Bahloul NEH, Boudjit S, Abdennebi M *et al.* A flocking-based on demand routing protocol for unmanned aerial vehicles. JOURNAL OF COMPUTER SCIENCE AND TECHNOLOGY 33(2): 263–276 Mar. 2018. DOI 10.1007/s11390-018-1818-3

A Flocking-Based on Demand Routing Protocol for Unmanned Aerial Vehicles

Nour El Houda Bahloul[1,2], Saadi Boudjit[2], Marwen Abdennebi[2], and Djallel Eddine Boubiche[1]

[1] *LaSTIC Laboratory, University of Batna 2, Batna 05078, Algeria*
[2] *L2TI Laboratory, University of Paris 13, Villetaneuse 93430, France*

E-mail: houda.bahloul@univ-batna2.dz; boudjit@univ-paris13.fr; marwen.abdennebi@univ-paris13.fr
de.boubiche@univ-batna2.dz

Received July 9, 2017; revised January 23, 2018.

Abstract The interest shown by some community of researchers to autonomous drones or UAVs (unmanned aerial vehicles) has increased with the advent of wireless communication networks. These networks allow UAVs to cooperate more efficiently in an ad hoc manner in order to achieve specific tasks in specific environments. To do so, each drone navigates autonomously while staying connected with other nodes in its group via radio links. This connectivity can deliberately be maintained for a while constraining the mobility of the drones. This will be suitable for the drones involved in a given path of a given transmission between a source and a destination. This constraint could be removed at the end of the transmission process and the mobility of each concerned drone becomes again independent from the others. In this work, we proposed a flocking-based routing protocol for UAVs called BR-AODV. The protocol takes advantage of a well known ad hoc routing protocol for on-demand route computation, and the Boids of Reynolds mechanism for connectivity and route maintaining while data is being transmitted. Moreover, an automatic ground base stations discovery mechanism has been introduced for a proactive drones and ground networks association needed for the context of real-time applications. The performance of BR-AODV was evaluated and compared with that of classical AODV routing protocol and the results show that BR-AODV outperforms AODV in terms of delay, throughput and packet loss.

Keywords unmanned aerial vehicle (UAV), AODV, Boids of Reynolds, mobility control

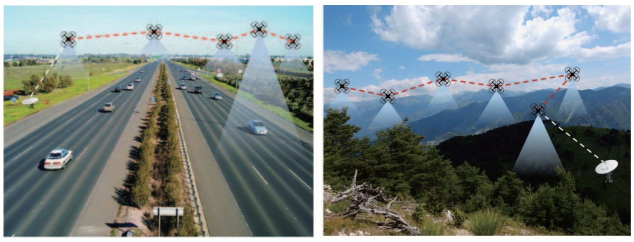
1 Introduction

Unmanned aerial vehicles (UAVs) are of increasing interest to researchers because of their various applications. They have long been a military tool; however, in recent years, their use has been extended to the civilian sector and presented a promising solution to the most dangerous, difficult and unsuitable missions for human pilots missions. The use of UAVs in such applications allows to save money since they can replace manned planes and helicopters. Indeed, there are small, lightweight, and cheap UAVs capable of replacing humans in civilian missions such as surveillance of environment, monitoring, search and rescue of survivors after disasters[1], and borders control[2]. In such missions, UAVs may also act as ad hoc relays for data exchange between two or more distant ground groups or users[3-4]. In order to improve the performance of UAVs on such missions, researches are conducted to make cooperative drones.

Indeed, a fleet of cooperative drones will be able to accomplish more efficiently complex missions. This kind of cooperative networks may be of interest in places where there is no cellular coverage due to the complexity to reach these places and install fixed relays or due to the damage of existing infrastructure after a natural disaster. Fig.1(a) shows a fleet of UAVs cooperating in an ad hoc manner to monitor a highway and transmit traffic information to ground stations. This application has recently been adopted by the French

Regular Paper
Special Section on Computer Networks and Distributed Computing
A preliminary version of the paper was published in Proceedings of ICCCN 2017.

highways operator VINCI①. The main encountered issue, however, is the limited radio range of the drones for a real-time transmission when the drones are far away from ground base stations and flying in areas where cellular coverage is missing. Indeed, when cellular coverage is missing, drones take and store pictures for later transmission. Another application is shown in Fig.1(b) where a fleet of drones cooperate to exchange and relay information from one another to monitor open and wild environments to detect the start of fire. Indeed, thousands of hectares burn down every year in south of France and in other Mediterranean countries due to the late detection of a fire especially in hard-to-reach areas[5]②. Monitoring these inaccessible areas using UAVs allows early fire detection. The civil security direction in France has been working for a few years on how to use UAVs to identify the counters of a disaster in real time③.



(a) (b)

Fig.1. UAVs surveillance scenarios. (a) Highway surveillance with collaborative UAVs. (b) Forest fire surveillance with collaborative UAVs.

The deployment of a fleet of collaborative UAVs with ad hoc routing mechanisms could be one of the possible solutions to set up this kind of applications. This solution, however, may be faced with many challenges, mainly the high mobility of the drones and connectivity maintaining. Indeed, the high and independent mobility of the drones may cause frequent and rapid changes in network topology and hence links failure. Moreover, in UAVs ad hoc networks, each drone has the possibility to move according to an independent pre-programmed flight plan and the network can often get partitioned. Our aim here is to propose a strategy to maintain the connectivity of links in a transmission path when transmitting data. To keep connectivity in such active paths, we combine the advantages of a well known on-demand routing protocol called AODV[6] suitable for ad hoc networks with high mobility, and the mechanism of Boids of Reynolds[7] to control the mobility of the drones involved in an active transmission path.

The rest of this paper is organized as follows. Section 2 presents a detailed specification of the problem. Section 3 is devoted to related work on routing in UAVs ad hoc networks. A brief overview on the core functioning of AODV is given in Section 4. The principle and details of Boids of Reynolds are presented in Section 5. Section 6 presents our proposed routing and connectivity maintaining solution for UAVs ad hoc network. The proactive side of the proposed routing protocol is presented in Section 7. Simulation results are presented and discussed in Section 8. Section 9 concludes the paper.

2 Problem Statement

Our problem is to study the maintenance of connectivity in UAVs ad hoc networks in order to ensure the availability of reliable communication channels between active nodes throughout a given mission. The problem of maintaining routes between mobile devices in communication networks is a well known problem in the mobile ad hoc NETworks (MANETs). Conventional routing protocols for ad hoc networks are designed to find, in a reactive or a proactive way, an end-to-end multi-hop route from a source node to a target node, assuming the existence of this route[6,8-9]. If such a route is not found, these protocols have no influence on the mobility of nodes for restoring a former route or creating a new one, leading to a lack of connectivity in such networks. Multiple routing algorithms have been developed to overcome this problem[10-11], but all assume that the movement of the network nodes is not controllable leaving no other alternative than the prediction of the nodes' movement according to existing models.

