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FANETs in Agriculture - A routing protocol survey

Georgios A. Kakamoukas[a,*], Panagiotis G. Sarigiannidis[a], Anastasios A. Economides[b]

[a]*Department of Informatics and Telecommunication Engineering,*
University of Western Macedonia, Kozani, Greece
[b]*Information Systems IPPS, University of Macedonia, Thessaloniki, Greece*

Abstract

Breakthrough advances on communication technology, electronics and sensors have led to integrated commercialized products ready to be deployed in several domains. Agriculture is and has always been a domain that adopts state of the art technologies in time, in order to optimize productivity, cost, convenience, and environmental protection. The deployment of Unmanned Aerial Vehicles (UAVs) in agriculture constitutes a recent example. A timely topic in UAV deployment is the transition from a single UAV system to a multi-UAV system. Collaboration and coordination of multiple UAVs can build a system that far exceeds the capabilities of a single UAV. However, one of the most important design problems multi-UAV systems face is choosing the right routing protocol which is prerequisite for the cooperation and collaboration among UAVs. In this study, an extensive review of Flying Ad-hoc network (FANET) routing protocols is performed, where their different strategies and routing techniques are thoroughly described. A classification of UAV deployment in agriculture is conducted resulting in six (6) different applications: Crop Scouting, Crop Surveying and Mapping, Crop Insurance, Cultivation Planning and Management, Application of Chemicals,and Geofencing. Finally, a theoretical analysis is performed that suggests which routing protocol can serve better each agriculture application, depending on the mobility models and the agricultural-specific application requirements.

Keywords: smart farming, precision agriculture, unmanned aerial vehicles (UAVs), flying adhoc networks (FANETs), routing protocols, mobility models

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1. Introduction

Precision agriculture is an innovative method that farmers use in order to optimize inputs such as water and fertilizers to enhance productivity, quality and yield [1]. This term also involves minimizing pests and diseases through spatially targeting the amount of pesticides [2]. Precision agriculture allows farmer to deal with each part of his field in an appropriate

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*Corresponding Author

Email addresses: gkakamoukas@uowm.gr (Georgios A. Kakamoukas), psarigiannidis@uowm.gr (Panagiotis G. Sarigiannidis), economid@uom.gr (Anastasios A. Economides)

way and empower him to cope with crops diversification. The fact that farmers are more precise on planting, harvesting, fertilizing leads to higher efficiency and productivity of the farm while ecological standards are respected.

Agriculture is a huge ecosystem that affects and is affected by large amount of data [3]. These data are related to both environmental quantitative features such as atmospheric temperature, soil temperature and chemical composition, humidity, solar radiation as well as qualitative data by the crop itself such as pest occurrence and plant disease. The collection of this data along with proper processing mechanisms will offer new prospects for rural development [4].

Information and Communication Technology (ICT) along with its advancements will facilitate the push to a more data-oriented agriculture [5]. Advancements such as Internet of Things (IoT) [6] and cloud computing [7] are combined in order to implement efficient data gathering [8],[9], intelligent data analysis [10] and effective information dissemination to agriculture stakeholders [11]. Moreover, geospatial technology such as Global Positioning System (GPS) [12] and Global Navigation Satellite System (GNSS) [13], can also play an important role in precision agriculture since they can incorporate the precise location of each component [14].

The rapid development of UAVs is also a very promising solution for real-time information gathering, since they are considered as one of the most promising technologies in the field of precision agriculture [15]. UAVs can be deployed in different processes of precision agriculture, since they can implement a set of actions such as data acquisition, data processing, data analysis and data management [14]. Their ability to fly makes them even more attractive since they can acquire valuable information that ground inspection cannot, in a shorter time. A major drawback is that the UAV is a complicated system and it requires integration and coordination of different sciences and technologies in order to function properly.

UAVs can be classified into two (2) main categories i) fixed wing, and ii) multi-rotor. A fixed wing has better aerodynamics, lower energy consumption resulting in longer flights and higher speed but demands large space for take-off and landing [16]. A multi-rotor can carry heavier payloads, it is easier to pilot, and both take-off and landing are executed vertically [14]. UAVs consist of six (6) main sub-modules that cooperate to build a valuable platform [17]: i) The UAV airframe is considered as the body of the UAV. It must be light enough in order to preserve energy consumption at a low level and strong enough to increase the payload of the UAV and tolerate accidents and crashes while it has limited space for avionics and no space for a pilot. ii) The flight computer is the “heart” of UAV. Its purpose is to collect aerodynamic information through a set of sensors (GPS, accelerometers, gyros, magnetometers, etc.), in order to direct the flight of the UAV according to its flight plan via the control surface mounted on the airframe. iii) The payload, which is a mission related characteristic composed by a set of sensors and actuators such as infrared sensors, thermal sensors, environmental sensors etc. These sensors gather the mission related data and either process it on-board or transmit it to a base station for further analysis. iv) The mission/payload controller, which is an on-board computer system that controls the operation of the sensors included in the payload. v) The base station which is a computer system on the ground that is used to control the UAV and its payload. vi) The communication infrastructure is the combination of communication techniques (radio, microwave etc.) that is designed to ensure the continuous communication between UAVs and base station.

There is an emerging area of research that focuses on the development of multi-UAV application in a variety of industries including agriculture. It is a fact that single UAV systems have monopolized the agricultural domain mainly due to the reason that multi-UAV communication protocols are still at a research stage [18].

Our purpose of this work is to distinguish and classify UAV applications in agriculture, and propose which routing protocol could efficiently support the multi-UAV communication for each application. The paper is organized as follows: The next section sums up the value of exploiting multiple UAV systems in smart farming and introduces the major fragment which functioned as a motive for this study. Section 3 presents the related work concerning UAV deployment in agriculture. Section 4 is separated into 2 subsections, in subsection 4.1 there is a literature review on mobile ad hoc network (MANET) and FANET routing protocols and in subsection 4.2 a mobility model survey is conducted. Section 5 includes the classification of UAV applications in agriculture. Section 6 proposes the routing protocol for each UAV application based on our theoretical analysis in previous sections. Finally, Section 7 triggers some discussion points and presents the conclusions of our study.

2. Motivation and Contribution

Malnutrition is one of the greatest challenges of the 21st century. One (1) out of seven (7) people in the earth do not receive the necessary quantity of food in order to survive [19] hile 80 % of available land is already cultivated [20]. Although technology is advancing and agricultural systems are being upgraded, crop production is declining instead of increasing because of water shortage, crop diseases and climate change. The problem becomes even more intense, considering that the earth population by 2050 is expected to reach 9 billion people [21].

This paper studies the deployment of UAV system in precision agriculture. Based on [14] UAVs can be applied in different applications of precision agriculture having both passive and active role. Passive role includes all the actions concerning data collection and processing, while active role includes the actions concerning interventions in the crop such as irrigation and application of fertilizers. A farmer benefits by several practical ways by the use of UAVs, such as: i) Counting the number of fruits on every tree, so the farmer will know how many fruits there are in every tree and can estimate the yield in the crop, optimizing the production chain downstream. ii)Letting the farmer to know the leaf area index, he will have a measure of how photosynthesis is possible in every plant, which reveals how healthy each plant is. The leaf area index is calculated by taking models of plants, constructing 3-dimensional reconstructions and from that estimate the canopy size and then correlate it to the amount of leaf area on every plant. iii) Combining visual and infrared information, the normalized Difference Vegetation Index (NDVI) can be computed. NDVI makes easier to identify productive and non-productive areas of a crop [22]. iv) Identifying plant diseases which have symptoms that affect the appearance of the plant such as chlorosis, skeletonisers, Gall Makers, Chewers, Sap Feeders. v) Remote sensing in water management and irrigation control applications. vi) Applying chemicals such as pesticides and fertilizers in each plant individually based on its needs.

The ”next big thing” in UAV technology is the transition from a single UAV system to a multi-UAV system. Based on an effective communication mechanism, UAVs can cooperate to complete a mission, building a system that outmatches a single UAV. The advantages of a multi UAV system that have been identified by the research community are summarized below:

- Cost: Single UAV is heavy and large and in case of a failure could pose a great danger to human life and property. Furthermore, acquisition and maintenance costs are far more expensive than small UAVs [23].
- Scalability and Speed: The efficiency of the UAV system is closely related to scalability and speed. Using a single UAV the area of coverage is limited, while using multi-UAVs the scalability of the operation can be easily extended [24]. Usually in a single UAV communication architecture a star topology network is used in which the UAV will be in the center of the star. That means that the UAV can collect only the data from the nodes that are in its range. This fact poses a great restriction to the size of the crop where a UAV can collect the data as well as the time of data gathering. It is intuitive that the more UAVs are available, the faster the data gathering process can be completed.
- Survivability: In case of a single UAV, a failure means that the whole mission has failed. In cases where the UAV needs to be replaced then the problem becomes even greater for farmerss, who have invested a lot of money in a single expensive UAV. On the contrary, multiple UAVs can share tasks among themselves thus the fault tolerant of the system increases significantly.
- Heterogeneity: The number of applications a single UAV can serve are proportional to the systems that can be installed on its board. For example, in [25] the UAV was equipped with sprayers in order to spritz the crop but was not equipped with a camera in order to provide the farmers with Red-Green-Blue (RGB) or near-infrared images. Using a multi-UAV system, different individual tasks can be completed by different UAVs. For example, UAV1 can collect aerial images, UAV2 can aggregate the collected data from the ground sensors while UAV3 can spray the crop and all these in parallel.

Despite the aforementioned advantages, there is the great challenge of communication and coordination among multiple UAVs [26]. To enable this cooperation, UAVs must stay within the communication range of one another while preserving a high degree of coordination and a robust inter-UAV communication in an ad-hoc manner. Ad-hoc networks using flying vehicles as nodes are called FANETs [26]. There are numerous papers that try to shed light in this domain mainly by proposing new networking models and protocols to guarantee the appropriate communication between UAVs. It is a fact that single UAV systems have monopolized the agricultural domain mainly due to the reason that FANET communication protocols are still at a research stage and there is a lack of field implementation and evaluation [18]. Our purpose is to distinguish and classify UAVs deployment cases in agriculture and conduct a theoretical analysis to identify which routing protocol would be suitable for each case.

The motivation of our research is based on the conclusions of [27],[28] where it is supported that the performance of a FANET depends heavily on the deployed routing protocol and the mobility model that effectively describes the motion of UAVs.

Our paper's research topic lies at the intersection of three (3) recent surveys (Figure 1). Bagheri et al. [29] classified the available routing protocols for FANETs and they mainly focused on position-based (also called geographic-based) routing protocols because of their ability to adapt better in networks where topology changes are frequent, and nodes' mobility is very high. They described routing protocols' functionalities and weaknesses along with the possible applications where FANETs could be deployed. Also, they presented a comparative analysis among the surveyed routing protocols.

Bujari et al. [27] described in depth the existing mobility models in terms of network connectivity, motion realism and collision avoidance, along with their advantages and disadvantages. Subsequently, they introduced some general cases and proposed which mobility model could sufficiently represent nodes' movement.

Sinha et al. [14] aggregated the applications concerning the deployment of UAVs in the agricultural sector and provided a guidance to understand the characteristics of each application. Subsequently, they classified their findings in passive (monitoring) and active (intervening) applications based on UAV's actions within agricultural production management tasks. They concluded their work by presenting current limitations along with forthcoming needs and suggestions.

The current study analyzes and combines the results of the aforementioned surveys. Based on the characteristics for every case proposed in survey [14] we choose the appropriate mobility model from survey [27]. Based on the mobility model and application itself, we propose the appropriate routing protocol according to our research along with the comparative analysis from survey [29].

3. Related work

The idea of deploying a UAV in the agricultural domain is not new. One of the first papers that introduced UAVs in cultivation was [30] in 2002 by Sugiura et al. who developed an unmanned helicopter which could generate the crop map with a 42cm error map. Fukagawa et al. [31] introduced a more innovative system since they could control the UAV remotely and added a multispectral image sensor to monitor the crop growth. Herzit et al. [32] developed a solar-powered UAV which was deployed in a coffee plantation. Based on the idea of UAV's remote-control Xiang and Tian [33] deployed a system that enabled the UAV to collect multispectral images from predefined waypoints of the crop. In 2010, Yang tried to distinguish which airborne imagery is better (multispectral or hyperspectral) for identifying root rot infestations and concluded that both approaches are equally efficient [34].

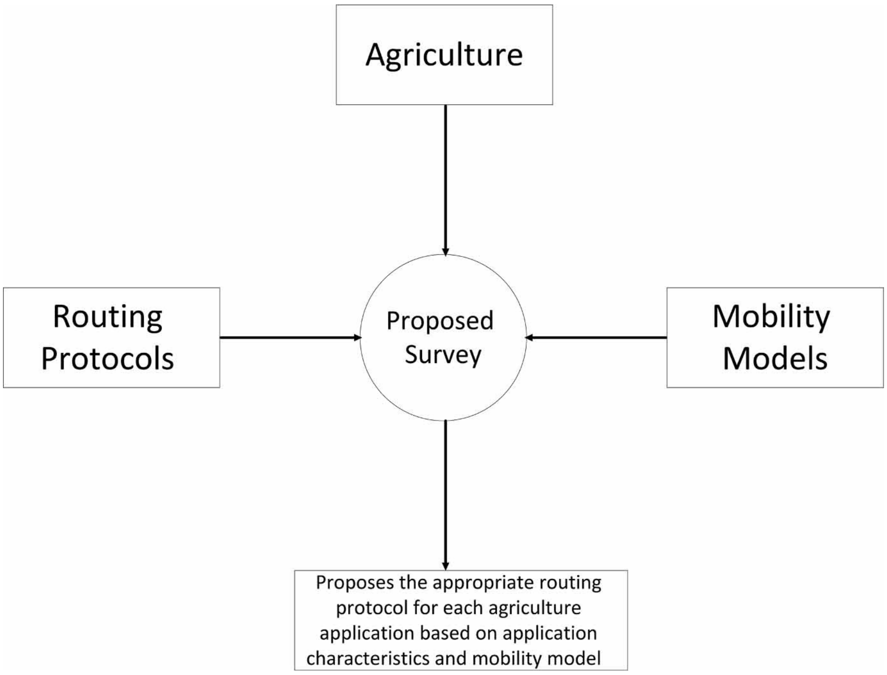


Figure 1: The 3 inputs of our paper are the 6 application cases of agriculture [14], the mobility models used in these cases [27] and the available routing protocols that have been proposed for FANETs [29].

In 2011, Xiang et al. [35] deployed a low-cost -compared to the up to that date literature- remote sensing image system based on unmanned autonomous helicopter equipped with a multispectral camera, to monitor an herbicide application in turf grass. They compared the image estimated herbicide damaged area with the corresponding ground survey and they ascertained that the difference between them was only 1.5 %. Taking into consideration that the time of elaborating a ground survey is proportional to the size of the cultivation, it is clear that UAVs' utilization can enhance the surveillance of the cultivation and consequently the agricultural management processes.

After 2011, the research for UAVs' deployment in the agricultural domain turned to low cost, low attitude, personalized and easy to implement systems. Primicerio et al. [36] conscripted NDVI maps to reveal crop heterogeneity in a vineyard, while Hung et al. [37] developed a system which could identify and segment objects upon trees using a low attitude UAV with spatial resolution 20 cm/pixel.

Vega et al. [38] proved that NDVI and grain yield, aerial biomass and nitrogen content in the biomass are closely related with a confidence level close to 99 %. Swain et al. [39] deployed a low attitude (20 meters over rice plots) remote sensing platform (LARS) which utilized a radio-controlled unmanned helicopter to acquire spatial and temporal resolution images in order to estimate yield and total biomass of a rice crop. They showed the applicability of LARS sensor-based images for estimating NDVI values which can help the farmers determine the total biomass for rice crops.

Aldana-Jague et al. [40] also deployed a low attitude system with a multispectral camera mounted on a UAV. They claimed that the proposed methodology can be used for monitoring soil characteristics such as the soil organic carbon (SOC) content and for precision agriculture. Bagheri et al. [29] developed a multispectral imaging system for wheat farms using a UAV. Based on their simulation, their approach proved to be very promising for monitoring temporal changes in the place of interest.

Huang et al. [41] developed an innovative UAV system which utilizes RGB and infrared cameras for remote sensing. Based on their experiment, the system could distinguish the weed species, identify specific plant diseases and conduct a crop damage assessment. A similar work was conducted by Di Martini et al. who developed [42] 2 different UAVs, one for precision agriculture and one for forest monitoring. They embedded vision and machine learning techniques inside their systems in order to identify diseases and distinguish pests. Mateen et al. [43] have also used an Object Based Image Analysis in order to identify patches on the surface of weeds. In order facilitate the process, they deployed a low-altitude UAV equipped with an RGB and a multispectral camera.

