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Performance Analysis of Mesh Routing Protocols for UAV Swarming Applications

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***Abstract*—Unmanned Aerial Vehicles (UAVs) are an emerging technology offering new opportunities for innovative applications and efficient overall process management in the areas of public security, cellular networks and surveying. A key factor for the optimizations yielded by this technology is an advanced mesh network design for fast and reliable information sharing between UAVs. In this paper, we analyze the performance of four available mesh routing protocol implementations (open80211s, BATMAN, BATMAN Advanced and OLSR) in the context of swarming applications for UAVs. The protocols are analyzed by means of goodput in one static and one mobile scenario using the same embedded hardware platform installed at UAVs in current research projects. Our results show that layer-2 protocols suit better for mobile applications in comparison to layer-3. On the other hand, they often cause routing flippings, which are unwanted route changes, in static scenarios imposing a small performance decrease. Hence, given the aforementioned routing protocols, we recommend to currently use open80211s or batman-advanced to establish a reliable multi-hop mesh network for swarming applications.**

I. INTRODUCTION

Recently the technological and research advances in autonomous air and land vehicles lead to a wide application of these vehicles. Due to their relatively low price, multiple micro Unmanned Aerial Vehicles (UAVs) can be brought together to form a swarm. To enable an autonomous behavior of such a swarm, intercommunication between all UAVs within the swarm is of paramount importance. The UAVs receive control and mission data and provide sensor data. This sensor data can be on the one hand small, in case temperature and gas sensors come into account, but is on the other hand often large, in case video and image data is transferred. A third kind of data could be Voice over IP data transmitted through an aerial network, which implies seamless network capabilities and high Quality of Service (QoS) demands. Considering the reception and transmission of data, several QoS aspects have to be considered. Control data is highly critical in terms of reliability (path stability) and round-trip time, but not critical in terms of throughput and bandwidth demands. Considering the transmission of large image data the demands are the opposite. In this case the time for transferring is important and the delay of the data packets is negligible. These demands can be directly transferred to the design of mesh networks. The key performance indicators are throughput, round-trip time, and path stability. In this paper, we focus on throughput measurements in one static and one mobile scenario.

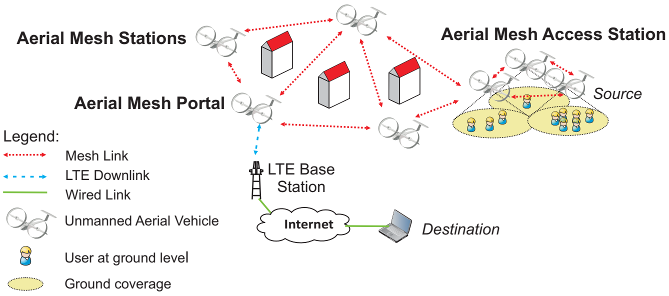

Fig. 1. Example Use Case Scenario: Aerial Network Coverage through an Autonomous Micro UAV Mesh Network

Figure 1 shows a network provisioning scenario where a combination of a mesh network, cellular network, fixed network together with highly mobile UAVs build a complex communication system [1]. The architecture shown in Figure 1 assumes an Aerial Mesh Network. On the right Aerial Mesh Access Stations provide network access to users at ground level. The traffic is relayed through the Aerial Mesh to an Aerial Mesh Portal, where a relay UAV provides a downlink to a cellular base station where the user-traffic is routed to the destination. In this scenario there is a need for both QoS demands. The UAVs need to exchange their mission and steering data with the least round-trip time and the users at ground level desire high throughput and low latency. A mesh architecture addresses the need for high data rates and short delays in order to fulfill these requirements. Relaying the traffic through the shortest and most efficient path is a great challenge, which is addressed in this paper.

Several reactive and proactive protocols like OLSR, BATMAN and BATMAN Advanced have been developed targeting heterogeneous application areas. The IEEE 802.11s standard sets crucial approaches in terms of QoS control, bringing the path selection to the MAC layer and making PHY data easier accessible for routing optimization. It also proposes a hybrid routing solution to combine the benefits of reactive and proactive routing protocols. Our approach is to evaluate the performance of the current open implementation of the IEEE 802.11s standard against an 802.11x WiFi Radio in combination with the aforementioned most common mobile ad-hoc routing protocols, making it a rudimentary mesh solution. The results show that all routing protocols are able to build a mesh network, showing only small differences in the static scenario. Considering mobility, the open80211s implementation outperforms the other protocols. Even in the static case, open80211s is slightly better.

