Article

A Comparative Performance Evaluation of Routing Protocols for Flying Ad-Hoc Networks in Real Conditions

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Abstract: Unmanned aerial vehicles (UAVs) are widely used in our modern society and their development is rapidly accelerating. Flying Ad Hoc Networks (FANETs) have opened a new window of opportunity to create new value-added services. However, the characteristics that make FANETs unique, such as node mobility, node distance, energy constraints, etc., imply that several guidelines need to be considered for their successful deployment. Although numerous routing protocols have been proposed for FANETs, due to the wide range of applications in which FANETs can be applied, not all routing protocols can be used. Due to this challenge, after breaking down and classifying the different types of existing routing protocols for FANET, this paper analyzes and compares the performance of several routing protocols (Babel, BATMAN-ADV, and OLSR) in terms of throughput and packet loss in a real deployment composed of several UAV nodes using 2.4 and 5 GHz WiFi networks. The results show that Babel achieves better performance in the studied metrics than OLSR and BATMAN-ADV, while BATMAN-ADV delivers significantly lower performance. This experimental study confirms the importance of choosing the proper routing protocol for FANETs and their performance evaluation, something that will be extremely important in a few years when this type of network will be common in our day-to-day life.

Keywords: ad hoc networks; experimental study; Flying Ad Hoc Networks; FANET; practical case; routing protocols; testbed; unmanned aerial vehicles; UAV; WiFi

1. Introduction

Ad hoc networks are becoming an essential part of our modern technological infrastructure, expanding the range of available applications and their characteristics. On the other hand, thanks to technological advances, unmanned aerial vehicles (UAVs) offer a wide range of possibilities (extending wireless coverage, use in agriculture, search and rescue, fire surveillance, etc.). The creation of an ad hoc network with UAVs also offers a significant advantage over other networks due to the high mobility of its nodes and their great versatility. This type of network is known as a Flying Ad Hoc Network (FANET) and is considered a subtype of Mobile Ad Hoc Networks (MANETs) or Vehicular Ad Hoc Networks (VANET). Due to the particular characteristics of UAVs, they bring new challenges for obtaining node mobility models, routing protocols, energy management, etc. Indeed, FANETs present high mobility of their nodes, both in speed and 3D mobility, frequent changes of network topology, or intense energy and weight restrictions. Consequently, it is essential to carry out a study of the different protocols for FANETs to identify the best ones to minimize the impact of the UAVs' characteristics and create a dynamic, agile, and efficient FANET network. A survey of mobility models, positioning algorithms, and propagation models can be found in [1–3].

In this work, after analyzing the types of routing protocols designed for FANETs, we focus on comparing, through a real deployment of a FANET using the IEEE 802.11 (WiFi) standard in the 2.4 GHz and 5 GHz bands, the performance offered by several routing

protocols. We believe that a real deployment can provide much more reliable results than those obtained by simulators. Therefore, we consider that the highlight of this article is the actual deployment of the FANET, something that, as we will see, very few articles do, which limits their investigation to simulated experiments. The chosen protocols are Optimized Link-State Routing (OLSR), Better Approach to Mobile Ad Hoc Networking Advanced (BATMAN-ADV), and Babel. They are compared in terms of throughput and packet losses in a network composed of several UAVs and an intermediate relay node. We chose these proactive routing protocols because of their high mobility range, low latency, widespread use in ad hoc networks, and good power consumption; similarly, they have relatively low complexity and computational demands, allowing us to simplify and automate some of the challenges mentioned in [1–3]. The results highlight the importance of the correct choice of routing protocol for FANETs, showing that Babel achieves higher performance in the studied metrics whereas BATMAN-ADV and OLSR show lower performance.

The rest of the article is organized as follows: in Section 2, we include a review of state-of-the-art case studies with FANETs, and we break down the different types of routing protocols proposed for ad hoc networks and FANETs. The FANET deployed for this study and the tools used are detailed in Section 3. The results are discussed in Section 4. Finally, conclusions and future works are presented in Section 5.

2. State of the Art

In this section, we will look at proposed works for FANETs. First, we will look at the proposed studies that perform a real FANET deployment, and then we will see the different routing protocols proposed for ad hoc networks and FANETs.

2.1. Real Experimental Studies

In this subsection, we will see a compilation of papers that analyze, by means of real experimental studies, the performance of FANETs deployed by UAVs. Due to the high cost and complexity of building large-scale networks with variable topologies, and the difficulties related to the repetition of scenarios, it is challenging to find works that include real deployments of FANETs. The vast majority of the work completed expects the simulators used to be capable of simulating real conditions to ensure that the results they obtain or the algorithms they propose can resemble what could be obtained. However, we believe that a real deployment, controlling as many variables as possible and repeating the experiments several times, can provide greater assurance. The results obtained are, by comparison, more trustworthy. That is why we consider this work very interesting, helping the reader to understand the impact of choosing a routing protocol on the FANET performance.