Actually, neither the routing, nor the topology control protocols offer an adequate solution to the problem of maintaining connectivity in multi-UAV systems. The routing protocols, as well as those in the topology control, assume hypotheses on nodes mobility and

①http://www.lefigaro.fr/societes/2015/08/01/20005-20150801ARTFIG00050-des-drones-pour-surveiller-le-trafic-sur-les-autoroutes.php, Jan. 2018.

②http://www.statistiques.developpement-durable.gouv.fr/lessentiel/ar/368/1239/feuxforet.html, Jan. 2018.

③https://www.interieur.gouv.fr/Archives/Archives-des-dossiers/2016-Dossiers/Les-drones-au-service-de-la-securite/Identifier-en-temps-reel-les-contours-d-un-sinistre, Jan. 2018.

their ability to move freely, which make these protocols unusable to solve the problem of maintaining connectivity. Hence, an alternative solution has to be drawn. In this purpose, nature could be a source of inspiration for us, as in UAVs networks we can take advantage of autonomous entities that control their own movements. Some biological systems are characterized by a large number of autonomous entities, interacting each other locally in order to self-organize and coordinate their actions adapting with the detected variations. We then focus on the UAV ability to control the mobility for solving the problem of maintaining connectivity in active paths of such networks like collective behavior achieved by the swarms of fish and flocks of birds[7]. When the UAVs are connected, this gives more reliability and efficiency to their collective behaviors. Therefore, rather than to undergo the mobility and adapt to it, it seems more effective to influence it by controlling the movements of active nodes. In this case, our goal consists in coordinating the UAVs movements so that the connectivity in the network will not be compromised when packets transfer has already started. We then talk about a UAVs network organized as a swarm and based on a kind of biological properties of swarms, such as, the velocity of the nodes, the distance between nodes, and the topology of the nodes for network self-organization.

3 Related Work

The initial UAVs studies and experiments were conducted with the existing classical MANET routing protocols. One of the first flight experiments with UAVs ad hoc architecture is developed in [12] with Dynamic Source Routing (DSR) protocol[8]. The main motivation to choose DSR is its reactive nature. The source tries to find a path to a destination, only if it has data to send. In [13], authors stated that DSR is more appropriate than proactive methods for UAVs ad hoc networks, where the nodes are highly mobile and the topology is unstable. In this case, 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 UAVs networks. In [14], proactive, reactive and position-based routing solutions for UAV networks have been compared. It was shown that Greedy Perimeter Stateless Routing (GPSR)[15], which is a position-based protocol, outperforms proactive and reactive routing solutions. Authors in [16] developed a simulation framework to study the position-based routing protocols for UAVs and it was stated that this category of protocols, mainly GPSR, can be suitable for densely deployed UAVs. However, the reliability can be a serious problem in case of sparse deployments. A combination of other methods should be used for the applications that require high reliability. Indeed, the same authors[16] proposed a hybrid routing protocol which is a combination of the principle of greedy geographical routing (geographic greedy forwarding) and reactive routing protocol AODV. This protocol is called RGR (reactive-greedy-reactive routing protocol) where each UAV transmitter sets a route to the destination based on the reactive method of AODV, and in the case of link failure at a given node along the transmission path due to mobility, the concerned node goes to the geographical method. In this last case, the packet is routed to the closest neighbor from a geographical point of view to the final destination.

Although the first UAVs implementations have used the existing MANET routing algorithms, most of these protocols are not adequate for UAVs, because of the specific issues related to drones such as rapid changes in the link quality and the very high node mobility[17].

Therefore, a number of UAVs ad hoc networks specific routing protocols have been proposed in literature in recent years. Most of them are designed to assure the connection between disjoint groups of mobile nodes on the ground. In those cases, UAVs nodes are mainly limited to play the role of relays for mobile ad hoc groups on the ground. In [18], the authors presented AODV-DTN protocol which is a combination of AODV and delay tolerant routing for a hybrid system composed of drones and ground nodes. UAVs in AODV-DTN are used to assure the connection between disjoint groups of mobile nodes on the ground. Its routing strategy is to use AODV to route mobile nodes messages between different groups on the ground while the DTN routing is applied between the drones. UAVs are allowed to receive and store packets until they are close to one another and a route is established to destination. This protocol is dedicated to delay tolerant systems and is not suitable for real-time traffic.

Another proposed routing protocol based on AODV is presented in [19]. Rather than using CSMA/CA for channel access, the Time-Slotted Aloha protocol is embedded into AODV routing protocol to be used within the context of autonomous mobile ad hoc unmanned vehicle systems (UVS) in formation. Maintenance of

UVS formations requires each node in the network to be peer-aware, which places a heavy demand on inner node communication. In order to mitigate the inner node network congestion, Time-Slotted Aloha protocol assigns time-slots and allows the designated nodes to communicate directly with other peer-nodes. This allows to reduce packet loss rate due to collisions. For reactive routing and UVS formation maintenance, classical AODV routing protocol is used but connectivity maintenance remains actually an issue.

In [20], a cross layer protocol called DOLSR for directional optimized link state routing protocol is presented. It is designed to achieve certain quality of services (QoS) in terms of end-to-end delay, traffic control and interference required by some UAVs applications. To that respect, authors in [20] proposed to use UAVs with directional antenna to extend the coverage area and reduce the number of hops. As for the routing protocol, the Optimized Link State Routing Protocol (OLSR)[9] is used.

In [21], a geographical routing protocol called GPMOR (Geographic Position Mobility Oriented Routing) is proposed for highly dynamic UAVs ad hoc networks. In this proposal, each UAV is supposed to be aware of its geographic location using GPS and periodically exchanges its position with its direct neighbors only. The period between two exchanges is set to a few seconds and for connectivity maintaining, drones try to predict the movement of their neighbors to define their new positions during this time interval. In this proposal, indeed, the drones move following the Gauss-Markov mobility model.

Another geographic routing protocol was proposed in [10]. This protocol, called LAROD (Location Aware Routing For Opportunistic Delay Tolerant), is a delay-tolerant routing protocol. It was evaluated by simulation in the context of a realistic scenario of a collaborative reconnaissance mission. It aims to discover the shortest route to each destination by choosing one or more relays. Indeed, all the neighbors who guarantee a minimum of progress towards the destination are potential relays. Each transmitter drone broadcasts the packets to its potential relays which trigger timers of randomly chosen durations. Only the first relay node having the timer expired can rebroadcast the packet to its neighbors. The others, listening to the transmission, remove their copies of the transmitted packet. In the case where a UAV cannot find a relay to ensure progress towards the target drone, it reacts according to the DTN principle. The packets remain temporarily stored until the mobility of the drone creates other paths.

Once the packet has reached its destination, this destination replies with an acknowledgment in order to prevent redundant packet retransmissions of the same packet between the nodes.

This protocol is not robust because in the case where a node fails for any reason, all the packets stored in that node will be lost unless they have duplicate copies in other nodes.

The Extended Hierarchical State Relating (EHSR)[22] is another example of hybrid hierarchical protocol where UAVs are used as relays for terrestrial nodes. In this routing protocol, nodes are grouped according to their altitudes: drones form a first group and terrestrial nodes form other groups. Two routing methods are used to route packets inside and outside the groups respectively. In order to communicate between different groups, the distance vector routing mechanism is used while for local or intra-group communication the link-state routing is applied.