Potena et al. [44] investigated the air-ground robot communication. They developed a cooperative system between a UAV and Unmanned Ground Vehicle (UGV), whose aim is to construct a map of the environment in an agriculture scenario. This map would incorporate and depict vegetation indexes on a Digital Surface Model (DSM). Cooperation lied in the fact that both UAV and UGV had to effectively align their maps from both aerial and ground perspective.

The aforementioned papers present UAV as the new tool for enhancing management processes in agricultural domain, while the following papers use UAV as part of the network. A UAV can be equipped with a wireless communication system so that it can communicate with a ground station, IoT nodes or wireless sensors for collecting data or send commands when it moves inside their communication range. Based on their autopilot function along with the time tolerant nature of the network, UAVs can cover areas where direct communication seems unable to. Such kind of deployment can increase communication range significantly and enhance data aggregation capabilities of data collector nodes.

Costa et al. [25] proposed a system for deploying UAVs and Wireless Sensor Network (WSN) in the agricultural domain. They installed a wireless communication system to enable data exchange between UAV and ground nodes. The UAV was also equipped with sprayers in order to spritz the crop according to the feedback received from ground sensors. Arnold et al. [45] developed a system where data processing would take place outside the field, but the UAV would act like a mobile gateway by collecting the data from each ground sensor. Similarly, De Freitas et al. [46] proposed a UAV-based solution to the connectivity problem of isolated nodes. In their approach the UAVs acted as mobile sinks that provide a backbone link between the WSN and the base station. Pang et al. [47] also utilized UAVs in order to collect data from ground sensors in harsh terrains considering also the possibility to wireless recharge sensor clusters.

The deployment of multiple UAV systems in real cases is at an early stage especially in the field of agriculture. According to our research we found only three (3) papers that cope with multiple UAV systems for agricultural purposes. Ju and Son [48] deployed UAVs in a remote sensing task. They created four (4) different cases: Auto-Single-UAV, Auto-Multi-UAV, Tele-Single-UAV and Tele-multi-UAV. Then they evaluated their performance according to total time of mission accomplishment, setup time, flight time, battery consumption, inaccuracy of land, haptic control effort and coverage ratio. The experimental results revealed that multi-UAV system has better performance comparing to a single UAV. Skobelev et al. [49] proposed another multi-UAV system for precision agriculture based on agents. Their prototype system has the ability to connect UAVs in a swarm, proposes coordinated flight plans and changes them when it is necessary. They conducted both simulations and test flights in order to evaluate its performance and their next step will be the in-field experiments. Rango et al. [50] proposed two (2) different bioinspired approaches of multiple UAV topology management in a precision agriculture scenario. According to their evaluation, the bioinspired approaches seems to outperform traditional approaches, with better results in terms of scalability and mission execution.

UAVs have attracted a lot of attention by the research community since their advantages clearly overcome the challenges they insert. They are smaller than aircrafts, less expensive and they do not put at risk the pilot's life. Their ability to move in a less stressful environment such as the air in low altitude can enhance decision making in different fields. However, the deployment of UAVs introduces some new challenges which must be addressed in order to make their operation as efficient as possible.

4. FANET Routing and Mobility

4.1. Routing Protocols in FANETs

There are two (2) different types of FANET architectures which can be established among the network nodes:

- Air to air wireless communication: This kind of communication can be used in cases where there is no infrastructure or when a UAV wants to forward a packet to a node that is outside its transmission range. Its rationale is based on pure ad hoc architecture thus it can support a wide range of applications where ground station set up is impossible.
- Air to ground wireless communication: When there is a ground station but not all UAVs can communicate with it because of limited transmission range, they use other UAVs as relay nodes that are inside ground station's transmission range in order to communicate with it.

Designing routing protocols for FANETs is not a trivial task mainly because of FANETs special characteristics such as the 3-dimension movements along the highly dynamic topology. Each routing protocol will follow either a specific or a combination of the following routing techniques (Figure 2):

- Store-carry and forward technique: In a high fragmented network, it might be impossible for a node to find a relay node inside its transmission range. In this case, the current node will carry the packet until it finds another suitable relay node or the destination itself in order to forward the packet. This technique introduces high delay due to the physical movement of the node.

- Greedy-based technique: This technique chooses the path to the destination based on the least number of hops. The rationale behind greedy forwarding is to choose as a relay node the geographically closest node to the destination. This technique is used mainly in FANETs with high node density.

- Single-path technique: There is only one path between two communicating nodes. This technique can simplify the management of the routing table in each node of the network but there are no alternative paths and in case of an error in the existing path packet losses will occur.

- Multipath technique: There are several paths between two communicating nodes. This technique increases the complexity of the routing tables management, but when an error occurs an alternative path can be identified in order to decrease packet losses.

- Path discovery technique: Every time the source node does not have a record to the destination in its routing tables, it initializes a path discovery process. The discovery process is based on Route Request (RREQ) packets dissemination either by broadcasting them to its neighbors, or using the flood technique so that every node that receives the RREQ packet, duplicates it and forward it to its neighbors. When the destination receives the RREQ packets it will reply by unicasting a Route Reply (RREP) packet back to the source. Then, this path will be used for the data packet transmission.

- Prediction based technique: It takes into consideration the future position of a node inside a network based on its geographical location, direction and speed. These three (3) parameters can provide the necessary information to accurately predict the next relay node location which can reduce the packet delivery ratio as well as the end-to-end delay.

There has been an extensive research in the field of routing protocols that are suitable for FANET applications. Topology-based routing protocols are protocols that use IP addresses, to uniquely identify each node and the network's existing path information to decide how to forward packets. Topology-based routing can be separated into:

- Proactive-based (also called table-driven): The routing tables contain routing paths between every pair of nodes.

- Reactive-based (also called on-demand): There is not a pre-established routing path between every pair of nodes registered in routing tables. The nodes use a discovery process on demand when they want to establish a connection.

- Hybrid-based: The network is divided into zones where inside each zone proactive routing is applied, while for the inter-zone communication reactive routing is applied.

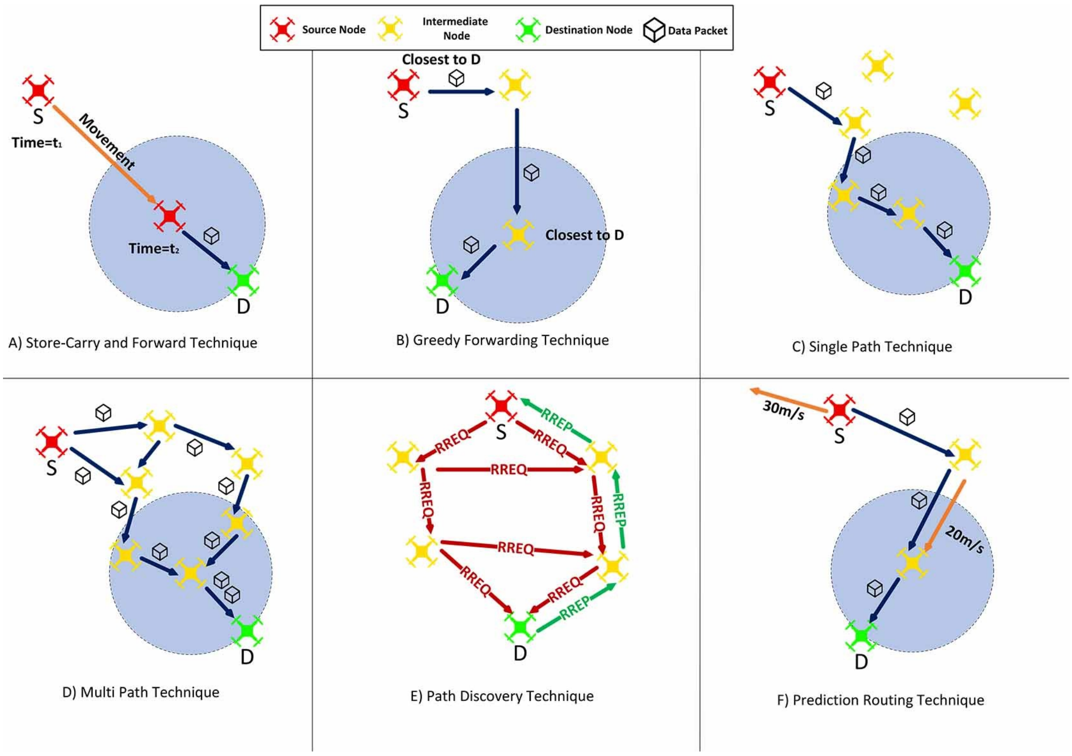
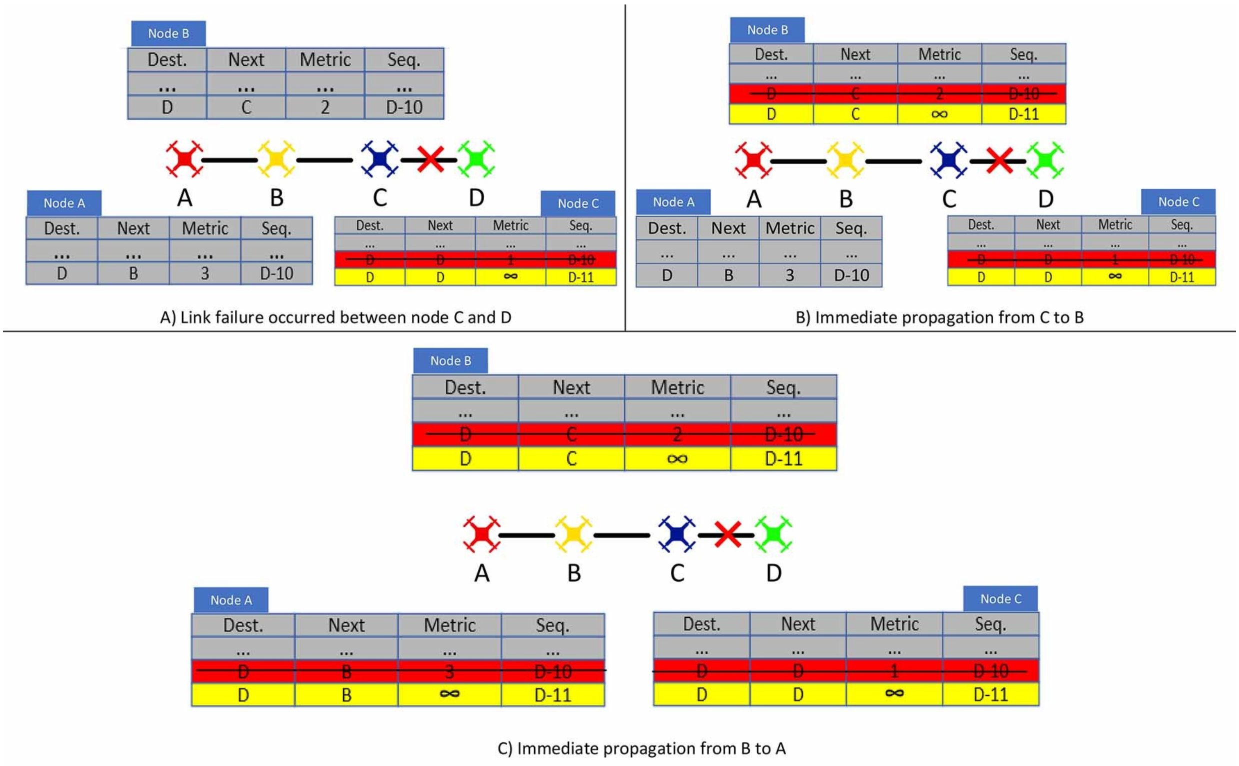


Figure 2: FANET routing techniques

4.1.1. *Topology-Based Routing Protocols*

Topology-based routing protocols are extensively used in ad hoc networks. However, they do not possess any special feature that would make them more attractive to high mobility networks with frequent topology changes such as FANETs. Out of all the protocols that have been proposed in literature so far, DSDV [51, 52], OLSR [51][53][54], along with its variations CE-OLSR[55], D-OLSR[56], NC-OLSR[57], M-OLSR[58], TORA [59],DSR [60, 61], and AODV [62] seem to monopolize the interest of researchers and are often adopted either as basic or as supportive protocol in networks that share similar characteristics with FANETs.

Destination Sequenced Distance Vector (DSDV) [51] is a proactive routing protocol. Its rationale is based on Distance Vector Routing principles based on which, each node constructs a one-dimensional array containing the distances (costs) to all other nodes and distributes that vector to its immediate neighbors. The frequency with which each node distributes the vector is of high importance since it can reduce overhead, network latency and power consumption significantly [63]. After each node has exchanged a few updates with its directly connected neighbors, all nodes will know the least-cost path to all the other nodes. In addition, nodes need to keep track of which node told them about the path that they finally used in order to update their list of distances effectively. Using these information they can calculate the cost for each path in order to create their forwarding table. In case a link is not reachable it is assigned an infinite cost. If any of the recipients of the information find a path shorter than the one they currently know about, they update their list to give the new path length and note that they should forward packets through that path.



Node B

Dest.	Next	Metric	Seq.
...	...	...	...
D	C	2	D-10

Node A

Dest.	Next	Metric	Seq.
...	...	...	...
D	B	3	D-10

Node C

Dest.	Next	Metric	Seq.
...	...	...	...
~~D~~	~~D~~	~~1~~	~~D-10~~
D	D	∞	D-11

A) Link failure occurred between node C and D

Node B

Dest.	Next	Metric	Seq.
...	...	...	...
~~D~~	~~C~~	~~2~~	~~D-10~~
D	C	∞	D-11

Node A

Dest.	Next	Metric	Seq.
...	...	...	...
D	B	3	D-10

Node C

Dest.	Next	Metric	Seq.
...	...	...	...
~~D~~	~~D~~	~~1~~	~~D-10~~
D	D	∞	D-11

B) Immediate propagation from C to B

Node B

Dest.	Next	Metric	Seq.
...	...	...	...
~~D~~	~~C~~	~~2~~	~~D-10~~
D	C	∞	D-11

Node A

Dest.	Next	Metric	Seq.
...	...	...	...
~~D~~	~~B~~	~~3~~	~~D-10~~
D	B	∞	D-11

Node C

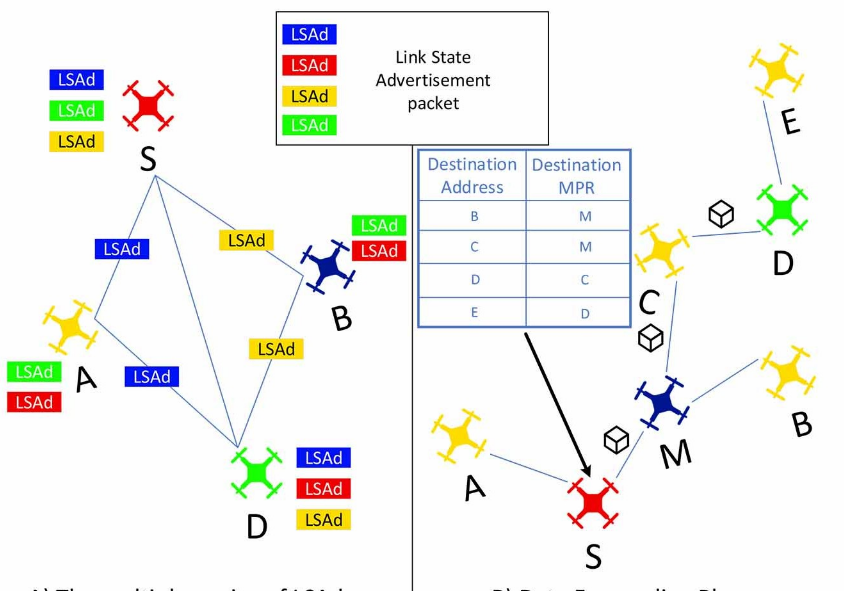
Dest.	Next	Metric	Seq.
...	...	...	...
~~D~~	~~D~~	~~1~~	~~D-10~~
D	D	∞	D-11

C) Immediate propagation from B to A

Figure 3: DSDV technique to overcome the count to infinity problem

DSDV uses additional features that enhance its performance and allow it to overcome the count to infinity problem (Figure 3). DSDV adds destination sequence numbers along with each entry. A node will update its table with a new route to a destination only if the route has higher sequence number that is originated by the destination, except the case when there is a link failure. In this particular case, the node responsible for the update of the sequence number is its neighbor node. In case of Figure 3 there is a link failure between C and D which triggers a change in the value of sequence number (Seq.) field from D-10 to D-11. After 2 successive distance vector updates, node B (intermediate) and node A (sender) will have received a vector where the field sequence number (Seq. equals D-11) is higher than the record that currently has (Seq. equals D-10). Hence, nodes B and A will change the record in their routing table accordingly. If there are not sequence numbers, then node B would receive a routing table from C notifying it that node D is not reachable by C and a routing table by A notifying it that it has route to D although node B doesn’t know that this information is not valid anymore. This ”ping-pong” of distance vector exchange would lead hop-metric value to infinity. The use of sequence numbers ensures that only the newest information from destination is used, thereby the count to infinity problem is solved. In case when sequence numbers are equal, the protocol selects the route with the better metric. In DSDV the routing table entry includes destination, next hop, distance, sequence number.

