RedeFINE: Centralized Routing for High-capacity Multi-hop Flying Networks

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***Abstract*—The advent of small and low-cost Unmanned Aerial Vehicles (UAVs) is paving the way to use swarms of UAVs to perform missions such as aerial video monitoring and infrastructure inspection. Within a swarm, UAVs communicate by means of a Flying Multi-hop Network (FMN), which due to its dynamics induces frequent changes of network topology and quality of the links. Recently, UAVs have also been used to provide Internet access and enhance the capacity of existing networks in Temporary Events. This brings up additional routing challenges not yet addressed, in order to provide always-on and high capacity paths able to meet the Quality of Service expected by the users.**

This paper presents RedeFINE, a centralized routing solution for FMNs that selects high-capacity paths between UAVs and avoids communications disruptions, by defining in advance the forwarding tables and the instants they shall be updated in the UAVs; this represents a major step forward with respect to traditional routing protocols. The performance evaluation of RedeFINE shows promising results, especially regarding Throughput and Packet Delivery Ratio, when compared with state of the art routing solutions.

***Index Terms*—Unmanned Aerial Vehicles, Flying Multi-hop Networks, Centralized routing.**

I. Introduction

In the last years, the usage of Unmanned Aerial Vehicles (UAVs) has become popular in various applications [1]. Some examples are surveillance and reconnaissance, fire-fighting and rescue, remote sensing and exploration, pesticide spraying and geophysical survey, logistics, and payload transport [2]. The advent of small low-cost UAVs has paved the way to the usage of swarms of UAVs. A swarm of UAVs can cooperatively perform missions more effectively and efficiently than standalone UAVs. However, cooperation increases complexity and requires reliable and stable inter-UAV communications for extended range, leading to the concept of Flying Multi-hop Networks (FMNs). FMNs bring up many challenges due to their highly 3-dimensional dynamic behavior, namely concerning network routing. Due to the high mobility of UAVs, frequent changes of network topology and quality of the radio links occur [3]. State of the art routing protocols do not react adequately to these changes; they are unable to avoid frequent path disruptions that interrupt the communications between UAVs.

More recently, UAVs carrying network hardware, including Wi-Fi Access Points and Long-Term Evolution (LTE) cells, have been proposed to form mobile and physically reconfigurable aerial network infrastructures. In [4], the authors propose a solution to provide Internet access and enhance the capacity of existing networks in Temporary Events (TEs), such as music festivals and disaster scenarios. Such scenarios bring up even more significant challenges, in order to permanently provide the Quality of Service (QoS) expected by the users participating in the TEs. Yet, in [4] the authors are focused on solving the problem of positioning the UAVs according to the users' traffic demands. The routing challenges associated with the provisioning of always-on broadband Internet connectivity have not been studied, namely the ability to select high-capacity and uninterruptible paths towards the Internet when the network topology is being reconfigured.

The main contribution of this paper is RedeFINE, a centralized routing solution for FMNs that selects high-capacity paths between UAVs, while simultaneously avoiding communications disruptions. RedeFINE complements the solution presented in [4], allowing to address the requirements of the WISE project [5]. The WISE project aims at developing a novel communications solution based on Flying Mesh Access Points (FMAPs) that position themselves according to the traffic generated by mobile terminals on the ground and relay it towards the Internet. RedeFINE represents a major step forward with respect to traditional routing, where typically nodes recover from link failures after they occur, which implies packet loss, throughput degradation, and longer delays, due to the time wasted updating the forwarding tables. RedeFINE does not use control packets for neighbor discovery and link sensing, which reduces the bandwidth required for control traffic. This is achieved by calculating in advance the forwarding tables and the instants they shall be updated in the UAVs. For that purpose, RedeFINE takes advantage of the holistic knowledge provided by a Central Station (CS), which is also responsible for defining the positions of the UAVs. The performance of RedeFINE is evaluated both theoretically and by means of simulation using network simulator 3 (ns-3). The performance has been evaluated in terms of throughput, Packet Delivery Ratio (PDR), and delays. Results show the RedeFINE superior performance when compared with state of the art solutions.

