J Intell Robot Syst
DOI 10.1007/s10846-013-9959-7

# Networking Models in Flying Ad-Hoc Networks (FANETs): Concepts and Challenges

**Ozgur Koray Sahingoz**

Received: 7 September 2013 / Accepted: 14 September 2013


**Abstract** In recent years, the capabilities and roles of Unmanned Aerial Vehicles (UAVs) have rapidly evolved, and their usage in military and civilian areas is extremely popular as a result of the advances in technology of robotic systems such as processors, sensors, communications, and networking technologies. While this technology is progressing, development and maintenance costs of UAVs are decreasing relatively. The focus is changing from use of one large UAV to use of multiple UAVs, which are integrated into teams that can coordinate to achieve high-level goals. This level of coordination requires new networking models that can be set up on highly mobile nodes such as UAVs in the fleet. Such networking models allow any two nodes to communicate directly if they are in the communication range, or indirectly through a number of relay nodes such as UAVs. Setting up an ad-hoc network between flying UAVs is a challenging issue, and requirements can differ from traditional networks, Mobile Ad-hoc Networks (MANETs) and Vehicular Ad-hoc Networks (VANETs) in terms of node mobility, connectivity, message routing, service quality, application areas, etc. This paper identifies the challenges with using UAVs as relay nodes in an ad-hoc manner, introduces network models of UAVs, and depicts open research issues with analyzing opportunities and future work.

O. K. Sahingoz (✉)
Computer Engineering Department,
Turkish Air Force Academy, Yesilyurt,
Istanbul, 34149, Turkey
e-mail: sahingoz@hho.edu.tr

**Keywords** Networking models · Multi-UAVs · FANET · VANET · Mobile networking · UAV networks

## 1 Introduction

In the last two decades, as a result of the rapid technological advancement in computation, sensor, communication and networking technologies, Unmanned Aerial Vehicles (UAVs) promise new application areas for military and civilian areas such as, relay for ad-hoc networks [1–3], search and rescue operations [4], electronic attacks in hostile areas [5], ground target detection and tracking [6, 7], automatic forest fire monitoring and measurement [8], wind estimation [9], disaster monitoring [10], remote sensing [11], airspeed calibration [12], agricultural remote sensing [13], etc.

It is a relatively easy task to use UAVs in an Unmanned Aerial System (UAS) for increasing communication range and data aggregation capability of nodes in a system. In case of infrastructure-less places, such as enemy territories or natural disaster areas, there is an immediate need to build a network between teams, and a

Published online: 02 October 2013

fast-deployed UAV can be an acceptable solution as a relay node.

In single-UAV applications, each ground node can easily communicate with the UAV, and thus establish a star topology network structure where the UAV is at the center of the star. By using this topology, a ground node can indirectly communicate with others over the UAV. However, single UAV systems have some challenging issues in peer-to-peer communication such as increasing transmission range, sending more data, and minimizing any interference. A solution to these problems is the use of high gain directional antennas instead of omnidirectional antennas. Undoubtedly, this leads to a limited improvement in the performance of UAS, and this is not satisfactory.

To provide a longer presence over the theatre of operation in order to carry powerful processors, sensors and communication hardware, a large UAV is preferred in single vehicle UASs, in which setting up a communication environment is easy. However, they are not only heavy and large but also pose a significant danger to human life and property in case of a failure. Moreover, they are expensive, and failure of a UAV can have a high cost.

On the other hand, technological advancement of electronics and sensor technologies have decreased the production cost of UAVs, and low-cost mini-UAVs are becoming more and more popular in both academic areas and practical applications. They are small in size and weight; therefore, they pose little or no threat to human life and buildings/properties. In addition, they can be reused for various types of applications. It is difficult to detect and track UAVs while they are flying, due to their size. They can fly at much lower altitudes, can be easily transported to different areas, and can be launched by an individual in any kind of terrain without a runway or a specific launching device. However, mini-UAVs have restricted capabilities such as power, sensing, communication, and computation; however, the use of a team with mini-UAVs, as multiple UAVs, improves the capability and capacity of UASs and provides a flexible platform for a variety of applications. Usage of multi-UAV systems has significant advantages over single UAV systems:

- Especially in search missions, the usage of a number of UAVs can parallelize individual tasks thus decreasing the completion time of a mission.
- In a single UAV system, if the UAV or a sensor/hardware fails, the UAV should return to the base. However, in multi-UAV systems, other UAVs can share tasks among themselves and this increases the fault tolerance of the system.
- In a heterogeneous UAV team, it is possible to use the capabilities of other UAVs.

On the other hand, these advantages and improvements have a challenging issue: *efficient communication and coordination of UAVs in the team*. Therefore, a multi-UAV system needs some required hardware and a well-defined networking model whose communication/network layer is depicted in Fig. 1.

To achieve effective management of multiple UAV systems, and to perform complex tasks,

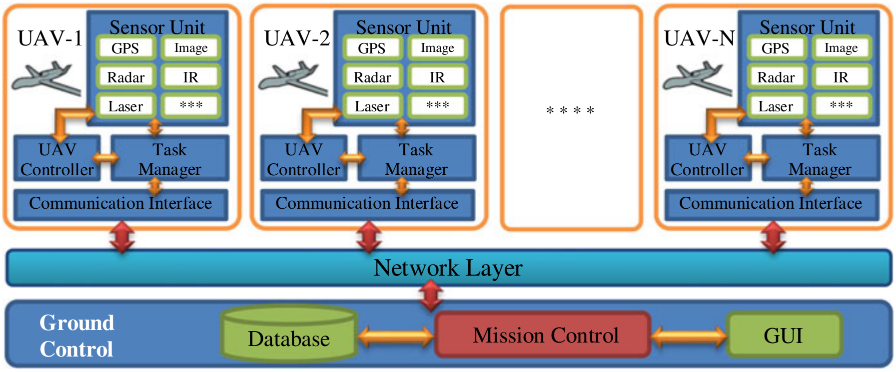



**Fig. 1** A multi-UAV system's processing units and communication/network layer

UAVs need to cooperate with others in the team. To enable this cooperation, UAVs are constrained to stay within the communication range of one another. UAVs must achieve a high degree of coordination and a robust inter-vehicle communication network in an ad-hoc manner. Traditionally, the communication technologies on fixed networks, Mobile Ad-hoc NETworks (MANETs), and slowly moving Vehicular Ad-hoc NETworks (VANETs) do not address the unique characteristics of these networks, which use highly mobile nodes. Therefore, there is a requirement of defining a new ad-hoc networking model, which differs from other kinds of ad-hoc networks along the connectivity, quality of services, sensor types, node movement features, data delivery, service discovery, etc.