Optimized Link State Routing (OLSR) [64] is based on Link State Routing (LSR) protocol on the basis of which, each node sends to its neighbor information, known as Link State Advertisement (LSAd), on a periodic basis. Once the node has the complete view of the network, it populates its routing table using a variant of Dijkstra algorithm for shortest path. LSAd is disseminated to every node in the network using flooding mechanism (Figure 4A). Flooding causes the reception of multiple copies of same LSAd which results in higher overhead and the wastage of network bandwidth. In OLSR every node selects which of its neighbors can flood LSAd packets. The selected nodes are called Multi Point Relays (MPR) and only they can retransmit the packets received by their neighbors, which are called MPR Selectors, to the rest of the network. In OLSR there are three (3) types of packets: i) Hello Packets, which are used to sense the state of the link and to determine whether the link is still valid or not, ii) Topology Control Packets, which are used to inform nodes which are the MPR nodes, and iii) MID Packets, which are used to inform about the multiple interfaces of a node. Thanks to the dissemination of Hello Packets, each node will learn its one (1) and two (2) hop neighbors. After that, each node must select its MPR node, using MPR selection algorithm. MPR nodes forward Topology Control packets which contain information about MPR Selector. Each node builds its routing tables based on the topology table that is created by Topology Control Packets.



Destination Address	Destination MPR
B	M
C	M
D	C
E	D

A) The multiple copies of LSAd B) Data Forwarding Phase

Figure 4: OLSR LSAd dissemination and packet forwarding

At some point of time, node S according to its topology table (Figure 4b) has been informed that both B and C has chosen M as their MPR, D has chosen C, E has chosen D. That means, when D, for example, sends a message, only C can retransmit it. Suppose that S wants to send data to D. S will search its table for entry D, and it will find out that D's MPR is C. That means that D is reachable through C. Then S will apply the same process to find entry C, which has M as its MPR hence its reachable through M. M is S's one (1) hop neighbor, an information that is stored in neighbor tables each node maintains. As a result S will construct the corresponding path and forward the data to D.

OLSR is an optimization over pure LSR as it compacts the size of information sent, while reduces the number of retransmissions originated by the flood mechanism in entire network [64].

In Temporarily Ordered Route Algorithm (TORA) [59], the node height represents the number of hops between the node itself in relation to the destination; each node other than the destination maintains its height, which is denoted by Height, in respect to the destination. Initially, the height of each node is set to null (i.e., Height[i] = (-,-,-,-,i)). The height of the destination is always 0 (i.e. Height[destination] = (0,0,0,0,destination). Also, every node maintains a height array for each neighbor. Figure 5 shows source node S sending a data packet to node D. Node S broadcasts a Query packet (QRY), which is annotated by a Route Request ID (RREQ-id) that is used to identify and then drop duplicates instead of broadcasting them again. When destination node D receives the QRY packet, it responds with a UPD packet. A node can send data only to neighbors that have lower height and consist part of the route path. Upstream links are responsible for the dissemination of heights and downstream link are responsible for sending data packets.

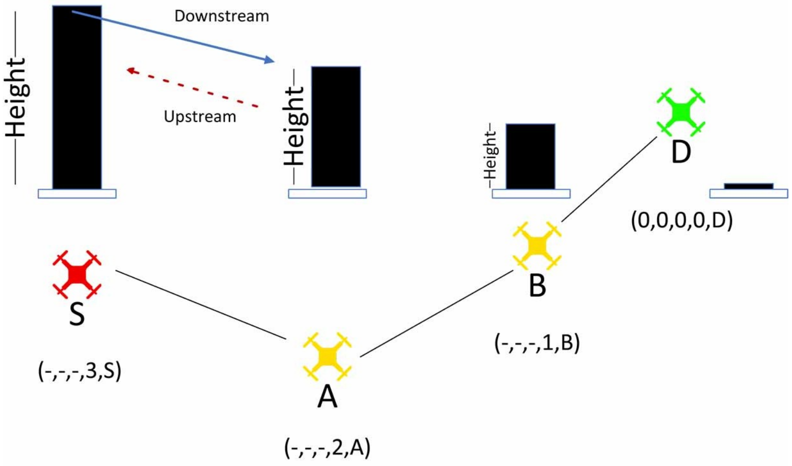


Figure 5: Node heights in relation to destination which indicate the upstream and downstream link in TORA

There are 3 cases for route maintenance. The first case is when a link is broken but nodes have other downstream links. In this case, there is no need to update the routing tables and no action is required since the routing procedure will be running successfully. The second case is when a link is broken and nodes do not have any downstream link, a new reference level must be created and sent to neighbors. In that case the height on the specific node is recalculated by changing the reference part of the formula. The neighbors of the corresponding node will receive the UPD packets containing the height information and their height has been recalculated. The height of node D is greater than the height of its neighbors, as a result the link direction will be changed. The third case is when a node does not have any downstream link because of the route maintenance process. In this case UPD packets are disseminated to the node that takes part in the path where the change occurred. An algorithmic procedure of comparing the height of each node is running until a node that provides a valid path to the destination enters the network or until r value of height formula equals 1. Then the source node replaces the “Height” of each node with null value, and the procedure to create a new path starts again. The aforementioned algorithmic procedure is quite complex, including the exchange of multiple UPD packets between the nodes, a characteristic that increases the overhead significantly.

The Dynamic Source Routing protocol (DSR) [60] is a simple and efficient reactive routing protocol designed specifically for use in multi-hop wireless ad hoc networks of mobile nodes.

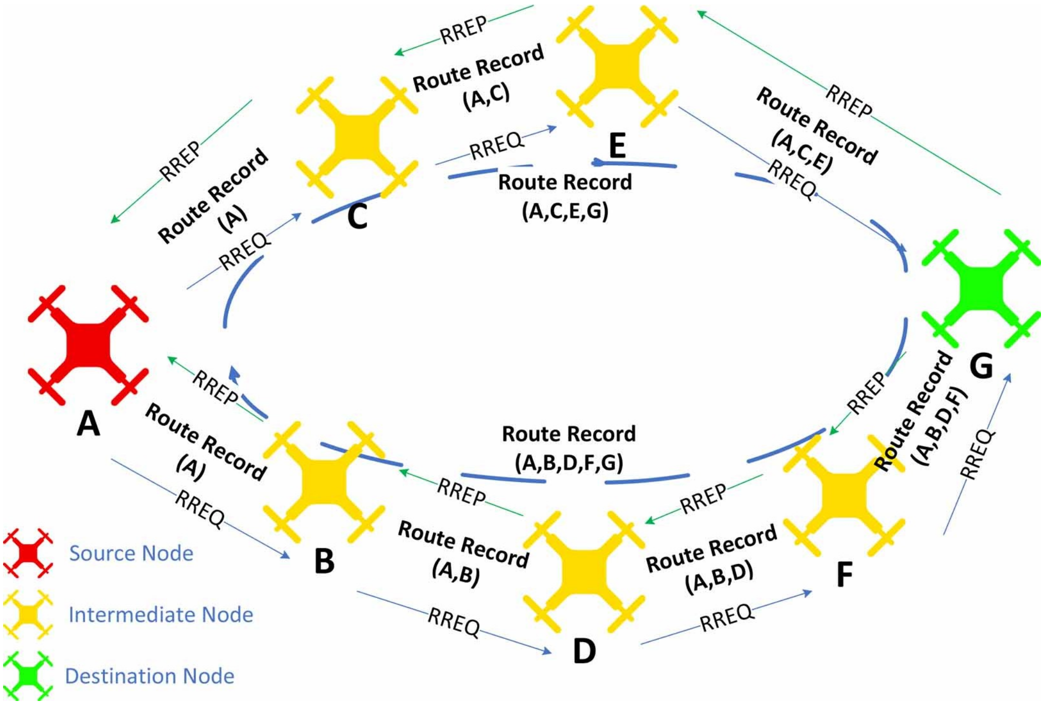


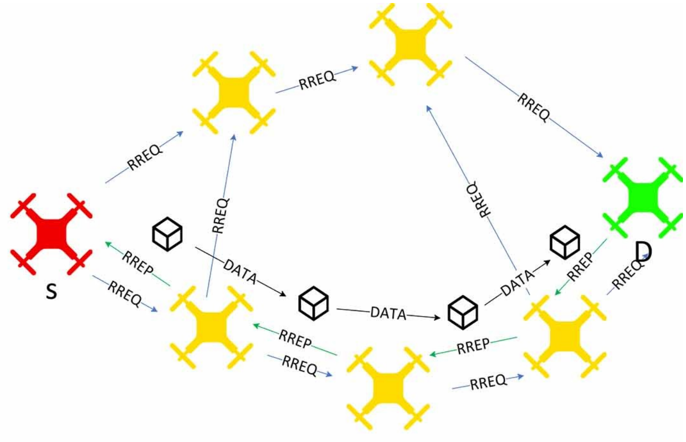
Figure 6: DSR route discovery and maintenance operation

The protocol can be separated into 2 phases, the ”Route Discovery” phase and the ”Route Maintenance” phase. Route Discovery phase is executed only when it is needed, that is why it is known as a Reactive routing protocol. Node S wants to send data to destination D (Figure 6). It asks about route D by broadcasting Route Request Packets (RREQ). RREQ packets among others, include a unique id, a list of nodes (initially empty), a source and a destination address. The use of explicit source routing through the list of nodes allows the sender to select and control the routes used for its own packets thus enhancing the performance of the network by supporting multiple routes to any destination (load balancing). Each node that receives the RREQ is checking its forwarding table for node D. If node D is in its routing table then the node adds itself to the list and broadcasts the packet. The same process is repeated until node D receives an RREQ. When that happens, node D will reply to the source node with a Route Reply (RREP) packet and will forward it to the nodes that are inside the list. As soon as node S receives the RREP it will send the data packet and include the route in the header of the packet which guarantees that the routes used are loop-free. Furthermore, node S as well as other nodes inside the network can cache this routing information for future purposes either by forwarding or overhearing any of these packets, since running again the route discovery process is inefficient, time consuming and creates useless overhead. Route Maintenance phase is executed when the Route Discovery phase has been done and a path between two nodes has been established. Its purpose is to identify a broken link (topology change) in the established path and to broadcast this information to all the nodes that take part in this path using a Route Error (RERR) packet. The nodes that will receive this information will remove the corresponding node from the cached route tables.

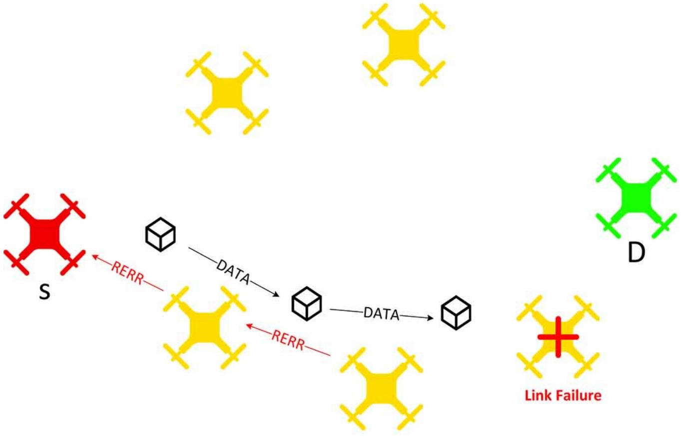
DSR has the ability to recover and maintain multiple paths between source and destination. As a result, each sender can select the forwarding path through multiple available routes considering network robustness or load balancing. Other advantages of this routing protocol include loop-free routing and support of unidirectional links. Its reactive nature also allows rapid recovery when network topology changes.

The Ad hoc On-Demand Distance Vector (AODV) [62] routing protocol is designed for use in multi-hop wireless ad hoc networks of mobile nodes. Route Requests (RREQs), Route Replies (RREPs), and Route Errors (RERRs) are the message types defined by AODV. These message types are received via UDP, and normal IP header processing applies. As long as the endpoints of a connection have valid routes to each other, AODV does not play any rolein the communication. When there is no route available towards destination, the source node broadcasts a RREQ to find a new route to the destination (Figure 7a). Every node maintains two counters, a Sequence Number and a Broadcast id which increments whenever the source issues a new RREQ. The source broadcasts an RREQ data packet which includes the source address, source sequence, broadcast id, destination address, destination sequence, hop counter, etc. When the RREQ reaches the destination node, then the destination node will respond by unicasting an RREP packet which contains the source address, destination address, destination sequence, hop counter, lifetime. In the reply process, depending on the case, the intermediate nodes can either broadcast the packet, or send an RREP if they have an active path with higher sequence number, or discard the packets as duplicates (Figure 7a). When a link break in an active route is detected, a RERR message is used to notify other nodes that a failure of that link occurred (Figure 7b). In AODV, HELLO messages are used for route maintenance and evaluation purposes and are disseminated in a proactive scheme basis.

AODV offers quick adaptation to frequent topology changes, low processing and memory overhead, low network utilization, and can determine unicast routes to destinations. AODV introduces some improvement over DSR, since it can manage bandwidth in a more efficient way. On the one hand, in DSR routing protocol, as the network size increases the path that is stored in the header of the packet also increases and as a result most of the network bandwidth is consumed in sending the path information instead of data. Furthermore, DSR capability of creating and maintaining multiple routes to the destination provides a higher quality of service in terms of load balancing and increased robustness, but also introduces extra overhead which consumes valuable bandwidth. On the other hand, AODV implements a dynamic establishment of route table entries which means that only the nodes in the active path have the ability to maintain routing information and if this information is not used recently, it will expire. Destination sequence numbers that are used by AODV allow it to avoid routing loops and old or broken routes.



A) AODV Route Discovery and Data Delivery



B) AODV Link Failure Response

Figure 7: AODV routing protocol operations

Following the presentation of the protocols, we searched for research papers that examine their performance in cases where conditions are approaching those of FANETs. According to [65], the performance of the protocol changes rapidly when there are changes in the number of nodes or their traffic patterns or changes in distances between them. In particular, DSDV achieves 100 % packet delivery ratio in the case where the nodes move at a slow speed while the corresponding ratio starts to decrease when the nodes increase their speed. TORA shows a high packet delivery rate of 90 %, however the overhead generated on the network is extremely high. Moreover, when the nodes exceeded twenty (20) the overhead increases dramatically resulting in a packet delivery ratio decrease. The performance of DSR is very good at all mobility rates and movement speeds even though the source routing maintains the overhead quite high. Finally, the AODV performs as well as the DSR in different mobility scenarios and movement speeds, eliminating the problem with the source routing overhead. However, the overhead is still quite high and in case when node mobility reaches extremely high rates, the overhead exceeds that of the DSR. The authors concluded that each protocol behaves ideally in some cases and shows significant disadvantages in others. The comparison of the protocols was done in a simulation environment using ns2 simulator.