The remainder of this paper is organized as follows. In Section II, we concentrate on recent work that has been carried out in the field of mesh networks. In Section III, we give a brief summary of the used standards and protocols, followed by a description of our testbed and measurement scenarios in Section IV. Our results are shown in Section V and finally a

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conclusion is presented in Section VI.

II. RELATED WORK

The performance evaluation of routing in MANET/WMN recently attracted many researchers. Nonetheless, most of the research work has been carried out in the simulation [2], which is very significant if network scalability, protocol controllability and scenario repeatability are of paramount importance. On the other hand, if performance parameters such as round-trip time and goodput are in demand, the degree of realism in simulation-study is not sufficient. The use of testbeds for comparison of routing protocols in terms of these parameters is an emerging phenomenon. Nowadays, the building and analysis of wireless networks using WiFi device or mesh routers has become quite popular due to the ubiquity and low cost of these devices. A good review of the research laboratories in this field are given in [3]. Some networks have been designed to look at how the BATMAN routing protocol performs in large networks. In [4] a performance comparison between OLSR and BATMAN with respect to mobility has been carried out in an experimental five node network. In this context, we proposed in [5] a testbed composed of gumstix-based mesh routers to evaluate the multi-hop throughput in UAV scenarios. However, very few works have considered the performance evaluation of the evolving IEEE 802.11s standard. Noteworthy is [6], where the authors provide a comparison between BATMAN and open80211s, which is a basic implementation of the IEEE standard. However, in that paper, the authors only considered the route stability and the recovery mechanism of both protocols and they neglected key performance indicators like throughput. Apart from that, in [7], a similar analysis has been proposed, where in addition to BATMAN and open80211s the OLSR protocol was considered. In that paper, however, the authors based their experiments on IEEE 802.11b, besides they did not deal with differences between layer-2 and 3. As a result, the novelty of our paper lies essentially in the experimental comparison of two layer-2 protocols (open80211s and BATMAN-adv) with two layer-3 protocols (BATMAN and OLSR) and furthermore on the comparison of the same protocol, namely BATMAN, on both layer-2 and 3.

III. OVERVIEW OF USED STANDARDS AND ROUTING PROTOCOLS

A. The IEEE 802.11s Standard

The IEEE 802.11s Task Group has been active for nearly seven years now. Its main goal was to derive a standard [8], which realizes co-existing 802.11 Mesh Networks. The standard defines several fields of improvements like medium access, power save support, security and new methods of routing and path selection. This section only focuses on the parts relevant for this work. The basic IEEE 802.11s architecture consists of three key elements:

- Mesh Station: The main task of a Mesh Station is to route the traffic within the core of the Wireless Mesh Network. In comparison to a legacy 802.11 station the Mesh Station has the ability to forward packets through the network. As more Mesh Stations are interconnected, they form a Mesh Basic Service Set (MBSS).
- Mesh Access Station: The Mesh Access Station serves as a connecting unit between the core Mesh Stations and gives access to legacy 802.11 Stations. It serves as an intermediate node between the Mesh Basic Service Set and the legacy Basis Service Set with the connected 802.11 Stations. Its main task is to provide connectivity to the Mesh Portal for the legacy 802.11 Stations.
- Mesh Station Portal: The Mesh Station Portal forms the root of the Mesh Network and often serves also as a root node for the routing activity in the Mesh Network. Its main task is to provide a connection to the Internet or create an interconnection with other 802.X Networks.

TABLE I
AIRTIME LINK METRIC PARAMETERS

Parameter	**Description**
O	Channel access overhead that includes frame headers, training sequences, protocol access frames. (Directly depends on PHY)
B_t	The length of the test frame in bits (constant)
r	Transmission data rate in Mb/s for transmission of B_t
e_f	Test frame error/loss rate for B_t

1) Hybrid Wireless Mesh Protocol: With the IEEE 802.11s standard, a new routing protocol called Hybrid Wireless Mesh Protocol (HWMP) has been introduced. The standard also allows the use of different routing protocols but implementing HWMP is mandatory for compatibility purposes. Methods of changing this to non-mandatory are currently considered for energy saving purposes. HWMP is a layer-2 routing protocol. Therefore an easy information exchange with the PHY-layer enables the usage of link quality information for creating an efficient routing metric. It supports two routing methods, a reactive and a proactive method. The reactive part consists of an on-demand mechanism that was derived from Ad hoc On-Demand Distance Vector (AODV) and the complementary part is built upon a tree based mechanism that serves as the proactive part. In the proactive part the root maintains all routes to its nodes or enforces the nodes to keep track of the route maintenance to the root node. Once a route through the root node is established a more efficient route can be discovered by the reactive part of HWMP.