In the literature, some academic researchers have defined the explained UAV networking model with different names, as depicted in Table 1.

Although, the used names have little differences in their definitions, it is a clearly seen fact that the new communication model is a subclass of VANET. However, VANET routing protocols are not feasible or does not provide sufficient throughput for networks with highly mobile nodes. Therefore, it is more appropriate to name this new networking model as a Flying Ad-Hoc Network *(FANET)* [14], a subclass of a VANET.

While considering the advancements in ad-hoc networking, it can be explicitly foreseen that UAVs will play an attractive function in setting up a highly mobile networks for enlarging the theatre of the operation. Therefore, the intent of this paper[1] is to introduce the challenges and networking models in FANET, and to present some open issues and future opportunities for researchers on this topic.

In the following, background information about UAS and MANET is given in Section 2. After that, the ad-hoc networking concepts with flying objects are introduced, and different networking models for FANET Network Layer are given in Sections 3 and 4, respectively. Subsequently, open issues and challenges are depicted in Section 5. Finally, the paper is concluded in Section 6.

**Table 1** Names of highly mobile networking model

| Given name | Reference |
|---|---|
| Airborne network (Airborne Telemetry Network, Airborne Communication Network, Airborne Backbone Network, etc.) | [15, 16] |
| Networked Aerial Robots | [17] |
| Unmanned Aeronautical Ad-Hoc Network (UAANET) | [18, 19] |
| UAV Ad-Hoc Network | [20] |
| Aerial Communication Network | [21] |
| Networks of UAVs | [22, 23] |
| Distributed Aerial Sensor Network | [24] |
| Flying Ad-Hoc Network (FANET) | [14] |

## 2 Background

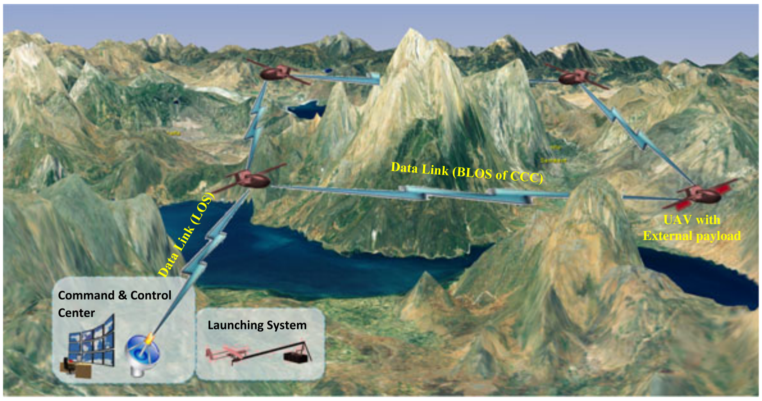
### 2.1 Unmanned Aerial System (UAS)

While UAV technology and markets develop; its cost, weight and size decrease and performance of sensors/processors increases. These results lead to a considerable interest and research on UAVs, and hence, UASs have shown exceptional promises for lots of application areas. A UAS consists of five main components (as depicted in Fig. 2):

- A **UAV** is a pilotless aircraft that does not require any direct human intervention for flying. It can navigate autonomously according to its pre-programmed software, or can be controlled remotely. Apart from basic plane components, it also contains some computing devices and sensors for determining its position and for gathering information from the mission area. A UAV can be categorized as a *"Fixed Wing Vehicle"*, which needs a launch system for take-off, or *"Rotor Wing Vehicle"* where vertical take-offs and landings (VTOL) are possible. UAVs are also classified as *"mini", "small", or "large"*, according to their weights.

[1] A preliminary version [25] of this paper was presented at ICUAS 2013, Atlanta.

**Fig. 2** Unmanned aerial system with components




- **Payloads** are essential systems in UAVs, and they are mainly the equipment added to the UAV for carrying out various operational missions. These include sensors, emitters, lethal/nonlethal weapons, stores, etc. Mainly, payloads are carried in an internal payload bay of the UAV; in some cases, they can also be attached to the UAV, but this can result in a mild **deterioration** of the **aerodynamic** properties of the UAV.
- **Command and Control Center** contains a *Ground Control Station (GCS)* and provides technological facilities for human interactions to the UAVs in the air.
- A **Launch System** is generally a catapult system, which gives a UAV its flight speed in an extremely short time and distance. At the same time, most of the mini-UAVs can be launched by hands while large UAVs need an airfield for take-off and landing.
- **Control and Data Transmission Links** are used to describe how information is sent/received both to/from the GCS and UAVs. If UAVs are in the line-of-sight (LOS), direct radio links can be used; however, if they are beyond line-of-sight (BLOS), then there is a need of higher level mediator such as satellites or another UAV.

Undoubtedly, UAV is the most crucial part of the above-mentioned components. Therefore, the performance, capacity, and operation theatre of the UAS directly related to its abilities, such as endurance, range, altitude, payload, etc. To use UASs in different application areas, there is a requirement of decreasing the personnel needs and increasing the autonomy of UAVs by which they can fly freely in the sky and carry out the mission without any centralized controller from the ground station.

## 2.2 Mobile Ad-Hoc Networking

A Mobile Ad-Hoc Network (MANET) is a dynamically self-organizing and infrastructure-less network of mobile devices such as laptop, palmtop, cellphones, walkie-talkies, etc. These devices can communicate over bandwidth-constrained wireless links such as IEEE 802.11 a/b/g/n, 802.16, etc. Each device in MANET can move randomly with different speeds; therefore, its links with other devices change frequently. For transferring data between two remote nodes, each mobile device must forward some data, which are unrelated to its own use; therefore, a MANET runs not only as a host but also as a router.

MANET nodes are traditionally small and have limited processor and energy capacities. It is difficult to build and maintain such a network in a longer time span. Therefore, some main functionality of network layers, such as routing, should be done by these mobile nodes dynamically.

With the rapid enhancement in technologies and sensors, there has been an increase in utilization rates, and application areas of MANET. As a result, mobile nodes have begun to embed in moving vehicles, such as cars, ambulances, fire engines, tanks, etc. This networking concept is called a Vehicular Ad-Hoc Network (VANET), which is a part of an Intelligent Transport System of smart vehicles with additional properties such as collision/distance warning, driver assistance, cooperative driving/cruise control, propagation of road information, etc.