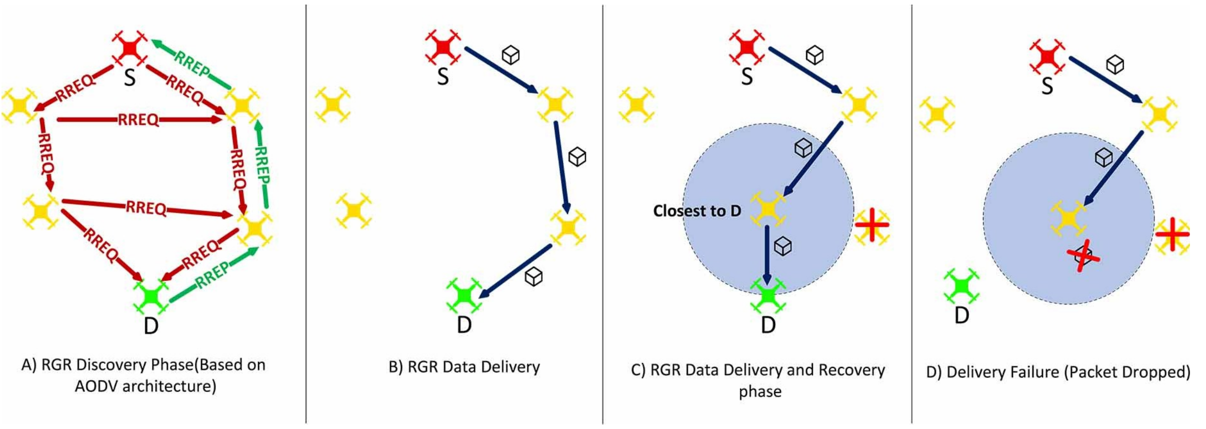
There is not a single algorithm or even a combination of algorithms that proved to be the best option for all network conditions. Each protocol has advantages and disadvantages and has specific cases where it suits well and some others that doesn't suit at all [66]. This is evidenced by the fact that the papers that compare topology-based routing protocols might end up in different results because of the different network parameters they used [67, 68].

There are also other routing protocols that have been proposed for ad hoc network that are useful in specific cases under certain conditions such as HWMP [69], ZRP [70], SHARP [71], HRPO [72] and their enhancements. However, the aforementioned protocols have not been tested for FANET applications regularly.

4.1.2. Position-Based Routing Protocols

Position-based routing protocols are protocols that have been built on top of topology-based protocols and its special characteristic is that they retrieve the geographical position of each node by exploiting GPS services.

Reactive Greedy Reactive Routing (RGR) [73] functions as reactive routing protocol in the route establishment phase, while embedding the capability of retrieving the geographic location of the destination (Figure 8). In the data delivery phase, it starts forwarding packets in a reactive way. In case a link to the destination fails, RGR uses Geographic Greedy Forwarding (GGF) technique to deliver the remaining packets. Route Requests (RREQs), Route Replies (RREPs), Route Errors (RERRs) and hello messages are the message types defined by RGR. RGR has been built on top of AODV thus the behavior and dissemination



A) RGR Discovery Phase(Based on AODV architecture)

B) RGR Data Delivery

C) RGR Data Delivery and Recovery phase

D) Delivery Failure (Packet Dropped)

Figure 8: RGR routing protocol operations

of these type of messages are similar to AODV except for the fact that now the messages are carrying location information too. When a node receives a data packet, it consults its routing table to check if there is a reactive path to the destination or to an appropriate relay node. If the path is broken, RGR exploits the geographical information of the destination by consulting the routing and neighbor table, in order to forward the packet. When a node receives a data packet via a greedy geographic forwarding technique, it examines whether there is a valid reactive route in its routing table. If indeed there is one, the packet will be forwarded to the next neighbor on that specific route. If there is a valid reactive route to the destination, but the next hop neighbor is not available (i.e. out of range), the node will consult the neighbor table to find another neighbor closer to the destination. If no neighbor node can be found, then the packet is dropped.

RGR as a combination of reactive (adopting AODV architecture) and geographic routing protocols proved that it can enhance the packet delivery ratio and end-to-end delay of a FANET mainly in searching missions [73]. In searching scenarios with higher mobility, RGR provides even lower packet latency comparing to other options. The results have also showed that switching to GGF allows to overcome the use of local repair, in cases of disconnections. RGR deployment is suggested in searching scenarios where the nodes are neither highly dense nor highly sparse [74]. RGR's weakness is that the geographic locations are not updated regularly and as a result data packets could be lost if they are forwarded to an outdated geographical position. In the discovery process where the RGR uses the AODV technique, it also adopts AODV's excessive use of control packets during the path discovery process.

Multipath Doppler Routing (MUDOR) [75] is a reactive routing protocol which is based on DSR, but it is different from it, since it takes into account nodes' mobility behavior. Its target is to enhance packet delivery ratio and decrease packet dropping by finding a path

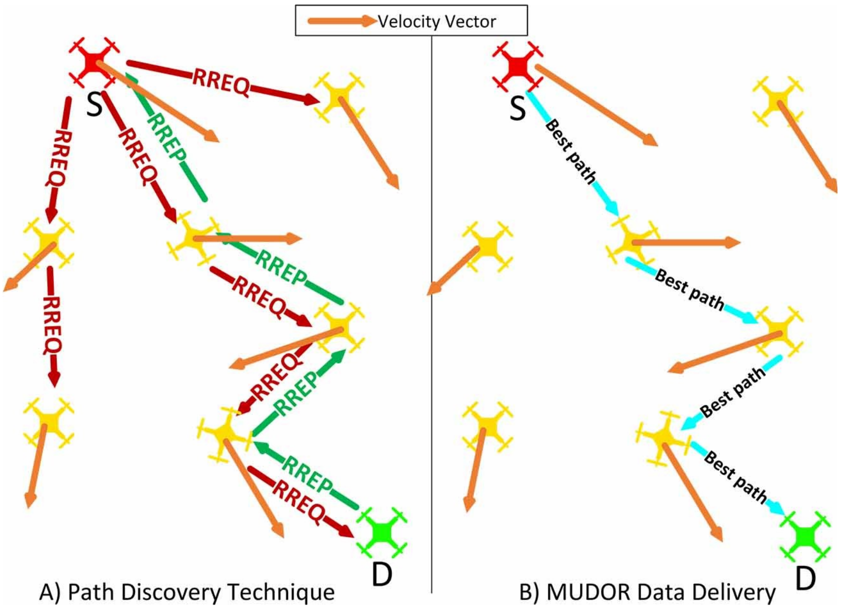


Figure 9: MUDOR routing protocol operations

which is stable enough to ensure complete transfer of the data. This choice is based on the bottleneck Doppler Value of the path which is an indicator that can determine which is the most stable path with the longest duration inside a network. MUDOR uses flooding as a route discovery process and incorporates the addresses of all the intermediate nodes in the RREQ packet (Figure 9). Its creation was based on a scenario where a node is requesting some data from other nodes that possess these data. So, there is no single destination and every node that could provide these data could play the role of destination to the requesting node. Obviously, MUDOR seems to be the optimal candidate in sharing applications where UAVs can act as content providers, connection providers etc.

Unlike most of the routing protocols, in the flooding process MUDOR rebroadcasts a number of duplicates RREQ packets so it can create different combination of nodes which result in a different combination of paths that are more stable leading to higher delivery ratio. In order to decrease the overhead that duplicates produce while they are re transmitted during the flooding process, MUDOR uses a mechanism where only packets with smaller Doppler Values than the previous identical packets are forwarded. A hop-count field that is decremented in each node is used to prohibit rebroadcasting of duplicates through the whole network.

MUDOR advantages [75] derive from its ability to acquire and disseminate data about the speed and direction of each node by exploiting the Doppler effect. As a result, network's performance could be upgraded since a path would be selected based on data that reveal nodes' mobility behavior. Although, sometimes Doppler value is not enough to determine whether a path is stable or not, thus more indicators and constraints need to be considered in order to optimize network's performance. In networks where the nodes present very high mobility and they are dispersed, the paths might fail, and a new discovery process needs to be executed regularly. As a result, the overhead will be increased to a higher level than the overhead other protocols might cause, because of the extra information concerning life duration MUDOR disseminates among nodes. Moreover, the absence of an efficient recovery strategy in case of failures triggers a new path discovery process which is costly enough in terms of overhead and therefore of network end-to-end delay.

Ad-hoc Routing Protocol for Aeronautical MANETs (ARPAM) [76] can be classified as a hybrid routing protocol since it combines reactive behavior with proactive readiness under specific cases. Its reactive behavior originated from the fact that it has been built on top of AODV. RREQ packets floods the network during the discovery process containing the velocity vector acquired directly from the node and the position of the source acquired by an external application (Figure 10). These two (2) parameters are exploited by intermediate nodes in order to estimate both current and future position of the source and consequently determine the shortest route based on criteria such as distance between nodes or the number of hops between them.

ARPAM advantages [76] derive from its ability to acquire information about velocity and geographical position of the source node which are useful for calculating the shortest path between source and destination, and establishing an end to end communication between them. As a result, the delay of delivering data decreases significantly and the high mobility problem becomes manageable in a certain point since the future position of the node or

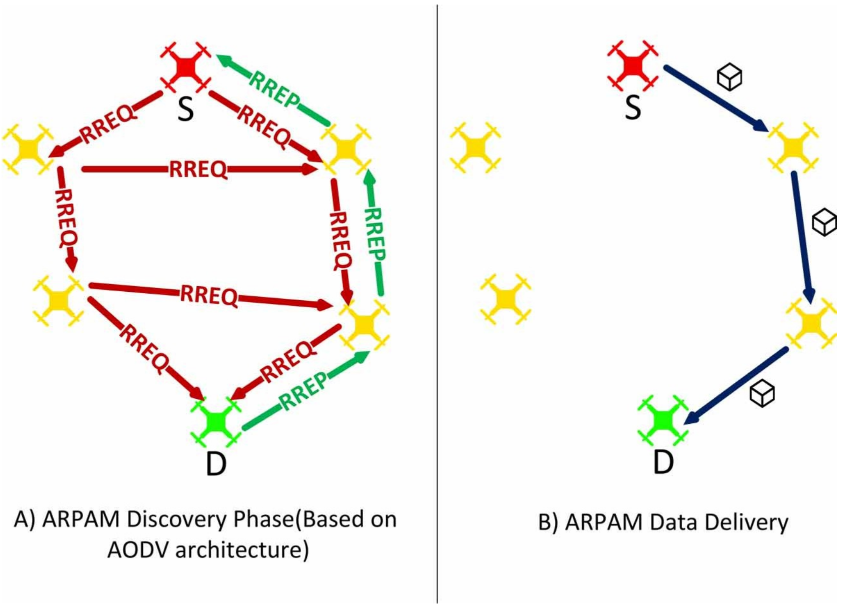
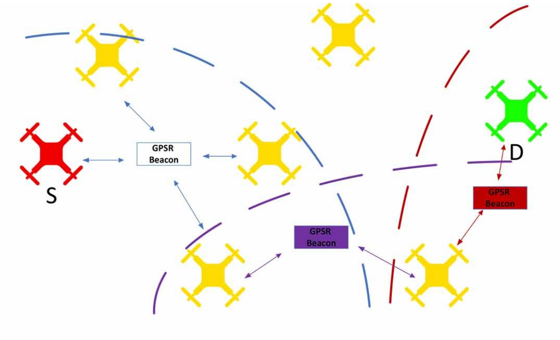


Figure 10: ARPAM routing protocol operations

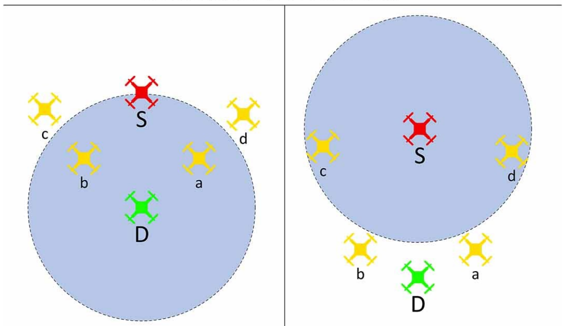
destination could be estimated. These facts makes ARPAM suitable candidate in time critical applications such as Voice over Internet Protocol (VoIP) and Video on Demand (VoD). However, in cases where packet loses occur, ARPAM loses control of routing process and cannot provide any alternatives to ensure data delivery.

Greedy Perimeter Stateless Routing (GPSR) [77] is a routing protocol for wireless networks that exploits nodes' positions and packets' destination to take greedy forwarding decisions following the Greedy Forwarding Technique. GPSR uses a proactive beaconing mechanism where each node transmits a beacon containing a unique identifier (usually IP) along with its position and repeats this process at a fixed time interval. In case a node does not receive a beacon from a neighbor during the time interval it deletes this neighbor from its routing table. There are however some topologies where greedy forwarding is not an option. Such an example is illustrated in Figure 11-B and 11-C, where S is closer to D than its neighbors c and d. Although the two following paths exist (S-c-D and S-d-a-D), but S will not forward neither to c nor d using greedy technique. In these cases, the protocol recovers by routing around the perimeter of the region. Each packet in GPSR includes a "Packet Mode" field in its header which can be either Greedy or Perimeter. When a node receives a greedy-mode packet for forwarding, it consults its neighbor table in order to find the neighbor which is geographically closest to the destination. If there is a record in the table, the node forwards the packet based on that record. If there is no record, the node changes the "Packet Mode" field into perimeter mode. GPSR advantages derive from its ability to keep on information only about the local topology, thus it scales better as the number of network nodes increases and can find correct new routes quickly when network topology suffers from frequent changes.

Geographic Position Mobility Oriented Routing (GPMOR) [78] was introduced for high



A) GPSR Proactive Beacon Mechanism



B) Greedy Forwarding Failure (D perspective)

C) Greedy Forwarding Failure (S perspective)

Figure 11: GPSR beacon dissemination and greedy forwarding failure

speed UAVs with mobility speed over 300 km/h which follow predefined trajectories. GPMOR purpose is to identify the next best hop in cases where the network suffers from serious fragmentation. In order to do that it exploits Gauss-Markov mobility model to predict UAV future position and a Metric To Connect (MTC) to identify the relationship between nodes and consequently select the next hop more accurately. GPMOR can be separated into two phases: the neighbor discovery phase and the data forwarding phase (Figure 12). During neighbor discovery phase a beacon mechanism identical to GPSR is used to disseminate nodes' velocity and position which is acquired by GPS. The maintenance of the neighbor table which is accomplished by using HELLO beacons, is used to calculate the distance from the destination as well as the MTC of each neighbor to take the routing decisions. Each node broadcasts periodically its position to its direct neighbors trying simultaneously to predict their new positions during a time interval. With this approach, the source node can choose the optimal relay node towards the destination. During the data forwarding phase, the source node calculates the immediate position of the destination and its neighbors considering their future movement. Then it chooses the neighbor that is closer to the destination and if there are more than one candidate then it selects the node with the higher MTC.

GPMOR advantages derive from its ability to acquire information about velocity and position of UAVs and to make predictions about their movements with the help of Gausian-Markov mobility model. Moreover, its ability to take into account the mobility relationship

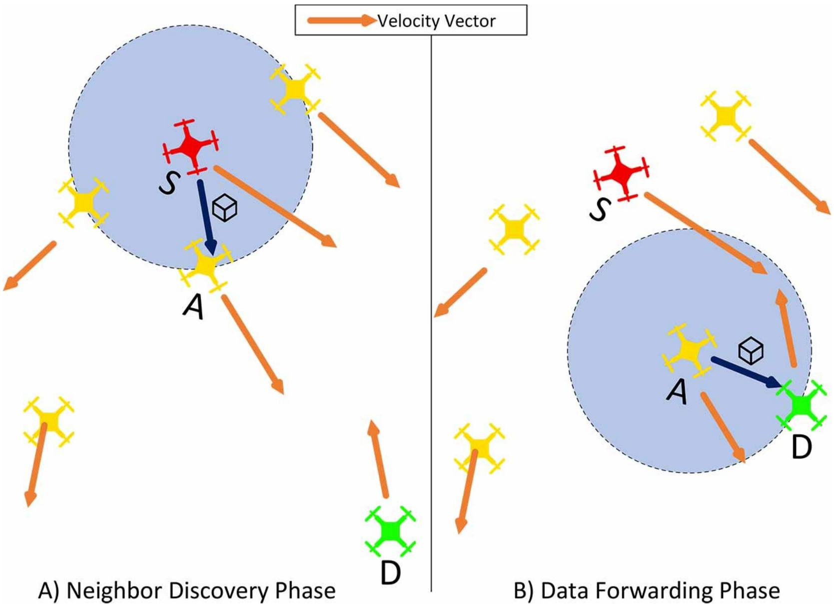


Figure 12: GPMOR routing protocol operations

between neighbors and destination, is a strategy that could provide a better option comparing the perimeter mode of GPSR, which is based on a random choice. As a result, network's average delay as well as packet delivery ratio could be enhanced since the forwarder will be selected based on its future position and its mobility relationship with destination. In cases where the network density is extremely low, GPMOR cannot function as expected resulting in a severe degradation of network performance mainly in terms of end-to-end delay.