Table 1 summarizes the previously presented protocols and classifies them according to the routing families to which they belong. This classification is based on the classification taxonomy proposed in [11] for wireless mobile ad hoc networks.

To the best of our knowledge, however, no one of the previously presented routing protocols offers adequate solution to the problem of connectivity maintaining. This makes them ineffective regarding the problem of active route failure caused by independent mobility of the drones. The originality of our work is the integration of a connectivity maintaining mechanism within the AODV routing protocol which is suitable to the context of UAVs, as well as a ground base stations discovery technique which is necessary to the context of real-time applications. These two mechanisms are based on Boids of Reynolds technique and on the periodic exchange of DNA (drone and network association) message respectively. The whole system provides an effective routing protocol for UAVs ad hoc networks.

4 Overview of AODV Routing Protocol

Since our proposal is mainly based on AODV routing protocol[6], we provide a brief overview on the core functioning of AODV to help understanding BR-AODV. Ad Hoc On-Demand Distance Vector (AODV) allows mobile nodes to obtain routes only if requested and hence reduces the size of routing tables as well as

Table 1. Classification of UAVs Routing Protocols

Routing Family	Routing Protocol	Short Description
Hybrid routing	RGR[16]	RGR is a combination of greedy geographic forwarding routing (GPSR) and the AODV reactive routing protocol. It has been proposed to solve the GPSR failure in the context of cooperative UAV networks.
Reactive routing	AODV-DTN[18]	A combination of AODV and a DTN tolerant routing protocol for a hybrid system of drones and ground nodes. It is dedicated to systems that tolerate delays and is not suitable for real-time traffic exchange.
	Time-Slotted AODV[19]	Based on AODV, this protocol allocates time slots for each node in order to transmit its packets to its neighbor. This reduces the rate of packet loss due to collisions and increases the reliability of the system.
Proactive routing	DOLSR[20]	Directed antennas are used with OLSR routing protocol to enhance packets delivery ratio and to decrease average latency. The use of directed antennas decreases the number of MPRs and improves network performance.
Geographic routing	GPMOR[21]	It predicts the movement of UAVs with Gauss-Markov mobility model and uses this information to determine the next hop.
	LAROD[10]	It is a delay-tolerant routing protocol; it aims to discover the shortest route to each destination by choosing one or more relays.
Hierarchical routing	EHSR[22]	This protocol combines different types of mechanisms (link state routing and distance vector routing) to route information within a group (between nodes of the same group) and outside the group (between different groups).

traffic. It is based on two main control messages, route request (RREQ) message and route reply (RREP) message. When a route is required between a source and a destination, AODV initiates a route discovery process to connect the pair of nodes as depicted in Fig.2.

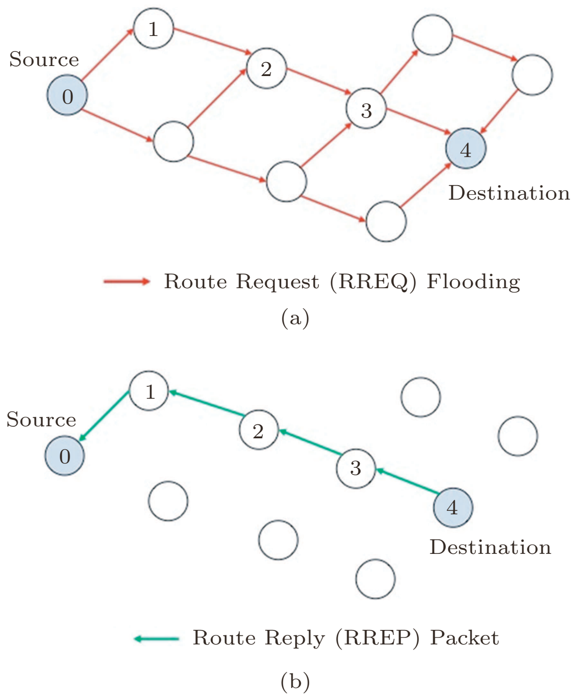


Fig.2. On demand route discovery mechanism. (a) Broadcast of the RREQ packet. (b) Unicast transmission of the RREP packet.

A source node diffuses an RREQ message to its direct neighbors and the recipients forward the RREQ message only if the route to destination is not found locally.

In this case, the recipients set up backward pointers to the source node and broadcast only the first copy of their received RREQ messages. Each intermediate node repeats the same process until the RREQ message reaches the destination node (Fig.2(a)). When the destination node (or any other intermediate node who knows the route to destination) receives the RREQ message, it proceeds with a unicast transmission of the RREP message along the shortest path to the source node. The nodes situated in this shortest path discard the RREQ entries in wait and update their routing tables by adding an entry for the destination node (Fig.2(b)). At the other nodes, the RREQ entries in wait are deleted when they expire. Each node maintains a routing table that contains an entry for each known destination. Entries in the routing table are created when the node receives RREQs for unknown destinations.

5 Boids of Reynolds

To cope with dynamic topology changing in an UAVs network and for the purpose of connectivity maintaining, a control module for UAVs movements has been added to AODV. This control module is based on the Boids of Reynolds and used by each UAV to verify:

1) if it participates in one or more active paths;

2) if so, it must plan its displacement when moving to avoid any disconnection in these paths.

5.1 Swarm Intelligence

Swarm intelligence (SI) is a discipline of artificial intelligence. It tries using the model of multi-agent systems to design intelligent artificial systems inspired by biological social systems (such as ants, flocks of birds and shoals of fish). The members of these societies are unsophisticated but, despite this, they are able to achieve complex tasks. Coordinated behavior of the swarm emerges from relatively simple interactions between individuals. The graphic animation, optimization algorithms, swarm robotics, and routing in telecommunication networks are the areas where the SI principles are applied successfully. The resulting systems are characterized in particular by the robustness and flexibility.

5.2 Boids of Reynolds

Flocking is a collective behavior of independent but interacting agents. Early work on flocking and swarm theory focused on mimicking realistic movements of flocking animals. The graphic animation was probably the first discipline to focus on the discoveries carried out on the decentralized organization of animal societies and SI. In 1986, Reynolds introduced three basic rules that achieved the first simulated flocking in computer animations[7]. Inspired by recent results on the formation of shoals of fish and flocks of birds, he achieved a graphical application where agents he calls Boids move coherently in a virtual environment, and modeled an emergent behavior where each boid acts autonomously while respecting some simple rules.

1) Too close to another boid, it tries to move away.

2) Too far from the group, it tries to get closer to its nearest neighbors so that the group keeps its cohesion.

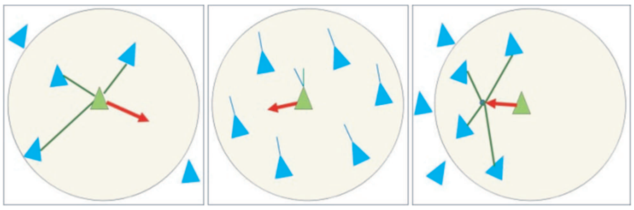
3) It continually seeks to adjust its speed to the average speed of its neighbors to keep movements coordinated.