## 3 Ad-Hoc Networking with Flying Nodes

With the increasing usage of multi-UAVs in an ad-hoc manner, a need for a new networking layer has emerged. The mobile nodes of the systems are highly mobile vehicles (UAVs); therefore, this layer is mainly a subclass of VANET, and this is located in a sub layer of an Aerial Network Layer, as depicted in Fig. 3 of a network-centric architecture [25]. A network layer is principally responsible for the routing process, which selects an appropriate path between the sender nodes and receiver nodes over different routers/nodes. The main task of a FANET Network Layer is to act as an intermediary between these layers while performing the traditional routing on its own level.

Using multi-UAVs in an ad-hoc network manner brings some advantages [14]:

- **Decreases the mission completion time:** The missions, such as reconnaissance, surveillance, search and rescue, can be carried out faster with proportional to the number of UAVs.
- **Decreases total/maintenance cost:** Instead of using a large and expensive UAV, the usage of multi-mini-UAVs costs are lowered in terms of acquisition and maintenance.
- **Increases scalability:** It increases the area of operation theatre by easily adding new UAVs. UAS dynamically reorganizes nodes' routing tables by taking into account newly added UAVs.
- **Increases survivability:** Multi-UAV systems are more tolerant to faults of hardware/ sensors. In the case of some sensors failing or a loss of control of a UAV, the mission can continue with any remaining UAVs.
- **Decreases detectability** (Low radar cross-section): A radar cross-section is extremely crucial for military applications. Mini-UAVs have low radar cross-sections, low infrared signatures, and low acoustic signatures due to their sizes and composite structures. Therefore, they may not be easily detectable by radars (especially compared to airplanes and large UAVs).

Although multi-UAV systems have some significant advantages; due to their dynamic network topology, communication of two distant nodes over other UAVs is still a challenging issue. Fueled by this requirement, in the literature,

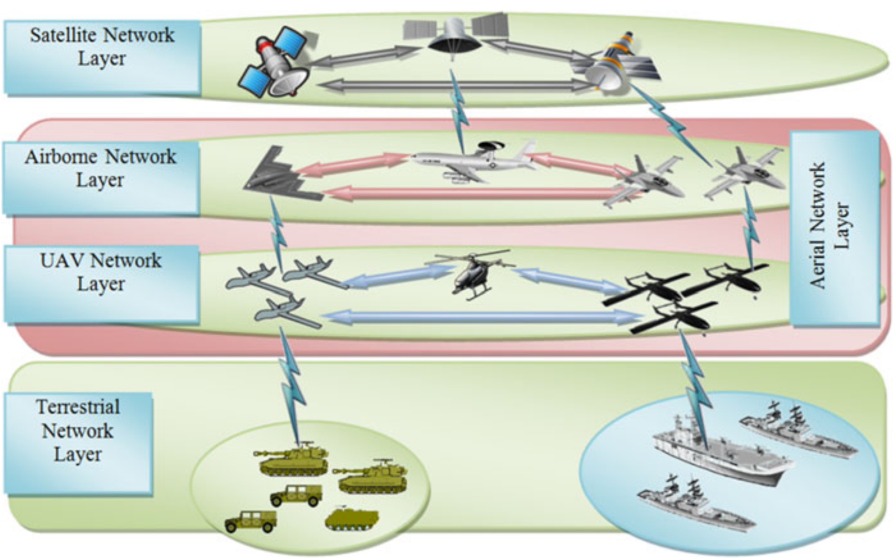



**Fig. 3** A network-centric architecture in a battlefield

some routing protocols have been proposed for FANETs. These protocols mainly depend on communication types. In a FANET, there are mainly two different communication types: *UAV-to-UAV* and *UAV-to-Infrastructure communications.*

*In UAV-to-UAV communication*, each UAV can communicate with others in order to meet the needs of different application areas, such as cooperative path planning and target tracking. Two UAVs can either directly communicate with each other, or a multi hop communication path can be constructed over other UAVs. UAVs can have short range, and long range of communication between them, selection of the range also depends on the needed data transfer rate.

*In UAV-to-Infrastructure communication*, UAVs communicate with a fixed infrastructure, such as ground stations, satellites, or warships near the operation theatre to provide information services for other users in the global networks.

Communication between UAVs and UAV-to-Infrastructure is also a challenging issue. To increase the data transfer rate and the performance of the system, different type of antennas and sensors can be used. With the usage of GPS receivers and directed antennas, like phased array antennas, communication links can be effectively set in FANET.

Namudiri et al. divides design principles of a network with flying nodes in four different dimensions, as depicted in Fig. 4 [26]. They claimed that the synergy between these components significantly improves the capabilities of a system. With the same goal, U.S. Unmanned Systems Roadmaps [27, 28] highlight some key enabling

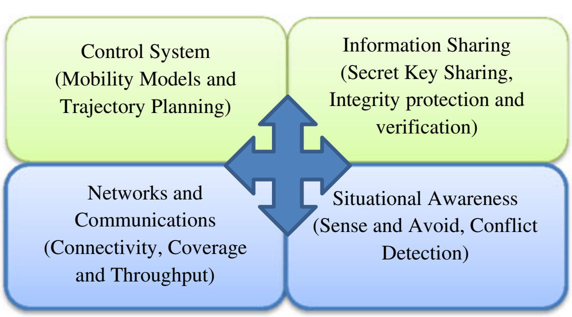



**Fig. 4** A network-centric architecture in a battlefield

networking technologies, which are planned to be developed as follows:

- Mobile ad-hoc networking protocols that enable high reliability command and control of autonomous UAVs.
- Better data compression, encryption and processing algorithms.
- Embedded network security with single-chip all-encapsulated encryption modules.
- High-gain, rugged, and lower cost multidirectional antennas.
- Highly efficient radios for low bandwidth and full-time high-speed communications links.
- Support of various path diversity techniques, integrated networking, and data diversity.

While these UAV technologies are evolving at a fast pace, the size of UAVs has been decreased, and the number of UAVs in UASs has been increasing. Hence, installing and maintenance of the networked communication between these UAVs and ground stations are emerged as crucial issues to solve. Especially in some application fields, which use heterogeneous UAVs with different payload capacity, sensors, avionics, communication range, and flight endurance; communication and coordination of UAVs are challenging tasks in order to achieve such a networked communication. In the following section, different routing protocols in Network Layer of FANET are described.