The rest of the paper is organized as follows. Section II presents the state of the art on routing solutions for FMNs. Section III defines the system model, including the network architecture. Section IV formulates the problem. Section V describes the RedeFINE concept and the routing metric used, and presents an analysis of a reference case. Section VI addresses the performance evaluation of RedeFINE, including the simulation setup, the simulation scenarios, the performance metrics studied, and the simulation results. Section VII discusses the simulation results and the pros and cons of RedeFINE. Finally, Section VIII points out the main conclusions and directions for future work.

II. State of the Art

Existing routing solutions for FMNs are based on the protocols employed in Mobile Ad Hoc Networks (MANETs) and Vehicular Ad Hoc Networks (VANETs). They may be divided into two categories: single-hop routing and multi-hop routing. In what follows, we give special emphasis to multi-hop routing.

In single-hop routing, a static pre-defined routing table is uploaded to the nodes and used to perform the routing decisions. In particular, UAVs load data from ground nodes and carry it to the destination. This routing solution is best suited to transport large amounts of delay-tolerant data. Since fault detection of invalid routes is typically not available, single-hop routing protocols are mainly suitable for networks with fixed topology [3, 6].

In multi-hop routing, the packets are forwarded hop by hop, along paths composed of multiple nodes. Multi-hop routing solutions include topology-based and position-based routing protocols.

Topology-based routing protocols use metrics such as hop-count and the quality of the wireless links to perform the routing decisions; they are classified as proactive, reactive, and hybrid [3]. Proactive protocols aim at maintaining the routing tables of all nodes always up-to-date, so that the routes can be defined in advance, thus reducing the time to forward packets. This is achieved by means of an update mechanism based on the broadcast of HELLO packets, for neighbor discovery, and the flooding of topology control packets for route announcement. However, proactive protocols consume significant radio resources and react slowly to network topology changes; hence, they are not suitable for highly mobile networks, such as FMNs [6, 7]. Conversely, reactive routing protocols follow an on-demand route establishment strategy, which allows to define the routes only when a packet needs to be sent. They aim at overcoming the overhead problem introduced by the proactive routing protocols; the price paid is the latency inherent to the routing discovery process. Therefore, reactive routing protocols are best-suited for highly dynamic networks operating under low traffic load [3, 6]. Finally, hybrid routing protocols are a combination of the proactive and reactive protocols, aiming to overcome the shortcomings of both by reducing the overhead of the proactive protocols and the latency introduced by the reactive routing protocols. Hybrid protocols are especially targeted at large networks, which are divided into a set of zones; intra-zone routing is performed using the proactive approach, while inter-zone routing is done using the reactive approach [3, 6, 8].

Position-based protocols rely on the geographic location of the communications nodes to perform the routing decisions, with the position of the communications nodes obtained using Global Positioning System (GPS) or other positioning mechanism. They aim at addressing the fast network topology changes of highly dynamic networks, which is a drawback of the proactive routing protocols, and accelerating the routing discovery process of the reactive routing protocols. However, position-based protocols are not adequate for sparse networks and have specific hardware requirements to determine the geographical position of the nodes with the best possible accuracy, in short time intervals [3, 6, 8].

The previous solutions rely on the distributed paradigm. However, the functionality of such routing protocols is limited and possible extensions are not straightforward; for example, load-balancing is difficult to implement, despite its usefulness. Therefore, a solution that performs routing decisions based on a holistic and centralized view of the network is worthy to be considered. In this sense, recently, the Software-Defined Networking (SDN) paradigm, which was successfully applied to wired networks, has been proposed for application in wireless networks, giving rise to the concept of Software-Defined Wireless Networking (SDWN). SDWN decouples the control and data planes of the network, taking advantage of a network control unit running on a logically centralized server. This paradigm provides a new layer of flexibility, for instance when it comes to mobility management and routing tasks. Yet, SDWN brings up new limitations, including radio link disruptions that may temporarily interrupt the communications between the network nodes and the SDWN controller, especially in the absence of a dedicated control channel [9]. To improve the robustness of an SDWN-based solution, the use of a redundant distributed routing protocol or a dedicated radio control channel between the network nodes and the SDWN controller have been proposed. However, these solutions follow a break before make approach, leading to the interruption of the communications. In order to overcome the interruptibility problem in UAV networks, a temporospatial component combined with the SDN paradigm is proposed in [10]. This temporospatial concept uses the physical position of the nodes, their trajectory, and the antennas bearing to predict the future state of the underlying network. Based on that, the required network topology changes are scheduled. However, to the best of our knowledge, the performance study of this paradigm has not yet been presented.

