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Review

A multi-tiered network with aerial and ground coverage

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ABSTRACT

This paper examines a special type of aerial network with multiple unmanned aerial vehicles (UAVs). It focuses on multiple-hop communication and self-organization among UAVs. Each airborne UAV can communicate directly with other UAVs in the air or with ground stations. We provide a vision for a multi-tiered network consisting of airborne UAVs and traditional networks on the ground. We study how communication and self-organization evolve when network disconnections or outages occur in dynamic or hostile environments. Such network disconnections can occur in the air due to the fast movement of UAVs and/or in the ground due to changes in terrain, disasters, or military missions. We discuss five key challenges in the design: scalability and reliability, network formation, network connectivity, information delivery, and energy management. These challenges cover a subset of key issues for this futuristic network structure.

1. Introduction

Unmanned aerial vehicles (UAVs) are popular for both commercial and military applications that include sensing-and-surveillance, searc h-and-rescue, network relay, delivery/transportation of goods, and navigating a military battlefield [1] in hostile environments. The U.S. military market only accounts for a single-digit percentage of the whole IT market in the United States, down from 25 percent in 1975. The civilian market, however, increasingly demands UAVs. General UAVs operated in the air with support from a ground network (consisting of ground stations as well as static and mobile users) are shown in Fig. 1. A UAV can be a small plane with fixed-wing or rotary-wing, a ballon, or a drone. UAVs can communicate among themselves or with ground stations. In general, there are four types of communication in such a *multi-tiered network*: air-to-ground (A2G) (downlinks), ground-to-air (G2A) (uplinks), air-to-air (A2A) (among UAVs), and ground-to-ground (G2G) (ground stations B_1 and B_2 in Fig. 1). The basic multi-tiered network consists of two tiers, one in the air and the other on the ground.

G2A communication is usually the transmission of control signals to UAVs in the infrastructure mode with the ground station acting as the central controller. UAVs can also operate in the ad-hoc (peer-to-peer) mode, where UAVs coordinate among themselves to make consensus decisions and perform data exchanges via A2A communication. In applications like sensing-and-surveillance and search-and-rescue efforts, UAVs capture images and videos on the ground and transmit them to ground stations (such as B_1 in Fig. 1). A2G usually transmits sensing data (such as imaging data) from the air to the ground. G2G communication corresponds to a traditional wired (Internet) or wireless (Wi-Fi, WiMax, and LTE) communication. In a search-and-rescue or military mission, ground stations may be disconnected. In these cases, UAVs act as relays to connect ground stations (B_1 and B_2 in Fig. 1). Delivery/transportation of goods can be viewed as a special case of general information dissemination where physical goods are treated as a special type of information. The only difference is that UAVs need to touch the ground to physically deliver goods.

There have been several surveys of UAVs with different focuses. UAVs with mobile ad hoc networks (MANETs) and vehicular ad hoc networks (VANETs) in different network layers, as well as highlights open research issues at these layers are compared in [2]. Routing protocols and other areas, including SDN, network organizations, and energy are discussed in [3]. Four types of UAVs applications and their special needs in terms of communication and networking are studied in [4]. Several university projects using UAVs for traffic surveillance are listed in [5]. However, whether the existing technologies can meet the communication and networking requirements of all UAVs applications, including the multi-tiered network discussed in this paper, remains unclear.

