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Survey Paper

Flying Ad-Hoc Networks (FANETs): A survey

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One of the most important design problems for multi-UAV (Unmanned Air Vehicle) systems is the communication which is crucial for cooperation and collaboration between the UAVs. If all UAVs are directly connected to an infrastructure, such as a ground base or a satellite, the communication between UAVs can be realized through the in-frastructure. However, this infrastructure based communication architecture restricts the capabilities of the multi-UAV systems. Ad-hoc networking between UAVs can solve the problems arising from a fully infrastructure based UAV networks. In this paper, Flying Ad-Hoc Networks (FANETs) are surveyed which is an ad hoc network connecting the UAVs. The differences between FANETs, MANETs (Mobile Ad-hoc Networks) and VANETs (Vehicle Ad-Hoc Networks) are clarified first, and then the main FANET design challenges are introduced. Along with the existing FANET protocols, open research issues are also discussed.

1. Introduction

As a result of the rapid technological advances on electronic, sensor and communication technologies, it has been possible to produce unmanned aerial vehicle (UAV) systems, which can fly autonomously or can be operated remotely without carrying any human personnel. Because of their versatility, flexibility, easy installation and relatively small operating expenses, the usage of UAVs promises new ways for both military and civilian applications, such as search and destroy operations [1], border surveillance [2], managing wildfire [3], relay for ad hoc networks [4,5], wind estimation [6], disaster monitoring [7], remote sensing [8] and traffic monitoring [9]. Although single-UAV systems have been in use for decades, instead of developing and operating one large UAV, using a group of small UAVs has many advantages. However, multi-UAV systems have also unique challenges and one of the most prominent design problems is communication. In this paper, Flying Ad-Hoc Network (FANET), which is basically ad hoc network between UAVs, is surveyed as a new network family. The differences between Mobile Ad-hoc Network (MANET), Vehicular Ad-hoc Network (VANET) and FANET are outlined, and the most important FANET design challenges are introduced. In addition to the existing solutions, the open research issues are also discussed.

Along with the progress of embedded systems and the miniaturization tendency of microelectromechanical systems, it has been possible to produce small or mini UAVs at a low cost. However, the capability of a single small UAV is limited. Coordination and collaboration of multiple UAVs can create a system that is beyond the capability of only one UAV. The advantages of the multi-UAV systems can be summarized as follows:

- Cost: The acquisition and maintenance cost of small UAVs is much lower than the cost of a large UAV [10].
- Scalability: The usage of large UAV enables only limited amount of coverage increases [11]. However, multi-UAV systems can extend the scalability of the operation easily.

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- Survivability: If the UAV fails in a mission which is operated by one UAV, the mission cannot proceed. However, if a UAV goes off in a multi-UAV system, the operation can survive with the other UAVs.
- Speed-up: It is shown that the missions can be completed faster with a higher number of UAVs [12].
- Small radar cross-section: Instead of one large radar cross-section, multi-UAV systems produce very small radar cross-sections, which is crucial for military applications [13].

Although there are several advantages of multi-UAV systems, when compared to single-UAV systems, it has also unique challenges, such as communication. In a single-UAV system, a ground base or a satellite is used for communication. It is also possible to establish a communication link between the UAV and an airborne control system. In all cases, single-UAV communication is established between the UAV and the infrastructure. While the number of UAVs increases in unmanned aerial systems, designing efficient network architectures emerges as a vital issue to solve.

As in a single UAV system, UAVs can also be linked to a ground base or to a satellite in a multi-UAV system. There may be variants of this star topology based solution [14]. While some UAVs communicate with a ground base, the others can communicate with satellite/s. In this approach, UAV-to-UAV communication is also realized through the infrastructure. There are several design problems with this infrastructure based approach. First of all, each UAV must be equipped with an expensive and complicated hardware to communicate with a ground base or a satellite. Another handicap about this network structure is the reliability of the communication. Because of the dynamic environmental conditions, node movements and terrain structures, UAVs may not maintain its communication link. Another problem is the range restriction between the UAVs and the ground base. If a UAV is outside the coverage of the ground base, it becomes disconnected. An alternative communication solution for multi-UAV systems is to establish an ad hoc network between UAVs, which is called FANET. While only a subset of UAVs can communicate with the ground base or satellite, all UAVs constitute an ad hoc network. In this way, the UAVs can communicate with each other and the ground base.

FANET can be viewed as a special form of MANET and VANET. However, there are also certain differences between FANET and the existing ad hoc networks:

- Mobility degree of FANET nodes is much higher than the mobility degree of MANET or VANET nodes. While typical MANET and VANET nodes are walking men and cars respectively, FANET nodes fly in the sky.
- Depending on the high mobility of FANET nodes, the topology changes more frequently than the network topology of a typical MANET or even VANET.
- The existing ad hoc networks aim to establish peer-to-peer connections. FANET also needs peer-to-peer connections for coordination and collaboration of UAVs. Besides, most of the time, it also collects data from the environment and relays to the command control center, as in wireless sensor networks [15]. Consequently, FANET must support peer-to-peer communication and converge cast traffic at the same time.
- Typical distances between FANET nodes are much longer than in the MANETs and VANETs [16]. In order to establish communication links between UAVs, the communication range must also be longer than in the MANETs and VANETs. This phenomenon accordingly affects the radio links, hardware circuits and physical layer behavior.
- Multi-UAV systems may include different types of sensors, and each sensor may require different data delivery strategies.

The main motivation of this paper is to define FANET as a separate ad hoc network family and to introduce unique challenges and design constraints. Although, there exists a few studies that address some specific issues of networked UAVs [17,18,14], to the best of our knowledge, this is the first comprehensive survey about FANETs.

The paper is organized as follows. In Section 2, we present several FANET application scenarios and introduce FANET design characteristics in Section 3. We provide an extensive review of the existing communication protocols and the open research issues in Section 4. We also present the existing multi-UAV test beds and simulation environments in Section 5. We conclude the paper in Section 6.

2. FANET application scenarios

In this section, different FANET application scenarios are discussed.

2.1. Extending the scalability of multi-UAV operations

If a multi-UAV communication network is established fully based on an infrastructure, such as a satellite or a ground base, the operation area is limited to the communication coverage of the infrastructure. If a UAV cannot communicate with the infrastructure, it cannot operate. On the other hand, FANET is based on the UAV-to-UAV data links instead of UAV-to-infrastructure data links, and it can extend the coverage of the operation. Even if a FANET node cannot establish a communication link with the infrastructure, it can still operate by communicating through the other UAVs. This scenario is illustrated in Fig. 1.

There are several FANET designs developed for extending the scalability of multi-UAV applications. In [19], a FANET design was proposed for the range extension of multi-UAV systems. It was stated that forming a link chain of UAVs by utilizing multi-hop communication can extend the operation area.

It should be noticed that the terrain also affects the communication coverage of the infrastructure. There may be some obstacles on the terrain, such as mountains, walls or buildings, and these obstacles may block the signals of the infrastructures. Especially in urban areas, buildings and constructions block the radio signals between the ground base and UAVs. FANET can also help to operate behind the obstacles, and it can extend the scalability of multi-UAV applications [20].

2.2. Reliable multi-UAV communication

In most of the cases, multi-UAV systems operate in a highly dynamic environment. The conditions at the beginning of a mission may change during the operation. If there is no opportunity to establish an ad hoc network, all UAVs must be connected to an infrastructure, as illustrated in Fig. 2a. However, during the operation, because of the weather condition changes, some of the UAVs may be disconnected. If the multi-UAV system can support FANET architecture, it can maintain the connectivity through the other UAVs, as it is shown in Fig. 2b. This connectivity feature enhances the reliability of the multi-UAV systems [16].