III. System Model

The network, hereafter named FMN, adopts a hierarchical architecture composed of three tiers, similarly to the one presented in [4]. We define a tier as a set of UAVs located at the same altitude. This architecture is especially targeted at taking advantage of short range radio links, in the mmWave spectrum, which provide high bandwidth channels. Two types of UAVs compose the FMN, as illustrated in Fig. 1: the Gateway UAV (GW UAV) and FMAPs, which are organized in different tiers, as detailed later.

The FMN is controlled by a CS, not represented in the figure, which is in charge of defining the FMN topology and

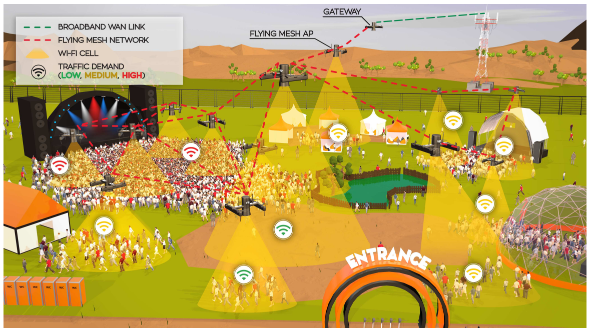


Fig. 1. The FMN deployed in a music festival providing Internet connectivity to the terminals on the ground.

calculating the forwarding tables to be used by the UAVs composing the FMN. The UAVs act as SDN switches. The CS benefits from a holistic knowledge of the network, including the UAVs geographical coordinates.

IV. Problem Formulation

In the following, we formulate the problem addressed in this paper. At a time instant $t_k = k \cdot \Delta t, k \in N_0$ and $\Delta t \in \mathbb{R}$, the FMN is represented by a graph $G(t_k) = (V, E(t_k), w(t_k))$, where V represents the set of UAVs forming the FMN, $E(t_k) \subseteq V \times V$ represents the communications links, and $w(t_k)$ represents the cost assigned to the communications links of G. $(i,j)_{t_k} \in E(t_k)$ represents the directional communications link from i to j available at t_k, where $i,j \in V$, and $w_{i,j}(t_k)$ represents the cost of link $(i,j)_{t_k}$. $X_i(t_k)$ represents the position of UAV i at time t_k and depends on its initial position at instant t_0 and its associated velocity and acceleration vectors defined by the CS that controls the UAV positions. The availability of the wireless links connecting the FMN UAVs changes along the time. The directional wireless communications link $(i,j)_{t_k}$ exists if and only if the power $P_{R_i}(t_k)$ received by UAV i at time t_k divided by the noise power N_i satisfies (1), that is, if the Signal-to-Noise Ratio (SNR) is higher than threshold S. The received power at UAV i, $P_{R_i}(t_k)$, results from the Friis path loss model defined in (2), where $P_{T_j}(t_k)$ describes the power transmitted by UAV j at time t_k, $\lambda_{i,j}$ denotes the link wavelength, and $d_{i,j}(t_k)$ expresses the Euclidean distance between UAV i and UAV j at time t_k.

$$\frac{P_{R_i}(t_k)}{N_i} > S \tag{1}$$

$$\frac{P_{R_i}(t_k)}{P_{T_j}(t_k)} = \left(\frac{\lambda_{i,j}}{4\pi \times d_{i,j}(t_k)}\right)^2 \tag{2}$$

We define a path as a set of adjacent links connecting UAV i to the GW UAV. Multiple paths may be available for UAV i at time t_k, but only one of them is used. We also define $C_{i,j}(t_k)$ as the maximum capacity, in bit/s, of the communications link available between UAV i and UAV j at time t_k, considering a constant value for the link bandwidth $B_{i,j}$ in Hz; Shannon-Hartley theorem is used for this purpose, as given by (3).

$$C_{i,j}(t_k) = B_{i,j} \times \log_2\left(1 + \frac{P_{R_i}(t_k)}{N_i}\right) \tag{3}$$