4) Finally, it avoids obstacles that appear in front of it.

In practice, these rules reflect the behavior of a boid when a neighbor boid enters its vicinity area which is divided into three zones, from the nearest to the farthest one: repulsion zone (separation rule), orientation area (alignment rule), and attraction area (cohesion rule).

As depicted in Fig.3, when a neighbor enters the repulsion zone the boid moves away to avoid collisions. When the neighbor is in the orientation zone the boid follows it, and when it is in the attraction area the boid moves towards it to be closer. In addition to the previously defined zones, another zone called dead angle wherein the boid cannot perceive its neighbors is in general defined in simulation.

By varying the ranges of different zones from one another, we can make emerge different structures which have strong similarities with what is observable in nature. Thus, large areas of attraction and repulsion coupled with an almost nonexistent orientation zone make emerge a swarm structure. By slightly increasing the orientation zone, there may be a toroidal structure, similar to some shoals of fish. By further increasing the orientation zone, we can observe a parallel group. The field of vision is also taken into consideration, if it is too small; it is much more difficult to obtain a structure. Finally, a weak attraction area tends to cause dispersion of boids. In short, each boid seeks to maintain a minimum distance with its neighbors. This depends on its vision and its local vicinity.



(a) (b) (c)

Fig.3. Local behavior on the movement of swarm boids. (a) Separation. (b) Alignment. (c) Cohesion.

6 BR-AODV Routing Protocol

In this section, we present the proposed Boids based routing protocol for UAVs ad hoc networks called BR-AODV. Since the message transmission between UAVs and the fixed gateway is requested only when needed, we choose as a basis the AODV protocol (ad hoc on-demand distance vector) which allows mobile nodes to obtain routes only if requested and hence reduces the size of routing tables as well as traffic. Many studies have shown that AODV routing protocol seems more appropriate and more efficient for networks with low density[23], which is our case of the considered drone network. Moreover, a proactive routing scheme in a highly dynamic context such as UAVs networks is not suitable. Indeed, barely computed, entries in the routing table become rapidly no longer valid due to the velocity of the drones and frequent topology changes.

As a result, the protocol BR-AODV uses almost the same basic elements of AODV, with the same exchanged types of packets, and the same structure of routing tables while changing its routes discovery mechanism and maintenance. Indeed, unlike AODV, in BR-AODV, the destination address of RREQ messages is set to broadcast address and is diffused to the direct neighbors of the source node. The recipients forward the RREQ message only if they do not have a direct link to a ground base station. Nodes with direct links to ground base stations proceed with a unicast transmission of the RREP message along the shortest path to the source node. At the end, the source node chooses the closest ground base station among all the received RREP messages.

BR-AODV attempts to minimize the number of launches of the discovery process of routes and to support maintaining of active paths as long as they are needed by the emitting sources. To do this, it replaces AODV routes maintaining process with a mobility control module, performed by applying the principle of maintaining training in Boids of Reynolds on the movement of UAVs based on the distance control between them (Fig.4).

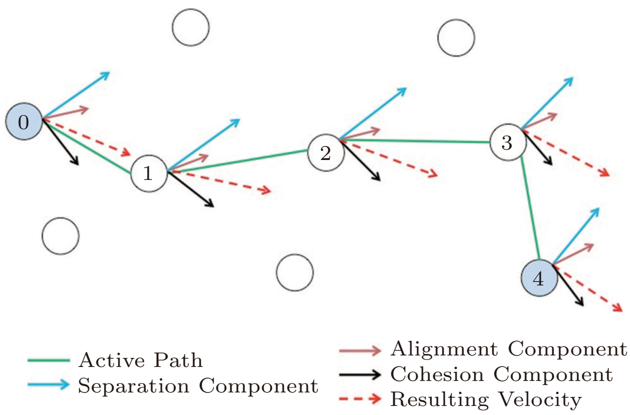


Fig.4. Mobility control mechanism of BR-AODV.

An active node is a node that has not gone through a sufficiently long silence period when it has neither received nor transmitted packets. This period T is an application driven parameter and is limited by parameter $T_{\max}$ which can be adjusted to help to differentiate between an active node and an inactive node.

- If $T > T_{\max}$, then the node is inactive.
- If $T \leqslant T_{\max}$, then the node is considered active.

When a packet is sent, T is reset to 0 and the time is recorded again for the node. If all nodes constituting a path are active, this path is then said to be active. If one node is inactive, then the considered path is said to be inactive. The proposed routing scheme is applied to a network of autonomous UAVs where the criteria are as follows.

- The network is asynchronous and of moderate scale.
- The multi-hop communication is based on AODV.
- The network is self-directed, self-organized and of N nodes.
- The number of UAVs N can change dynamically when nodes join or leave the network.
- Each node has a unique identifier ID in the network; it can be an MAC address or an IP address.

In our architecture we assume the followings.

- Each UAV i has a velocity v_i and a two-dimentional position $p_i(x_i, y_i)$ which is referred to as p_i in the rest of the paper.
- Each UAV detects locally its neighboring nodes δ_i.

In order that a node i can define its neighbor list δ_i, it proceeds as follows: the node i must calculate the distance between its current location and the other nodes of the network, by sending them Hello messages. When the signal returns toward node i, it calculates the attenuation ratio (signal power), and according to this delivered power, it can define its neighborhood. To simulate this technique, we transformed this problem to a geometric problem, where node i calculates the distances that separate it from the positions of all other nodes in the network by the Pythagoras formula. After the calculation of this separation distance, the node compares the obtained distances with the radius of its radio range z. If the distance between i and another node is smaller than or equal to the radio range of $i(z)$, this node is added to the list of neighbors of i. We also have to take into consideration the following assertions.

- Drones are homogeneous: they are similar in their processing capacity, communication, storage and energy.
- Each node can move and leave the network arbitrarily.
- Each node has a dynamic routing table with an entry for each already computed route. Each entry contains essentially a destination address, the next hop to this destination, the distance in terms of number of hops, and the expiration time of the entry in the table.
- All the network nodes move independently from each other following a personalized road map for each node, except those which take part in a route establishment process or those situated in active transmission paths on which the rules of Boids of Reynolds are applied.
- A node whose movement is subject to Boids of Reynolds rules will be released from this constraint when the routing paths where it contributes have expired their lifetime (the paths have been idle for a

while). This node uses its own mobility road map again.

The principle of Boids of Reynolds is applied to the nodes movements that participate in one or more active paths. Each node which contributes to routing data in these paths is handled as a boid in a swarm (comprised of all active nodes in the $z$range and belonging to active paths) where its movement should observe the following three rules.

• Separation: avoids collisions with the nearest neighbors by keeping a minimal distance with them (v_s (1)).

• Alignment: adapts its speed to those of its neighbors, and remains in the common direction of displacement (v_a (2)).

• Cohesion: stays close to its neighbors while approaching to the swarm center (v_c (3)).

In simulation terms, the problem formalization is made by a group of boids $B = \{b_1, b_2, \ldots, b_n\}$ which represents all the UAVs constituting the active paths, where each is placed in a position p_i. Variable δ_i is defined as the group of boids situated inside the zone of radius z around boid b_i which is its radio range. Each boid b_i moves with a velocity v_i.