Mobility Prediction based Geographic Routing (MPGR) [79] follows the same principles as GPSR. It uses the GGF technique using the usual metrics (i.e. shorter path based on hops) or more sophisticated metrics (i.e. Reliable Next Hop (RNH)). Meanwhile, MPGR is able to predict UAVs' movement based on the Gaussian distribution factor in order to minimize the impact of the high mobility of nodes resulting in a lower overhead which is caused by the transmission of control packets. The movement prediction phase can also ensure that the relay node will remain inside the communication range of the sender during the data delivery phase.

MPGR follows the same approach and methodologies with GPSR in terms of perimeter mode and GPMOR in terms of neighbors' future position prediction (Figure 13). However, the structure of its packets is differentiated since it broadcasts a Neighbor Discovery (ND) packet in order to identify its neighbors and chooses the relay node based on the Reply Packet (RP). MPGR advantages derive from its ability to acquire the link state information and to predict the future movement of each node inside a FANET. Thus, packet loses happen rarely and network packet delivery ratio is significantly increased. However, MPGR does not take into account the link expiration time and does not factor the planned trajectory of next hops in their future position prediction. Furthermore, as in GPSR, MPGR cannot use the perimeter mode in cases where a local maximum occurs (Figure 11-B, 11-C).

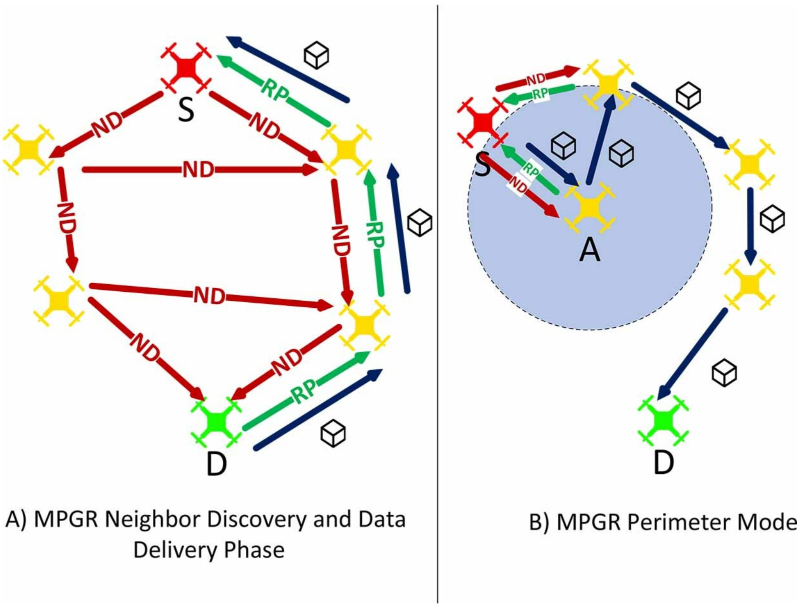


Figure 13: MPGR routing protocol operations

Geographic Load Share Routing (GLSR) [80] is inspired by GPSR and extends its capabilities since it can establish multiple paths between source and destination. The selection of each path is made using a) a metric called Distance Advance (DA), which is calculated as the difference of the distance between the node that carries the packet and the next hop candidate from the destination and b) a metric called Speed Advance (SA) in order to select the optimal neighbor to forward the packet. If DA is positive, it means that the intermediate node A can approach the destination even closer before to forward the packet. Then GLSR consults the queues that each node preserves which contain the packets to be sent and it selects the optimal path (Figure 14).

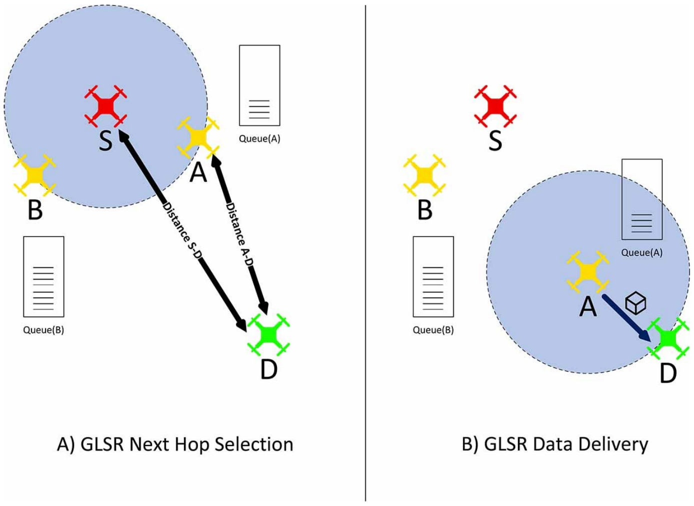
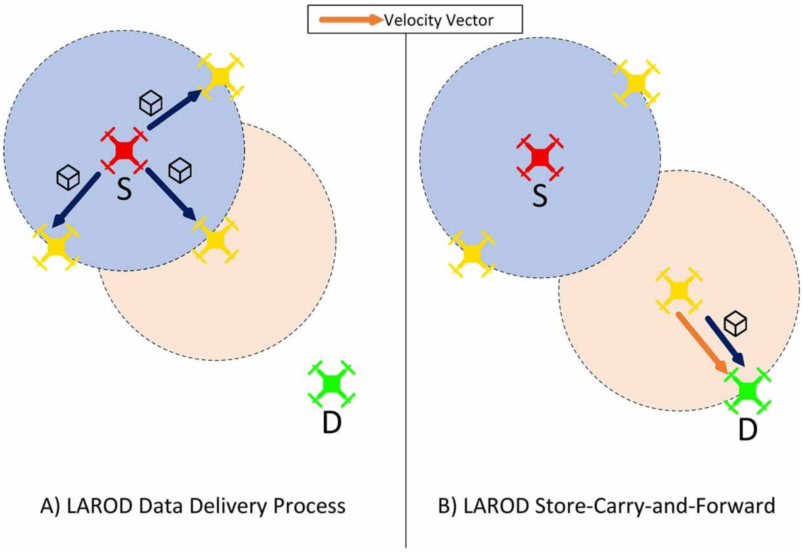


Figure 14: GLSR routing protocol operations

GLSR advantages derive from its ability to create and use multiple paths between source and destination and in combination with the utilization of DA and SA it can balance the load of the network using position and velocity information. Consequently, the network can provide higher quality of services (i.e. VoIP, VoD) as it will be more reliable, with lower end to end delay and higher throughput. GLSR does not possess a recovery process and in cases where no relay node is approaching the destination, the packet it carries is dropped. Another major drawback is that GLSR does not take into consideration other parameters between the intermediate nodes when it chooses the next hop of the routing path.

Location Aware Routing for Opportunistic Delay Tolerant (LAROD) [81] operation depends on the network conditions and it uses either greedy forwarding or store-carry-and-forward technique.



A) LAROD Data Delivery Process

B) LAROD Store-Carry-and-Forward

Figure 15: LAROD routing protocol operations

In cases where the network is sparsely connected the UAV that carries the packet (source or intermediate node), exploits store-carry-and-forward technique until it reaches either a relay node which has a route to the destination or the destination itself. In cases where the network has a higher density, the greedy forwarding technique is deployed based on a timer that each node has at its disposal (Figure 15). Each neighbor receives the packet but only the node with the timer that expired first, is considered as the best relay node and only this node can re-broadcast the packet which traverses the network until it reaches the destination following the same strategy. Every node that re-broadcasts a packet is responsible to overhear the next hop's re-broadcasting in order to ensure that the packet has received successfully. If not, it has to re-broadcast the packet to its neighbors which they have to restart their timers.

LAROD advantages derive from its beacon-less strategy which reduces the total overhead of the network and thanks to store-carry-and-forward technique, LAROD can enhance the packet delivery ratio of the network. However, the store-carry-and-forward technique introduces a high delay of data delivery. As a result, LAROD does not constitute an option neither in delay sensitive applications nor in applications that take place in urban areas due to the reason that overhearing is not very accurate in areas with many obstacles. However, LAROD can be a good candidate in mapping, video making and reconnaissance applications.

Geographic Routing protocol for Aircraft Ad hoc Network (GRAA) [82] has been built on top of GPSR routing protocol, thus it automatically adopts GPSR's locally decision-making strategy.

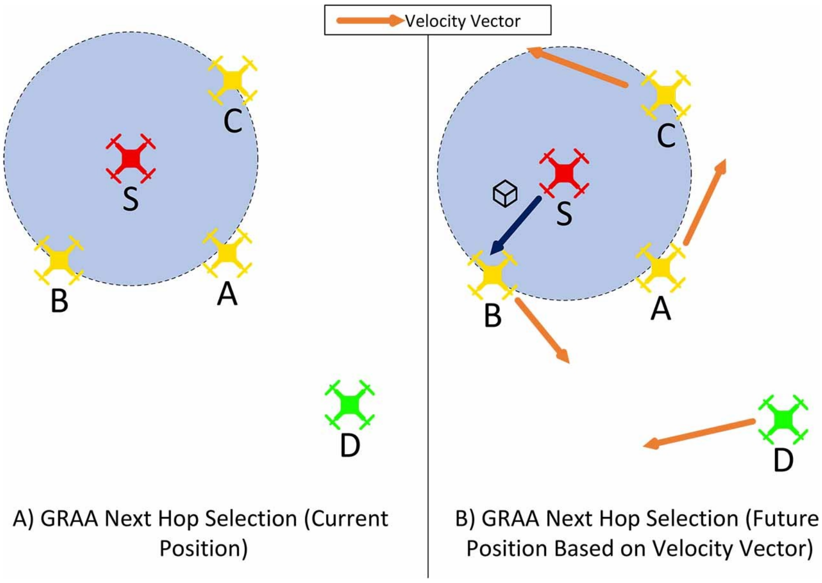


Figure 16: GRAA routing protocol operations

During the data delivery process, each node takes into account the current position and velocity vector for its neighbors as well as the destination and recalculates their new position for a certain time period. Following the greedy forwarding technique, the data are forwarded to the neighbor that will be closer to the destination based solely on its future movement. As shown in Figure 16, node A is closer to the destination than node B. Although the source S forwards the data to node B since its future movement will bring it closer to destination D, while node A is moving away. In case the network is sparsely connected, the node that carries the data continue to keep on them until it reaches either a relay node that has a valid route to the destination or the destination itself.

GRAA decreases the end-to-end delay thanks to the movement prediction capability that facilitates the optimal selection of the next hop. The delivery ratio in partially connected networks is high enough because of GRAA's mode of carrying data until the destination has been reached. However, in movement prediction process, GRAA's calculations do not take into account the environment of the network (obstacles, weather, etc.) that can directly affect network conditions and resulting in performance degradation. Thus, GRAA can be a good candidate in applications where nodes follow predefined paths and data forwarding process is done automatically.

Load Carry and Deliver Routing (LCAD) [83] is deployed when multiple networks in distant location need to communicate. LCAD was introduced in a case where the source node (base station) wants to deliver data in a distant network. After route discovery process is complete, the source node discovers that the destination is not reachable by any of the relay nodes inside the network, so it realizes that the node is to a distant network outside of their range (Figure 17). LCAD will exploit the available UAVs which play the role of relay nodes between source and destination using the store-carry-and-forward technique.

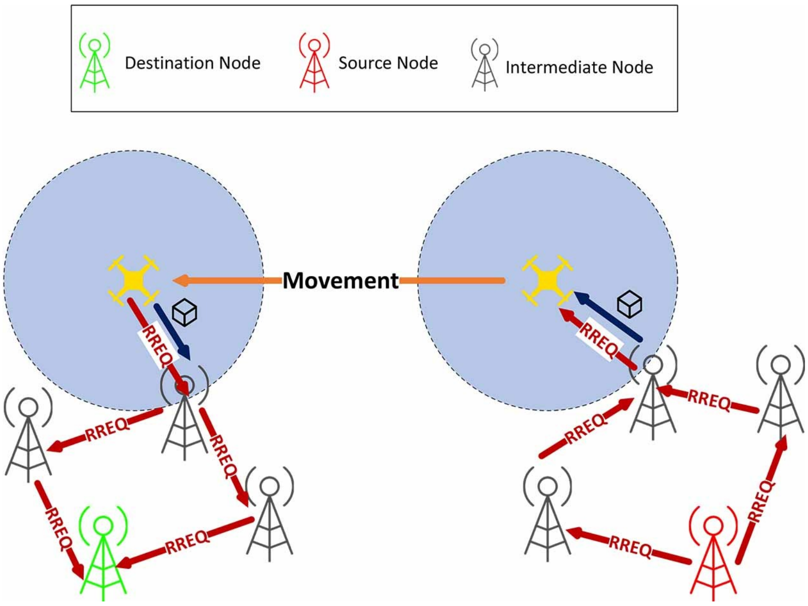


Figure 17: LCAD routing protocol enables communication between distant networks

LCAD advantages mainly derive from the architecture itself. LCAD is based on predefined UAV's trajectory. It can connect distant networks and deliver data wherever the destination is located. Moreover, the utilization of the store-carry-and-forward technique provides a high delivery ratio with the cost of an increase in end-to-end delay. The absence of any data concerning destination's current and future position can decrease the performance of the protocol especially in cases when the destination is a mobile node. As a result, LCAD can be a good candidate for delay-insensitive application such as data gathering from fixed sensors, tracking and reconnaissance missions.

Connectivity-based Traffic Density Aware Routing using UAVs for VANETs (CRUV) [84] operation depends heavily on the network conditions. After the path selection and in order to ensure the data delivery success, CRUV considers either the greedy forwarding or the store-carry-and-forward technique. A peculiarity of CRUV is that the only nodes that take forwarding decisions are the nodes located in the intersections of the network (Figure 18). These nodes are using a score system to evaluate the team of nodes (segment) around them and the segment with the higher score constitute the best candidate to receive and forward the packet. Meanwhile, UAVs are flying over the network overhearing the best score calculated before. When the nodes that take forwarding decisions sense the presence of

UAVs, they create a decision table in order to select the next relay node between the segment with the higher score and the UAV. Then the chosen relay node forwards the packet to the next intersection. This process is repeated until it reaches an intersection which has an available route to destination.

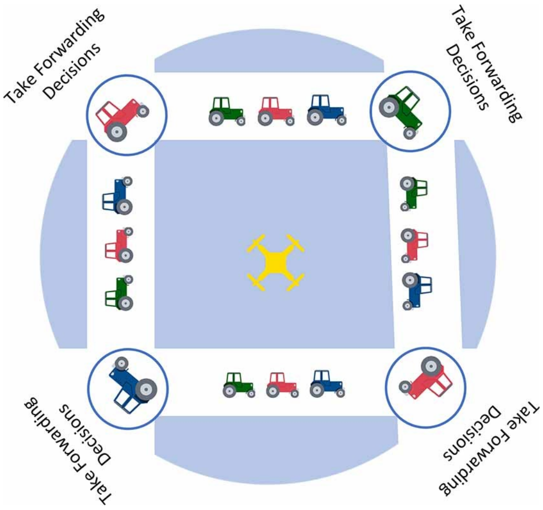


Figure 18: CRUV routing protocol topology

CRUV advantages mainly derive from its ability to identify connected segments that was impossible to identify using only ground nodes. As a result, CRUV constitutes a promising option in sparsely connected networks since UAVs increase significantly the chance to find a connected segment to ensure data delivery. Consequently it can be deployed in service providing application (i.e. access to the Internet). The use of the store-carry-and-forward technique increases the delay of the network, a fact that makes CRUV incapable of managing time sensitive applications.

UAV-Assisted VANET Routing Protocol (UVAR) [85] is an extension of CRUV since it tries to enhance its performance both in terms of average delay and throughput by incorporating information about connectivity, density, distance between current node and destination and real distribution of ground nodes. UAVs collect this information by overhearing the exchanged Hello packets between ground nodes.

UVAR advantages derive from the exploitation of the aforementioned information which allows to select the best segment for the data delivery. As a CRUV's extension, UVAR shares the high delay drawback due to the store-carry-and-forward technique plus the fact that UAVs can be used as relay nodes only when there is no segment to receive and forward the data to destination.

Cross-layer Link quality and Geographical-aware beaconless opportunistic routing protocol (XLinGo) [86] was introduced in a case where a UAV wants to transmit a video to another node with a known location. UAV includes in the packet header its own geographical position as well as the destination's geographical position too and broadcasts it to the neighbors. Based on these geographical positions, two forwarding areas emerged: a) Positive Progress Area (PPA) and b) Negative Progress Area (NPA). According to XLinGo, the nodes that are located inside NPA drop the packets immediately, and only one out of all neighbors inside PPA will forward the packet, while the others will also discard it (Figure 19). The selection of this node is done using the concept of Dynamic Forwarding Delay (DFD) which dictates that the node which is closer to destination generates the lower DFD and forwards the packet.