This paper will look at a high-level model and protocol design. The focus is on multiple UAVs using multiple-hop communication and P2P coordination among UAVs through self-organization. We also examine some challenges in constructing a multi-tiered network with both aerial (UAVs) and ground networks. This multi-tiered network can also be extended to include autonomous underwater vehicles (AUVs) as another tier. The multi-tiered concept can further be applied to UAVs at different altitudes. In Fig. 1, u_3 is at a different tier with a higher altitude, called high altitude and with long endurance (HALE), compared to u_1 and u_2. In terms

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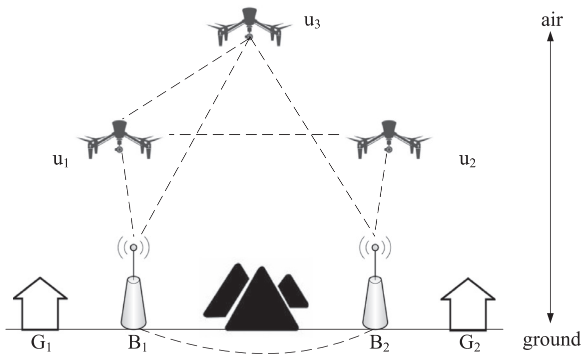

Fig. 1. A multi-tired network with aerial (UAVs) and ground networks.

of network types, the multi-tiered network can be homogeneous, as in a commercial network, or heterogeneous, like in a military network.

The remainder of this paper will address some key challenges in the network modeling and protocol design of the multi-tiered network. The focus will be on the general information dissemination. We will examine the following five aspects and associated challenges: (1) scalability and reliability, (2) network formation, (3) network connectivity, (4) information delivery, and (5) energy management. These aspects are by no means exhaustive, but they address some key issues in the design. We contrast UAVs with MANETs [6,7], VANETs [8,9], and AUVs [10,11] when appropriate to see how they are different from similar networks in relatively mature fields. We assume that UAVs in the multi-tiered network have a clear joint mission instead of working individually. Throughout the discussion, we focus solely on abstract models and designs without going into specific details/terminology of protocols and standards, which have been covered in various surveys. Note that details about protocols and standards are important in the design. For example, while there are communication standards for similar networks, like the dedicated short range communication (DSRC) standard for VANETs, there are no communication standards for UAVs, probably due to their wide and diverse ranges of applications.

2. Scalability and reliability

The current simple UAV model uses one ground controller to control one or more UAVs. This ground controller connects UAVs directly without any A2A communication among UAVs. This approach, though efficient, does not scale well. To minimize the number of deployed UAVs, area coverage (distance among UAVs) must be maximized. The centralized controller does not scale well for a large area or for a large number of UAVs. In Fig. 1, assume that B_1 cannot reach u_2 due to the distance between them. Adding extra ground controllers (B_2 in Fig. 1) may help, but they will add the cost of an extra facility and increase control complexity. A2A will facilitate multi-hop communication (B_1 reaches u_2 via u_1) to support scalability. Using more small UAVs instead one or more large UAVs can also increase scalability in area coverage at the cost of control complexity.

Another way to boost scalability is to reduce A2G and G2A communication. This can be done through clustering among UAVs, as shown in Fig. 2 with clusterheads (CHs): u_1, u_2, and u_3. CHs are usually connected, and each non-clusterhead UAV is directly connected to one or more CHs. Only CHs carry out both A2G (mainly data, including image and video) and G2A (mainly command signals) communication. The selection of CHs depends on the geographical locations of UAVs in a general setting and the capability of UAVs in a heterogeneous setting. CHs are usually connected to form a star or mesh structure, as discussed in [3]. Because UAVs are dynamic, CHs are dynamically changed as well. A more sophisticated structure formation through self-organization is discussed in the network formation section. As UAVs are operated in a 3D space, we assume that UAVs associated with a particular tier operate

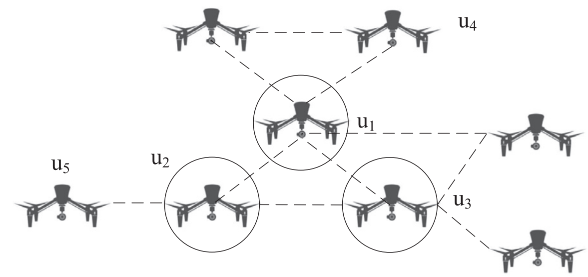

Fig. 2. A clustered formation with multiple clusterheads u_1, u_2, and u_3 among eight UAVs.

at a particular range of altitudes. For a consumer UAV, the maximum altitude is 400 feet based on the current FAA guideline; for a military UAV, the maximum altitude can be tens of thousands of meters. A similar approach has also been used in AUVs under the sea [11]. Scalability in a time 3D space is still an open issue, and except for heterogeneous and multi-tiered military networks [1] based on different waveforms, little work has been done in commercial networks.