The above rules are expressed by the following formulas and for each boid b_i, the calculation should take into account each of its boid neighbors (in radio range z) b_j in group δ_i, with their parameters, i.e., position p_i and velocity v_j. The vectors defined by the positions of boid b_i and each visible boid b_j are summed and the separation velocity denoted by v_{s_i} is calculated as the negative sum of these vectors:

$$v_{s_i} = -\sum_{b_j \in \delta_i : d(b_j, b_i) < Z} (p_i - p_j).$$

The alignment velocity denoted by v_{a_i} is calculated as the average speed of the visible neighbors of b_i. The boid b_i slows or accelerates according to its neighbors b_j. If a boid accelerates too much, it may go out of the visibility fields of the other boids and out of the group eventually. If there is no boid directly visible, v_{a_i} is equal to zero:

$$v_{a_i} = \frac{1}{|\delta_i|} \sum_{b_j \in \delta_i} v_j - v_i.$$

The cohesion of boid b_i is denoted by v_{c_i}. It acts as a complement to the separation and is calculated in two steps.

First, the center of the set δ_i of the directly visible boids b_j is computed. This center is denoted by c_i and corresponds to the density center of all visible boids. Then v_{c_i} is calculated as follows:

$$v_{c_i} = c_i - p_i, \quad \text{where} \quad c_i = \frac{1}{|\delta_i|} \sum_{b_j \in \delta_i} p_i.$$

There is a special case where no boid is visible around b_i and $|\delta_i| = 0$. In this case, the center is not defined and no cohesion is applied.

With these three formulas, we can compute the movement speed of each boid i at time $t+1$ as follows:

$$\begin{aligned} v_i(t+1) = {} & \alpha(w_s v_{s_i}(t) + w_a v_{a_i}(t) + w_c v_{c_i}(t)) + \\ & ((1-\alpha) \times v_i(t-1)), \end{aligned}$$

where the smoothing parameter α in [0 ,1] interval indicates how much previous information gathered by a node is incorporated into its new deployment decision. Note that the current velocity of a node may have been formed by previous separation or cohesion behaviors. Therefore, the current velocity of a node may include important information about the previous interactions of the node. Hence, smoothing parameter α can be considered as a memory parameter.

Parameters v_{s_i}, v_{a_i} and v_{c_i} are the velocities of node i due to separation, alignment, and cohesion behaviors, respectively, and w_s, w_a and w_c are their corresponding weights taken in the [0, 1] interval. The new velocity of node i is a combination of its current velocity and the new information gained by its separation, alignment, and cohesion behaviors. These coefficients indicate the influence rate of each force and current perception of an UAV on its decision to move. By setting weights w_s, w_a and w_c, various node behaviors can be modeled. The new position p_i of the UAV at time $t+1$ is calculated from its previous position at time t and its velocity at time $t+1$.

The resulting motion is expressed by the following formula:

$$p_i(t+1) = p_i(t) + v_i(t+1).$$

The calculation and the displacements above concern each node belonging to the boid; they are summarized in the presented connectivity maintaining algorithm (Algorithm 1) where we can see the velocity vector affectation for each node i, after computing the separation, the alignment, and the cohesion velocities with each neighbor j respectively.

The displacements of the nodes that do not participate in the routing of active paths are not concerned by these rules; they rather obey to the strategy adopted by the task to achieve.

Algorithm 1. Connectivity Maintaining Algorithm at $node_i$

for each $node_i$ **in** $nodes$ **do**
  begin separation: $v^{Sep}_{node_i} = 0$, $neighbors = 0$
    for each $other\_node$ **in** $nodes$ **do**
      if $(dist(node_i, other\_node) \leqslant z_{sep})$
        $v^{Sep}_{node_i} \leftarrow v^{Sep}_{node_i} - (node_i.position - other\_node.position)$
        $neighbors{+}{+}$
      end if
    end for
    $v^{Sep}_{node_i} \leftarrow v^{Sep}_{node_i} / neighbors$
  end separation
  begin alignment: $v^{align}_{node_i} = 0$, $neighbors = 0$
    for each $other\_node$ **in** $nodes$ **do**
      if $(dist(node_i, other\_node) \leqslant z\_align)$
        $v^{\text{align}}_{node_i} \leftarrow v^{align}_{node_i} + (other\_node.velocity - node_i.velocity)$
        $neighbors{+}{+}$
      end if
    end for
    $v^{align}_{node_i} \leftarrow v^{align}_{node_i} / neighbors$
  end alignment
  begin cohesion: $v^{coh}_{node_i} = 0, neighbors = 0$
    for each $other\_node$ **in** $nodes$ **do**
      if $(dist(node_i, other\_node) \leqslant z_{coh})$
        $node_i.c \leftarrow node_i.c + node_i.position$
        $neighbors{+}{+}$
      end if
    end for
    $node_i.c \leftarrow node_i.c / neighbors$
    $v^{coh}_{node_i} \leftarrow node_i.c - node_i.position$
  end cohesion
  $node_i.velocity \leftarrow (1-\alpha) node_i.velocity + \alpha(w_s v^{Sep}_{node_i} + w_a v^{align}_{node_i} + w_c v^{coh}_{node_i})$
  $node_i.position \leftarrow node_i.position + node_i.velocity$
end for

7 Ground Base Stations Discovery

Drones may store the collected information for later use (delay tolerant applications) or retransmit it on real time to distant servers through ground base stations (time sensitive applications). In the case of time sensitive applications, ground base stations should be equipped with at least two network interfaces, one wireless interface with the UAVs MANET and the other interface which does not participate in the UAVs MANET. These non-UAVs MANET interfaces may be point-to-point connections to other singular hosts or may connect to separate networks. As targeted applications in this paper are real time, ground base stations are needed in network topology architecture. Indeed, a source drone should send its data to any other destination drone having an already established connection with one or more ground base stations. In order to provide this connectivity in a proactive manner, a ground base station should be able to inject external route information to the UAVs MANET. To provide this capability of injecting external routing information into a UAVs MANET, each ground base station periodically issues a special message called DNA for drone and network association containing sufficient information for the recipients to construct an appropriate routing entry to the closest base stations. The recipients are the drones situated in the vicinity of the base stations, in other words, the 1-hop drones of the base stations as depicted in Fig.5.

The DNA message is inspired from HNA (Host and Network Association) of OLSR routing protocol[9] except that the DNA message is not relayed.