2.3. UAV swarms

Small UAVs are very light and have limited payload capacity. In spite of their restricted capabilities, the swarm behavior of multiple small UAVs can accomplish complex missions [21]. Swarm behavior of UAVs requires coordinated functions, and UAVs must communicate with each other to achieve the coordination. However, because of the limited payloads of small UAVs, it may not be possible to carry heavy UAV-to-infrastructure communication hardware. FANET, which needs relatively lighter and cheaper hardware, can be used to establish a network between small UAVs. By the help of the FANET architectures, swarm UAVs can prevent themselves from collisions, and the coordination between UAVs can be realized to complete the mission successfully.

In [22], Cooperative Autonomous Reconfigurable UAV Swarm (CARUS) is proposed with FANET communication architecture. The objective of CARUS is the surveillance of a given set of points. Each UAV operates in an autonomous manner, and the decisions are taken by each UAV in the air rather than on the ground. Ben-Asher et al. have introduced a distributed decision and control mechanism for multi-UAV systems using FANET [23]. In [24], a FANET based UAV swarm architecture is proposed to convey UAVs to a target location with cooperative decision-making. Quaritsch et al. have developed another FANET based UAV swarm application for disaster management [25]. During a disaster situation, rescue teams cannot rely on fixed infrastructures. The aim of the project is to provide quick and accurate information from the affected area.

2.4. FANET to decrease payload and cost

The payload capacity problem is not valid only for small UAVs. Even High Altitude Low Endurance (HALE) UAVs must consider payload weights. The lighter payload means the higher altitude and the longer endurance [16]. If the communication architecture of a multi-UAV system is fully based on UAV-to-infrastructure communication links, each UAV must carry relatively heavier communication hardware. However, if it uses FANET, only a subset of UAVs use UAV-to-infrastructure communication link, and the other UAVs can operate with FANET, which needs lighter communication hardware in many cases. In this way, FANET can extend the endurance of the multi-UAV system.

3. FANET design characteristics

Before discussing the characteristics of FANETs, we provide a formal definition of FANET and a brief discussion about the definition to understand FANET clearly.

FANET can be defined as a new form of MANET in which the nodes are UAVs. According to this definition, single-UAV systems cannot form a FANET, which is valid only for multi-UAV systems. On the other hand, not all multi-UAV systems form a FANET. The UAV communication must be realized by the help of an ad hoc network between UAVs. Therefore, if the communication between UAVs fully relies on UAV-to-infrastructure links, it cannot be classified as a FANET.

In the literature, FANET related researches are studied under different names. For example, aerial robot team is a collaborative and autonomous multi-UAV system, and generally, its network architecture is ad hoc [26]. In this sense, ad hoc based aerial robot teams can also be viewed as a FANET design. However, aerial robot team studies mostly concentrate on the collaborative coordination of multi-UAV systems, not on the network structures, algorithms or protocols [27]. Another FANET related topic is

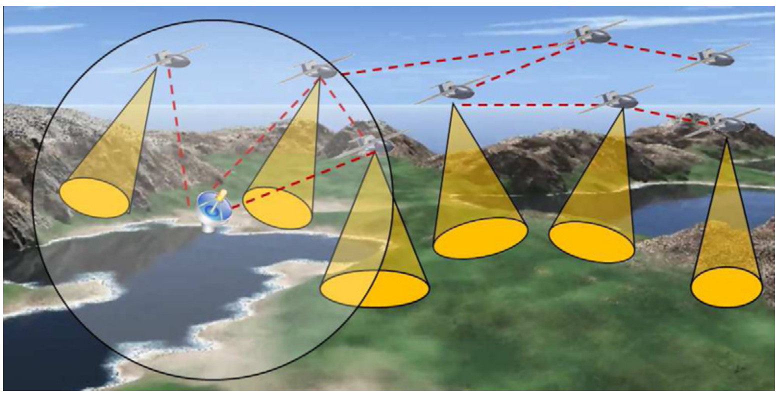

Fig. 1. A FANET scenario to extend the scalability of multi-UAV systems.

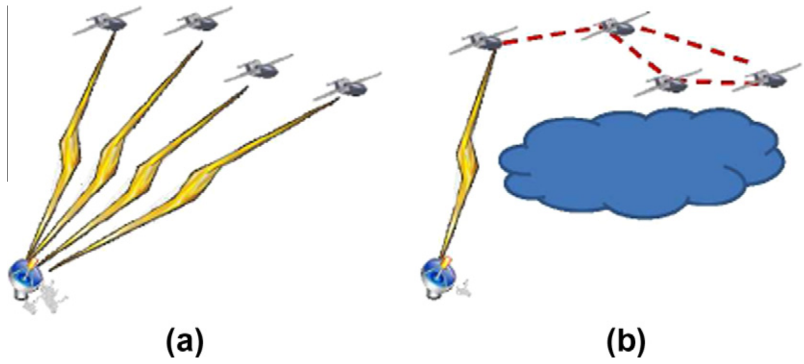

Fig. 2. A FANET application scenario for reliable multi-UAV communication network.

aerial sensor network [28–30]. Aerial sensor network is a very specialized mobile sensor and actor network so that the nodes are UAVs. It moves around the environment, senses with the sensors on the UAVs and relays the collected data to the ground base. In addition, it can act with its actors on the UAVs to realize its mission. It is a perception issue to name the problem as flying ad hoc network or aerial sensor network. The basic design challenges of a traditional sensor network are energy consumption and node density [31], and none of them is related with multi-UAV systems. Generally, UAVs have enough energy to support its communication hardware, and node density of a multi-UAV system is very low when it is compared to traditional sensor networks. Under the light of these discussions, it is better to classify the multi-UAV communication system based on UAV-to-UAV links as a specialized ad hoc network, instead of a specialized sensor network. UAV ad hoc network [32] is another topic, which is closely related to FANETs. In fact, there is no significant difference between the existing UAV ad hoc network researches and the above FANET definition. However, FANET term immediately reminds that it is a specialized form of MANET and VANET. Therefore, we prefer calling it as Flying Ad-Hoc Network, FANET.

3.1. Differences between FANET and the existing ad-hoc networks

Wireless ad hoc networks are classified according to their utilization, deployment, communication and mission objectives. By definition, FANET is a form of MANET, and there are many common design considerations for MANET and FANET. In addition to this, FANET can also be classified as a subset of VANET, which is also a subgroup of MANET. This relationship is illustrated in Fig. 3. As an emerging research area, FANET shares common characteristics with these networks, and it also has several unique design challenges. In this subsection, the differences between FANET and the existing wireless ad hoc networks are explained in a detailed manner.

3.1.1. Node mobility

Node mobility related issues are the most notable difference between FANET and the other ad hoc networks. MANET node movement is relatively slow when it is compared to VANET. In FANET, the node's mobility degree is much higher than in the VANET and MANET. According to [16], a UAV has a speed of 30–460 km/h, and this situation results in several challenging communication design problems [33].

3.1.2. Mobility model

While MANET nodes move on a certain terrain, VANET nodes move on the highways, and FANET nodes fly in the sky. MANETs generally implement the random waypoint mobility model [34], in which the direction and the speed of the nodes are chosen randomly. VANET nodes are restricted to move on highways or roads. Therefore, VANET mobility models are highly predictable.