Analyzing works that focus on real FANET deployments, Rosati et al. [4] studied the performance offered by Predictive-OLSR (P-OLSR) and OLSR in a FANET composed of two small fixed-wing UAVs (called "eBee"). Their results showed that, because P-OLSR uses GPS information, the performance obtained both in simulation and in experimental tests improves that obtained with OLSR, reducing the number of communication interruptions.

Furthermore, the P-OLSR performance was compared against OLSR and Babel in [5]. The results showed that P-OLSR, for the scenario they proposed (up to three UAVs with a highly dynamic ad hoc network), could provide more reliable multi-hop communication than Babel and OLSR.

In [6], the authors compared two modes of operation of the 802.11 WiFi standard (access point and ad hoc using BATMAN-ADV) in a real experimental scenario in terms of coverage, throughput, and energy efficiency with up to two quadcopter UAVs. The results revealed a better performance of the access point mode in terms of received signal strength and throughput but worse performance in terms of power consumption than the ad hoc mode.

The work presented by Lee et al. [7] proposed an approach similar to P-OLSR, in which the UAV nodes employed GPS information to improve the routing protocol, called Ground Control System-Routing (GCS-R). A real experiment was conducted with up to six

UAVs in a network-coverage application scenario. The results showed that their proposed routing algorithm outperformed OLSR and DSDV in terms of throughput, stability, and network outage time. However, given that it suggests a centralized algorithm, it has a single point of failure that could be critical because of the instability of the UAV nodes and presents serious scalability problems.

On the other hand, in [8], the authors showed the deployment of a FANET using BATMAN as the routing protocol, showing the capabilities that this type of network can offer in terms of coverage and throughput. They used a UAV in three different scenarios, and the results showed that the maximum distance they could transmit without packet loss was 117 m.

Finally, the authors of [9] proposed a security protocol for FANETs called SUAP, which incorporates geographical leashes, hash chains, and public-key cryptography into the AODV routing protocol. Although SUAP proved to be effective in encrypting messages exchanged between nodes against various attacks, it did not provide a robust mechanism to recover from disconnections between nodes. According to the experimental result performed with three nodes, the delay to re-establish a new route when a node failure occurred was considerable, especially for real-time applications such as video capture, monitoring, and aerial photography. Moreover, its performance should be evaluated in a network with a high density of nodes. A summary of the reviewed papers can be seen in Table 1.

Table 1. Related works that included a real FANET deployment. Also detailed are the routing protocols employed and the number of UAVs.

Work	Routing Protocols	Number of UAVs
Rosati et al. [4]	OLSR, P-OLSR	2
Rosati et al. [5]	Babel, OLSR, P-OLSR	3
Guillen et al. [6]	BATMAN-ADV	2
Lee et al. [7]	GCS-R, DSDV, OLSR	6
Kaysina et al. [8]	BATMAN	1
Maxa et al. [9]	SUAP	2

2.2. Routing Protocols

Routing protocols are responsible for guaranteeing the delivery of a message from a source node to a destination node. Routing protocols must adapt to the essential characteristics of FANETs: high mobility, energy efficiency, constant changes in the topology, etc. In addition, due to the wide variety of application fields, the requirements of routing protocols in FANETs can be very diverse. For example, a constant jitter would be necessary for real-time video applications, whereas a high level of reliability would be necessary in applications that extend telecommunication coverage in case of disasters (regardless of delay and jitter). Most FANETs' routing protocols are extensions of well-known MANET protocols, such as AODV, OLSR, or DSR [10]. However, there is still a lack of routing protocols that fit all FANETs' needs.

In this subsection, we will examine the different routing protocols proposed for FANETs and group them into five main categories: (i) topology-based, (ii) position-based, (iii) clustering/hierarchical, (iv) swarm-based, and (v) delay-tolerant network (DTN).

2.2.1. Topology-Based Routing Protocols

Topology-based routing protocols base their operation on using the links information for data forwarding. Within this category, four types of protocols can be distinguished: (i) static, (ii) proactive, (iii) reactive, and (iv) hybrid.

Static Routing Protocols

The nodes in this network have static routing tables which are configured at the beginning of a task and do not change. Networks that implement these protocols must

have a constant topology, and therefore, being unable to adapt dynamically to changes, are susceptible to failures. The static routing protocols include Load Carry and Deliver Routing (LCAD) [11], Multi-Level Hierarchical Routing (MLHR) [12], and Data-Centric Routing (DCR) [13]. LCAD is based on the Store-Carry-Forward (SCF) paradigm [14]. The nodes capture the data and transport it, physically moving the message to a relay or destination node. It is usually used in DTN networks. MLHR solves the problem of scalability by clustering the nodes of the network and allowing a head node to communicate with the other head nodes of other clusters. Thus, the size and area of operation increase, but this head node can be a bottleneck and is a single point of failure [15]. DCR bases the routing on the information contained in the message. Thus, this protocol sends the information to several nodes that want specific data.