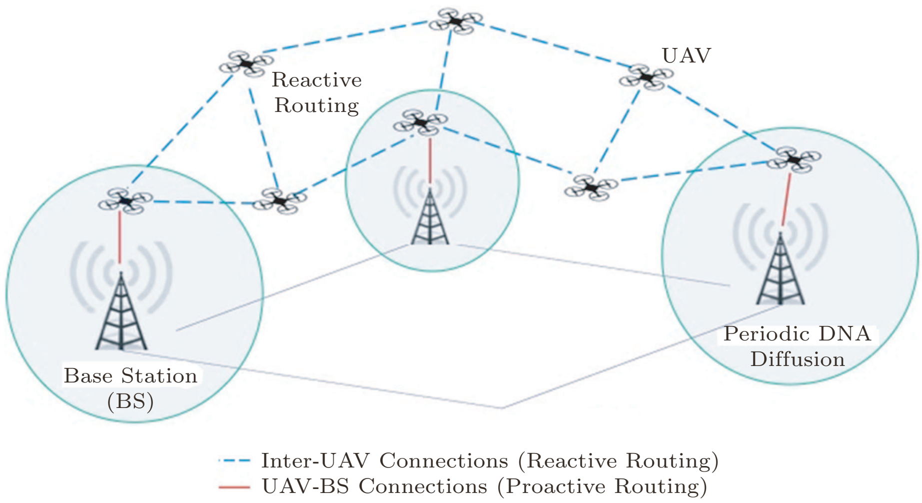


Fig.5. Base stations discovery.

It is sent as the data part of the general IP packet format with the TTL field set to 1 to limit its diffusion to the 1-hop neighborhood of the ground base stations. Each ground base station should periodically generate a DNA message containing pairs of (network address, netmask) corresponding to the connected hosts and networks as shown in Fig.6. DNA messages should be transmitted periodically every DNA-INTERVAL which is set to 5 s in our case. By periodically receiving these messages, the drones situated in the 1-hop neighborhood of the ground base stations detect the existence of these deployed base stations and compute entries to them in their routing tables in a proactive manner. However, the inter-drones routing is computed in a reactive manner using AODV which is more suitable to this context as shown in Section 6.

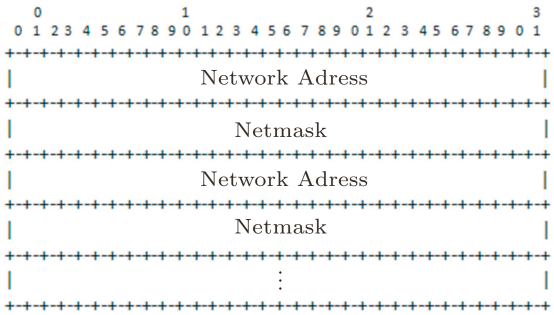


Fig.6. DNA message format.

DNA messages are not relayed and their diffusion is limited to the 1-hop drones of the ground base stations since the topology of the drones is very dynamic and subject to frequent changes. The objective behind DNA messages is the automatic ground base stations discovery and a proactive calculation of the last link to join them.

8 Simulation Results

Though DNA messages are not relayed and the impact of their periodic exchange on the global overhead is limited, the periodic ground base stations discovery mechanism has also been implemented in our simulation as well as the core functioning of BR-AODV. Moreover, as mentioned in the related work, UAVs nodes in most of the proposed routing protocols for UAVs in the literature are mainly limited to play the role of relays for disjoint mobile ad hoc groups on the ground and their objectives are completely different from that of BR-AODV. Hence, we thought more appropriate to compare the performance of BR-AODV with that of AODV rather than those of any other proactive or hybrid routing protocols. Thus, we evaluated the performance of BR-AODV and compared it with that of regular AODV. The testing scenario consists in several UAVs deployed and moving independently while they organize themselves as a flock, or swarm, to maintain the connectivity when it is needed. This happens after an exogenous event that grabs the attention of a single UAV which then needs to follow it, i.e., sensing (video) and end-to-end transmitting sensed data (from a target). In this case, it is important to maintain the connectivity of the active transmission path, and make the implicated relaying nodes move as a flock along with the transmitter. In this purpose, we defined the considered relaying nodes as part of the flock, as well as the transmitter UAV. We then simulated a traffic flow transmission between two UAVs in the UAV fleet separated by four hops, which means three additional AODV relaying nodes, and hence a total of five UAVs or nodes 0, 1, 2, 3, 4. Each node is equipped with the IEEE 802.11g radio interface.

Fig.7 shows the simulated scenario where node 4 is initiating the transmission as well as the movement of the swarm following the target (v represents its velocity). The entire swarm (nodes 0∼4), led by the transmitter (node 4) is represented by colored circles. Once the scenario defined, the UAVs swarm must move following the Reynolds rules. The online available implementation of the Boids of Reynolds[4] was modified and initialized with the positions of the nodes given above to obtain the entire movement of the swarm for a duration of about 12 minutes which is long enough for the convergence of the measurements. We considered a large area of $1\,000 \times 1\,000$ meters to fit with a realistic flight environment of UAVs, and as boids parameters, we fixed the separation distance to 200 meters, the alignment distance to 220 meters and the cohesion distance to 250 meters with a maximum UAV speed set to 10 m/s. The silence period $T_{\max}$ is set to 10 s; however, it has no impact on the obtained results since each node in our simulation generates or retransmits a packet every 1 ms and then never goes to inactive state. These parameters values are set according to the maximum range of the UAVs radio transmitter, the IEEE 802.11g radio range values, and the UAVs most frequently encountered velocities. We then set the weight parameters w_s, w_a and w_c to 1 to make the separation, alignment and

[4]https://processing.org, Jan. 2018.

cohesion velocities equally important. Finally, we set the smoothing or memory parameter α to 0.5 to moderately consider the importance of the previous velocity of a node in the computation of its current velocity.

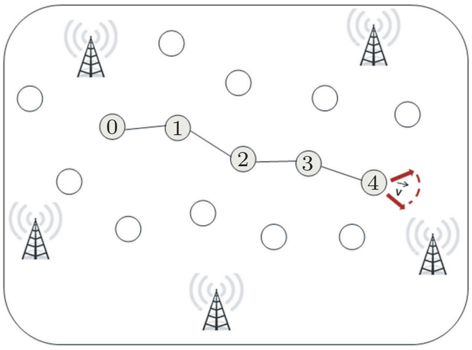


Fig.7. Simulated scenario.

We then used network simulator NS2 to simulate the considered scenario (which will be used as a mobility scene trace file for the simulator). For the performance testing, we defined a best effort transfer between node 4 and node 0 and we measured its goodput (useful bitrate at the receiver), its packet drop rate, and its end-to-end delay for various background traffic load conditions and a free space propagation model to simulate an outdoor rural condition which is the closest one to the UAVs environment. In this purpose, we added 10 nodes that generate this background traffic load, at a constant bit rate, in addition to five ground base stations which periodically broadcast DNA messages every five seconds in their vicinity.

The results show that our proposed reactive routing protocol outperforms AODV for all these metrics thanks to its ability to maintain active paths connectivity and to avoid re-routing mechanisms.

Fig.8 shows the obvious good results in terms of goodput obtained thanks to our proposed mechanism. In fact, as the BR-AODV routing protocol is only performed by the swarm, the background traffic generated by other nodes will not affect the received throughput. Actually, the only impact of the background traffic in BR-AODV case is due to the interferences/noise generated, while in AODV, the background traffic impacts routing nodes bandwidth since all the nodes take part in forwarding UAV packets.

Fig.9 shows that our proposal slightly outperforms AODV in terms of packet drop rate except for high traffic load where results become almost the same.