2) Path Selection: As mentioned before the HWMP uses a special routing metric - the airtime link metric (C_a) - for path selection. It can be derived from the following equation and is explained in detail in Table I:

$$C_a = \left[O + \frac{B_t}{r} \right] \frac{1}{1 - e_f} \tag{1}$$

B. Mobile Ad-Hoc Routing Protocols

1) OLSR: It is the most deployed proactive link state routing protocol [9]. Nodes, implementing this protocol, maintain topology information about the whole network based on periodically exchanged link-state messages. To minimize the negative impact of a simple flooding of these messages on the overall performance, OLSR uses the Multi Point Relaying (MPR) method, which is the key concept of this protocol. Herewith, nodes select only a subset of neighboring nodes to relay data instead of every node acting as a relay. These nodes are called MPR. Any node, which is not in the MPR set, can read and process each packet but does not retransmit it. MPRs are selected based on periodically broadcasted list of one hop neighbors. From this list, each node defines a subset of one hop neighbors, namely MPR, covering all of its two hop neighbors. The use of MPRs decreases the flooding of control messages. This optimization works well for large and dense networks. The larger and denser the network, the better is the optimization achieved. OLSR uses two main types of control messages: HELLO and Topology Control (TC). HELLO messages perform the tasks of link sensing, neighbor detection and MPR signaling. TC messages carry out topology declaration (advertisement of link state). OLSR selects the shortest path between a source and a destination, using a hop-count metric.

2) BATMAN: OLSR has been designed with a moderate number of nodes in mind targeting generic MANET applications. Thus, due to the increasing communities of mesh networks, e.g., Freifunk Berlin and because of the inefficiency inherited in link-state algorithms due to topology-graph's recalculations (a particularly challenging task for embedded mesh router HW constraints), the limits of OLSR have become a challenge. A simple pragmatic approach to mesh routing in large static mesh networks is provided by BATMAN [10]. It has been published in [11]. In BATMAN all nodes periodically broadcast hello packets, also known as originator messages (OGM), to its neighbors. These OGMs are used to determine, for each destination in the WMN, the neighbor that can be used as best next hop towards the destination. To find the best route towards a destination, BATMAN counts the number of OGMs originated by that node and received from the different neighbors. Then, it selects the neighbor as next hop, from which it has received the highest number of OGMs within a sliding window (packet count metric), i.e., the path with best quality. In this way, a node does not maintain the full route to a destination but every node on the path only knows the next hop to reach it. While this feature eliminates routing loops because no global topology information is flooded, the self-interference caused by data traffic leads to oscillations in the throughput as we will see in our experiments.

3) BATMAN Advanced: BATMAN was first realized as a classic layer-3 routing protocol, using UDP packets to exchange routing information. Later on, an extension called BATMAN Advanced (in short, BATMAN-adv) was developed to work at layer-2. Nodes implementing this version appear to be attached by a direct link and all protocols operating on top of it are not aware of the multi-hop nature of the underlying network. The main difference of BATMAN in comparison to its layer-2 implementation is the maintainability of MAC addresses instead of IP addresses. This feature makes BATMAN-adv able to handle a possible switch from IPv4 to IPv6 and is therefore future-proof and lightweight. As a conclusion, this protocol offers a suitable opportunity to compare routing on both layers 2 and 3.

IV. TESTBED AND MEASUREMENT SCENARIOS

A. Mesh Units

In order to have a mobile and flexible mesh testbed, we built special dedicated Mesh Units. The heart of the units is a Roboard RB110 with a VortexX86 32-bit CPU at $1000\,\mathrm{MHz}$ and $256\,\mathrm{MB}$ DRAM. It provides USB, serial ports and a miniPCI slot. In our case we used a Wistron DMNA92 miniPCI WLAN Device, which is capable of the IEEE 802.11a/b/g/n standards.