## 4 FANET Networking Models

In the literature [29, 30], many routing protocols exists in wireless and ad-hoc networks such as precomputed routing, dynamic source routing, on-demand routing, cluster based routing, flooding, etc. Due to a shortage of energy, to increase the FANET operation time, there are some needs to decrease transmitting power by sending a message to closer nodes (UAVs) and by using multi-hop routing between the sender and receiver nodes over highly mobile UAVs as relay nodes. FANET is a subclass of VANET and MANET; therefore, firstly typical MANET routing protocols are preferred and tested for FANET. Due to the UAV-specific issues, such as quick changes in link quality, most of these protocols are not directly applicable for FANET. Therefore, to adopt this new networking model, both some specific ad-hoc networking protocols have been implemented and some previous ones have been modified in the literature. These protocols can be categorized in four main classes;

- **Static protocols** have static routing tables there is no need to refresh these tables.
- **Proactive protocols**, also known as table driven protocols, are periodically refreshed routing tables.
- **Reactive protocols**, also called on-demand protocols, discover paths for messages on demand.
- **Hybrid protocols** use both proactive and reactive protocols.

By using these routing protocols, a FANET can dynamically discover new routes between communicating nodes, and this network may allow addition and subtraction of UAV nodes dynamically.

### 4.1 Static Routing Protocols

In static routing protocol, a routing table is computed and loaded to UAV nodes before a mission, and cannot be updated during the operation; therefore, it is static. In this type networking model, UAVs typically have a constant/fixed topology [31]. Each node can communicate with a few numbers of UAVs or ground stations, and it only stores their information. In case of a failure (of a UAV or ground station), for updating the tables, it is necessary to wait the end of the mission. Therefore, they are not fault tolerant and appropriate for dynamic environments.

*Load Carry and Deliver Routing (LCAD)* [32, 33] is one of the first routing models in FANET. In this model, a UAV loads data from a ground node (or gets video image of its path); after that, it carries these valuable data to the destination by flying; and finally it delivers the data to a destination ground node (such as a military team or a ground control station), as depicted in Fig. 5. Although, in the initial definition of LCAD, a single-source and a single-destination networking scenario was considered, in practice, multiple-source multiple-destination networking scenarios can also be implemented easily. Due to the distant location of communicating nodes (the use of ground nodes and no other UAVs used for multi-hop communication), LCAD is free of interference in the same networking system, and this increases the throughput of the system. This routing methodology is a feasible solution especially for bulk data transfer (such as latency-insensitive video images) and delay-tolerant applications (such as secure transfer) with minimum hops [34]. LCAD routing aims to maximize the throughput while increasing the security. However, as the distance of communicating parts increases, the transmission delay becomes extremely large and intolerable. In this case, transmission time depends mainly on how fast a UAV can fly this distance. At the same time, a UAV can get data from the source nodes/places, only when it is over them. If there is only one UAV, it is not possible to capture each event on a specific area or load data from the source node when it is produced. To decrease the transmission time; more than one UAV can be used on the same path, speed of UAVs can be increased, and a LCAD network can be divided into smaller LCAD sub-networks.

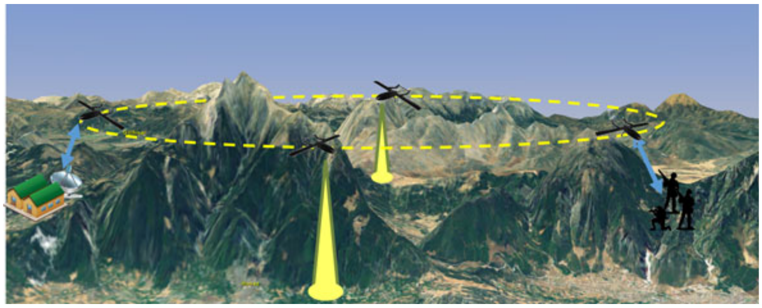


**Fig. 5** Load carry and deliver routing model

*Multi-Level Hierarchical Routing*: Due to the structure of the typical VANET environment, the routing protocols are especially organized as flat routing in two dimensional space. However, in UAV-based network applications, the flying environment is generally modeled in three dimensional space, and nodes have different attributes such as size, flight height, energy usage capabilities, types of sensors, etc. Large-scale VANET applications with hundreds/thousands of mobile nodes and typical FANET applications with classical flat routing result in a certain performance degradation. To solve this problem and to increase the network scalability, one appropriate solution is the use of hierarchical routing protocols [35, 36], which divide FANET into clusters of UAVs.

Hierarchically organized UAV networks consist of a number of clusters to operate in different mission areas, as shown in Fig. 6. Each cluster has a cluster head (CH), which represents the whole cluster, and it is possible to assign different functionalities to each cluster. Each CH is in connection with the upper/lower layers (ground stations, UAVs, satellites, etc.) directly or indirectly. To disseminate data (by broadcasting) and control information to other UAVs in the cluster, CH should be in direct transmission range of other UAVs in cluster. This model is better if UAVs are organized in different swarms, the mission area is large, and many UAVs are used in the network.

*Data Centric Routing*: Due to the nature of the wireless communication structure of UAVs, one-to-many data transmission can be preferred to one-to-one data transmission [37, 38]. This routing is preferred when the data is requested by a number of nodes, and it is distributed according to on-demand algorithms. Data-centric routing is a promising paradigm of routing mechanism and can be adapted for FANET [39, 40]. In this model, the data request and collection is done according to data attributes rather than sender or receiver nodes' IDs as depicted in Fig. 7. This model is generally practiced with cluster structures and publish-subscribe model, which depicts its efficiency on distributed computing models [41, 42].

In this model, the consumer node (can be a ground node or a UAV) disseminates queries (such as "get photo images of area A if there is a change of more than % 5") as subscription message in order to collect specific data from a specific area. The producer node decides which information to publish and starts data dissemination. When published data reach a UAV (as a relay node), it checks the subscription messages on it and forwards these data accordingly. Routing is done with respect to the content of data; and if needed, data aggregation algorithms can be used for energy-efficient data dissemination. Although, query dissemination and data collection processes add some extra burden to the network load; due to the elimination of redundant transmissions,