In some multi-UAV applications, global path plans are preferred. In this case, UAVs move on a predetermined path, and the mobility model is regular. In autonomous multi-UAV systems, the flight plan is not predetermined. Even if a multi-UAV system uses predefined flight plans, because of the environmental changes or mission updates, the flight plan may be recalculated. In addition to the flight plan changes, the fast and sharp UAV movements and different UAV formations directly affect the mobility model of multi-UAV systems. In order to address this issue, FANET mobility models are proposed. In [35], Semi-Random Circular Movement (SRCM) mobility model is presented, and the approximate node distribution function is derived within a two dimensional disk region. In [36], two new mobility models are proposed for multi-UAV systems. In random UAV movement model, UAVs move independently. Each UAV decides on its movement direction, according to a predefined Markov process. In the second model, the UAVs maintain a pheromone map, and the pheromones guide their movements. Each UAV marks the areas that it scans on the map, and shares the pheromone map with broadcasting. In order to maximize the coverage, UAVs prefer the movement through the areas with low pheromone smell. It was shown that the use of a typical MANET mobility model may result in undesirable path plans for cooperative UAV applications. It was also observed that the random model is remarkably simple, but it leads to ordinary results. However, the pheromone based model has very reliable scanning properties.

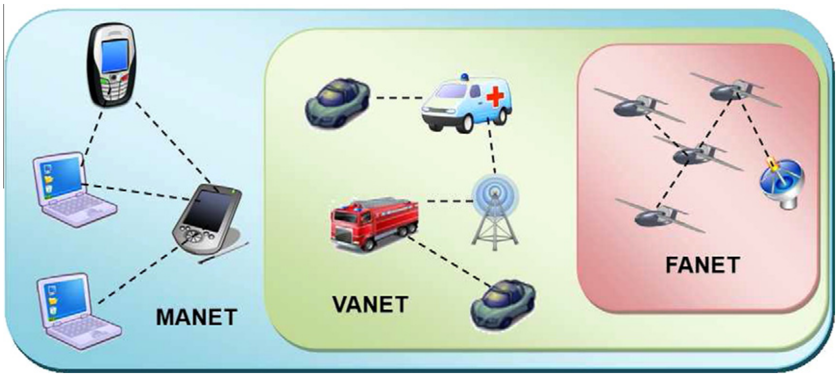

Fig. 3. MANET, VANET and FANET.

3.1.3. Node density

Node density can be defined as the average number of nodes in a unit area. FANET nodes are generally scattered in the sky, and the distance between UAVs can be several kilometers even for small multi-UAV systems [37]. As a result of this, FANET node density is much lower than in the MANET and VANET.

3.1.4. Topology change

Depending on the higher mobility degree, FANET topology also changes more frequently than MANET and VANET topology. In addition to the mobility of FANET nodes, UAV platform failures also affect the network topology. When a UAV fails, the links that the UAV has been involved in also fail, and it results in a topology update. As in the UAV failures, UAV injections also conclude a topology update. Another factor that affects the FANET topology is the link outages. Because of the UAV movements and variations of FANET node distances, link quality changes very rapidly, and it also causes link outages and topology changes [38].

3.1.5. Radio propagation model

Differences between FANET and the other ad hoc network operating environments affect the radio propagation characteristics. MANET and VANET nodes are remarkably close to the ground, and in many cases, there is no line-of-sight between the sender and the receiver. Therefore, radio signals are mostly affected by the geographical structure of the terrain. However, FANET nodes can be far away from the ground and in most of the cases, there is a line-of-sight between UAVs.

3.1.6. Power consumption and network lifetime

Network lifetime is a key design issue for MANETs, which especially consist of battery-powered computing devices. Developing energy efficient communication protocols is the goal of efforts to increase the network lifetime. Especially, while the battery-powered computing devices are getting smaller in MANETs, system developers have to pay more attention to the energy efficient communication protocols to prolong the lifetime of the network. However, FANET communication hardware is powered by the energy source of the UAV. This means FANET communication hardware has no practical power resource problem as in MANET. In this case, FANET designs may not be power sensitive, unlike most of the MANET applications. However, it must be stated that power consumption still can be a design problem for mini UAVs [39].

3.1.7. Computational power

In ad hoc network concept, the nodes can act as routers. Therefore, they must have certain computation capabilities to process incoming data in real-time. Generally, MANET nodes are battery powered small computers such as laptops, PDAs and smart phones. Because of the size and energy constraints, the nodes have only limited computational power. On the other hand, both in VANETs and FANETs, application specific devices with high computational power can be used. Most of the UAVs have enough energy and space to include high computational power. The only limitation about the computational power is the weight. By the help of the hardware miniaturization tendency, it is possible to put powerful computation hardware in UAV platforms. However, the size and weight limitation can still constitute serious constraints for mini UAVs, that have very limited payload capacity.

3.1.8. Localization

Accurate geospatial localization is at the core of mobile and cooperative ad hoc networks [40]. Existing localization methods include global positioning system (GPS), beacon (or anchor) nodes, and proximity-based localization [41].

In MANET, GPS is generally used to receive the coordinates of a mobile communication terminal, and most of the time, GPS is sufficient to determine the location of the nodes. When GPS is not available, such as in dense foliage areas, beacon nodes or proximity-based techniques can also be used.

In VANET, for a navigation-grade GPS receiver, there is about 10–15 m accuracy, which can be acceptable for route guidance. However, it is not sufficient for cooperative safety applications, such as collision warnings for cars. Some researchers use assisted GPS (AGPS) or differential GPS (DGPS) by using some type of ground-based reference stations for range corrections with accuracy about 10 cm [42,43].

Because of the high speed and different mobility models of multi-UAV systems, FANET needs highly accurate localization data with smaller time intervals. GPS provides position information at one-second interval, and it may not be sufficient for certain FANET protocols. In this case, each UAV must be equipped with a GPS and an inertial measurement unit (IMU) to offer the position to the other UAVs at any time. IMU can be calibrated by the GPS signal, and thus, it can provide the position of the UAV at a quicker rate [44,45].

Because of the above-mentioned differences between FANET, MANET and VANET; we prefer to investigate FANET as a separate ad hoc network family. The differences between MANET, VANET and FANET are outlined in Table 1.

3.2. FANET design considerations

The distinguishing features of FANET impose unique design considerations. In this subsection, the most prominent FANET design considerations; adaptability, scalability, latency, UAV platform constraints, and bandwidth requirement are discussed.

3.2.1. Adaptability

There are several FANET parameters that can change during the operation of a multi-UAV system. FANET nodes are highly mobile and always change their location. Because of the operational requirements, the routes of the UAVs may be different, and the distance between UAVs cannot be constant.

Another issue that must be considered is the UAV failures. Consequent to a technical problem or an attack against multi-UAV system, some of the UAVs may fail during the operation. While UAV failures decrease the number of UAVs, UAV injections may be required to maintain the multi-UAV system operation. UAV failures and UAV injections change the FANET parameters.

Environmental conditions can also affect FANET. If the weather changes unexpectedly, FANET data links may not survive. FANET should be designed so that it should be able to continue to operate in a highly dynamic environment.

The mission may also be updated during the multi-UAV system operation. Additional data or new information about the mission may require a flight plan update. For example, while a multi-UAV system is operated for a search and rescue mission; after the arrival of a new intelligence report, the mission may be concentrated on a certain area, and the flight plan update also affects FANET parameters.

FANET design should be developed so that it can adjust itself against any changes or failures. FANET physical layer should adapt according to the node density, distance between nodes, and environmental changes. It can scan the parameters and choose the most appropriate physical layer option. The highly dynamic nature of FANET environment also affects network layer protocols. Route maintenance in an ad hoc network is closely related to the topology changes. Thus, the performance of the system depends on the routing protocol in adapting to link changes. Transport layer should also be adapted according to the status of FANET.

3.2.2. Scalability

Collaborative work of UAVs can improve the performance of the system in comparison to a single-UAV system. In fact, this is the main motivation to use multi-UAV based systems. In many applications, the performance enhancement is closely related with the number of UAVs. For example, the higher number of UAVs can complete a search and rescue operation faster [12]. FANET protocols and algorithms should be designed so that any number of UAVs can operate together with minimal performance degradation.