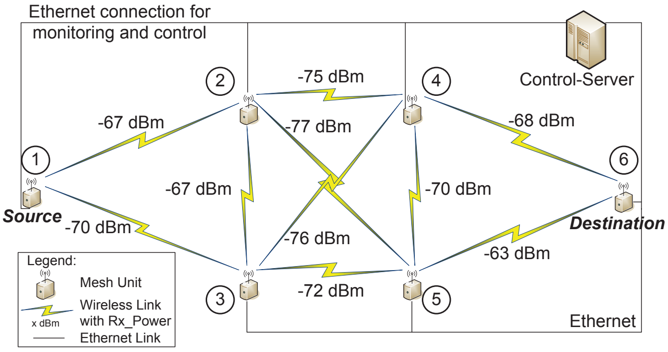

Fig. 2. Mesh Testbed for Static Scenario

TABLE II
PROTOCOL PARAMETERS FOR STATIC AND MOBILE SCENARIO

Protocol	Parameters	Static	Mobile
Open80211s	retry_timeout	0.1 s	0.1 s
	confirm_timeout	0.1 s	0.1 s
	holding_timeout	0.1 s	0.1 s
	path_refresh_time	1.0 s	0.5 s
	min_discovery_timeout	0.1 s	0.1 s
	hwmp_active_path_timeout	5000 TUs	500 TUs
BATMAN	OGM Interval	1.0 s	0.25 s
BATMAN-Adv.	OGM Interval	1.0 s	0.25 s
OLSR	HELLO Interval	2 s	0.25 s
	HELLO Validity	20 s	0.75 s
	TcInterval	5 s	1 s
	TcValidityTime	300 s	3 s

The miniPCI WLAN Device uses the ATH9K Linux driver, which is also supported by the open80211s implementation. The unit is equipped with two omni-directional dual band $(2.4 + 5.0\,\mathrm{GHz})$ antennas with a gain of $5\,\mathrm{dBi}$. Furthermore every unit is equipped with a static power supply and an additional $5000\,\mathrm{mAh}$ battery for mobility purposes. The units provide an Ethernet port, which is used for monitoring and configuration purposes.

B. Software Configuration

As for the software configuration we used Debian Squeeze with the 2.6.37 Linux Kernel. The open80211s implementation is included in that kernel. For the routing protocols the following versions were evaluated: BATMAN-adv 2011.1.0, BATMAN 0.3.2 and OLSRd 0.6.1.

C. Static Scenario

Within a swarm of UAVs, especially in case of quadrocopters [1], a static scenario is reasonable, due to the slow relative velocity between each UAV within the swarm. In order to achieve a real multi-hop scenario, the nodes were placed in an indoor scenario with a limited transmit power of $4\,\mathrm{dBm}$. All Mesh Units were tuned to WiFi-channel 40

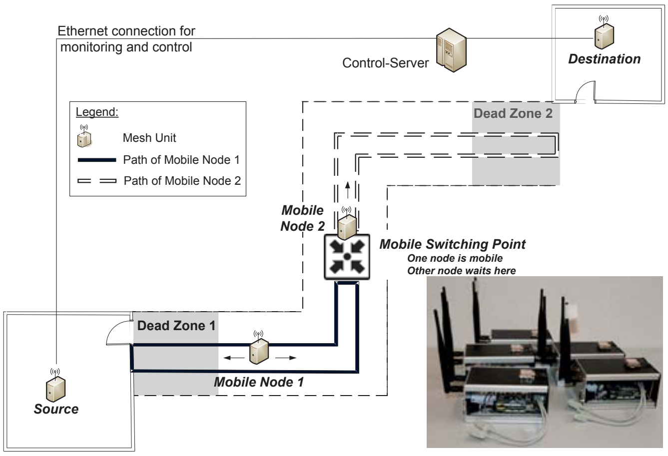

Fig. 3. Mesh Testbed for Mobile Scenario

(5.2 GHz). The spectrum of this channel was scanned prior to the measurements using a WiSpy channel analyzer to avoid interferences from outside the network under test. We tested the visibility of each node with ping tests. For the tests, an indoor setup that is similar to the application scenario depicted in Figure 1 was created. Hereby, all protocols were evaluated using their default settings as illustrated in Table II. Figure 2 shows our configuration topology setup for the static scenario with the received signal strength in mesh mode. All units are additionally connected through a LAN interface in order to monitor and access their settings on the fly. Hence, a switch from Ad-Hoc Mode to Mesh Mode or a switch between routing protocols can be performed seamlessly. The tests were run from Mesh Unit 1 serving as the client to Mesh Unit 6, which hosts the server. Using iperf, a constant load between 512 kbit/s and 8 Mbit/s was offered at the source. The goodput was measured at the destination node. All measurements were performed in UDP mode, using 1470 byte datagrams. Each measurement had a duration of 500 seconds and five repetitions for each measurement were performed.