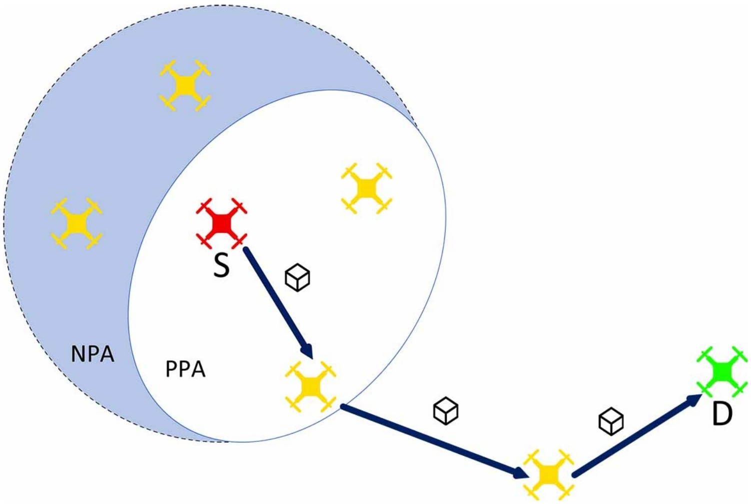


Figure 19: XLinGo routing protocol operations

According to its creators, XLinGo can operate without congestion problems and reduces the bandwidth overhead significantly. In their simulations they included only one source of video producer and it remains unknown how it scales with more. Obviously, XLinGo can be a candidate in serving multimedia applications.

Table 1 summarizes the compilation of the aforementioned routing protocols. It is worth to mention that several other routing protocols have been proposed for ad hoc networks, e.g., the Position-Aware, Secure, and Efficient mesh Routing (PASER) [87] and the Secure UAV Ad hoc routing Protocol (SUAP) [88] which are focused to ensure secure data exchange through the nodes. However, security is out of the scope of this survey. On the other hand, Figure 20 summarizes the dependencies, extensions, and enhancements of the aforementioned routing protocols combined with their corresponding packet forwarding techniques. Moreover, it classifies the protocols based on their MANET or FANET behavior as well as on their capability to handle mobility speed.

Routing Protocol	Protocol Classification	Protocol Approach	Protocol Novelty	Pros	Cons
DSDV[52]	Topology-based	Proactive-based	Overcome the count to infinity problem	Decrease network latency due to its proactive nature Able to control overhead, network latency and power consumption by controlling the frequency of vector distribution	Increase overhead and network latency due to its proactive nature
OLSR [51][53][54]	Topology-Based	Proactive-Based	Controll Flooding Process using Multi Point Relays	Decrease overhead because of controlled flooding	Still high overhead compared to other protocols Increase network bandwidth wastage
DSR [61]	Topology-Based	Reactive Based	Multi-path availability Routing table caching Support Unidirectional Links	Decrease overhead due to its reactive nature Able to provide QoS by choosing the best route to destination Loop free routing	Increase bandwidth wastage due to the path size information Increase network latency due to its reactive nature
AODV [62]	Topology-Based	Reactive Based	Support Unidirectional Links dynamic establishment of route table entries	Quick adaptation to topology changes Decrease processing power Decrease overhead Manage bandwidth more efficient than other reactive protocols	Increase network latency due to its reactive nature
TORA [59]	Topology-Based	Hybrid-based	Drop duplicates mechanism	Decrease overhead compared to other proactive routing protocols	Increase overhead due to its proactive nature
RGR [73]	Position-based	Multi-path Reactive and Greedy-based	GGF technique in case of a failure	Decrease network latency	Decrease packet delivery ratio due to outdated geographical positions
MUDOR [75]	Position-based	Multipath Reactive-based	Incorporates nodes’ mobility behavior Multi-path availability	Increase packet delivery ratio	No recover strategy
ARPAM[76]	Position-based	Multipath Hybrid and Prediction based	Aware of source’s and destiation’s movements	Decrease network latency	No alternative to ensure data delivery
GPSR[77]	Position-based	Single path Greedy based	Keep information only about the local topology	Better scalability Quick adaptation to network changes	Increase overhead due to its proactive nature
GPMOR[78]	Position-based	Single path Greedy and Prediction based	Nodes’ movement prediction based on mobility models	Increase packet delivery ratio	Increase network latency in sparce networks
MPGR[79]	Position-based	Single path Greedy and Prediction-based	Combines GGF and movement prediction	Increase packet delivery ratio	Does not consider link expiration time Does not consider the trajectory of next hopes
GLSR [80][89]	Position-based	Single path Greedy based	Multi-path Proactive	Increase packet delivery ration Able to provide QoS by choosing the best route to destination	No recovery process Packet is dropped when there is no available relay node
LAROD[81]	Position-based	Single path Greedy-based	Combines GGF and store-carry and forward Implements a beaconless strategy	Increase packet delivery ratio Reduce overhead	Increase network latency
GRAA[82]	Position-based	Single path-Prediction based	Movement prediction	Decrease network latency Increase packet delivery ratio in sparse connected networks	Not able to consider network’s environmental parameters
LCAD[83]	Position-based	Multipath Heterogeneous	Special Architecture	Connect distant networks Increase packet delivery ratio	Limitation of pre-defining nodes’ trajectories Destination must be fixed Increase network latency
CRUV[84]	Position-based	Multipath Heterogeneous	Only nodes located in network’s intersections take forwarding decisions	Increase packet delivery ratio for sparse connected networks	Increase network latency
UVAR[85]	Position-based	Multipath Heterogeneous	Enrich CRUV approach with network information	Increase packet delivery ratio	Increase network latency
XLinGo[86]	Position-based	Multipath Heterogeneous	Uses dynamic DFD concept	Eliminate conjestion Reduce bandwidth wastage	Application-specific limitation

Table 1: Routing protocols for Ad Hoc Networks

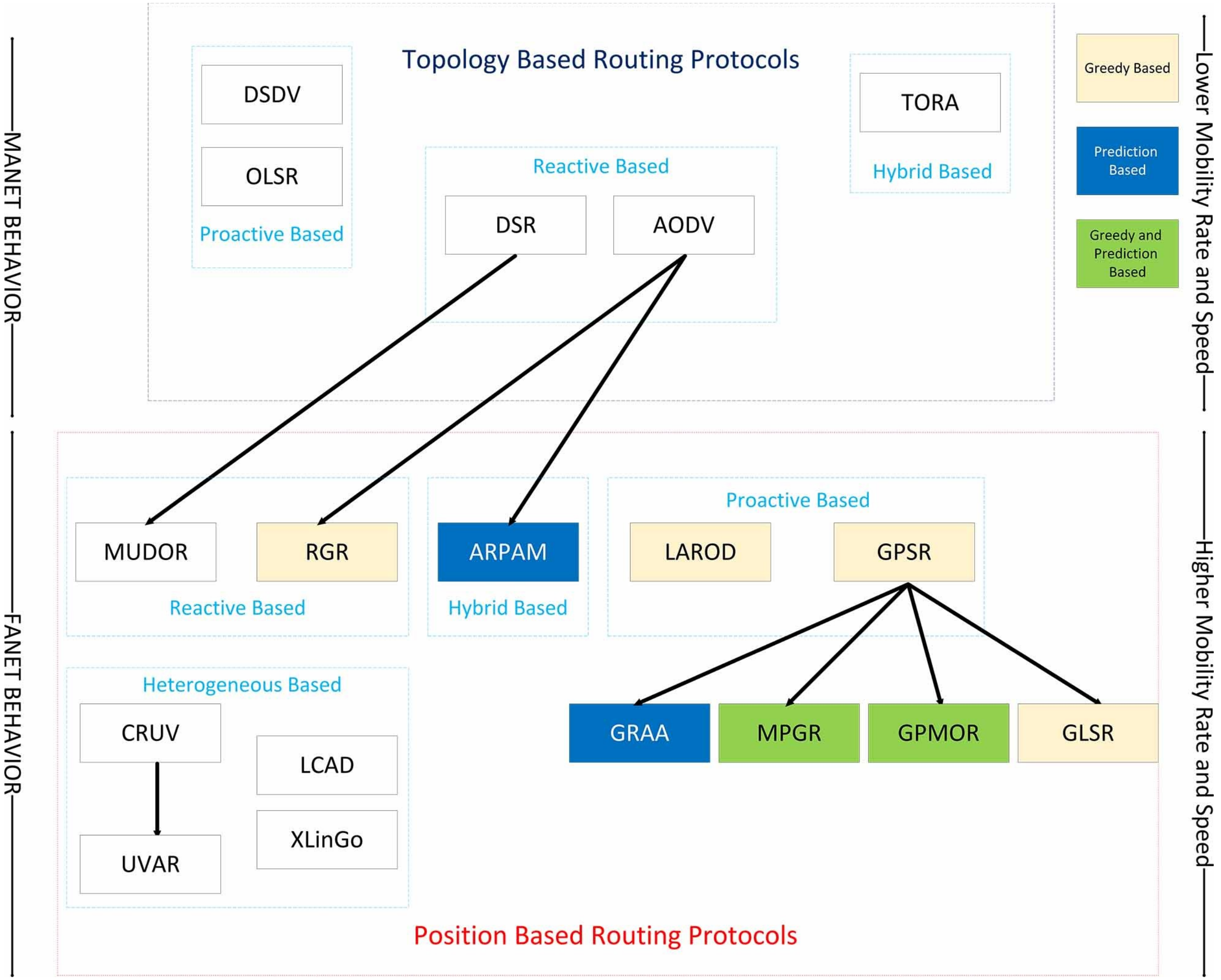


Figure 20: Dependencies, extensions and enhancements of surveyed routing protocols in combination with packet forwarding techniques.

As authors in [90] stated, the performance of a routing protocol is application-specific and achieves different results under different circumstances. Furthermore, some protocols have been built exclusively to solve specific requirements in some special cases. Such a case is the communication between heterogeneous nodes inside a FANET (e.g. communication between UAVs and ground nodes).

According to Khare et al. [91] proactive routing protocols are characterized by very low delay in path construction but very high network overhead, much more bandwidth consumption and high delay in new topology adaptation. On the other hand, reactive protocols create less overhead inside the network and can be adapted quicker to a new topology but produce high delays in path construction. That is the reason why reactive protocols seem to be the ideal candidate for FANET deployment compare to proactive and hybrid protocols [91],[92]. Furthermore, Oubbati et al. [28] suggest that position-based routing protocols are the most suitable for highly dynamic networks such as FANETs since they share all the capabilities of topology-based routing protocols plus their ability to identify the exact geographic position of each node individually using GPS services. That have been said, the routing protocols we will propose for each agricultural application will be position-based protocols.

4.2. Mobility models in FANETs

Medjo et al. [93] studied and showed that mobility models can affect FANET performance significantly. Moreover, Oubbati et al. [28] claimed that the successful design of the unique characteristics of a FANET (UAV density, [94], topology [26], scalability [95] and localization [96]) relies on the selection of an adequate mobility model. The use of multiple UAVs that collaborate with each other, introduces important issues in terms of networking and QoS [97]. Inter UAV packet transmissions, UAV to base station communication, limited communication range (especially in cases of small UAVs), line of sight problem combined to the high mobility levels of UAVs are some of the issues that make routing one of the most critical tasks in FANET deployment [98].

In order to explore the aforementioned issues, many researches have been conducted in order to develop the communication protocols presented in section 2. Since multi-UAVs cooperation is not yet well explored and its deployment in real cases is prohibited in terms of safety and cost, the majority of multi-UAVs communication protocols have been deployed and tested in simulation environments. Researchers use simulations as a validation tool in order to examine the performance metrics of the proposed routing protocol. Simulations that involve a single UAV require an accurate model of realistic UAV movements, dimensions and communications. Simulations that involve multi-UAVs cooperation require a mobility model to represent how the nodes change their position while they are communicating in order to examine protocol's performance under mobility [99],[100]. According to our research there are six (6) mobility models that have been proposed so far:

- As its name suggests, static mobility model does not imply any movement at all, which means that the node is essentially fixed in a specific position.

- In pure randomized mobility models, UAV movement is completely random in terms of direction, speed, time of movement. This kind of models do not take into consideration parameters such as speed, paths or environmental conditions thus they serve more as point of reference [99],[100].

- In time dependent mobility models, UAV movement depends on the previous speed and direction. This kind of models avoid intensive or sudden changes in speed or direction. Smooth changes in both cases can be done using 3 different mathematical equations: Boundless Simulation Area [70], Gauss Markov [101] and Smooth Turn [102].

- In path planned mobility models, UAV movement is strictly defined based on pre-defined paths. Specifically, each UAV follows a certain pattern until it reaches the end of the pre-defined path where either it changes pattern randomly or it repeats the same pattern. In Manhattan Grid mobility model nodes move on horizontal and vertical predefined paths [103]. Semi Random Circular movement [104] is designed for the curved movement scenarios of a UAV. Its strength is the minimization of potential collisions between UAVs and its weakness is that its movement is not realistic since sudden 90-degree change direction is impossible from a UAV perspective. On the other hand, Paparazzi model is a model that have been tested in FANET deployment with specific routing protocols and the results proved to be very promising [91],[92]. In the Paparazzi mobility model, before each flight the UAV must already know which pattern to follow, the take-off position and the flight speed. After its take-off it chooses a random altitude and follows it until it starts the procedures for landing.

- Group mobility models in contrast with the aforementioned models, insert the notion of spatial restrictions between mobile nodes. While in pure randomized, time dependent and path planned mobility models it is assumed that the motion behavior of a UAV is completely independent on the motion behavior of other UAVs in the same group, in group mobility model, UAVs belonging into the same group must move together following a certain point. That means that there is a spatial dependency between UAVs. The mobility model which acts as a reference is called reference point group model [105] and there are 3 models based on that, which describe specific cases [106]. Column mobility model where each UAV moves uniformly on an imaginary line keeping specific distance from its neighbor UAVs. Nomadic community mobility model where UAVs move randomly around a certain point with a pre-defined radius without any spatial restriction. Pursue mobility model which is similar to Nomadic but the mobile nodes follow a certain target which moves at a certain distance.

- Topology control based mobility model besides spatial information between mobile nodes belonging into the same group, it also incorporates information about mission constraints. Topology control mobility models are the new generation of mobility models since they enable network topology control using data communication between the mobility nodes of the network. Based on this kind of models, the randomness of

> the mobility model is replaced by control mechanisms which are focused on network constraints of mission objectives. Distributed Pheromone Repel mobility model [107] is used when UAVs execute a reconnaissance mission while moving randomly in the space although network connectivity is not considered. Self-deployable Point Coverage mobility model [108] is suitable for emergency cases when communication infrastructure in an area is damaged. The UAVs can replace the communication infrastructure with this mobility model which is designed in order to serve the maximum number of people in the area.

The proper selection of a mobility model strongly depends on the type of application case that a FANET is involved in. The performance of a FANET (e.g. packet delivery ratio, end to end delay etc.) can vary significantly with a different mobility model. Thus the proper choice of a mobility model is of high importance [27]. Table 2 presents the proposed mobility models for several applications while Table 3 presents mobility models that serve agricultural-specific applications.

Application Class	Mobility Model	Case Description
Search and Rescue Operations	Boundless Simulation Area, Gauss-Markov, Smooth Turn	Random Search on a predefined target area
	Paparazzi	Each UAV selects the scan pattern in random position
	Semi Random Circular Movement	Scanning in a circular area
	Distributed Pheromone Repel	Scanning an area through repeated checks
	Self-Deployable Point Coverage	Reaching victims on a disaster area
Traffic and Urban monitoring	Static	UAVs as fixed cameras at crossroads
	Manhattan Grid	Surveillance of on city streets
	Semi Random Circular Movement	Patrolling of an accident before aid arrives
Reconnaissance and patrolling	Static	Static first line of defense and patrol
	Semi Random Circular Movement	Surveillance of a target
	Boundless Simulation Area, Gauss-Markov	Missions without path prediction by adversaries
	Pursue	Pursuing of a critical moving target
	Distributed Pheromone Repel	Real-time missions with awareness of critical areas

Table 2: Proposed Mobility models for applications adjacent to agriculture

Authors in [28] claim that path planned mobility models such as Paparazzi, Semi Random Circular Movement and topology control Based mobility models such as Distributed Pheromone Repel are considered the most suitable for FANETs because of the mission constraints of this kind of networks. The results of [93] also revealed that Random Waypoint, Random Direction, Smooth Turn and Gauss-Markov cannot support FANETs since they are designed for lower mobility cases such as Mobile Ad-hoc Networks (MANETs).