3.2.3. Latency

Latency is one of the most important design issues for all types of networks, and FANET is not an exception. FANET latency requirement is fully dependent on the application. Especially for real-time FANET applications, such as military monitoring, the data packets must be delivered within a certain delay bound. Another low latency requirement is valid for collision avoidance of multiple UAVs [14,46].

In [47], an analysis of one-hop packet delay was conducted for IEEE 802.11 based FANETs. Each node was modeled as M/M/1 queue and the mean packet delay was derived analytically. The numerical results were verified with a simulation analysis. Based on the data collected from the simulation analysis, it was observed that packet delay can be approximated with Gamma distribution. Zhai et al. studied packet delay performance of IEEE 802.11 for traditional wireless LANs, and stated that the MAC layer packet service time can be approximated by an exponen-

Table 1
The comparison of MANET, VANET and FANET.

	MANET	VANET	FANET
Node mobility	Low	High	Very high
Mobility model	Random	Regular	Regular for predetermined paths, but special mobility models for autonomous multi-UAV systems
Node density	Low	High	Very low
Topology change	Slow	Fast	Fast
Radio propagation model	Close to ground, LoS is not available for all cases	Close to ground, LoS is not available for all cases	High above the ground, LoS is available for most of the cases
Power consumption and network lifetime	Energy efficient protocols	Not needed	Energy efficiency for mini UAVs, but not needed for small UAVs
Computational power	Limited	High	High
Localization	GPS	GPS, AGPS, DGPS	GPS, AGPS, DGPS, IMU

tially distributed random variable [48]. It also shows that the packet delay behaviors are different for MANETs and FANETs, and the protocols developed for MANET may not satisfy the latency requirements of FANET. New FANET protocols and algorithms are needed for delay sensitive multi-UAV applications.

3.2.4. UAV platform constraints

FANET communication hardware must be deployed on the UAV platform, and this situation imposes certain constraints. The weight of the hardware is an important issue for the performance of the UAVs. Lighter hardware means lighter payload, and it extends the endurance. Another opportunity that comes with the lighter communication hardware is to deploy additional sensors on the UAV. If the total payload is assumed as constant and the communication hardware is lighter, more advanced sensors and other peripherals can be deployed.

Space limitation is another UAV platform related constraints for FANET designs. Especially for mini UAVs, the space limitation is very important for communication hardware that must be fitted into the UAV platform [39].

3.2.5. Bandwidth requirement

In most of the FANET applications, the aim is to collect data from the environment and to relay the collected data to a ground base [25]. For example, in surveillance, monitoring or rescue operations; the image or video of the target area must be relayed from the UAV to the command control center with a very strict delay bound, and it requires high bandwidth. In addition, by the help of the technological advancements on sensor technologies, it is possible to collect data with very high resolution, and this makes the bandwidth requirement much higher. The collaboration and coordination of multiple UAVs also need additional bandwidth resource.

On the other hand, there are many constraints for the usage of available bandwidth such as:

- capacity of the communication channel,
- speed of UAVs,
- error-prone structure of the wireless links,
- lack of security with broadcast communication.

A FANET protocol must satisfy the bandwidth capacity requirement so that it can relay very high resolution real-time image or video under several constraints.

4. Communication protocols for FANETs

In this section, the FANET communication protocols and the open research issues are presented. We survey the existing FANET protocols proposed for the physical layer, medium access control (MAC) layer, network layer, transport layer, and their cross-layer interactions.

4.1. Physical layer

The physical layer deals with the basic signal transmission technologies, such as modulation or signal coding. Various data bit sequences can be represented with different waveforms by varying the frequency, amplitude and phase of a signal. Overall, in the physical layer, the data bits are modulated to sinusoidal waveforms and transmitted into the air by utilizing an antenna.

MANET system performance is highly dependent on its physical layer, and the extremely high mobility puts extra problematic issues on FANET. In order to develop robust and sustainable data communication architectures for FANET, the physical layer conditions have to be well-understood and well-defined. Recently, UAV-to-UAV and UAV-to-ground communication scenarios have been broadly studied in both simulation and real-time environments. Radio propagation models and antenna structures are investigated as the key factors that influence FANET physical layer design.

4.1.1. Radio propagation model

Electromagnetic waves radiate from the transmitter to the receiver through wireless channels. The characterization of radio wave propagation is expressed as a mathematical function, which is called radio propagation modeling [49]. FANET environment has several unique challenges in terms of radio propagation when compared to the other types of wireless networks. Some of the challenges are summarized as follows:

- Variations in communication distance.
- Direction of the communicating pairs in the antenna radiation pattern.
- Ground reflection effects.
- Shadowing resulting from the UAV platform and onboard electronic equipment.
- The effect of aircraft attitude (pitch, roll, yaw etc.) on the wireless link quality.
- Environmental conditions.
- Interferences and hostile jamming.

Because of the above-mentioned factors, communication links exhibit varying quality over time in FANETs [50].

Ahmed et al. studied the characterization of UAV-to-UAV, UAV-to-ground, and ground-to-UAV communication links [51]. In this study, free space and two-ray ground approximation models are compared for each link type, and the presence of gray regions is observed, when the UAVs are close to the ground. Gray regions showed that the radio propagation model of UAV-to-UAV links is similar to two-ray ground model, and FANET protocol designers must be aware of the presence of the gray zones due to fading.

Zhou et al. investigated the channel modeling problem for UAV-to-UAV communications [52]. In this study, it was observed that the error statistics of the wireless channels between UAVs are non-stationary. Depending on the changes of the distance between UAVs, a two-state Markov model was proposed to incorporate the effects of Rician fading, which is suitable for strong line-of-sight path, as in FANET. The simulation results showed that the proposed model is able to simulate packet dropouts with non-stationary error statistics.

A Nakagami-m based radio propagation model was also proposed for FANET communication in [53]. Nakagami-m suitably agrees with the empirical data measured for VANET networks [54,55]. This model estimated the received signal strength for a multi-path environment with covering fading effects, and it was represented as a function of two parameters: the average received radio signal strength and the fading intensity. A mathematical expression for the outage probability over Nakagami-m fading channel has been derived for a cooperative UAV network.

In [56], the performance analysis of multi-carrier relay based UAV network was modeled analytically over fading channels. A general analytical formula was provided for the outage probability of UAV-to-UAV and UAV-to-ground link. It was stated that fading channel model should be chosen according to the operation environment. For example, while Rayleigh fading can be more suitable for low altitude crowded area applications, Nakagami-m and Weibull fading with high fading parameters best fit for high altitude open space missions.

4.1.2. FANET antenna structure

The antenna structure is one of the most crucial factors for an efficient FANET communication architecture. The distance between UAVs is longer than typical node distance of MANETs and VANETs, and it directly affects the FANET antenna structure. More powerful radios can be used to overcome this problem, but high link loss and variation could still arise at longer distances. In order to overcome this phenomenon, multiple receiver nodes can be deployed to boost packet delivery rates by exploiting the spatial and temporal diversity of the wireless channel [57]. It is shown that UAV receiver nodes exhibit poor packet reception correlation at short time scales, which ultimately necessitates the usage of multiple transmitters and receivers to improve packet delivery rates.

Antenna type is another factor that affects the FANET performance. In the literature, there are two types of antennas deployed for FANET applications: directional and omnidirectional. While omnidirectional antennas radiate the power in all directions, directed antenna can send the signal through a desired direction.