Proactive Routing Protocols

Each node has its routing table which is periodically updated and shared with the other nodes. The routing tables contain the routes to send a message from a source node to any destination node in the network. The main advantage of these types of protocols is their low delay in sending messages because the path is known beforehand. However, if there are many nodes in the network, the periodic updating of the routing tables severely consumes bandwidth and energy. In addition, proactive protocols react slowly to changes in topology, having to update the routing tables of all nodes in the network. Due to these disadvantages, these protocols are not usually used in applications with FANETs with a large number of UAVs with high mobility or when energy consumption must be low. The most important protocols proposed or adapted for FANETs are Optimized Link-State Routing (OLSR) [16], Destination Sequence Distance Vector (DSDV) [17], Better Approach to Mobile Ad Hoc Network (BATMAN) [18], and Directional OLSR (DOLSR) [19]. The OLSR protocol is currently the most widely used routing protocol in ad hoc networks. The approach of this protocol is to put a *cost* to each link (link-state) in the network. Each node evaluates the *cost* of sending a message through a link that is directly connected and shares it with its neighboring nodes using a flooding strategy. This *cost* can be the distance, delay, losses, bandwidth, etc. Once the view of the network has been updated, the route is searched applying the shortest path algorithm (*Dijkstra*). DSDV is a protocol based on the Bellman-Ford algorithm. It adds two parameters to vector-distance routing, which are a sequence number, to avoid loops and determine the freshness of the routes and the *Dampling* parameter. In addition, it uses two types of packages for route updates: full-dump and incremental. The full-dump packages contain all the information in the routing table, and due to its size, it is not usually transmitted. The incremental packet is used to update the routes in the last full-dump packet. DSDV has been used extensively in the field of FANETs, as can be seen in [20–22]. The BATMAN routing protocol is a relatively new proactive protocol that is used in MANETs. The BATMAN protocol does not discover the entire network; the protocol only learns from the nodes directly connected to them. In addition, BATMAN-Advanced (BATMAN-ADV) [23] is an improvement of the original BATMAN protocol in terms of performance due to its integration in the protocol stack. Numerous comparative studies of BATMAN-ADV performance in ad hoc networks and FANETs have been carried out [23,24]. DOLSR was specifically designed for FANETs and is a variant of OLSR. One of the most important performance factors in OLSR is the selection of multipoint relay (MPR) nodes. Thus, in DOLSR the number of MPRs is reduced to decrease the overhead. Each node selects a set of MPRs so that it can cover two-hop neighbors. DOLSR has the advantage of minimizing end-to-end delay, which is crucial for real-time applications and offers security improvements as it is resistant to jamming. In addition to the protocols explained, there are a variety of protocols with variants that are used in FANETs, such as Predictive-OLSR (P-OLSR) [5], Mobility and Load-Aware OLSR (ML-OLSR) [25], Contention-Based OLSR (COLSR) [26], Modified-OLSR (M-OLSR) [27], Cartography-Enhanced OLSR (CE-OLSR) [28], Topology Broadcast Based on Reverse-Path Forwarding (TBRPF) [29], Fisheye State Routing (FSR) [30], and Babel [31]. Babel builds on

the ideas of DSDV, AODV, and other routing protocols to derive a loop-avoiding distance vector routing protocol that is designed to be robust and efficient in both relatively stable and highly dynamic networks.

Reactive Routing Protocols

Due to the large bandwidth consumption that periodically occurs in the network discovery process of proactive protocols, reactive protocols use on-demand network discovery processes, which makes reactive protocols bandwidth-efficient. These protocols have a great advantage over proactive protocols as it gives them a great dynamism, something necessary in FANETs, but it has a great disadvantage in the latency produced by the route-search process. The most important reactive routing protocols are Dynamic Source Routing (DSR) [32], Ad Hoc On-Demand Distance Vector (AODV) [33], and Time-Slotted AODV (TS-AODV) [34]. DSR is a source-routing protocol. The complete route that a packet must follow is indicated in the header and only the source node can indicate the route. AODV is the most popular reactive routing protocol and is typically used in MANETs, VANETs, and FANETs. During the route lookup process, the source node searches its routing table to see if a route to the destination node has been established in the past. If no route exists, a route request process is initiated. TS-AODV is a time slot routing protocol centered on FANETs and based on the AODV protocol. Due to the large number of UAVs that may exist in FANETs, TS-AODV uses the time-division mechanism to avoid collisions in the transmission of information, significantly reducing packet losses and increasing the available bandwidth. In addition to the reactive protocols explained above, there are other routing protocols used in the literature on ad hoc networks and FANETs, such as Multicast AODV (MAODV) [35] and AODV Security (AODVSEC) [36].