According to [109], Paparazzi mobility model is good for mini UAVs and it can be used in many cases thanks to its five (5) movement patterns. Based on our previous analysis, we conclude that the proper choice of the mobility model along with a suitable routing protocol based on FANETs' mission and unique characteristics, is crucial for FANETs' performance in terms of evaluation metrics such as packet delivery ratio, end to end delay and network overhead.

In the following sections we will attempt to describe as thoroughly as possible the six (6) different applications of UAV utilization in agricultural sector. We are going to:

- Identify the unique characteristics of each case in terms of FANET deployment (UAV density, topology, propagation model, scalability and localization)
- Suggest the proper mobility model which could better describe each case
- Propose the corresponding routing protocol

Application Class	Mobility Model	Case Description
Agricultural management	Column	Field condition checking
	Paparazzi	UAV actions on cultivated fields
Environment sensing	Static	UAVs as stationary sensor nodes
	Paparazzi	UAVs follow some predefined paths that cover several sensors
Relaying network	Static	Static UAV communication infrastructure
	Manhattan Grid	Vehicle-to-vehicle connectivity among urban vehicles

Table 3: Mobility models that serve agriculture-specific applications [27].

5. UAVs in agriculture

As mentioned in section 2, UAVs play a significant role in agriculture domain. Their ability to carry on-board sensors constitutes probably the most cost and time effective solution for collecting data inside the crop [25],[110]. The utilization of the collected data is applicable to a number of agricultural activities such as production appraisal [29], disease detection [111], crop stress recognition [112]. In addition, technologies such as IoT and multi-spectral cameras [113], drive the market to more sophisticated services, such as 3D crop imaging and qualitative data presentation in Geographic Information Systems (GIS) [114]. Last but not least, the development of aeronautics for UAVs has enabled UAVs to carry bigger and heavier loads, which is an improvement that will allow them to be transformed from passive data collectors into valuable actuators. Based on related work presented in section 3 as well as [14], we came up with 6 realistic and enriched applications, a UAV can serve: Crop Scouting, Crop Surveying and Mapping, Crop Insurance, Cultivation Planning and Management, Application of Chemicals, and Geofencing.

Crop Scouting: Crop scouting is a complicated, multi-tasking process that helps the farmers to acquire, process, analyze and manage key features in crop production [115]. Crop scouting is of high importance in the agricultural sector since it is the only way to evaluate the economic risk of important tasks and critical decisions, determine the appropriate countermeasures and inspect the performance of the production in real time. Sensors, specialized field instruments, portable computers, GPS devices and recently UAVs enable allocating geographical identification metadata in media such as photographs and videos of crop. The aforementioned tools and methods comprise a new generation of crop scouting systems that allow specialists to collect the necessary data and to accurately locate and tag crop problems, visualize them and take decisions accordingly. Crop scouting is not an easy process and depending on the field where it is deployed, it can be extremely complicated. The most important stage is the preparation stage in which, various information of crop production such as environmental conditions, soil characteristics, field geotagged location, weeds, crop growth stage, row width and pest presence need to be collected. Consequently, field history needs to be surveyed since both field and landscape characteristics can have a serious impact in pest distribution, symptom expression, crop injury and crop recovery.

UAVs make frequent examination easier and can easily expand the sample area. Usually, the minimum frequency in cases of crop scouting, is once in a week during growing period. In cases where the infections grow rapidly, or the weather favors their expansion then scouting can be performed even more frequently and is some cases even daily. During crop scouting, in areas that are up to 400.000 square meters the farmer usually creates at least 5 sampling areas of 0.25 square meters while in crops over 400.000 square meters the sampling areas are at least 10. Then specific patterns are applied in order to produce safe conclusions for the cultivation in general.

We separated crop scouting actions into two (2) types of actions, Data collection from on-board sensors and data collection from ground sensors [25],[47]. In days past, a crop scouter should carry multi-nature equipment such as gardening tools, metering tools, carrying tools etc. in order to execute a proper crop scouting but nowadays small, energy efficient sensors can gather these data of interest. Moreover, the scouting frequency is not an issue anymore since sensors can collect time-tagged data 24/7 allowing experts to have the complete view but also the ability to dig into the specific time of interest which is defined by crop's or pests' lifecycle. Image collection using on-board cameras with different wavelength bands, which are low-cost but have high spatial-resolution [110][116][113] provide information that eye is impossible to capture (Table 4). The evolution of technology in terms of software and hardware leads to higher processing power. More sophisticated cameras, enhancements in digital image processing have led to images that could provide critical information for the crop condition.

In Tables 4 and 5 we present a review of the information that can be extracted from the crop collection images, as well as useful indices and their use, using different types of on-board cameras.

Monitoring Crop Status	Specific Tasks
Health Status	Discrimination of Invasive Weeds [117] Identification of irregularities in fertilization delivery system [32][118]
Crop Growth	Crop growth variability [119] Dependency between plant treatment and crop performance [119] Map crop vigor [120]
Maturity	Determine ripeness analysis [32][118][121]

Table 4: Information provided by crop imagery

Crop Surveying and Mapping: The technological marvels regarding high resolution camera's and laser scanner's hardware and software made the creation of 3D (GIS) possible [122]. Aerial images acquired by UAVs can be used for the development of high geographical resolution models and crop maps [123]. These in turn can enrich the cultivation data of a GIS and provide more sophisticated details for controlling automated processes inside crop as well as the activities related to production management such us volume estimates, irrigation and drainage models, pesticide and fertilizer application.

Crop Insurance: In India, insurance companies are willing to use UAVs for crop damage assessment purposes deciding for the amount of compensation much quicker and accurately [14]. Data collected from ground sensors corresponding to environmental conditions and aerial images collected from UAVs' on-board cameras could be extremely valuable for prompt identification or even prediction of crop diseases [14]. Crop industry can deploy a comprehensive risk analysis based on the history of the cultivation, climate, collected data and spread this information among stakeholders of agriculture industry offering them a higher level of readiness. Moreover, aerial images can also be deployed for the revelation of

Indices	Index Description	Type of lens
Spectral Signature	It reveals whether and to what extent plants grow well or whether their growth is blocked by factors such as drought, lack of nutrients, or is under the influence of pests	Visible Band Near Infrared Multispectral
Photochemical Repentance Index Water Band Index Normalized Pigment Chlorophyll Radio Index	They are useful for plant's water diagnosis and nutrient situation	Multispectral
Hyper Spectral Indices	They are useful for plant's water diagnosis, nutrient situation and pest presence while minimize the signals from different sources [117]	Hyper-Spectral

Table 5: Information gathered (index) depending on type of camera

insurance fraud, deterring compensations for the same piece of land multiple times or claim compensations for damages that never exist [124].

Cultivation Planning and Management: Penetration of UAVs in different levels of agriculture such as inspection, management, intervention show the way for policy makers and management personnel to estimate or even predict the expected crop yield and plan countermeasure strategies in cases where it is required (e.g. pest infestation) [125]. The aggregation of the aforementioned data in combination with data related to socioeconomic conditions, management tactics, biophysical conditions, can be used for the creation of risk assessment statistical models. Such a tool enhance could not only the protection of the cultivation from pest infestation but also the harvesting processes.

Application of Chemicals: Assessment of the level of pest presence inside a crop in relation to the crop performance is of high importance. For example, there is no reason in allocating time and resources in treatment of a pest where damage is insignificant. On the contrary, treatment when the damage has exceeded a certain level is economically and environmentally insignificant. Dealing with pest damage constitutes a major part of agricultural process and it is as old as agriculture, since there was always a need to keep crops free from pests. In the beginning of this century, the global crop losses due to pests aggregated a percentage around 10,8 among all the causes of crop loss. Defining the damage done, is of major importance since human response actions depend heavily on it. This response could vary from tolerance to deterrence or even attempts to eliminate the pests completely. UAVs tasks are not limited to crop management operations but UAVs are also capable of performing more sophisticated and precise operations inside the cultivation. Although the research is not very extensive, especially in multi-UAVs deployment, there have been attempts to develop aerial platforms for crop spraying [126][127]. This prospect seems very attracting for human health, as it can avoid pesticides, and chemical application in areas where soil morphology or environmental conditions do not excuse their use (e.g. slopes mountains, wet ground, etc.). As stated in [14] a spraying task could be simulated with a “search and destroy” pest control mission, where the UAV has to identify the pest and destroy it using the appropriate chemicals.

Geofencing: Geo-fencing is a virtual boundary or an area that surrounds any other area. Geofencing is mainly used for security purposes and can be a critical asset in the hands of farmers for ensuring the cultivation integrity, by controlling undesirable entry into the area of interest. In the field of agriculture, the incidents of cultivation destruction by animals such as sheep or birds are very common, thus a search and tracking mission by UAVs seems a suitable countermeasure. Apart from its conventional uses, geofencing can also be used to land arrogation between adjacent farmers and consequently the net cultivated area can be increased by utilizing the land area that is wasted in making bunds for field separation [14].

Figure 21 illustrates a novel design, where agriculture is segmented into blocks. In each block, we defined UAV roles and activities that are necessary to accomplish the goal of each block.

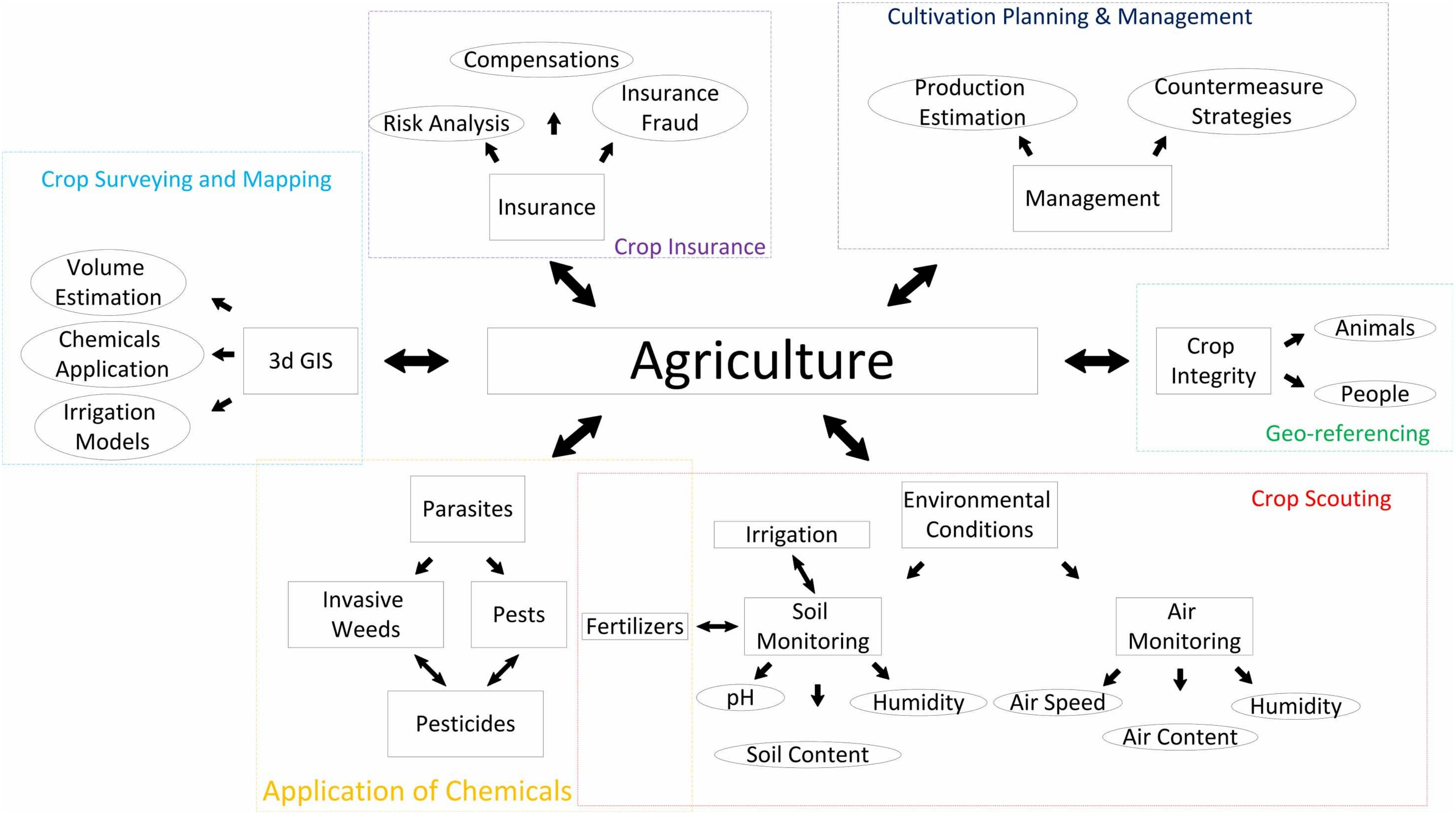


Figure 21: A novel segmentation of agriculture into individual tasks that a UAV can accomplish.

6. FANET Application in Agriculture

According to [68] the performance of a FANET depends on the routing protocol, the special characteristics of each application, and the mobility model adapted by the nodes (Figure 22). In agriculture applications we take for granted that node density is quite low, due to the fact that the rural areas we are focusing on have low height vegetation thus line of sight can be very high [28]. In Table 6, for each one of the 6 agricultural applications, we have classified the UAV actions into strictly defined applicable tasks, identified the mobility model based on the application and characterized each task as time tolerant or time intolerant.

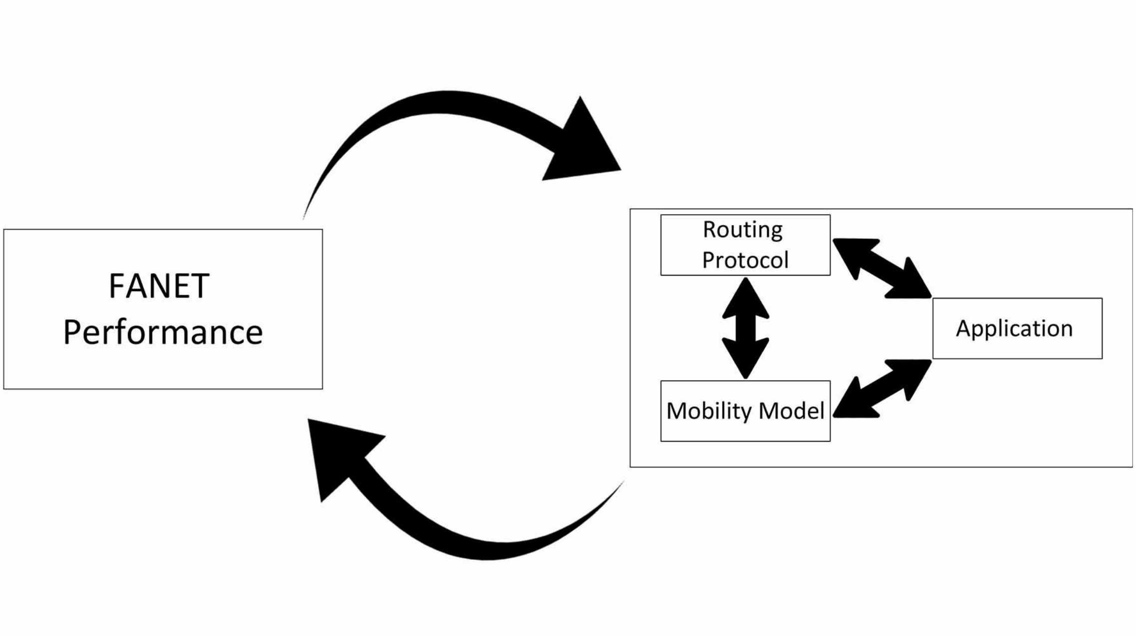


Figure 22: FANET performance is related to routing protocol and mobility model [27],[28]. Routing protocol is related to both application nature and mobility model of the network's nodes while mobility model is related to application nature.

The reason why crop scouting, crop surveying and mapping, crop insurance and cultivation planning and management are presented in one cell in Table 6 is because crop scouting is the process that will provide the data which are required as inputs by the rest applications. In other words, crop scouting is the process where UAV activities (take-off, fly over the crop in a sample area or in the whole cultivation, collect the data, take the aerial images and landing) are defined and executed. Crop surveying and mapping, crop insurance and cultivation planning and management do not change UAVs activities, they just choose what kind of data they need in order to accomplish their individual tasks.