In highly mobile environments, as in FANET, the node locations change frequently and omnidirectional antennas have a natural advantage to transmit and receive signals. In omnidirectional antennas, node location information is not needed. However, directional antennas also have several advantages when compared to omnidirectional antennas. Firstly, the transmission range of a directed antenna is longer than the transmission range of an omnidirectional antenna [58]. It can be an important advantage for FANET, where the distance between nodes is longer than the distance between typical MANET nodes [37]. The longer transmission range decreases hop count, and it can enhance the latency performance [59]. Especially, in real time FANET applications, such as military monitoring, latency is one of the most dominant design factors.

There is a trade-off between communication range and spatial reuse for omnidirectional antennas [60]. Directional antenna based systems can handle communication range and spatial reuse problem for FANETs, at the same time. While it can increase communication range, it does not limit spatial reuse [61]. Depending on the higher spatial reusability, the capacity of a network with directed antenna is higher than the capacity of a network with omnidirectional antenna.

Security is another issue that can be enhanced by the help of the directed antennas. Omnidirectional antenna based systems are more prone to jamming than the directed antenna based systems [62]. A brief comparison of omnidirectional and directional antennas is provided in Table 2.

4.1.3. Open research issues

The characteristics of the physical layer affect the design of the other layers and the overall FANET performance directly. The existing FANET physical layer related studies, which are summarized in Table 3, concentrate on the radio propagation models and antenna structures.

Although the nodes are located in a 3D environment in real FANET applications, most of the existing studies assume 2D FANET topology structures. The FANET studies have shown that the antenna behaviors in 3D can be different from the antenna behaviors in 2D [51], and it can affect the physical layer directly. The performance analysis of the existing physical layer protocols and developing new physical layer designs for 3D are largely unexplored issues for FANETs.

4.2. MAC layer

Although MANET, VANET and FANET have different challenges and characteristics, they have also several common design considerations. Basically, FANET is a special subset of MANET and VANET. In this sense, the first FANET examples use IEEE 802.11 with omnidirectional antennas [34,32], which is one of the most commonly used MAC layers for MANETs. By the help of the request-to-send (RTS) and clear-to-send (CTS) signal exchange mechanism, IEEE 802.11 can handle the hidden node problem [63].

4.2.1. Challenges of FANET MAC layer

High mobility is one of the most distinctive properties of FANET, and it presents new problems for the MAC layer. Because of the high mobility and the varying distances between nodes, link quality fluctuations take place in FANETs frequently. Link quality changes and link outages directly affect FANET MAC designs. Packet latency is another design problem for FANET MAC layer design. Especially for real time applications, packet latency must be bounded and it

Table 2
The comparison of omnidirectional and directional antennas for FANETs.

Attribute	Omnidirectional	Directional
Signal direction	All	Desired
Node orientation	Not needed	Needed
Transmission range	Shorter	Longer
Latency	Higher	Lower
Spatial reusability	Lower	Higher
Capacity	Lower	Higher
Prone to jamming	Higher	Lower

Table 3
An overview of physical layer related studies for FANETs.

Physical layer study	Short description
Characterization of FANET communication links [51]	The gray regions were observed in FANET experiments and it showed that the radio propagation model of UAV-to-UAV links is similar to two-ray ground model, rather than free space model
Channel modeling of FANET links [52]	Rician fading based two-state Markov model was developed to model wireless channel between UAVs. The simulations showed that the proposed model can simulate packet dropouts
Nakagami-m based FANET radio propagation model [54,55,53]	A mathematical expression for the link outage probability over Nakagami-m fading channel was derived for FANETs
General link outage model for FANETs [56]	A general analytical formula was provided for the outage of UAV-to-UAV and UAV-to-ground links over various fading channels. Rayleigh, Nakagami-m, and Weibull models were studied as fading channels
Multiple transmitters and receivers [57]	UAV receiver nodes can achieve poor packet reception correlation at short time scales. The usage of multiple transmitters and receivers improves packet delivery rates dramatically

imposes new challenges. Fortunately, there are new technologies that can be used to meet the FANET requirements in MAC layer. Directional antenna and full-duplex radio circuits with multi-packet reception are some examples of promising technological advancements that can be used in FANET MAC layer [58,64].

4.2.2. Directional antenna based FANET MAC layer

Directional antennas have several advantages over omnidirectional antennas for FANETs, as it is provided in the physical layer subsection. Besides the advantages of directional antennas, it also brings unique design problems, especially for the MAC layer. An extensive survey about directional antenna based MAC protocols can be found in [65].

While most of the existing directional antenna based MAC layers are proposed for MANET and VANET, there are also a few researches about FANET MAC layer design with directional antennas. In [66], Alshbatat and Dong have proposed Adaptive MAC Protocol Scheme for UAVs (AMUAV) [66]. While AMUAV sends its control packages (RTS, CTS, and ACK) with its omnidirectional antenna, DATA package is sent by directional antennas. It is proved that directed antenna based AMUAV protocol can improve throughput, end-to-end delay and bit error rate for multi-UAV systems.

4.2.3. MAC layer with full-duplex radio and multi-packet reception

In traditional wireless communication, reception and transmission cannot be performed at the same time. With the recent advancements on the radio circuits, it is now possible to realize full-duplex wireless communication on the same channel [58]. Another restriction of the traditional wireless communication is about the packet reception. If there is more than one sender, the receiver cannot receive the data correctly. Fortunately, data reception from more than one source is possible by the help of the multi-packet reception (MPR) radio circuits [64]. Full-duplex and MPR radio circuits have significant impacts on the FANET MAC layer.

Channel state information (CSI) is one of the most important parameters for full-duplex radios, and it is almost impossible to determine the perfect CSI, in highly dynamic environments, as in FANETs. In [67], a new token-based FANET MAC layer was proposed with full-duplex and multi-packet reception (MPR) radios. It aims frequent CSI update so that UAVs can have the latest CSI information at any time. Token-based structure of CSI updates eliminates packet collisions. Performance results have shown the effectiveness of the proposed MAC layer, even if the resulting channel knowledge is imperfect.

4.2.4. Open research issues

Providing a robust FANET MAC layer necessitates to address and overcome some unique challenging tasks such as link quality variations caused by high mobility, and longer distance between nodes. Although the first FANET test beds have used IEEE 802.11 with omnidirectional antennas, it cannot respond to the requirements of FANETs. There are only a few studies about FANET MAC layers which are presented in Table 4.

In order to overcome the unique challenges of FANET, directed antenna technology, which can send the signal to a desired direction, is a promising technology. Location estimation of the nodes and sharing this information are vital issues for directed antenna based MAC layers, and they are more challenging for FANETs, where the nodes are highly mobile. Most of the existing directed antenna based MAC layers assume that the location information is maintained by the upper layers and cannot offer a robust and integrated solution in the MAC layer [65]. Localization service can be integrated in the MAC layer to find the locations of the other UAVs that are constantly changing their coordinates.

Although there are several unique challenges of FANET, it has also a number of opportunities for MAC layer design. In most of the MANET designs, energy is one of the most considerable constraints. However, FANET protocols have to work on UAVs and there is no practical energy restriction on UAVs. FANET nodes can include and operate more advanced hardware than the MANET nodes. This opportunity can be used to develop more efficient FANET MAC layers.

4.3. Network layer

The initial FANET studies and experiments are designed with the existing MANET routing protocols.

One of the first flight experiments with FANET architecture is performed in SRI International [68]. In this research, Topology Broadcast based on Reverse-Path Forwarding (TBRPF) [69], which is basically a proactive protocol, is used as the network layer to minimize the overhead. In

Table 4
An overview of FANET MAC layer protocols.