Hybrid Routing Protocols

To solve the problems of bandwidth consumption of control messages and the low dynamism of proactive protocols, as well as the long delay in the route search of reactive protocols, hybrid routing protocols were introduced. These hybrid protocols are particularly suitable for large networks since they base their operation on the division of the network into sub-networks or zones. Thus, a proactive routing protocol operates within each zone and a reactive routing protocol is used for communication between zones. For hybrid solutions, the Zone Routing Protocol (ZRP) [37] is the most popular. ZRP divides the network into clusters of nodes in which their maximum separation distance is predefined. Within the clusters, a proactive routing protocol is applied, and nodes in different zones are routed to a subset that is common to both zones. There are other hybrid protocols designed or modified for FANETs, such as the Temporarily Ordered Routing Algorithm (TORA) [38], Rapid-reestablish TORA (RTORA) [39], Hybrid Wireless Mesh Protocol (HWMP) [40], Sharp Hybrid Adaptive Routing Protocol (SHARP) [41], and Hybrid Routing Protocol (HRP) [42].

2.2.2. Position-Based Routing Protocols

These routing protocols base their operation on the knowledge of the geographical position of the nodes. Therefore, they are the most suitable routing protocols for FANETs with high mobility. Protocols in this category can be divided into (i) reactive-based, (ii) greedy-based, and (iii) heterogeneous.

Reactive-Based Routing Protocols

These types of protocols are based on a reactive technique and use the position of the nodes to obtain higher performance. In this category, we highlight the Reactive-Greedy-Reactive (RGR) algorithm [43]. RGR is based on the reactive routing protocol AODV [33] for the on-demand route lookup process, and for message delivery, it is based on the Greedy Geographic Forwarding (GGF) protocol [44]. Other reactive-based protocols are

Ad Hoc Routing Protocol for Aeronautical Mobile Ad Hoc Networks (ARPAM) [45] and Multipath Doppler Routing (MUDOR) [46].

Greedy-Based Routing Protocols

This set of protocols searches the path with the least number of hops between nodes through the Greedy Forwarding approach [47], minimizing message delay. One of the most prominent protocols of this category is Geographic Position Mobility-Oriented Routing (GPMOR) [48]. GPMOR was designed considering some characteristics of FANETs and bases its operation on the predictive approach. Based on the Gauss–Markov mobility model [1] and the geographical positions of the nodes, GPMOR predicts the node positions and selects the next closest forwarding node to the receiver optimally, following the Greedy approach. Other greedy-based routing protocols are Mobility Prediction-Based Geographic Routing (MPGR) [49], Geographic Load Share Routing (GLSR) [50], Geographic Greedy Perimeter Stateless Routing (GPSR) [51], Greedy-Hull-Greedy (GHG) [52], Greedy-Random-Greedy (GRG) [53], Greedy Distributed Spanning Tree Routing 3D (GDSTR-3D) [54], and UAV Search Mission Protocol (USMP) [51].

Heterogeneous Routing Protocols

This set of protocols is applied to networks where the nodes that form them are of different natures, i.e., the network can be formed by fixed or mobile nodes on the ground and the aerial nodes of a FANET. This architecture has several advantages including increased coverage and performance. Within this set of protocols, Connectivity-Based Traffic Density Aware Routing Using UAVs for VANETs (CRUV) [55] stands out. CRUV relies on the existence of a DTN VANET supported by a FANET, which allows the interconnection of the DTN. In addition, there are also the following: UAV-Assisted VANET Routing Protocol (UVAR) [56], Position-Aware Secure and Efficient Routing (PASER) [57], Cross-Layer Link Quality and Geographical-Aware Beaconless (XLinGo) [58], and Secure UAV Ad Hoc Routing Protocol (SUAP) [9].

2.2.3. Clustering/Hierarchical Routing Protocols

In this category, UAV nodes are grouped into clusters, in a hierarchical fashion, and within each cluster, there is a node (cluster head) that enables inter-cluster communication via other cluster heads. In these routing protocols, the selection of the node acting as cluster-head is a critical task since the overall performance of the network will depend in part on this node. Within this category of protocols, the Clustering Algorithm of UAV Networking (CAUN) [59], and Mobility Prediction Clustering Algorithm for UAV Networking (MPCA) [60] may be mentioned. The operation of CAUN is quite simple: the initial cluster is built on the ground depending on the mission application, and once the network is deployed, the cluster adapts according to real-time conditions. On the other hand, MPCA predicts network topology updates, and, in turn, determines cluster formation based on UAV mobility, allowing for more stable clusters. In addition to the protocols described above, there are other protocols belonging to the category of clustering/hierarchical routing protocols, such as Landmark Ad Hoc Routing (LANMAR) [61], Multi-Meshed Tree Protocol (MMT) [62], Cluster-Based, Location-Aided DSR (CBLADSR) [63], and Disruption Tolerant Mechanism (DTM) [64].

2.2.4. Swarm-Based Routing Protocols

Swarm-based routing protocols are inspired by the behavior of animals and nature. Thus, for example, as swarm-based routing protocols that are created for FANETs, we highlight the BeeAdHoc [65] algorithm that bases its operation on the behavior of bees, as well as AntHocNet [66], and APAR [67] algorithms, both inspired by the behavior of ants.