D. Mobile Scenario

The mobile scenario consists of two fixed nodes and two mobile nodes, as depicted in figure 3. Similar to the static scenario, a constant load of 2 Mbit/s was offered. The challenge of the investigation in the mobile scenario is to force a route switch while always providing an alternative route. The alternative route needs to be properly identified and used by the routing protocol. In order to achieve this goal, the mobile nodes were moved along a predefined path at a speed of 1 m/s. From communication point of view, this speed reflects the relative movements of UAVs within a controlled swarm behavior. Although their effective speed might be significantly higher, we focus in a first step on this low mobility within the swarm. The protocols' parameters were tweaked according to Table II, to better suit the mobile scenario. In order to ensure reproducible route switches, a mobile switching point was established in the center of the scenario. While one node is moving, the other one waits at the mobile switching point. While the mobile node is moving in the dead zone for 30 seconds, the link over this node is deliberately broken. Meanwhile, the node waiting at the mobile switching point provides an alternative hop for the route between source and destination. The resulting goodput between source and destination is a key performance indicator of the routing protocol, as the delayed or failed route switches lead to a goodput decrease correspondingly.

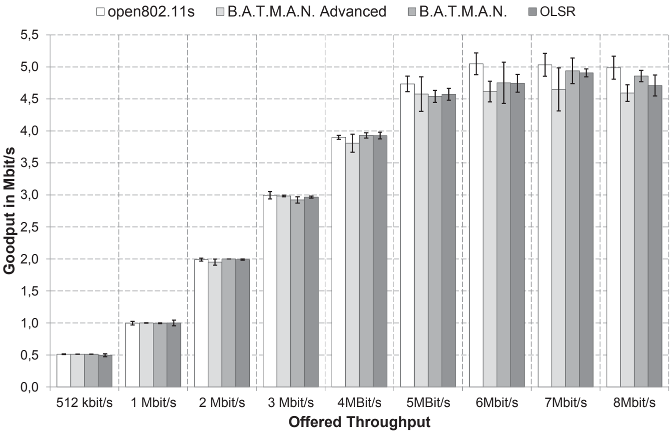

Fig. 4. Goodput Measured in the Static Scenario

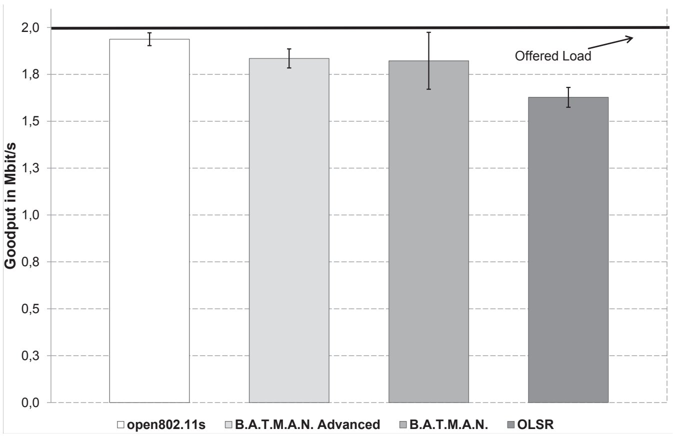

Fig. 5. Goodput Measured in the Mobile Scenario

V. RESULTS

In Figure 4, the mean and the 95% confidence intervals of the goodput at the destination node no. 6 (see Figure 2) are presented. It is noticeable that up to 4 Mbit/s there are no significant differences between the routing protocols. The goodput increases with an increased offered throughput until the offered throughput rises above 6 Mbit/s, which the maximum offered WiFi data rate at the configured transmit power. For higher offered throughputs, the network is unable to transmit all offered traffic, including protocol control packets and iperf traffic. A remarkable result can be found in the performance of open80211s as it reaches the best goodput of 5.0 Mbit/s compared to the other protocols. As only the reactive part of open80211s was activated, this result is explained by both less control overhead in the network and less routing flippings. Comparing BATMAN at layer-3 and BATMAN-adv at layer-2, there is a slightly better performance of the layer-3 routing protocol at the higher loads. This is