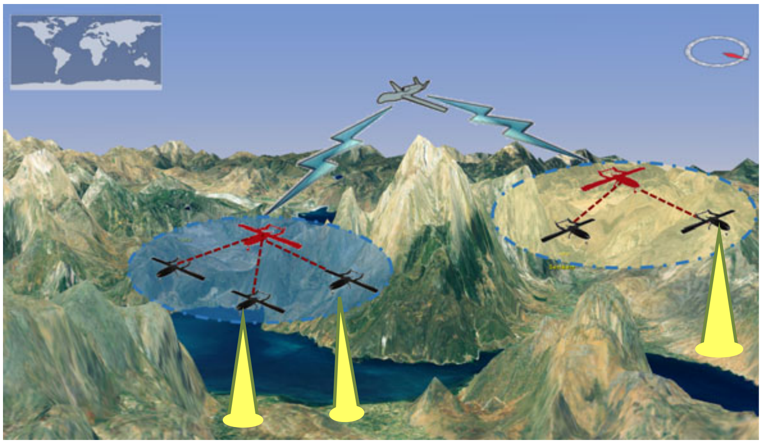
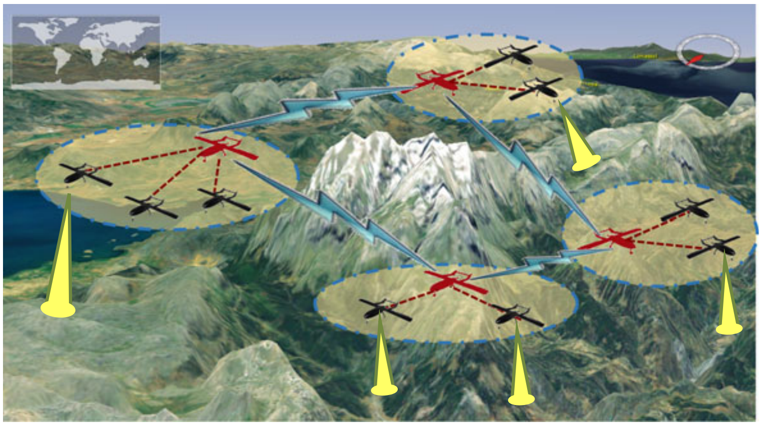


**Fig. 6** Hierarchical routing model

**Fig. 7** Data centric routing model



usage of this model results total efficiency increase. This type routing performs three dimensions of decoupling;

- **Space decoupling** means that communicating parties do not need to know each other's ID or location.
- **Time decoupling** means that communicating parties do not need to be on-line at the same time to communicate.
- **Flow decoupling** results in an asynchronous communication structure; therefore, message sending process is not blocked by outside interactions.

A data centric routing model, especially preferred for the cluster structured UAS, drives the UAV mission along a predetermined flight-plan and does make high level cooperation between clusters.

### 4.2 Proactive Routing Protocols

Proactive routing protocols (PRP) use tables to store all the routing information of each other's node or nodes of a specific region in the network. Various table-driven protocols can be used in FANET, and they differ in the way of update mechanism of the routing table when the topology changes. The main advantage of proactive routing is that it contains the latest information of the routes; therefore, it is easy to select a path from the sender to the receiver, and there is no need to wait. However, there are some explicit disadvantages. Firstly, due to the need of a lot of message exchanges between nodes, PRPs cannot efficiently use bandwidth, which is a limited communication resource of FANET; therefore, PRPs are not suitable for highly mobile and/or larger networks. Secondly, it shows a slow reaction, when the topology is changed, or a failure is occurred. Two main protocols are widely used in VANETs: Optimized Link State Routing (OLSR) and Destination-Sequenced Distance Vector (DSDV) protocols.

- **Optimized Link State Routing (OLSR)** is a proactive link-state routing protocol, which uses two types of messages (hello and topology control messages) to discover neighbors [43]. Hello messages are used for detecting neighbor nodes in the direct communication range. This message contains the list of known neighbors, and it is periodically broadcast to one-hop neighbors. On the other hand, topology control messages are used for maintaining topological information of the system. These messages are used periodically to refresh topology information; therefore, each node can re-calculate the routes to all nodes in the system. This periodic flooding nature of the protocol results a large amount of overhead. Therefore, to reduce this overhead Multi Point Relay (MPR) mechanism is used. In this mechanism, each node selects its own MPRs from its neighbors and only those nodes are responsible for forwarding the routing messages.

- **Destination Sequenced Distance Vector (DSDV)** is a table-driven proactive routing protocol, which mainly uses the Bellman–Ford algorithm with small adjustments to be more appropriate for ad-hoc networks. In DSDV, each node maintains a routing table (with sequence number) for all other nodes, not just for the neighbor nodes [44]. Whenever the topology of the network changes, these changes are disseminated by the protocol's update mechanisms (periodic and/or triggered updates). These updates can result to routing-loops within the network. To solve this problem and to determine the freshness of a route, DSDV uses sequence numbers, which are assigned by destination nodes. A route with higher sequence number is preferred instead of a route with lower sequence number. The main advantages of DSDV are both the simplicity of the algorithm and the usage of these sequence numbers, which guarantees the protocol to be loop free. However, it has some drawbacks. To enable up-to-date routing table, each node periodically broadcast routing table updates, and this brings an overhead to the network.

### 4.3 Reactive Routing Protocols

Reactive Routing Protocol (RRP) is known as on-demand routing protocol, which means if there is no communication between two nodes, there is no need to store (or to try to store) a route between them. RRP is designed to overcome the overhead problem of PRP. In RRP, a route between communicating nodes is determined according to the demand from the source node. There are two different messages in this routing model: *RouteRequest* messages and *RouteReply* messages. *RouteRequest* messages are produced and dispatched by flooding to the network by the source node, and the destination node replies to this message with a *RouteReply* message. By receiving a *RouteReply* message the communication begins. As a result, each node maintains only the routes that are currently in use. There is no periodic messaging in this protocol; therefore, RRP is bandwidth-efficient. On the other hand, the procedure of finding routes can take a long time; therefore, high latency may appear during the route finding process.

- **Dynamic Source Routing (DSR)** is a simple and effective RRP, which is designed mainly for multi-hops for wireless mesh networks [45]. In DSR, the source node broadcasts a route request message to its neighbor nodes, which are in the wireless transmission range. In the whole communication process, there can be many route request messages. Therefore, to avoid confusion, the source node adds a unique request-id number to the produced message. DSR is a source demanding routing protocol and the source node stores the entire hop-by-hop route of the destination node. If the source node is unable to use its current route, due to changes in the network topology, then the route maintenance mechanism is activated. In such case, the source node has to use another route to the destination; if there is none, a new route discovery phase is started. This routing protocol was implemented by Brown et al. in [46] and they reported that finding a new route in UAV network with DSR can be irritating.
- **Ad-hoc On-demand Distance Vector (AODV)** is a reactive protocol, which has same on-demand characteristics with DSR with different maintaining mechanisms of routing table [47]. In AODV, each node stores a routing table, which contains a single record for each destination; while in DSR, each node can store multiple entries in its routing table for each destination. Another difference with DSR stems out from the fact that DSR data packets carry the complete path between source and the destination nodes. In AODV, the source node (and also other relay nodes) stores the next-hop information corresponding to each data transmission. AODV routing protocol consists of three phases: route discovery, packet transmitting and route maintaining. If the source node has packets to send, it first starts a route discovery process to locate the destination node and then dispatches these packets over a determined route. Discovery process enables determined routes without a

loop, and it uses a sequence number to determine an up-to-date route of the destination. An expiration time is used to keep a route's freshness. In this process, intermediate nodes also update their routing tables. After a route-id constructed, packets can be transferred over it. As a result of mobile nodes, some link failures may occur, and this connection loss triggers a repairing process to maintain the routes.