2.2.5. Delay-Tolerant Network (DTN) Routing Protocols

Delay-tolerant routing protocols are proposed for networks with constant outages, partitions, and topology changes, such as FANETs. Thus, these protocols make use of the Store-Carry-and-Forward (SCF) technique when nodes lose connectivity. This technique eliminates the overhead since no control messages are transmitted but greatly increases the communication delay. The most widespread protocol of this group is Location-Aware Routing for Opportunistic Delay Tolerant (LAROD) [68]. LAROD is based on the combination of two approaches: SCF and Greedy Forwarding techniques, depending on the situation, and uses the beaconless strategy to reduce the overload of the network. In addition, within this category, it is worth highlighting the following algorithms: AeroRP [69], Geographic Routing Protocol for Aircraft Ad Hoc Network (GRAA) [70], Epidemic [71], Maxprop [72], Spray and Wait [73], and Prophet [74].

Table 2 shows a summary of the different classes of routing algorithms, their subclasses in this section, and their algorithms.

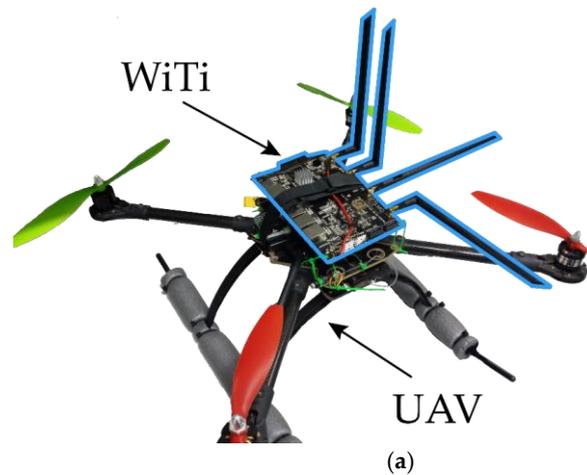**Table 2.** A summary of routing algorithms and their classes and subclasses.

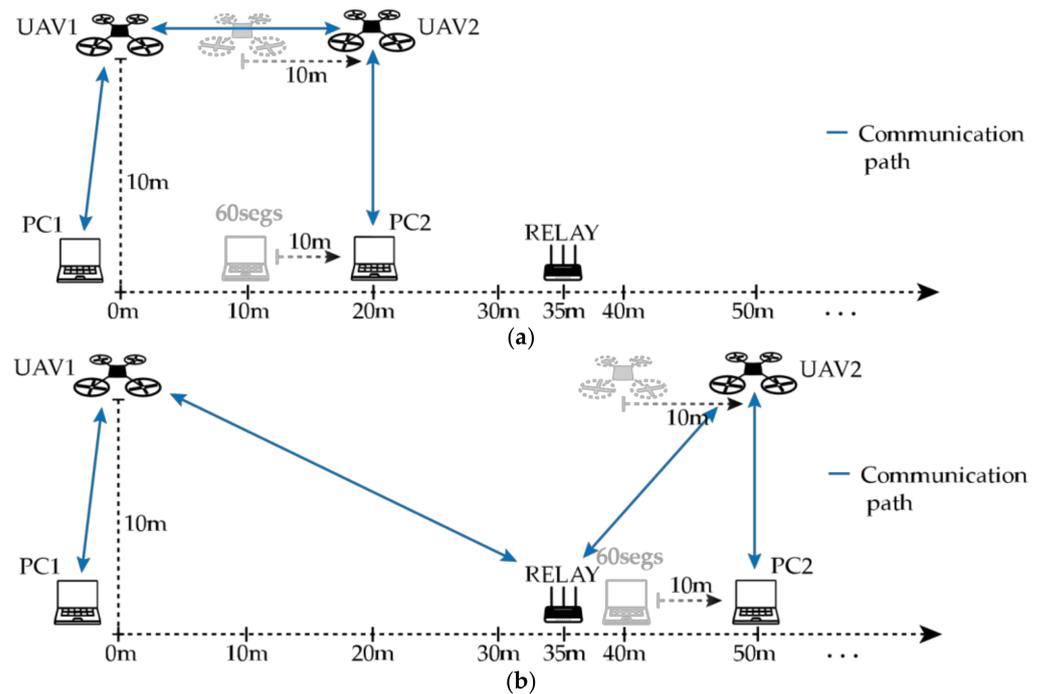| Type	Subtype	Routing Algorithm
Topology-Based	Static	LCAD [11], MLHR [12], DCR [13]
	Proactive	OLSR [16], DSDV [17], BATMAN [18], BATMAN-ADV [23], DOLSR [19], P-OLSR [5], ML-OLSR [25], COLSR [26], M-OLSR [27], CE-OLSR [28], TBRPF [29], FSR [30], Babel [31]
	Reactive	DSR [32], AODV [33], TS-AODV [34], MAODV [35], AODVSEC [36]
	Hybrid	ZRP [37], TORA [38], RTORA [39], HWMP [40], SHARP [41], HRP [42]
Position-Based	Reactive-Based	RGR [43], GGF [44], ARPAM [45], MUDOR [46]
	Greedy-Based	GPMOR [48], MPGR [49], GLSR [50], GPSR [51], GHG [52], GRG [53], GDSTR-3D [54], USMP [51]
	Heterogeneous	CRUV [55], UVAR [56], PASER [57], XLinGo [58], SUAP [9]
Clustering/Hierarchical		CAUN [59], MPCA [60], LANMAR [61], MMT [62], CBLADSR [63], DTM [64]
Swarm-Based		BeeAdHoc [65], AntHocNet [66], APAR [67]
Delay-Tolerant Network		LAROD [68], AeroRP [69], GRAA [70], Epidemic [71], Maxprop [72], Spray and Wait [73], Prophet [74]