Radio propagation in the air is also unique - A2A communication among UAVs is characterized by clear light-of-sight in the air, but communication quality is highly dynamic because of the relatively high mobility of UAVs. The communication range of UAVs is long, but communication is not necessarily reliable. The environment (urban vs. rural and indoor vs. outdoor) also plays an important role. Therefore, maximizing the physical connectivity among UAVs is required to form a reliable relay network. Physical connectivity will also increase the number of parallel paths among UAVs. However, this objective is in direct conflict with the other objectives of cost minimization and area coverage maximization. Possible directions to improve reliability without deploying extra UAVs include multi-path communication, multiple directional antennae, and special communication coding.

3. Network formation

Network formation deals with the formation of UAVs as well as the formation of multi-tiered networks, including ground networks. One main challenge lies in managing a large number of mobile UAVs and several static ground stations.

A large set of small UAVs (such as multi-rotors) can be considered as a set of *intelligent swarms* [12] that represent a group of simple interacting agents, inspired by the behavior of ants and birds in nature. The intelligence of the swarms lies in the networks of interactions that occur both among UAVs and between UAVs and the environment (in the air and on the ground). Intelligent clustering formation through self-organization is such an example. Ideally, a self-organized structure meets several conditions:

1. Local interactions with global properties to support scalability. In UAVs, each UAV interacts with its neighboring UAVs locally, but achieves global properties, such as global connectivity.
2. Minimizing maintained states at each UAV for usability and efficiency. For example, each UAV maintains 2-hop neighborhood information (i.e., neighbors and their neighbors) or just neighbors' location information.
3. Adaptation to changes with self-healing capability. For example, UAVs can self-organize to reconnect themselves after a disruption in connection.
4. Implicit coordination among UAVs without the need for synchronization. For example, there is no need for synchronization of UAV beacon signals for discovery of neighbors.

In MANETs, using self-organized *connected dominating set* for CHs formation looks promising. Dominating set is a subset of nodes, called dominating nodes, such that every other node in the network is a neighbor of at least one dominating node. The connected dominating set selection can be used for CHs selection, using either a 2-hop neighborhood or neighbor location information as follows: A UAV is a CH if it has two unconnected neighbors. In Fig. 2, u_1 is a CH since its two neighbors u and u_4 are not connected; u_4 is not a CH because its neighbors are pair-wise connected. Note that UAVs usually need accurate localization data with smaller time intervals. Regular GPS information needs to be augmented with an inertial measurement unit (IMU) on board to offer each UAV position to neighbor UAVs. In [13], an iterative refinement approach is proposed that performs the CH pruning process in multiple steps. In these steps, network topology also changes due to node movement in MANETs. This approach can seamlessly integrate CH pruning and neighborhood adjustment caused by topology changes. However, the effectiveness of this approach in UAVs, with fast movement but long-range communication, needs to be validated for its applicability.

In a multi-tiered network, it is also important to study network formation on the ground, especially during a disaster or a military mission where network outages occur frequently. The notion of designated locations for information dissemination prior to a natural diaster, called deployable base stations (DBSs) is introduced in [14]; these are pre-deployed before the disaster strikes. DBSs are static ground locations for information dissemination, gathering or fetching for mobile nodes (persons) on the ground. During a disaster that results in a network outage on the ground, information dissemination on the ground can be carried out by UAVs in the air.