### 4.4 Hybrid Routing Protocols

Hybrid routing protocol (HRP) is a combination of previous protocols, and is presented to overcome their shortcomings. By using HRP, the large latency of the initial route discovery process in reactive routing protocols can be decreased and the overhead of control messages in proactive routing protocols can be reduced. It is especially suitable for large networks, and a network is divided into a number of zones where intra-zone routing is performed with the proactive approach while inner-zone routing is done using the reactive approach.

- **Zone Routing Protocol (ZRP)** is based on the concept of zones [48]. In this protocol, each node has a different zone, which is defined as the set of nodes whose minimum distance (in terms of number of hops) to this node which is not greater than predefined radius $\rho$. Therefore, the zones of neighboring nodes overlap. In MANET, the largest part of the whole traffic is directed to nearby nodes. The routing inside the zone is called as intra-zone routing, and it uses proactive approach to maintain routes. If the source and destination nodes are in the same zone, the source node can start data transmission immediately. The inter-zone routing is responsible for sending data packets to outside of the zone. It uses reactive approach to maintain routes. The delay caused by the route discovery is minimized by using bordercasting. Bordercasting is used instead of traditional broadcasting, and reply messages are only produced by border nodes of a zone. These border nodes then repeat either inter- or intra-zone routing as needed.
- **Temporarily Ordered Routing Algorithm (TORA)** is a hybrid distributed routing protocol for multi-hop networks, in which routers only maintain information about adjacent routers (i.e., one-hop knowledge) [49]. Its aim is to limit the propagation of control message in the highly dynamic mobile computing environment, by minimizing the reactions to topological changes. Although, it mainly uses a reactive routing protocol, it is also enhanced with some proactive approaches. It builds and maintains a Directed Acyclic Graph (DAG) from the source node to the destination. There are multiple routes between these nodes in DAG. It is preferred for quickly finding new routes in case of broken links and for increasing adaptability. TORA does not use a shortest path solution, and longer routes are often used to reduce network overhead. Each node has a parameter value termed as "height" in DAG, and no two nodes have the same height value. Data flow as a fluid from the higher nodes to lowers. It is structurally loop-free because data cannot flow to higher height nodes. In the route discovery phase, this height parameter is returned to the querying node, and in this process all intermediate nodes updates their routing tables (TORA table) with the incoming route and heights.

## 5 Open Issues and Challenges

A FANET is somewhat different from traditional MANETs and VANETs; however, the fundamental idea is the same: having mobile nodes and networking in an ad-hoc manner. Hence, in a FANET, some challenges are valid as in a VANET while facing with additional challenges. Although, many researches have been performed to increase the efficiency of network with flying nodes, there are still many unsolved problems, which should be explored in future works:

(1) National Regulations: UAVs are increasingly used in many application areas, and

they get their places in the modern information age. While UAVs increasingly become a part of each country's national airspace system, most of countries' current air regulations do not allow controlled UAV operations in civil airspace. This can be seen as the biggest current barrier to the development of UASs in civilian areas. Therefore, there is a serious need to define distinctive rules and regulations to integrate UAV flights into the national airspace.

(2) Routing: In a FANET, due to the fast movement of UAVs, network topology can change quickly. Data routing between UAVs faces a serious challenge, which is different from low mobility environment. The routing protocols should be able to update routing tables dynamically according to topology changes. Most of previous routing algorithms in MANET are partly fail to provide a reliable communication between UAVs. Therefore, there is a need of developing new routing algorithms and networking model for constructing a flexible and responsive integration model.

(3) Path Planning: In a large-scale mission area and multi-UAV operation, cooperation and coordination between UAVs are not only desirable but also crucial feature to increase efficiency. In the operation theatre, there can be some dynamic changes like addition/removal of UAVs, physical static obstacles, dynamic threats (such as mobile radars), etc. In such cases, each UAV has to change its previous path, and new ones should be re-calculated dynamically. Thus, new algorithms/methods in dynamic path planning are required to coordinate the fleets of UAVs.

(4) Quality of Service (QoS): A FANET can be used for many types of applications, and it transports different types of data, which include GPS locations, streaming video/voice, images, simple text messages, etc. FANET need to support some service qualities to satisfy a set of predetermined service performance constraints like delay, bandwidth, jitter, packet loss, etc. Defining a comprehensive framework for QoS-enabled middleware is a crucial challenge that should be overcome due to the highly mobile and dynamic structure of FANET.

(5) Integration with a Global Information Grid (GIG): GIG is a worldwide surveillance network and computer system intended to provide Internet-like capability that allows anyone connected to the system to collaborate with other users and to get process and transmit information anytime and anywhere in the world. A FANET should connect to future Information Grids as one of the main information platforms to increase efficiency of a UAS by using a UAV's communication packages, equipment suites, sensors, etc.

(6) Coordination of UAVs and manned aircrafts: It is inevitable that, in the future, flights of UAVs with other manned aircraft are likely to increase. This coordination will enable the destruction of enemy aircraft with minimal losses. At the same time, these UAVs can be used as electronic jammers and for real time video reconnaissance in enemy areas. Therefore, the collaboration of UAVs and manned aircraft should be in a networked environment.

(7) Standardize FANETs: A FANET uses various wireless communication bands such as VHF, UHF, L-Band, C-band, Ku-Band, etc. These bands also used in different application areas like GSM networks, satellite communication, etc. To reduce the frequency congestion problem, there is a need to standardize these communications bands, signal modulation and multiplexing models.

(8) UAV mobility and placement: Mini-UAVs are smaller in size and can carry limited payloads, like a single radar, infrared camera, thermal camera, image sensor, etc. If there is a need to use different sensors, they should be loaded on different UAVs, e.g., one UAV can be loaded with an infrared camera, while another UAV is equipped with a high-resolution camera. This allows multiple images to be taken from the same

area, which can be hundreds and thousands of square meters. There is an open issue in this topic to optimize the UAV placement to reduce energy consumption while increasing the taken information.