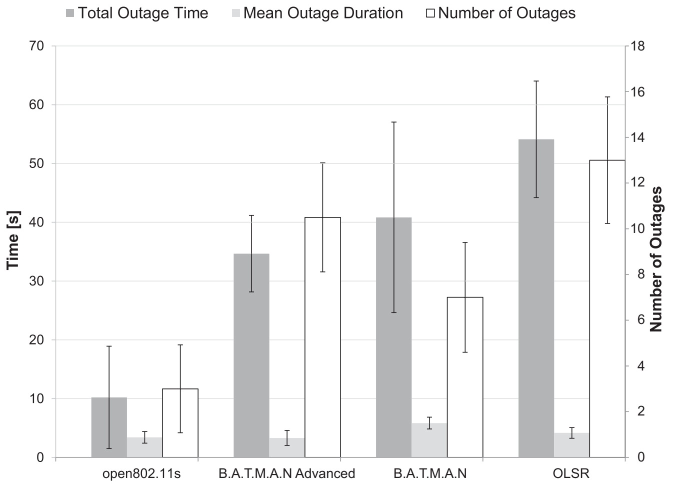

Fig. 6. Number and mean Duration of Outages for each Protocol in Mobile Scenario

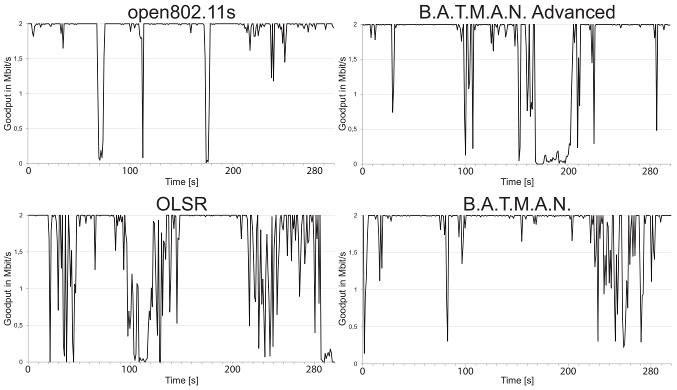

Fig. 7. Goodput vs. Time of One Example Measurement for Each Protocol in Mobile Scenario

justified by the high sensitivity of the layer-2 version to WiFi-ACK packets: any reception failure of those packets often causes a routing change, i.e., a slight packet loss, which is also known as routing flipping. The performance of OLSR is slightly worse than BATMAN layer-3 in case of high data rates. This is caused by the repeated broadcast of more than one packet (topology control, hello etc.) in comparison to the lighter control overhead (OGMs) in BATMAN.

Figure 5 shows the results for the mobile scenario with respect to goodput. Compared to the static scenario, all protocols show a lower goodput but the impact of the mobility is quite different. Again open80211s outperforms the other routing protocols, because its reactive behavior is ideally suited to the small network size, which reflects the typical small scale UAV application. BATMAN as well as OLSR suffers from increased signaling overhead due to the route switches. But again BATMAN proofs to be more efficient than OLSR. Apart from that, Figure 6 and 7 once again shed the light on the faster reaction of layer-2 protocols to network changes. Moreover, they demonstrate that the reactive open80211s has an edge over the other protocols by the number of outages. While, in case of open80211s, these outages are solely caused by the forced route switches of the mobile scenario, additional outages occur using other protocols due to their proactive character.

VI. CONCLUSION AND FUTURE WORK

In this paper, we analyze the performance of four mesh routing protocols on layer-2 and 3, to relay traffic between UAVs in regions with insufficient network coverage. In this context, we investigate the goodput of constant bit rate traffic, comparable to a live video stream transmitted by a UAV, in a static and mobile experimental scenario. Our results show that in high-overloaded scenarios with harsh environmental conditions (low received power), available implementations of the layer-2 protocols (open80211s and BATMAN-adv) are mature enough to satisfy the performance requirements. They outperform layer-3 protocols in terms of throughput and stability. For our future work, we will rely on open80211s and its open implementation while closely observing the progress on the proactive part development. Apart from that, we will extend our evaluation to investigate larger scale scenarios in outdoor UAV environments in a dedicated UAV testbed.

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