MAC layer protocol	Short description
Adaptive MAC protocol scheme for UAVs (AMUAV) [57]	It sends its control packages (RTS, CTS, and ACK) with its omnidirectional antenna, and DATA package is sent by directional antennas. It can improve throughput, end-to-end delay and bit error rate for multi-UAV systems
Token-MAC [57]	It is based on a token-based technique to update channel information and update link states. It eliminates code collision problem with its token-based structure. It can also decrease the latency and improve the throughput with the usage of full-duplex and MPR radio circuit

[70], Brown et al. developed another FANET test bed with Dynamic Source Routing (DSR) [71] protocol. The main motivation to choose DSR is its reactive structure. The source tries to find a path to a destination, only if it has data to send. There are also some other FANET studies that use DSR. Khare et al. stated that DSR is more appropriate than proactive methods for FANETs, where the nodes are highly mobile, and the topology is unstable [72].

Because of the high mobility of the FANET nodes, maintaining a routing table, as in proactive methods, is not optimal. However, repetitive path finding before each packet delivery, as in reactive routing, can also be exhaustive. A routing strategy only based on the location information of the nodes can satisfy the requirements of FANET. In [73], proactive, reactive and position-based routing solutions are compared for FANETs. It was shown that Greedy Perimeter Stateless Routing (GPSR) [74], which is a position-based protocol, outperformed proactive and reactive routing solutions. Shirani et al. developed a simulation framework to study the position-based routing protocols for FANETs [75]. It was stated that greedy geographic forwarding based routing protocols can be used for densely deployed FANETs. However, the reliability can be a serious problem in case of sparse deployments. A combination of other methods, like face routing, should be used for the applications that require 100% reliability.

Although the first FANET implementations have used the existing MANET routing strategies, most of the MANET routing algorithms are not ideal for FANETs, because of the UAV specific issues such as rapid changes in the link quality and very high node mobility [32]. Therefore, FANET specific routing solutions are developed in recent years.

Alshbatat et al. proposed a novel FANET routing protocol with directional antenna called Directional Optimized Link State Routing Protocol (DOLSR) [76]. This protocol is based on the well-known Optimized Link State Routing Protocol (OLSR) [77]. One of the most important factors that affect the OLSR performance is to choose multipoint relay (MPR) nodes. The sender node chooses a set of MPR nodes so that the MPR nodes can cover two hop neighbors. Through the use of MPRs, the message overheads can be reduced, and the latency can be minimized. One of the most decisive design parameters for OLSR is the number of MPRs, which affects the delay dramatically. Simulation studies showed that DOLSR can reduce the number of MPRs with directional antennas, and it results in lower end-to-end latency, which is an important design issue for FANETs.

Time-slotted on-demand routing protocol is proposed in [78] for FANETs. It is basically time-slotted version of Ad-hoc On-demand Distance Vector Routing (AODV) [79]. While AODV sends its control packets on random-access mode, time-slotted on-demand protocol uses dedicated time slots in which only one node can send data packet. Although it reduces the usable network bandwidth, it mitigates the packet collisions and increases the packet delivery ratio.

Geographic Position Mobility Oriented Routing (GPMOR) was proposed for FANETs in [80]. The traditional position-based solutions only rely on the location information of the nodes. However, GPMOR predicts the movement of UAVs with Gaussian-Markov mobility model, and it uses this information to determine the next hop. It is reported that this approach can provide effective data forwarding in terms of latency and packet delivery ratio compared to the existing position-based MANET routing protocols.

Another set of routing solutions for FANETs is the hierarchical protocols, which are developed to address the network scalability problem. Here, the network consists of a number of clusters in different mission areas. Each cluster has a cluster head (CH), and all the nodes in a cluster are within the direct transmission range of the CH. The CH is in connection with the upper layer UAVs or satellites directly or indirectly as they represent the whole cluster. On the other hand, CH can also disseminate data by broadcasting to its cluster members. This model can produce better performance results when the mission area is large, and the number of UAVs is higher as depicted in Fig. 4.

One of the most crucial design issues for hierarchic routing is the cluster formation. Mobility prediction clustering is a cluster formation algorithm developed for FANET [81]. The high mobility structure of FANET nodes results in frequent cluster updates, and the mobility prediction clustering aims to solve this problem with the prediction of the network topology updates. It predicts the mobility structures of UAVs by the help of the dictionary Trie structure prediction algorithm [82] and link expiration time mobility model. It takes a weighted sum of these models and the UAV with the highest weight among its neighbors is selected as the CH. The simulation studies showed that this CH selection scheme can increase the stability of the clusters and the CHs.

In [83], a clustering algorithm for UAV networking is proposed. It first constructs the clusters on the ground, and then updates it during the operation of the multi-UAV system. Ground clustering planning calculates the clustering plan, and then chooses the CHs according to the geographical information. After the deployment of UAVs, the cluster structure is adjusted according to the mission information. Simulation studies showed that it can effectively increase the stability and guarantee the ability of dynamic networking.

Data-centric routing algorithms can also be used for FANETs. UAVs are regularly produced for application-specific missions, and it is difficult to adapt the multi-UAV system for different missions. Data-centric routing solutions can be used in FANETs for different types of applications on the same multi-UAV system. Publish-subscribe model is typically used for this type of communication architecture [84,85]. It automatically connects data producers, which are called publishers, with data consumers, which are called subscribers. Data-centric solutions are needed to perform in-network data aggregation. Unlike flooding, it only dispatches the registered data types/contents to the subscribers. In this case, point-to-multipoint data transmission can be preferred to point-to-point data transmission. Data-centric communications are decoupled in three dimensions:

- Space decoupling: Communicating parties can be anywhere.
- Time decoupling: Data can be dispatched to the subscribers immediately or later.
- Flow decoupling: Delivery can be performed reliably.

This model can be preferred when the system includes a limited number of UAVs on a predetermined path plan, which requires minimum cooperation.

4.3.1. Open research issues

Routing is one of the most challenging issues for FANETs. Because of the unique FANET challenges, the existing MANET routing solutions cannot satisfy all the FANET requirements. The existing FANET routing solutions are presented in Table 5.

Peer-to-peer communication is essential for collaborative coordination and collision avoidance of multi-UAV systems. However, it is also possible to use FANET to collect information from the environment as in wireless sensor networks, which generate different traffic pattern. All the data are routed to a limited set of UAVs that are directly connected to an infrastructure. Developing new routing algorithms that can support peer-to peer communication and converge cast traffic is still an open issue.

Data centric routing is a promising approach for FANETs. By the help of the publish-subscribe architecture of

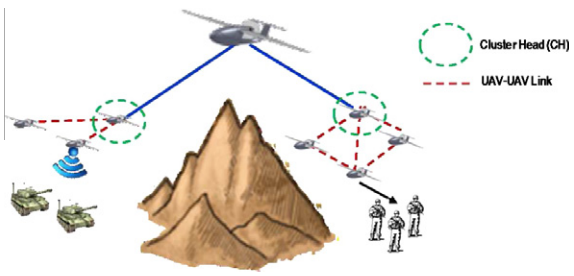

Fig. 4. Hierarchical routing in FANET.

data centric algorithms, it can be possible to produce multi-UAV systems that can support different applications. To the best of our knowledge, data centric FANET algorithms are totally unexplored.

4.4. Transport layer

The success of FANET designs is closely related to the reliability of the communication architecture, and setting up a reliable transport mechanism is essential, especially in a highly dynamic environment.

The main responsibilities of a FANET transport protocol are as follows:

- Reliability: Reliability has always been the primary responsibility of transport protocols in communication networks. Messages should be reliably delivered to the destination node to ensure proper functionalities. Data may be simple text/binary in which 100% reliability is required, or it may be multimedia streams in which low reliability is acceptable. FANET transport protocol should support different reliability levels for different FANET applications.
- Congestion control: The typical consequences of a congested network are the decrease in packet delivery ratio and the increase in latency. If a FANET is congested, collaboration and collision avoidance between UAVs cannot be performed properly. A congestion control mechanism is necessary to achieve an efficient and reliable FANET design.
- Flow control: Because of a fast sender or multiple senders, the receiver may be overloaded. Flow control can be a serious problem especially for heterogeneous multi-UAV systems.