3. Materials, Methods, and Scenario

In this section, we will explain the testbed and tools employed in this study. By using this deployment, we demonstrate the communication capabilities that FANETs can offer, comparing the performance achieved with various proactive routing protocols, specifically OLSR, BATMAN-ADV, and Babel. The 3 protocols were selected based on the criteria of "state of the art" technology, experience working with them, suitability for the proposed scenario, and compatibility with the communications module.

For this purpose, a WiFi network composed of several UAVs was deployed. Each UAV had a specific communication module (WiTi [75]); see Figure 1a. These communication modules had a dual 2.4/5 GHz communication band, using the IEEE 802.11g standard for the 2.4GHz band and the IEEE 802.11a standard for the 5GHz band, and 2 antennas for each frequency band. The tool *iperf3* [76] was employed to evaluate the performance of the different routing algorithms, analyzing throughput and packet losses. To analyze packet losses in an efficient way, the UDP communication protocol was used. In the deployed scenario (see Figure 1b), 5 communication nodes were placed: specifically, 2 UAVs (quadcopters), 2 PCs, and 1 ground node. The 2 PCs were located under the UAVs to simulate devices in a coverage extension scenario. They also allowed monitoring of the network status. On the other hand, the ground node operated as a relay base station, acting as an intermediate node between the drones when the distance between the nodes

required its use. The relay node was located at 35 m from PC1 (UAV1). Whereas UAV1 was kept at a fixed location, UAV2 flew horizontally, stopping every 10 m to take performance measurements. Each measurement had a duration of 60 s and consisted of sending data between the 2 PCs through the UAVs. Both UAVs flew at an altitude of 10 m, calibrating all distances, positions, and heights with the UAVs' GPS modules. A representation of the deployed scenario can be seen in Figure 2a,b. For instance, this scenario could simulate a situation where a coverage extension is required due to an emergency, to solve a specific moment of overload of the communications network, or for remote surveillance.

(**a**)

(**b**)

Figure 1. (**a**) UAV with WiFi communication module (WiTi). (**b**) Flying field, "Los Halcones de la Rambla", Murcia, Spain.

Figure 2. Real testbed FANET with relay node. (**a**) Communication before 35-m mark. (**b**) Communication after 35-m mark. Note that after the 35-m mark, communication between the 2 UAVs (UAV1 and UAV2) was performed through the relay node. Before this mark, the communication was completed through a direct path. Performance measurements were taken between the 2 UAVs every 10 m step and each measurement had a duration of 60 s. The PCs were used to monitor the network and followed their UAV. The height of the UAVs was 10 m. The first UAV (UAV1) was located at the 0-meter mark. The relay node was located at the 35-m mark. The second UAV (UAV2) was positioned for 60 s at the measurement points located 10 m from the 0-meter mark. That is, the first measuring point was located at 10 m, the second at 20 m, and so on.
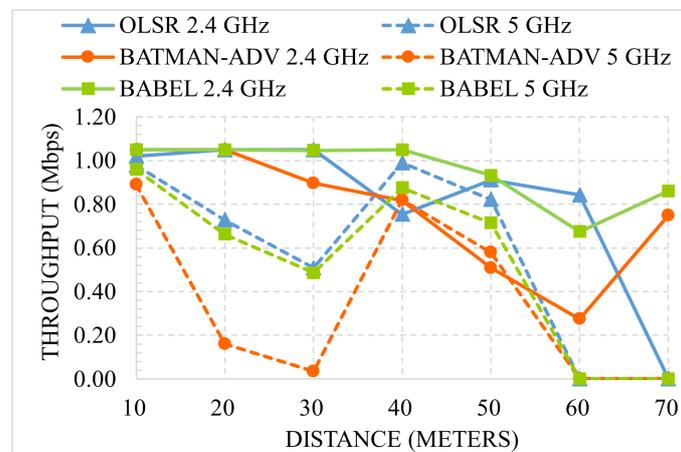
4. Results

This section will analyze the results obtained in the tests detailed in the previous section, comparing in terms of throughput and packet losses the different routing algorithms presented.