The author of this paper personally experienced Hurricane Wilma in 2005, which isolated a population of four million in South Florida from the rest of world for a few days or weeks. This isolation could have been avoided if a location in each city or town had been designated as a DBS before the hurricane. Information dissemination could have been carried out by UAVs, originated from different nearby cities, say Orlando or Tampa, to DBSs.

In a multi-tiered network, UAVs are mobile while ground stations are static. Traditionally, UAVs are treated as a relay network, e.g., connecting B_1 and B_2 via u_2 in Fig. 1. In reality, the static ground station can also act as a relay for UAVs, such as B_1 for u_1 and u_3. The functions of a UAV in the air and the ground station in overall multi-tiered network formation is an interesting topic for further exploration.

4. Network connectivity

Network connectivity deals with mechanisms used to ensure connectivity among AUVs, including soft handoff and horizontal/vertical handoff in intra-/inter-networks [3]. In case of frequent topology changes and delay-tolerant information delivery, we can potentially apply the information dissemination techniques used in delay-tolerant networks (DTNs) [15]. In DTNs, data are delivered through a store-carry-forward process rather than the store-and-forward process of a connection-based system. Consider the example in Fig. 1 after a network outage occurs on the ground, we also assume that u_1 and u_2 are the same node that appears at different time steps. In store-carry-forward process between B_1 and B_2 using a mobile node, the mobile node at u_1 first stores the data from B_1 and carries it to the location of u_2, before forwarding the data to B_2.

In DTNs, opportunistic contact/reply can be used for A2A, A2G, and G2A communication. Since the ground station is static, A2G and G2A can be more predictable; A2A communication, based on opportunistic contact, is more involved because contacts between two UAVs depend on their moving trajectories. Mobility in UAVs has its own special constraints, including temporal and spatial correlation; smooth turns are necessary because of mechanical and aerodynamic constraints, as discussed in various surveys on the mobility model [16].

In sensing and surveillance applications, the movement of a UAV is usually cyclic. In general, cyclic movement can be handled with better predictability [17]. For example, Fig. 3 shows that u_2 follows a mobility model called semi-random circular movement (SRCM) [18], in which u_2 moves on 2D disks with a fixed center but different radii. Suppose there is another UAV, u_1, that moves in a straight line. Contact probability can be estimated based on communication radius. A more practical model is the *spiral model* in AUVs, frequently used in Navy applications. In the spiral model, an underwater vehicle follows an inside-out spiral movement from a fixed point that serves as the circling center. The vehicle moves back from outside to the fixed point in a straight line before repeating the spiral circling trajectory.

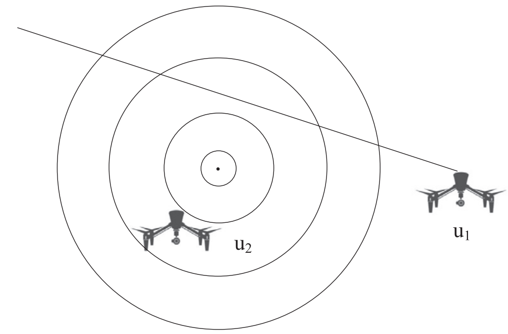

Fig. 3. Probabilistic contacts between two UAVs on different mobility models: u_1 on a straight line and u_2 on the SRCM model.

Whether or not the collection-less, delay-tolerant communication can be easily integrated with classic connection-based communication in UAVs is still an open problem. This depends on the timing requirement of information delivery discussed in the next section.

5. Information delivery

In this section, we briefly discuss several special methods of information delivery for A2A, A2G, and G2A. Information delivery for G2G has been extensively studied in the classic network settings for both wired and wireless and will not be discussed further here. We include a control signal for G2A and A2A and data for A2G and A2A. Data can be *delay-tolerant, periodic*, or *real-time*. For periodic data, an update frequency of 10 Hz or larger is needed for ground personnel tracking of a moving target in a search and rescue mission. Differentiated service can be applied depending on the urgency of the data. For example, in an aerial surveillance application, video captured on a UAV can be pre-processed on board before streaming the data to the ground station. When an emergency or abnormal situation is detected, the real-time result should be sent back to the ground station without further delay. For delay-tolerant data, it can be copied and streamed when the UAV touches the ground. Data can also be *low-rate, bursty*, or *high-rate*; therefore various resource allocations and scheduling methods are needed in the network design.