The first FANET systems were implemented based on the existing transport protocols. Elston et al. developed a multi-UAV system with FANET communication architecture. It was operated on IP-based addressing, and the transport layer of the system supported both TCP and UDP transport schemes [86]. However, TCP performs poorly in MANET environments and it is also unsuited for FANETs [87,88]. TCP flow control functionality is based on the framing mechanism and its window size changes constantly. An accurate estimation of the round trip time is a challenging issue.

Joint Architecture for Unmanned Systems (JAUS) is an emerging standard for messaging between unmanned systems [89]. Although JAUS was firstly produced for ground systems, as Joint Architecture for Unmanned Ground Systems, it was later generalized to all kinds of unmanned vehicles (aerial, ground, surface-of-water and undersea vehicles). AS5669a [90] defines data communications for JAUS, and it enables the use of efficient transport protocols, which have their own packet formats and semantics. In AS5669a, JTCP/JUDP is designed on top of the TCP/UDP as a wrapper. JAUS also suggests JSerial protocol for data-transparent transports, which support variable length data packets when low bandwidth serial links are employed.

NATO has also a Standardization Agreement (STANAG 4586), which defines a common transport protocol for net-

Table 5
An overview of network layer protocols for FANETs.

Network layer related algorithms	Routing type	Short description
DOLSR [76]	Proactive	It utilizes directed antennas in OLSR [77] to enhance packet delivery ratio and to decrease average latency
Time-slotted on-demand routing [78]	Reactive	It embeds time-slotted reservation schema into AODV [79] to eliminate collisions
GPMOR [80]	Geographic	It predicts the movement of UAVs with Gauss–Markov mobility model, and uses this information to determine the next hop
Mobility prediction clustering [81]	Hierarchical	It utilizes the dictionary Trie structure prediction algorithm and link expiration time mobility model to predict network topology updates. In this way, it can construct more stable cluster formations
Clustering algorithm of UAV networking [83]	Hierarchical	It constructs the clusters on the ground, and then updates the clusters during the operation of the multi-UAV system

work centric operations/warfare between nodes in a multinational UAV network [91]. STANAG 4586, depicted in Fig. 5, was aimed to promote interoperability between one or more Ground Control Stations, UAVs and C4I (Command, Control, Communication, Computer and Intelligence) network, particularly in joint operational settings [92]. Unlike JAUS, STANAG 4586 is specifically developed for supporting UAV systems.

4.4.1. Open research issues

Contrary to the wired networks and MANETs, FANETs are characterized by highly mobile nodes and wireless communication links with high bit error rates. They have frequent link outages according to the positions of UAVs and ground stations. Reliability is a critical issue for FANET transport layers.

FANET applications use different types of data such as target images, acoustic signals, or video captures of a moving target. These applications require different reliability levels. While typical data communication requires 100% reliable transport protocol, multimedia application reliability requirement is lower. On the other hand, multimedia data traffic has some other strict requirements on delay, bandwidth, and jitter. Therefore, new transport layer solutions must be developed to address the requirements of different FANET applications. To the best of our knowledge, there is no transport layer specially designed for FANETs. Many aspects of FANETs, which affect the reliable and efficient data transfer protocol, are still unexplored.

4.5. Cross-layer architectures

Although layered architectures have served well for wired networks, they are not suitable for many wireless communication applications [93]. Cross-layer architectures are proposed to overcome the performance problems of the wireless environment. Cross-layer design can be defined as a protocol design by the violation of the layered communication architecture [94]. There are several ways for cross-layer architecture design. Unlike the layered design principles, the adjacent layers can be designed as a super layer. Another cross-layer protocol is to support interactions between non-adjacent layers. It is also possible to share protocol state information across all the layers to meet the specific requirements [95].

A FANET cross-layer architecture is introduced in [96], where the interaction between the first three layers of OSI reference model is facilitated. In this study, a novel directional antenna based MAC layer protocol, Intelligent Medium Access Control Protocol (IMAC-UAV), is used. Directional Optimized Link State Routing (DOLSR) protocol [76] is the network layer of this system. Cross-layer design is based on the information sharing between the first three layers. It is shown that based on the aircraft attitude variations (pitch, roll and yaw); the performance of a FANET application can be improved by the help of this cross-layer architecture.

Huba and Shenoy have proposed meshed-tree algorithm based on the directed antennas [97]. This solution integrates clustering and scheduling for MAC layer along with the routing strategy for the network layer. It can handle MAC layer and network layer with a single algorithm that can form the clusters, route the data from UAVs to the cluster heads, and schedule the time slots in a TDMA based MAC layer. This approach results in a robust and scalable solution. Performance studies have shown that it can notably enhance packet delivery rate and end-to-end latency.

4.5.1. Open research issues

As in the other types of highly dynamic wireless networks, cross-layer architecture is an effective technique to meet the strict requirements of FANET. Although there are some studies about cross-layered FANETs, which are presented in Table 6, the area is largely open for new protocols. By the help of the interactions between layers, it is possible to enhance the FANET performance. Especially, link quality status, which is related with the physical layer, can be an important parameter for the upper layers. For example, transport layer can update its operation mode to satisfy the reliability requirement of the FANET application according to the current link qualities. Another cross-layer protocol opportunity is to combine all layers into a single protocol. This unified cross-layer approach can help to design more efficient FANET architectures for multi-UAV systems.

5. FANET test beds and simulators

In this section, the existing FANET test beds and simulators are investigated to provide a quick guideline for new FANET researchers.

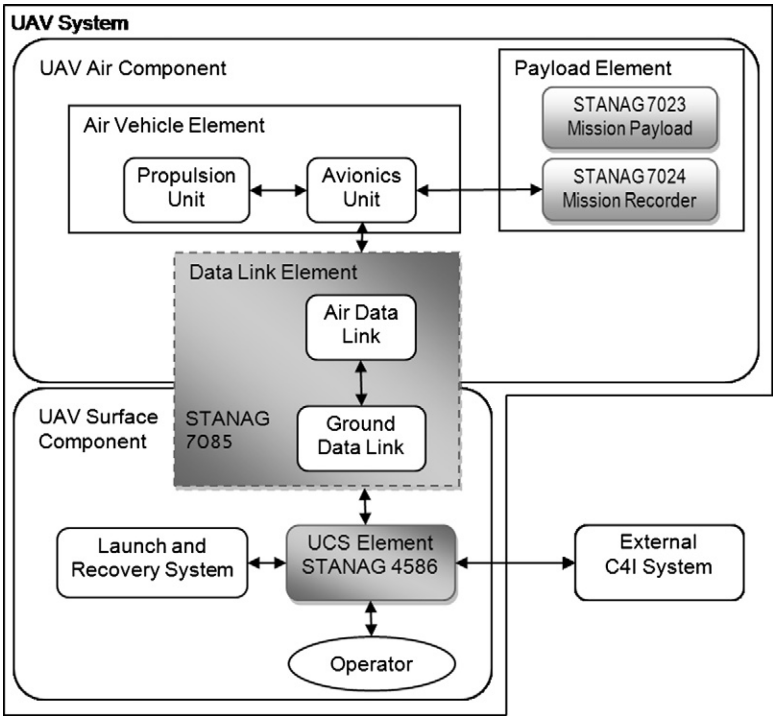

Fig. 5. UAV system interoperability architecture with STANAG 4586.

Table 6
Cross-layer FANET communication protocols.