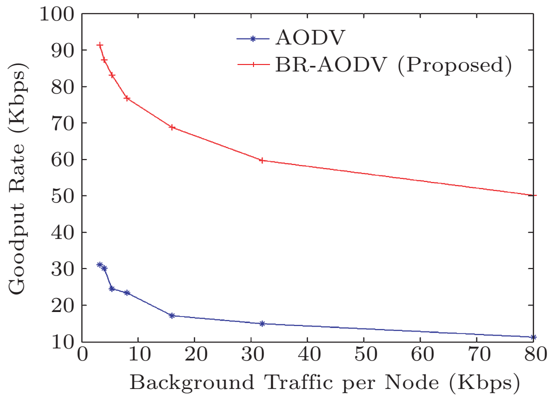


Fig.8. Goodput rate vs background traffic load.

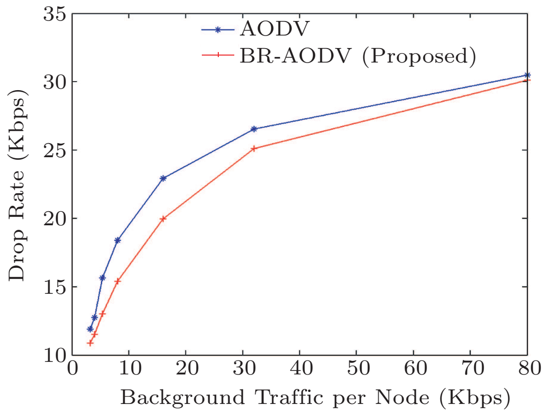


Fig.9. Drop rate vs background traffic load.

This is due to the fact that the drop rate is more impacted by the traffic load that increases collisions in the network than by the mobility and/or the number of hops. Another improvement of our proposal is the reduction of the higher end-to-end delay pick values that can exceed threshold limits.

In our proposed BR-AODV, the delay variation is only due to traffic load while in AODV it is highly impacted by UAV mobility, re-routing and AODV protocol signaling messages.

Fig.10 shows this fluctuation reduction for each packet sent according to simulation time evolution for 80 Kbps traffic load per node. We clearly see that in our proposal the end-to-end delay never exceeds the threshold of 365 ms while for AODV it regularly exceeds the threshold of 450 ms.

Fig.11 shows that the end-to-end delay of BR-AODV is almost stable even when traffic load increases as our algorithm maintains active paths connectivity and avoids re-routing.

We choose to enlarge the background traffic load simulation window to show the impact of BR-AODV on the delay for this high traffic. For lower traffic (less than 30 Kbps per node), as other nodes (not involved in the swarm) could be less loaded, the AODV protocol could be able to find a lower delay route while the UAV head is moving.

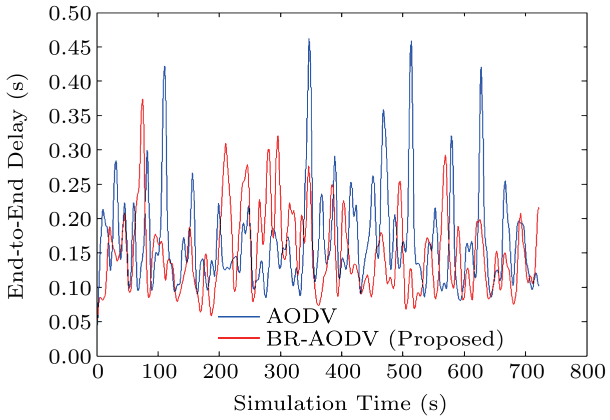


Fig.10. End-to-end delay vs simulation time.

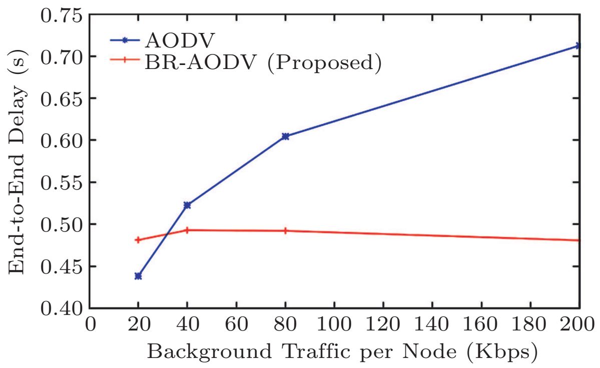


Fig.11. End-to-end delay vs background traffic load.

This is due to a potential existence of another shortest route that was discovered by AODV protocol while our proposed protocol continues to maintain the same route (swarm nodes) during the transmission process. However, the proposed BR-AODV solution becomes more effective for higher traffic load as the swarm nodes, in charge of the UAV traffic, do not take part in routing the background traffic while in AODV all the nodes are potentially involved. Hence, the swarm nodes involved in the BR-AODV routing will not be impacted by the background traffic load increase.

9 Conclusions

In this paper, we proposed a routing protocol for UAVs called BR-AODV. The protocol takes advantage of AODV, a well known routing protocol for ad hoc networks suitable for UAVs ad hoc networks for on-demand route computation, and the Boids of Reynolds mechanism for active paths connectivity and route maintaining while data is being transmitted. Moreover, an automatic ground base stations discovery mechanism was introduced for an association of proactive drones and ground networks. This mechanism is necessary in the context of real-time applications. The performance of BR-AODV was evaluated and compared with that of classical functioning of AODV and the obtained results showed that BR-AODV outperforms AODV in terms of end-to-end delay, throughput and packet loss rate. Though BR-AODV is designed for UAVs networks of moderate size, we are planning in future work to test the behavior of the proposed protocol in a large-scale environment. We are also investigating a hardware validation of the protocol. Indeed, we recently have acquired a kit of CRAZYFLIE 2.0 hardware platform[5] drones and are in the phase of implementing BR-AODV on it.

[5]https://www.seeedstudio.com/Crazyflie-2.0-p-2103.html, Jan. 2018.

References

[1] Maza I, Caballero F, Capitán J, Martínez-De-Dios J R, Ollero A. Experimental results in multi-UAV coordination for disaster management and civil security applications. *Journal of Intelligent & Robotic Systems*, 2011, 61(1/2/3/4): 563-585.

[2] 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 Networks*, 2011, 9(3): 468-477.

[3] Han Z, Lee Swindlehurst A, Ray Liu K J. Smart deployment/movement of unmanned air vehicle to improve connectivity in MANET. In *Proc. the IEEE Wireless Communications and Networking Conf.*, April 2006, pp.252-257.

[4] Chandrashekar K, Dekhordi M R, Baras J S. Providing full connectivity in large ad-hoc networks by dynamic placement of aerial platforms. In *Proc. IEEE Military Communications Conf.*, November 2004, pp.1429-1436.

[5] Tedim F, Xanthopoulos G, Leone V. Forest fires in Europe: Facts and challenges. In *Wildfire Hazards Risks and Disasters*, Paton D, Shroder J F (eds.), Elsevier, 2015, pp.77-99.

[6] Perkins C E, Royer E M, Das S. Ad hoc on-demand distance vector (AODV) routing. RFC 3561, 2003. https://tools.ietf.org/html/draft-ietf-manet-aodv-02, Jan. 2018.

