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, reliable microwave or free-space optical communication technologies. Below we list promising research directions for future investigations.

- **FANET Procotol 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 multi-tasking situations. Finally, meritorious gateway selection algorithms have to be designed for satisfying 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 multi-tasking 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 about 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, personal information, etc. is of critical concern.

Furthermore, the bandwidth allocation, resource distribution, etc. 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.

VI. 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 pointed out some possible research directions for future investigations. Indeed, a promising era for FANET research!

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