In environmental sensing, UAV's task is to aggregate environmental parameters via onboard or ground wireless sensor networks [128]. UAVs follow a predefined path, which has been planned based on the location of static sensors. Moving UAVs gather the corresponding data from a sensor wirelessly, and then return to the base station. This case suggests the

Agriculture Application	UAV Task	Mobility model	Real time	Routing Protocol
Crop Scouting	Environment Sensing	Paparazzi	Yes	ARPAM LAROD GPSR GRAA MPGR GPMOR GLSR
Crop Scouting Crop Surveying and Mapping Normalized Pigment Chlorophyll Radio Index	Agricultural Management	Paparazzi	Yes	MUDOR RGR LAROD XLinGo
Application of Chemicals	Search and Destroy	Paparazzi	Yes	MUDOR RGR
Geofencing	Tracking	Distributed Pheromone Repel	Low	GRAA MPGR GPMOR GLSR

Table 6: The suggested routing protocols for the surveyed agriculture applications

adoption of a path-planned mobility model, such as Paparazzi, which can be also customized to adapt in the desired path model (e.g. a path that covers all the sensors on the area) [68].

In agricultural management, the UAVs activities are related to the acquisition of crop imagery and typically require a one-time movement. The mobility models suggested by [68] for agriculture management are: Paparazzi mobility model and column mobility model. Because of the rectangular shape of cultivation fields, a scan pattern from Paparazzi model seems the best solution [68].

Paparazzi model is suitable for small size UAVs and is considered ideal for FANETs because of their mission constraint nature [28]. Concerning time sensitivity, the research community is somewhat divided. On the one hand, authors in [14] stated that crop scouting is a task that require real time data. Data acquisition in real time for functional, operational and structural requirements, especially in a cultivated environment, can lead to higher and sustainable crop production avoiding last minute interventions that usually cause damage to environment [14]. On the other hand, authors in [27] claim that neither environmental sensing nor agricultural management have real time requirements and can be characterized as delay tolerant applications.

The extent of the damage caused by high data delivery delays, is what makes an application real time or not. Since our literature research cannot give us a clear answer on whether crop scouting is considered as a real time application or not, we referred to rules and practices from rural development organizations. One such organization is the Canadian department of rural development [129] which provides detailed information on important pieces of agricultural management including crop scouting. According to their experience, there are cases when prompt information can be extremely valuable for the sustainability of the crop (e.g. fire detection information on a cultivation, which is a part of crop scouting process and belongs to environmental sensing tasks [14]. Such information is critical and must be sent in real time since even the slightest of delay can be devastating for the crop. Information about the growth of locusts population, which is also part of crop scouting process and belongs to environmental sensing tasks, is also of high importance and requires direct treatment by the farmer). On the contrary, a delivery delay of data delivery that are used to calculate the indexes in Table 5, which is classified as agricultural management task, will not be proved detrimental for the cultivation.

Having that said, networks that serve Environmental Sensing data will be characterized as Non-Delay Tolerant Networks (Non-DTNs) even if some of the data are not so critical in terms of delivery time. On the contrary, networks that serve Agricultural Management data will be characterized as Delay Tolerant Networks (DTNs). The performance of a routing protocol in FANETs is application specific and has different performance under different conditions [90]. According to [28] the most important criteria for determining the most suitable routing protocol in FANETs are: the nature of the applications that the UAVs are deployed for, and the mobility models of the application.

Based on our analysis in routing protocols section 4, the suggested protocols will be the position-based routing protocols combining one or multiple forwarding techniques. In addition it is equally important to have a recovery mechanism in case of a path failure.

Crop scouting as an environmental sensing task demands real time or near real time data transmission. As a result reactive protocols are insufficient since the on demand path construction introduces high end-to-end delay rates. Consequently, proactive and hybrid based protocols seem the ideal candidate for this task. Namely, ARPAM, LAROD, GPSR, GRAA, MPGR, GPMOR and GLSR are the possible candidates. LAROD uses store-carry-and-forward technique as its main packet forwarding technique which despite its proactive nature, introduces high end-to-end delay, thus LAROD is rejected as an option. All the protocols that have been built on top of GPSR, namely GRAA, MPGR, GPMOR, and GLSR constitute a very promising solution in this kind of application. Exploiting its ability to create and use multiple paths, GLSR provides higher quality of service than the other candidates but the fact that it does not support any recovery strategy results in decreasing packet delivery ratio. MPGR and GPMOR thanks to their greedy and prediction based capabilities constitute a trusted solution in this case, except only the case where UAVs are very dispersed. Routing protocols that adopt methods and techniques from classical ad-hoc have a significant advantage over the latest protocols, due to the fact that these methods and techniques have been subjected to experimentation and simulations many times in the past resulting to a rich information concerning their performance. Such information is recommended in Table 7, which shows the behavior of three (3) ad-hoc protocols when the network nodes follow the Paparazzi mobility model. Last candidate is ARPAM. Despite the absence of a trusted recovery strategy, the fact that ARPAM has been built on top of AODV gives it a precedence over the other protocols considering that AODV has been tested with Paparazzi mobility model and the results (Table 7), were very promising.

Crop scouting, crop surveying and mapping, crop insurance, and cultivation planning and management, are considered as part of a wider task that is agricultural management. Agricultural management in contrast with environmental sensing does not demand real time data transmission. Reactive based protocols seem the ideal candidate for this task thus MUDOR and RGR are considered as possible solutions. However, thanks to application specificity that some other protocols present, they can also be considered as possible candidates in the specific task. LAROD and XLinGo are such candidates from proactive and heterogeneous based protocols respectively. LAROD with its beacon-less strategy can support mapping and video recording application. However, the store-carry-and-forward technique that uses, introduce high end-to-end delay. XLinGo is another beacon-less routing protocol which was built exclusively for the case when a UAV wants to transmit a video to another UAV. The fact that XLinGo deploy an evaluation test in order to select the next forwarder UAV allow it to operate without congestion problems, achieving a satisfying packet delivery ratio. Both RGR and MUDOR have been built on top of classical ad-hoc routing protocols but the fact that RGR posses a recovery strategy in case of link failures makes it a better candidate in comparison to MUDOR. The fact that RGR has been built on top of AODV gives it a precedence over the other protocols considering that AODV has been tested with Paparazzi mobility model and the results (Table 7), were very promising.

	AODV	DSR	DSDV
Packet Delivery Ratio	96.63	100.00	99.79
End-to-End delay (ms)	498.54	60.43	60.45
Throughput (Mbps)	0.376	0.390	0.389
Routing Overhead	486	30	178.4

Table 7: Performance comparison of AODV, DSDV and DSR routing protocols with Paparazzi mobility model [68]

Application of chemicals is considered as a search and destroy task. A typical pattern for a search and “do something” operation, is a simple scan scheme derived from Paparazzi mobility model, since the whole layout of the cultivation is usually of rectangular shape. In a situation where a multi-UAV system is deployed to speed up the completion of a mission, each UAV can follow its own path using the scanning technique. Another suitable mobility model is Semi Random Circular Movement but Paparazzi model is preferable for all the reasons mentioned so far. Search and destroy tasks using Paparazzi mobility model does not require any cooperation in spotting and destroying process because each UAV will have its own area to cover following its mobility model. However, the cooperation is useful in the sense that the information will traverse the network in order to reach the person of interest. The value of this information does not decrease in case of a normal delay. Thus, application of chemicals as described above, can be considered as delay tolerant application. Consequently, reactive based protocols MUDOR and RGR as the ideal candidates for this task. RGR protocol is the most prevalent for the same reasons mentioned in agricultural management task.

Geofencing is considered as a tracking task. A typical mobility pattern for tracking mission is Distributed Pheromone Repel. Wild animals are moving irregularly inside crop and their movements are clearly not in a rectangular shape. Another suitable mobility model is Semi Random Circular Movement but Distributed Pheromone Repel model is preferable for all the reasons mentioned in section 4.2. Geofencing demands real time data transmission since even the slightest delay in identifying an undesirable presence in the field can cost crop owner dearly. As a result, reactive protocols are insufficient since the on demand path construction introduces high end-to-end delay rates. Consequently, proactive and hybrid based protocols resemble once more as the ideal candidate for this task. Namely, ARPAM, LAROD, GPSR, GRAA, MPGR, GPMOR and GLSR are again the possible candidates. However, thanks to application specificity that some other protocols present, they can also be considered as possible candidates in the specific task. RGR and LCAD are such candidates from reactive and heterogeneous based protocols respectively. Although, both RGR and LCAD uses store-carry-and-forward technique which increases end-to-end delay significantly. The same applies to LAROD. All the protocols that have been built on top of GPSR, namely GRAA, MPGR, GPMOR, and GLSR constitute a very promising solution in this kind of application. Thanks to their greedy and prediction based capabilities MPGR and GPMOR constitute a trusted solution in this case, except only the cases where network density is very low. Exploiting its ability to create and use multiple paths, GLSR provides higher quality of service than the other candidates but the fact that it does not support any recovery strategy results in decreasing packet delivery ratio. In this case ARPAM has no precedence over the other protocols as there has been no work evaluating the protocol on a network that adopts this particular mobility model. Instead, that fact that it does not support a proper recovery mechanism leaves it considerably behind the other candidates.

7. Discussion

It is widely accepted that starvation is probably the biggest problem we are facing as humanity in the 21st century. The fact that more than 80 % of available land is already cultivated [20] dictates the need for effective innovative technology to increase agriculture efficiency. Significant part of this evolution is precision agriculture, which aspires to lead farms' efficiency and productivity to the highest point while ecological standards are equally respected. The recent enhancements in technologies like UAVs, sensors, smartphones, cloud computing have already led the way to concepts like precision agriculture, but progress and revolutionary technologies are still necessary. Scientific community needs to find ways to improve what it could be improved, optimize what it could be optimized, hone what it could be honed. In the aforementioned problem, scientists must intensify their effort in making precision agriculture even more precise.

UAVs have already been deployed in different tasks of precision agriculture, since they can acquire, process, analyze and manage data from different sources. Their ability to fly makes them even more attractive since they can acquire valuable information that ground inspection cannot provide and in a shorter amount of time. The first stage of optimization in UAV deployment is the transition from a single UAV system to a multi-UAV system where multiple UAVs could collaborate in a way that they could execute a wider range of tasks in a faster, safer and more efficient way. The deployment of multi-UAV systems requires stable and efficient communication schemes which will guarantee the proper communication and coordination among multiple UAVs inside a FANET. From the different aspects of a communication scheme, this survey focuses mainly on routing protocols, since they are probably the most critical factor for a successful multi-UAV communication.

To the best of our knowledge, the proposed survey is the first attempt of proposing specific routing protocols for multi-UAV communication, in the whole spectrum of agricultural activities. However, finding a single routing scheme, comprised of one routing protocol and one mobility model that will be able to adapt to all unique agricultural characteristics, and at the same time provide perfect outcomes, is very hard. In the field of agriculture there are very few proposed routing schemes, that cope with the communication challenge inside a FANET and there are a lot of issues that have not been resolved.

The proposed survey lays the foundations for the multi-UAVs communication through a theoretical study of more than 30 routing protocols combined with the available UAV mobility models, under the common target of precision agriculture which has been classified down into 6 different applications based on UAV's tasks: Crop scouting, crop surveying and mapping, crop insurance, cultivation planning and management, application of chemicals, geofencing.

Over the last 30 years, the ad-hoc networks have drawn the attention of the research community leading to a steady and continuous development. Consequence of this development is the attempt to implement the already known protocols, but also new ones, in networks such as FANET. Classical protocols such as DSDV, OLSR, DSR, and AODV which are widely used in MANETs, have been the basis for pushing on new protocols that have the ambition to adapt to the dynamic characteristics of FANET. However, entirely new protocols have also been proposed trying to satisfy the new demands of FANETs. From the extensive description of the aforementioned routing protocols we have identified some basic principles that seem to be followed by all the protocols that aspire to serve these networks.

- Mobility prediction: The most recent protocols include a mechanism for predicting the movement of intermediate nodes in order to make the best selection of the next relay node. If the current node is able to know the next movement of the intermediate nodes then the network efficiency would be increased while the packet losses would be minimized. However, this implies the exchange of more data among the nodes of a network, which leads to a significant overhead increase.

- Overhead Decrease: A basic obstacle that most modern protocols try to overcome is the reduction of the overhead that causes network quality degradation. The hitherto approach to reducing overhead is the adoption of reactive techniques that will lead to a reduction in overhead but at the same time contribute to an increase of end-to-end delay. Hybrid techniques utilization such as the one adopted by ARPAM is a promising solution provided that the change from proactive to reactive will be based on parameters related to the network environment and/or the application characteristics.

- Heterogeneous based routing protocols constitute a promising category of routing protocols. Communication between networks of a different nature such as FANET-to-VANET communication is expected to provide solutions to problems that affect conventional VANETs. The development of protocols such as the CRUV and its extension (UVAR) is a basis for research to proceed.

- Cultivation, and the subject of smart farming and precision agriculture in particular, have already adopted the use of UAVs in their task routine. The agricultural applications to which they can assist have been extensively analyzed in a multitude of articles and publications. However, the literature regarding the use of multiple-UAVs in the task routine of an agricultural enterprise is limited. The benefits of multiple UAVs in the agricultural industry are simple and intuitive, but the technical requirements that need to be guaranteed are many and are laying in multiple levels of the system, such as hardware, software, architecture, communication protocols, etc. .

- As the research in the domain of agriculture and UAVs grows, new applications may arise. Such an application is the protection of organic farming. Testing for field contamination in organic crop from pesticides coming from neighboring crops (via air, water, air-spraying, etc.) by deploying a multi-UAV system, is another application which could guarantee the quality of organic products.

- Our theoretical analysis was application-specific and mobility-specific based on the research in [27],[28]. However, the performance of a routing protocols is related also to the environmental conditions. That is the reason why Table 6 is a good basis but should be enriched with additional parameters in order to reveal more challenges on the topic.

- Routing protocols are not the only issue that interests the research community. The constraints introduced by the hardware are deemed important and they should be taken into consideration when testbeds are deployed in real environments. Hardware limitations concerning the area of communication between FANET nodes, are mainly related to the supply and consumption of energy in the aircraft's telecommunication infrastructure and its processing power. The energy spent on telecommunications infrastructure is a parameter that is directly affected by the nature of the network. For example, the denser the network is, the lower the transmission power, which in turn reduces the energy consumption for node communication. It is therefore possible to define the appropriate parameters (such as network density, number of nodes etc.) in order to achieve the optimum energy allocation based on the purpose of the network. Processing power is also related to the communication area of a FANET. The more complex the environment of network as well as the telecommunication protocol is, the greater the demands on resources. Higher resources requirements has serious impact over the size, weight and power consumption of the processing unit.

8. Conclusions and Future Research

In this paper, we proposed a scheme of six (6) different UAV applications in agriculture. We surveyed the related literature and we ended up with a novel design where agriculture is segmented into blocks. In each block, we defined UAV roles and activities that are necessary to accomplish the goal of each block. We also identified agricultural indices along with the corresponding type of on-board sensors that are used to collect the necessary data for each index calculation.

Consequently, we surveyed FANET deployment in agriculture. We highlighted the multi-UAV system characteristics that clearly overcome the capabilities of single UAV systems. We investigated one of their greatest challenge which is the communication and coordination between flying nodes and we proposed specific routing protocols as possible candidates for each agriculture application.

The results of our project have many recipients: i) Researchers working on FANET routing protocols supporting real world application. Through our project, they can instantly get information on the evolution of protocols, and the cases that these protocols can be proposed. (ii) Farmers seeking modern ways of optimizing the agricultural process on multiple levels. Through our work, they can find new ways to benefit from the use of UAVs in their cultivation. (iii) UAVs Manufacturers searching new capabilities of UAV deployment. Through our project they can explore the potential of the multiple-UAV market in the domain of agriculture, and intensify their efforts also in this direction. (iv) Software developers searching for UAV customization or new UAV applications. Through our research, we give an holistic aspect of UAV ecosystem, define its components and describe specific UAV applications.

Based on our research so far, we believe that researchers should turn to the implementation of new simulations that focus on specific applications, including more realistic conditions. An important obstacle to the advancement of research in this area is the lack of real-world or simulation experiments due to the absence of simulation software suitable for FANETs. The simulation programs that have been used in the surveyed papers are Opnet, NS-2, OMNeT, but none of them can accurately simulate the conditions of a FANET. Prerequisite for developing new protocols capable of meeting the requirements of a FANET, is to modify the existing software or create new ones that will simulate as accurately as possible a FANET environment and show emphasis on mobility models other than random ones.

The long-term goal should be to implement a real FANET network with real UAVs communicating using the proposed protocols. This will result in determining more practical requirements that have not been identified by the theoretical approaches so far.

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