Cross-layer protocols	Short description
IMAC-UAV with DOLSR [96]	It uses IMAC-UAV as the MAC layer and DOLSR as the network layer protocol for directed antennas. The first three layers communicate through the shared data set. In this way, the transmission parameters can be adjusted dynamically. It reduces end-to-end delay with respect to original OLSR network protocol
Meshed-tree algorithm [97]	It integrates the MAC layer and the network layer in a single protocol, which can form the clusters, route the data from UAVs to the cluster heads and schedule the time slots in a TDMA based MAC layer. It enhances packet delivery ratio and end-to-end latency

One of the first FANET test beds was implemented in University of Colorado [32]. It was developed and realized with IEEE 802.11b radio equipment mounted on small UAVs with Fidelity-Comtech bidirectional amplifier up to 1 W output and a GPS. Dynamic Source Routing (DSR) was chosen as the network protocol, and a monitoring system was embedded into the radios for detailed performance characterization and analysis.

Berkley Aerobot Team (BEAR) [98] is another multi-UAV test bed that can support UAV-to-UAV communication. BEAR research facility features a fleet of BEAR helicopter UAVs, fixed-wing UAVs, unmanned ground robots, and a mobile ground station. Rotorcraft-based Unmanned Aerial Vehicles (RUAVs) in BEAR include 802.11 wireless network cards that can be used for FANET.

Xiangyu et al. developed a new multi-UAV system based on ad hoc networking architecture [99]. The multi-UAV system successfully validated the effectiveness and feasibility of wireless ad hoc networking between UAVs.

Sensing Unmanned Autonomous Aerial Vehicles (SUAAVE) project [26] aims to create and control a UAV swarm with ad hoc networking between UAVs. The project is not limited with a particular scenario, but the platform was developed based on a search-and-rescue operation. Although the first examples of the project were planned with IEEE 802.11 protocol, SUAAVE can be used to develop new communication architectures and protocols for UAV swarms.

The UAV Research Facility (UAVRF) [100] conducts UAV related researches at Georgia Institute of Technology. The UAVRF operates different multi-UAV systems and conducts flight tests to validate research findings. Christmann et al. developed a FANET implementation with IEEE 802.11 communication hardware in UAVRF [101].

The above-mentioned multi-UAV test beds are designed to work in outdoor conditions. In order to create a more controlled environment for rapid prototyping and initial tests, there are also indoor test beds. Indoor multi-UAV test beds are designed to test UAV perfor-

Table 7
FANET test beds and simulators.

Project	University/Institution/Lab	Type	Internet address
Test bed for a wireless network on small UAVs [32]	University of Colorado, Interdisciplinary Telecommunications Electrical and Computer Engineering	Outdoor test bed	http://itd.colorado.edu/
Berkley Aerobot team (BEAR) [98]	University of California, Berkeley, Robotics Lab	Outdoor test bed	http://robotics.eecs.berkeley.edu/
Multi-UAV system for verification of autonomous formation [99]	Beihang University, School of Automation Science and Electrical Engineering	Outdoor test bed	http://id.buaa.edu.cn/IDO/English/
Sensing Unmanned Autonomous Aerial Vehicles (SUAAVE) [26]	SUAAVE consortium (UCL, Oxford, Ulster with Engineering and Physical Sciences Research Council)	Outdoor test bed	http://www.suaave.org/
The UAV Research Facility (UAVRF) [100]	Georgia Institute of Technology, UAV Lab	Outdoor test bed	http://controls.ae.gatech.edu/wiki/UAV_Research_Facility
Real-time indoor Autonomous Vehicle test ENvironment (RAVEN) [102]	MIT, Aerospace Controls Laboratory	Indoor test bed	http://acl.mit.edu/
General Robotics, Automation, Sensing, and Perception (GRASP) Micro UAV Test Bed [103]	University of Pennsylvania, GRASP Lab	Indoor test bed	https://www.grasp.upenn.edu/
Real time multi-UAV simulator (RMUS) [104]	The University of Sydney, Australian Center for Field Robotics	Simulator	http://www.acfr.usyd.edu.au/research/index.shtml
Simulator and Test bed for Micro-Aerial Vehicle Swarm Experiments (Simbeeotic) [106]	Harvard School of Engineering and Applied Sciences	Simulator	http://robobees.seas.harvard.edu

mances in restricted and controlled large rooms. The Aerospace Controls Laboratory at MIT utilizes a UAV test bed facility, Real-time indoor Autonomous Vehicle test Environment (RAVEN) [102]. RAVEN uses a motion capture system to enable rapid prototyping of aerobatic flight controllers for helicopters and airplanes; robust coordination algorithms for multiple helicopters; and vision-based sensing algorithms for indoor flight. General Robotics, Automation, Sensing, and Perception (GRASP) [103] is another indoor test bed developed in University of Pennsylvania. It is developed to support research on coordinated, dynamic flight of micro UAVs with broad applications to reconnaissance, surveillance, manipulation and transport.

Another way to investigate FANET designs is to simulate the developed algorithms with a realistic multi-UAV system simulator which can support ad hoc networking. Although there are many multi-UAV simulators, most of them do not model UAV-to-UAV communication links. Real time multi-UAV simulator (RMUS) [104], which is designed to work with IEEE 802.11, is one of the first multi-UAV simulators that support the direct communication links between UAVs. It is implemented as both a testing and validation mechanism for the real demonstration of multiple UAVs conducting decentralized data fusion and control [105].

A Simulator and Test bed for Micro-Aerial Vehicle Swarm Experiments (Simbeeotic) [106] is proposed as an open source simulator in Harvard University for UAV swarms that consist of up to thousands of mini or micro UAVs. It can simulate the physical movements of the UAV swarm as well as the communication architecture between UAVs. It is possible to develop algorithms and rapid prototyping with Simbeeotic. It supports both pure simulation and hardware-in-loop experimentation. Simbeeotic can cover a complete view of the UAV swarm system, including actuation, sensing, and communication.

A list of the existing FANET test beds and simulators is given in Table 7.

5.1. Open research issues

Although the existing multi-UAV test beds and simulators can support a certain variety of UAVs, they enable very restricted variety of network protocols, like IEEE 802.11. On the other hand, the existing network simulators, such as OPNET [107] and ns-2 [108], can simulate different communication protocols with different parameters. However, they cannot readily model multi-UAV system specifications and mobility structures. Although there are several FANET researches simulated on OPNET, it has no built-in UAV node structure or UAV communication channel model to simulate FANETs. ns-2, which is one of the common network simulators, cannot model 3D communication, which is an important parameter for FANET design [51].

In order to simulate new FANET designs, a multi-UAV simulation tool that can simulate various UAV platforms and network protocols is needed. The FANET simulator must be able to model different UAV specifications, different multi-UAV formations, different multi-UAV mobility structures, along with different network protocols.

6. Conclusion

Communication is one of the most challenging design issues for multi-UAV systems. In this paper, ad hoc networks between UAVs are surveyed as a separate network family, Flying Ad-hoc Network (FANET). We formally define FANET and present several FANET application scenarios. We also discuss the differences between FANET and other ad hoc network types in terms of mobility, node density, topology change, radio propagation model, power consumption, computational power and localization. FANET design considerations are also investigated as adaptability, scalability, latency, UAV platform constraints, and bandwidth. We provide a comprehensive review of the recent literature on FANETs and related issues in a layered approach. Furthermore, we also discuss open research issues for FANETs, along with the cross-layer designs. The existing FANET test beds and simulators are also presented.

To the best of our knowledge, this is the first article which surveyed flying ad hoc network as a separate ad hoc network family. Our main motivation is to define multi-UAV ad hoc network problem, and to encourage more researchers to work for the solutions to open research issues as described in this paper.

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