## 6 Conclusion

The capabilities and roles of Unmanned Aerial Vehicles (UAVs) are promising, and they will play an increasingly prominent role in a large operation area, in a broader range of applications and complicated missions. Progressively, UAVs need to cooperate with each other in order to perform complex tasks especially in areas that are relatively inaccessible from the ground, and there is a need to quickly and easily deploy a networked system. These cooperating UAVs form a multi-UAV system, which also aims to decrease the mission completion time and increase reliability of the system for aerial missions compared with a single large-UAV system. To increase the scalability of the system, there is a need of new networking standards concepts in multi-UAV systems. Networking of multi-UAVs is not only desirable but also a crucial feature to increase the efficiency of the system by ensuring connectivity of the systems in non-LOS, urban, hostile, and/or noisy environmental management systems. Because of the highly mobile nodes, the networking structure should be constructed in ad-hoc manner, and is called as Flying Ad-Hoc Network (FANET), which requires scalable, reliable, real-time and peer-to-peer mobile ad-hoc networking between UAVs and ground stations.

Networking between UAVs is significantly different from traditional ad-hoc networking assumptions Mobile Ad-Hoc Networks (MANET) and Vehicular Ad-Hoc Networks (VANET) in terms of connectivity, data delivery, latency, service and etc. In this article, various networking protocols in FANET and its different application areas are surveyed. At the same time, it is aimed to motivate researchers to find solutions for the open research issues, which have been detailed in the paper.

## References

1. Jiang, F., Swindlehurst, A.L.: Dynamic UAV Relay Positioning for the Ground-to-Air Uplink. IEEE Globecom Workshops (2010)
2. Sahingoz, O.K.: Multi-level dynamic key management for scalable wireless sensor networks with UAV. In: The 7th International Conference on Ubiquitous Information Technologies & Applications (CUTE 2012). Ubiquitous Information Technologies and Applications. Lecture Notes in Electrical Engineering, vol. 214, pp. 11–19 (2013)
3. Sahingoz, O.K.: Large scale wireless sensor networks with multi-level dynamic key management scheme. J. Syst. Archit. Available online 5 June 2013. ISSN 1383-7621. doi:10.1016/j.sysarc.2013.05.022 (2013)
4. Manathara, J., Sujit, P.B., Beard, R.: Multiple UAV coalitions for a search and prosecute mission. J. Intell. Robot. Syst. **62**(1), 125–158 (2011)
5. Cevik, P., Kocaman, I., Akgul, A., Akca, B.: The small and silent force multiplier: a swarm UAV—electronic attack. J. Intell. Robot. Syst. **70**(1–4), 595–608 (2013)
6. York, G., Pack, D.: Ground target detection using cooperative unmanned aerial systems. J. Intell. Robot. Syst. **65**(1–4), 473–478 (2012)
7. Zhu, S., Wang, D., Low, C.: Ground target tracking using UAV with input constraints. J. Intell. Robot. Syst. **69**(1–4), 417–429 (2013)
8. Merino, L., Caballero, F., Martínez-de-Dios, J.R., Maza, I., Ollero, A.: An unmanned aircraft system for automatic forest fire monitoring and measurement. J. Intell. Robot. Syst. **65**(1–4), 533–548 (2012)
9. Cho, A., Kim, J., Lee, S., Kee, C.: Wind estimation and airspeed calibration using a UAV with a single-antenna GPS receiver and pitot tube. IEEE Trans. Aerosp. Electron. Syst. **47**, 109–117 (2011)
10. Maza, I., Caballero, F., Capitan, J., Martinez-De-Dios, J.R., Ollero, A.: Experimental results in multi-UAV coordination for disaster management and civil security applications. J. Intell. Robot. Syst. **61**(1–4), 563–585 (2011)
11. Xiang, H., Tian, L.: Development of a low-cost agricultural remote sensing system based on an autonomous unmanned aerial vehicle. Biosyst. Eng. **108**(2), 174–190 (2011)
12. Cho, A., Kim, J., Lee, S., Kee, C.: Wind estimation and airspeed calibration using a UAV with a single-antenna GPS receiver and pitot tube. IEEE Trans. Aerosp. Electron. Syst. **47**(1), 109–117 (2011)
13. Xiang, H., Tian, L.: Development of a low-cost agricultural remote sensing system based on an autonomous unmanned aerial vehicle (UAV). Biosyst. Eng. **108**(2), 174–190 (2011)
14. Bekmezci, I., Sahingoz, O.K., Temel, S.: Flying Ad-Hoc Networks (FANETs): a survey. Ad Hoc Netw. **11**(3), 1254–1270 (2013)
15. Cheng, B.N., Moore, S.: A comparison of MANET routing protocols on airborne tactical networks.