The results showed that the Babel and OLSR protocols obtained higher throughput in both the 2.4 GHz and 5 GHz bands. Besides, the expected inverse relationship between packet losses and throughput was demonstrated since one increases while the other decreases. It was also observed that the 5 GHz band presented a faster throughput decay. Because the received power is inversely proportional to frequency and distance, the 2.4 GHz band will present a higher received power at equal transmitted power and communication distance, which will allow the maintenance of a more stable and robust communication. Only at 10 m, 40 m, and 50 m, the performance of both bands is comparable. For the 10 m point, the communication between the UAVs was direct on both bands, so propagation losses were low and communication was very stable. For the 40 m and 50 m points, the communication for the 2.4 GHz band was still direct. However, for the 5 GHz band, the communication made an intermediate hop through the relay node, decreasing the distance between the communication nodes. Throughput results can be seen in Table 3 and Figure 3. Likewise, packet loss results are shown in Table 4 and Figure 4.

Table 3. Average throughput (Mbps) obtained between PCs-UAVs at different gap distances for OLSR, BATMAN-ADV, and Babel, for 2 frequency bands: 2.4 and 5 GHz. Each measurement had a duration of 60 s.

Routing Protocol	Frequency Band	Distance						
		10 m	20 m	30 m	40 m	50 m	60 m	70 m
OLSR	2.4 GHz	1.02	1.05	1.05	0.75	0.91	0.84	0.00
	5 GHz	0.98	0.73	0.51	0.99	0.82	0.00	0.00
BATMAN-ADV	2.4 GHz	1.05	1.05	0.90	0.82	0.51	0.27	0.75
	5 GHz	0.89	0.16	0.03	0.82	0.58	0.00	0.00
Babel	2.4 GHz	1.05	1.05	1.05	1.05	0.93	0.67	0.86
	5 GHz	0.96	0.66	0.49	0.88	0.71	0.00	0.00

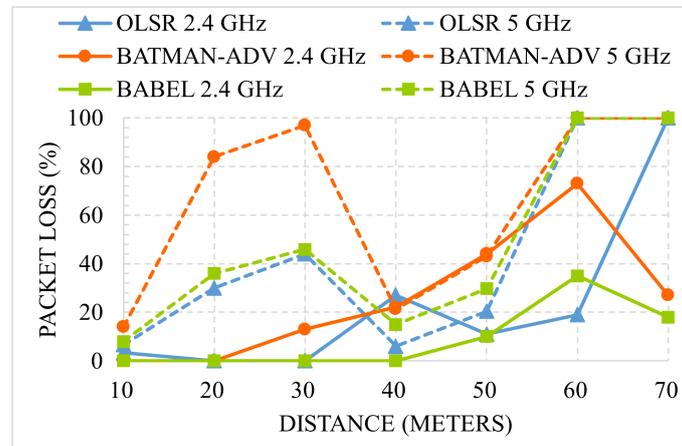**Figure 3.** Average throughput (Mbps) vs. distance (meters) for each protocol and frequency band.

Table 4. Average packet loss (%) obtained between PCs-UAVs at different gap distances for OLSR, BATMAN-ADV, and Babel, for 2 frequency bands: 2.4 and 5 GHz. Each measurement had a duration of 60 s.

Routing Protocol	Frequency Band	Distance						
		10 m	20 m	30 m	40 m	50 m	60 m	70 m
OLSR	2.4 GHz	3.3%	0%	0%	27%	11%	19%	100%
	5 GHz	6.6%	30%	44%	6%	20.4%	100%	100%
BATMAN-ADV	2.4 GHz	0%	0%	13%	22.1%	44%	73%	27%
	5 GHz	14%	84%	97%	21.3%	43%	100%	100%
Babel	2.4 GHz	0%	0%	0%	0%	10%	35%	18%
	5 GHz	8%	36%	45.9%	15%	29.7%	100%	100%

For the 2.4 GHz band, as shown in the results, especially in Figures 3 and 4, the routing protocols present a different behavior. OLSR switches from direct communication to relay communication between the measurement points located at 40 m and 50 m. However, both BATMAN-ADV and Babel switch between 60 m and 70 m. This can be verified by the fact that there is a change of trend in the metrics studied at these two measurement points and the corresponding change in the routing table.

If we now focus on the 5 GHz band, the trend change occurs between the measurement points located between 30 and 40 m. Between these two points, communication switched from direct UAVs communication to relay mode. After this change in communication, the metrics improved, to rapidly decline again with distance. Additionally, for the 5 GHz frequency band, the maximum distance at which we were able to establish communication

between two nodes was 40 m. This is again reflected above 40 m, which is the distance at which the intermediate hop to the relay node existed. If the relay node had been located more than 40 m away, it would have been impossible to use it as an intermediate communication node in the 5 GHz band.

Figure 4. Average packet loss (%) vs. distance (meters) for each protocol and frequency band.

We can conclude that Babel and OLSR obtained better results than BATMAN-ADV, given the results obtained. This may have been expected because BATMAN-ADV has a too-high routing update period that was originally not intended for FANETs. Finally, between Babel and OLSR, Babel offered the best overall performance, guaranteeing more stable results in both frequency bands.