There are also trade-offs on delivery control signals through uplinks from the ground station. For example, for a network that sends control signals without resorting to A2A communication, control commands can be sent via G2G communication to another ground station that has direct access to the corresponding UAV, such as B_1 to u_2 via B_2 in Fig. 1. In a network that supports A2A communication, the single ground controller can first send the command to any UAV in a connected set of UAVs via A2A communication. The destination UAV will eventually receive the control command via a sequence of A2A communications, such as B_1 to u_2 via u_1 in Fig. 1.

Adaptability in information delivery poses another challenge. In a search-and-rescue effort, the periodic model of the searching process should be switched to the real-time mode when a target has been identified. The network protocols may need to adapt to meet the needs of traffic changes. Software-defined network (SDN) can potentially be applied here to provide a way to programmatically control networks, although with few exceptions [19,20], SDN has been traditionally used in static and ground networks.

6. Energy management

UAVs are powered by either gas or battery. Therefore, the life span of UAVs is limited by the capacity of gas tank or battery. Energy saving can be managed in several ways through power-saving modes (PSMs) in AUVs similar to those in MANETs and wireless sensor networks (WSNs).

UAVs, however, consume a large energy consumption for UAVs to stay in the air even when there is no transmission or reception. One energy-saving option is to use small, lightweight UAVs that carry a light payload. However, small UAVs usually have a shorter lifespan before refilling/recharging is necessary. Various power-saving approaches can be adopted, including path planning to shorten the distance of a path in information dissemination. Other power-saving approaches are used at different layers of the protocol stack [3] such as making some nodes (e.g., CHs) active and other nodes sleep. A joint energy-efficient optimization problem that considers 3D placement and mobility of UAVs, together with several other factors is studied in [21].

Even with the aforementioned energy-saving methods, UAVs still eventually require refilling/recharging at charging stations (e.g., G_1 and G_2 in Fig. 1). Several wireless energy transfer strategies, using electromagnetic radiation and magnetic resonant coupling, among mobile nodes, are studied in [22]. The selection of mobile nodes for refilling/recharging depends on the lifespan of mobile nodes: long-life with infrequent refilling/re-charging and short-life with frequent refilling/recharging. In this case, the traditional energy refill/recharge is carried out at charging stations on the ground and/or at wireless energy recharging location on the ground or in the air. This is an active energy refilling/recharging process, in contrast to passive energy harvesting or scavenging opportunity. Note that it is possible to refill regular commercial and military planes in the air, but no research has been done on relatively low-cost UAVs. The possibility of energy transfer and refill also brings various scheduling challenges that need to balance cost-effectiveness and produce different trade-offs among multiple competing objectives.

7. Conclusion

In this paper, we provide a vision for a futuristic, multi-tiered network with both aerial and ground coverage. This network supports both multi-hop communications and four different modes of aerial and ground communication. We look at five selected areas in terms of opportunities and challenges in supporting general information dissemination. These areas are by no means exhaustive, but they are important subsets in such a complex network setting. There are other important aspects, including safety (i.e. collision avoidance in the flying robot community), security (i.e. FAA requirements for the altitude limits of civilian UAVs and secured communications), and privacy (especially for camera-equipped UAVs), that are not discussed due to space limitation. Although we use aerial and ground networks to illustrate some detailed challenges in the multi-tiered network, the structure can span to more tiers, both logically and geographically, and can include autonomous underwater vehicles (AUVs).

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.comcom.2018.07.007

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