In: Military Communications Conference—MILCOM 2012, pp. 1–6 (2012)
16. Frew, E.W., Brown, T.X.: Airborne communication networks for small unmanned aircraft systems. Proc. IEEE **96**(12), 2008–2027 (2008)
17. Aloul, F.A., Kandasamy, N.: Sensor deployment for failure diagnosis in networked aerial robots: a satisfiability-based approach, theory and applications of satisfiability testing, SAT 2007. Lect. Notes Comput. Sci. **4501**, 369–376 (2007)
18. Shirani, R., St-Hilaire, M., Kunz, T., Zhou, Y., Li, J., Lamont, L.: Combined reactive-geographic routing for unmanned aeronautical ad-hoc networks. In: 8th International Wireless Communications and Mobile Computing Conference (IWCMC-2012), pp. 820–826 (2012)
19. Li, Y., St-Hilaire, M., Kunz, T.: Enhancements to reduce the overhead of the reactive-greedy-reactive routing protocol for unmanned aeronautical ad-hoc networks. In: 8th International Conference on Wireless Communications, Networking and Mobile Computing (WiCOM), pp. 1–4 (2012)
20. Cai, Y., Yu, F.R., Li, J., Zhou, Y., Lamont, L.: Medium access control for Unmanned Aerial Vehicle (UAV) ad-hoc networks with full-duplex radios and multipacket reception capability. IEEE Trans. Veh. Technol. **62**(1), 390–394 (2013)
21. Reynaud, L., Rasheed, T.: Deployable aerial communication networks: challenges for futuristic applications. In: Proceedings of the 9th ACM Symposium on Performance Evaluation of Wireless Ad-Hoc, Sensor, and Ubiquitous Networks (PE-WASUN '12), pp. 9–16 (2012)
22. Bök, P.-B., Tuchelmann, Y.: Context-aware QoS control for wireless mesh networks of UAVs. In: International Conference Computer Communications and Networks (ICCCN), pp. 1–6 (2011)
23. Li, Y., St-Hilaire, M., Kunz, T.: Improving routing in networks of UAVs via scoped flooding and mobility prediction. In: IFIP Wireless Days (WD), pp. 1–6 (2012)
24. Rohde, S., Goddemeier, N., Daniel, K., Wietfeld, C.: Link quality dependent mobility strategies for distributed aerial sensor networks. In: GLOBECOM Workshops, pp. 1783–1787 (2010)
25. Sahingoz, O.K.: Mobile networking with UAVs: opportunities and challenges. In: International Conference on Unmanned Aircraft Systems (ICUAS-2013), pp. 933–941 (2013)
26. Namuduri, K., Wan, Y., Gomathisankaran, M., Pendse, R.: Airborne network: a cyber-physical system perspective. In: Proceedings of the First ACM MobiHoc Workshop on Airborne Networks and Communications (Airborne '12), pp. 55–60 (2012)
27. Clapper, J., Young, J., Cartwright, J., Grimes, J.: Unmanned systems roadmap 2007–2032. Technical Report, Department of Defense (2007)
28. Winnefeld, J.A., Kendall, F.: Unmanned systems integrated roadmap FY 2011-2036. Technical Report, Department of Defense (2011)
29. Hyland, M.T.: Performance evaluation of ad hoc routing protocols in a swarm of autonomous unmanned aerial vehicles. PhD Thesis, Air Force Institute of Technology (2007)
30. Gu, D.L., Pei, G., Ly, H., Gerla, M., Zhang, B., Hong, X.: UAV aided intelligent routing for ad-hoc wireless network in single-area theater. In: IEEE Wireless Communications and Networking Conference-(WCNC 2000), vol. 3, pp. 1220–1225 (2000)
31. Franchi, A., Secchi, C., Ryll, M., Bulthoff, H.H., Giordano, P.R.: Shared control: balancing autonomy and human assistance with a group of Quadrotor UAVs. IEEE Robot. Autom. Mag. **19**(3), 57–68 (2012)
32. Cheng, C.M., Hsiao, P.H., Kung, H.T., Vlah, D.: Maximizing throughput of UAV-relaying networks with the load-carry-and-deliver paradigm. In: IEEE Wireless Communications and Networking Conference (WCNC 2007) (2007)
33. Le, M., Park, J.S., Gerla, M.: UAV Assisted disruption tolerant routing. In: Military Communications Conference, MILCOM 2006, pp. 1–5 (2006)
34. Jonson, T., Pezeshki, J., Chao, V., Smith, K., Fazio, J.: Application of Delay Tolerant Networking (DTN) in airborne networks. In: IEEE Military Communications Conference-(MILCOM 2008), pp. 1–7 (2008)
35. Lamont, G.B., Slear, J.N., Melendez, K.: UAV swarm mission planning and routing using multi-objective evolutionary algorithms. In: IEEE Symposium on Computational Intelligence in Multicriteria Decision Making, pp. 10–20 (2007)
36. Sun, Z., Wang, P., Vuran, M.C., Al-Rodhaan, M.A., Al-Dhelaan, A.M., Akyildiz, I.F.: BorderSense: border patrol through advanced wireless sensor networks. Ad Hoc Netw. **9**(3), 468–477 (2011)
37. Ko, J., Mahajan, A., Sengupta, R.: A network-centric UAV organization for search and pursuit operations. In: IEEE Aerospace Conference, pp. 2697–2713 (2002)
38. López, J., Royo, P., Pastor, E., Barrado, C., Santamaria, E.: A middleware architecture for unmanned aircraft avionics. In: ACM/IFIP/ USENIX International Conference on Middleware companion (MC '07) (2007)
39. de Jong, E.: Flexible data-centric UAV platform eases mission adaptation. White paper, Available online. http://www.rti.com/whitepapers/RTI_Data-Driven_Approach_to_UAV.pdf (2011). Accessed 3 Aug 2013
40. Koller, A.A., Johnson, E.N.: Design, implementation, and integration of a publish/subscribe-like Multi-UAV communication architecture. In: AIAA Modeling and Simulation Technologies Conference and Exhibit, pp. 1–17 (2005)
41. Sahingoz, O.K., Sonmez, A.C.: Fault tolerance mechanism of agent-based distributed event system. Lect. Notes Comput. Sci. **3993**, 192–199 (2006)
42. Sahingoz, O.K., Erdogan, N.: MAPSEC: mobile-agent based publish/subscribe platform for electronic commerce. Lect. Notes Comput. Sci. **2869/2003**, 348–355 (2003)

43. Clausen, T., Jacquet, P.: Optimized Link State Routing Protocol (OLSR) RFC 3626. http://www.ietf.org/rfc/rfc3626 (2003). Accessed 3 Aug 2013
44. Perkins, C.E., Bhagwat, P.: Highly dynamic Destination-Sequenced Distance-Vector Routing (DSDV) for mobile computers. In: Proceedings of the Conference on Communications Architectures, Protocols and Applications (SIGCOMM '94), pp. 234–244 (1994)
45. Johnson, D.B., Maltz, D.A.: Dynamic source routing in ad hoc wireless networks. In: Mobile Computing, Chapter 5, pp. 153–181. Kluwer Academic Publishers (1996)
46. Brown, T.X., Argrow, B., Dixon, C., Doshi, S., Thekkekunel, R.G., Henkel, D.: Ad hoc UAV ground network (AUGNet). In: 3rd AIAA Unmanned Unlimited Technical Conference, pp. 29–39 (2004)
47. Murthy, S., Garcia-Luna-Aceves, J.J.: An efficient routing protocol for wireless networks. In: ACM Mobile Networks and Applications, pp. 183–197 (1996)
48. Haas, Z.J., Pearlman, M.R.: Zone Routing Protocol (ZRP) a hybrid framework for routing in ad hoc networks, 2nd edn. Ad hoc Networking, vol. 1, chapter 7, pp. 221–253. Addison-Wesley (2001)
49. Park, V., Corson, S.: Temporarily-Ordered Routing Algorithm (TORA) Version 1. Internet draft, IETF MANET working group. http://tools.ietf.org/html/draft-ietf-manet-tora-spec-04. Accessed 3 Aug 2013