[7] Reynolds C W. Flocks, herds and schools: A distributed behavioral model. *ACM SIGGRAPH Computer Graphics*, 1987, 21(4): 25-34.

[8] Johnson D, Hu Y, Maltz D. The dynamic source routing protocol (DSR) for mobile ad hoc networks for IPv4. RFC 4728, 2007. https://tools.ietf.org/html/rfc4728, Jan. 2018.

[9] Jacquet P, Clausen T. Optimized Link State Routing Protocol (OLSR). RFC 3626, 2003. https://www.heise.de/netze/rfc/rfcs/rfc3626.shtml, Jan. 2018.

[10] Kuiper E, Nadjm-Tehrani S. Geographical routing in intermittently connected ad hoc networks. In *Proc. the 22nd Int. Conf. Advanced Information Networking and Applications-Workshops*, March 2008, pp.1690-1695.

[11] Lee M J, Zheng J L, Hu X H, Juan H H, Zhu C H, Liu Y, Saadawi T N. A new taxonomy of routing algorithms for wireless mobile ad hoc networks: The component approach. *IEEE Communications Magazine*, 2006, 44(11): 116-123.

[12] Brown T X, Doshi S, Jadhav S, Henkel D, Thekkekunnel R G. A full scale wireless ad hoc network test bed. In *Proc. the Int. Symp. Advanced Radio Technologies*, January 2005, pp.50-60.

[13] Khare V R, Wang F Z, Wu S N, Deng Y H, Thompson C. Ad-hoc network of unmanned aerial vehicle swarms for search & destroy tasks. In *Proc. the 4th Int. IEEE Conf. Intelligent Systems*, September 2008, pp.6-65-6-72.

[14] Hyland M T, Mullins B E, Baldwin R O, Temple M A. Simulation-based performance evaluation of mobile ad hoc routing protocols in a swarm of unmanned aerial vehicles. In *Proc. the 21st Int. Conf. Advanced Information Networking and Applications Workshops*, May 2007, pp.249-256.

[15] Karp B, Kung H T. Greedy perimeter stateless routing for wireless networks. In *Proc. the 6th Annual ACM/IEEE Int. Conf. Mobile Computing and Networking*, August 2000, pp.243-254.

[16] Shirani R, St-Hilaire M, Kunz T, Zhou Y F, Li J, Lamont L. The performance of greedy geographic forwarding in unmanned aeronautical ad-hoc networks. In *Proc. the 9th Annual Communication Networks and Services Research Conf.*, May 2011, pp.161-166.

[17] Brown T X, Doshi S, Jadhav S, Himmelstein J. Test bed for a wireless network on small UAVs. In *Proc. the 3rd AIAA "Unmanned Unlimited" Technical Conf.*, September 2004, pp.20-23.

[18] Le M, Park J S, Gerla M. UAV assisted disruption tolerant routing. In *Proc. MILCOM 2006-2006 IEEE Military Communications Conf.*, October 2006.

[19] Forsmann J H, Hiromoto R E, Svoboda J. A time-slotted on-demand routing protocol for mobile ad hoc unmanned vehicle systems. In *Proc. the SPIE Unmanned Systems Technology IX*, May 2007, Article No. 65611P.

[20] Alshbatat A I, Dong L. Cross layer design for mobile adhoc unmanned aerial vehicle communication networks. In *Proc. Int. Conf. Networking Sensing and Control*, April 2010, pp.331-336.

[21] Lin L, Sun Q B, Li J, Yang F. A novel geographic position mobility oriented routing strategy for UAVs. *Journal of Computational Information Systems*, 2012, 8(2): 709-716.

[22] Gu D L, Pei G Y, Ly H, Gerla M, Hong X Y. Hierarchical routing for multi-layer ad-hoc wireless networks with UAVs. In *Proc. the 21st Century Military Communications Conf.*, October 2000, pp.310-314.

[23] Karthikeyan B, Kanimozhi N, Ganesh S H. Analysis of reactive AODV routing protocol for MANET. In *Proc. the World Congress on Computing and Communication Technologies*, February 27-March 1, 2014, pp.264-267.

Nour El Houda Bahloul received her M.Sc. degree in computer science from the University of Batna 2, Batna, in 2013. She is currently working towards her Ph.D. degree in computer science jointly at University of Batna 2 and University of Paris 13. Her research interests include wireless vehicular ad hoc network, wireless sensor network, and parallel and distributed protocols.

Saadi Boudjit received his Ph.D. degree in computer science from the National Institute for Research in Computer Science and Control (INRIA Paris) in 2006 and was a research fellow with Telecom ParisTech (2006~2007). He is currently an associate professor and a member of the L2TI Laboratory at the University of Paris 13 (since 2007), Villetaneuse. Dr. Boudjit is the initiator and chair of ACM MobileHealth Workshop which aims at providing a forum for the interaction of multiple areas related to pervasive wireless healthcare systems. He also acted and still acts as TPC member of several IFIP, ACM and IEEE conferences and workshops (HealthCom, MobileHealth, ICC, Globecom, CAMAD, WCNC, WONS, Wireless Days, etc). His research interests include wireless networks, parallel and distributed computing, protocols and architecture design in mobile ad hoc networks, wireless sensor networks, vehicular ad hoc networks, and protocols and architecture design for eHealth systems.

Marwen Abdennebi received his M.Sc. engineering degree in telecommunications from SupCom, University of Carthage, Tunisia, in 2002, and his Ph.D. degree in computer science in 2008 from the University of Versailles, France. He worked as an application engineer at STMicroelectronics and later as an associate researcher at the CNRS PRiSM Laboratory. He is currently an associate professor (since 2010) at the University of Paris Nord (France) and researcher in the L2TI Laboratory, Villetaneuse. His research interests are in broadband radio MAC/PHY, B3G networks, LTE/LTE-A, particularly in traffic modelling and mobility management in radio networks. He has published many papers in international journals and conferences. They include some proposals on enhancing radio MAC interface for voice and video support, for dynamic spectrum sharing, proposals for mobility management in mesh and ad hoc networks, and scheduling policies improvement in LTE/LTE-A networks and Satellite. Marwen Abdennebi is also a lecturer at SupGalilée Engineering School, and he is the responsible for radio and communications academic program.

Djallel Eddine Boubiche received his HDR diploma (habilitation to conduct research) in 2015 from Batna 2 University, Batna, and his Ph.D. degree in computer science from UHLB University, Algeria, in 2013. He is currently an associate professor at the Computer Sciences Department of University of Batna 2, Algeria. He is also a member of the LaSTIC Laboratory and the scientific committee in the Computer Sciences Department of Batna 2. His research interests include wireless communication, embedded systems, intelligent multi-agent systems, distributed computing and sensor networks. Dr. Boubiche's research has been published in various renowned international journals and conferences. He frequently serves as a program committee member, a program chair, a general chair and co-chair of international conferences and tracks. Dr. Boubiche is the guest editor of several special issues organized in international indexed journals (International Journal of Computational Science and Engineering, International Journal of Artificial Intelligence and Soft Computing, and IEEE Communications Magazine).