5. Conclusions

The potential of FANETs can increase in the coming years with the advent of new communication technologies and standards such as 6G, the Internet of Things (IoT), and connected autonomous vehicles (CAVs). The benefits that FANETs can offer are immeasurable (coverage extension, application in emergency communications, search and rescue, agriculture, etc.). When deploying FANETs, it is essential to be able to find the path that a packet must follow to reach its destination. Due to the characteristic constant changes in the network topology of FANETs, the selection of the routing protocol is a crucial task for effective deployment and successful operation. After detailing the different routing protocols that have been proposed for FANETs, this paper performed a case study comparing the performance offered, in terms of throughput and packet loss, of three proactive routing protocols: OLSR, BATMAN-ADV, and Babel. The scenario studied could simulate a coverage extension scenario in emergencies, search and rescue, or remote surveillance. The results obtained showed that Babel achieved higher performance in the studied metrics, outperforming OLSR and BATMAN-ADV. Besides, it was shown that BATMAN-ADV performed significantly worse than OLSR and Babel due to its low frequency of routing-table updating. In particular, the sending period of messages in charge of finding alternative routes in BATMAN-ADV is 1 s (OGM interval). In FANETs, the network topology can vary a lot in 1 s, hence discouraging its use for FANETs. As future work, we consider that an extension of the routing protocols to be evaluated would be a logical next step, employing a more significant number of UAVs with different characteristics and comparing experimental results and propagation models such as those presented in [77].

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Abbreviations

AeroRP	Aeronautical Routing Protocol.
AODV	Ad Hoc On-Demand Distance Vector.
AODVSEC	AODV Security.
APAR	Ant Colony Optimization-Based Polymorphism Aware Routing Algorithm.
ARPAM	Ad Hoc Routing Protocol for Aeronautical Mobile Ad Hoc Networks.
BATMAN	Better Approach to Mobile Ad Hoc Network.
BATMAN-ADV	BATMAN-Advanced.
CAUN	Clustering Algorithm of UAV Networking.
CBLADSR	Cluster-Based Location-Aided DSR.
CE-OLSR	Cartography-Enhanced OLSR.
COLSR	Contention-Based OLSR.
CRUV	Connectivity-Based Traffic-Density Aware Routing Using UAVs for VANETs.
DCR	Data-Centric Routing.
DOLSR	Directional OLSR.
DSDV	Destination-Sequenced Distance Vector.
DSR	Dynamic Source Routing.
DTM	Disruption-Tolerant Mechanism.
DTN	Delay-Tolerant Network.
FANET	Flying Ad Hoc Network.
FSR	Fisheye-State Routing.
GCS-R	Ground Control System-Routing
GDSTR-3D	Greedy Distributed Spanning Tree Routing 3D.
GGF	Greedy Geographic Forwarding.
GHG	Greedy-Hull-Greedy.
GLSR	Geographic Load-Share Routing.
GPMOR	Geographic Position Mobility-Oriented Routing.
GPSR	Geographic Greedy Perimeter Stateless Routing.
GRAA	Geographic Routing Protocol for Aircraft Ad Hoc Network.
GRG	Greedy-Random-Greedy.
HRP	Hybrid-Routing Protocol.
HWMP	Hybrid Wireless Mesh Protocol.
LANMAR	Landmark-Routing Protocol.
LAROD	Location-Aware Routing for Opportunistic Delay Tolerant.
LCAD	Load Carry and Deliver Routing.
MANET	Mobile Ad Hoc Network.
MAODV	Multicast AODV.
MLHR	Multi-Level Hierarchical Routing.
ML-OLSR	Mobility and Load-Aware OLSR.
MMT	Multi-Meshed Tree Protocol.
M-OLSR	Modified-OLSR.
MPCA	Mobility Prediction Clustering Algorithm.
MPGR	Mobility Prediction-Based Geographic Routing.
MUDOR	Multipath Doppler Routing.
OLSR	Optimized Link-State Routing.
PASER	Position-Aware Secure and Efficient Routing Approach.
P-OLSR	Predictive-OLSR.
RGR	Reactive-Greedy-Reactive.

RTORA	Rapid-Reestablish TORA.
SHARP	Sharp Hybrid Adaptive Routing Protocol.
SUAP	Secure UAV Ad Hoc Routing Protocol.
TBRPF	Topology Broadcast Based on Reverse-Path Forwarding.
TORA	Temporarily Ordered Routing Algorithm.
TS-AODV	Time-Slotted AODV.
UAV	Unmanned Aerial Vehicle.
USMP	UAV Search Mission Protocol.
UVAR	UAV-Assisted VANET Routing Protocol.
VANET	Vehicular Ad Hoc Network.
XLinGo	Cross-Layer Link Quality and Geographical-Aware Beaconless.
ZRP	Zone-Routing Protocol.

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