Considering the throughput $R_i(t_k)$, in bit/s, as the bitrate of the flow from UAV i received at the GW UAV at time t_k, and N UAVs generating traffic towards the GW UAV, we aim at maximizing at any time instant t_k the amount of bits received by the GW UAV during time interval Δt. As such, our objective function can be defined as:

$$\max \sum_{i=0}^{N-1} R_i(t_k) \times \Delta t \tag{4}$$

The factors influencing $R_i(t_k)$ include the capacity of the path used by UAV i, which should be limited by the link in the path having the smallest capacity, the number of flows traversing the links, medium access protocol behaviour, and interference between the communications nodes. This is a complex optimization problem since the last two factors are not easily characterized.

In order to solve this problem we will attempt to find a path for each UAV i for each time instant t_k, so that we meet (4).

V. RedeFINE

RedeFINE is presented in this section, including the concept, the routing metric, and an analysis of a reference case.

A. Concept

RedeFINE was designed to take advantage of the centralized view of the FMN available at the CS. By considering a) the future positions of the FMN UAVs, which are pre-defined by the CS to fulfill the traffic demands of the terminals on the ground, and b) the velocity of the UAVs following a straight line between source and destination, RedeFINE selects periodically the best path for each UAV. We will define the best path as the path which has the smallest cost. In RedeFINE we define the cost of a link $w_{i,j}(t_k) = d_{i,j}(t_k)$, that is, we assume the Euclidean distance as the link cost; a path cost is the sum of the costs of its composing links. As the distance decreases, the capacity of the link (cf. (3)) increases. Using distance as path cost fulfills the objective function defined in (4). RedeFINE assumes a strong Line-of-Sight (LoS) component between the communications nodes, which is characteristic of the communications links between UAVs flying dozens of meters above the ground. To find the shortest path between UAVs, RedeFINE employs the Dijkstra's algorithm [11].

As described, RedeFINE uses the linear Euclidean distance between neighbors as routing metric. An alternative metric would be the logarithmic distance; however, the linear scale has been confirmed to be most suitable to evaluate the effect of distance on the link quality. Fig. 2 depicts the distance variation along the time, in both linear (continuous lines) and logarithmic (dashed lines) scale, between a moving node and two static nodes – node A (without marker) and node B (with marker). In the linear scale each unit of change between both curves is represented by the same distance (cf. left Y-axis).

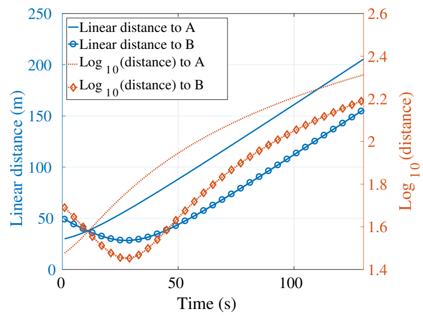


Fig. 2. Distance between a moving node and two static nodes along the time, in linear and logarithmic scale. Linear scale is the most suitable to evaluate distance changes.

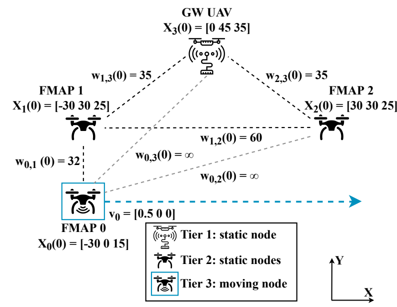


Fig. 3. Scenario used as reference case. For the initial position of FMAP 0, the wireless links between FMAP 0 and both FMAP 2 and GW UAV are not available, due to the SNR threshold constraint.

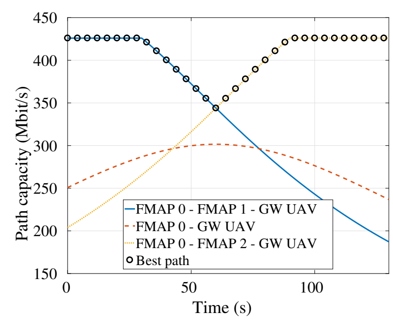


Fig. 4. Theoretical capacity values for the paths between FMAP 0 and the GW UAV. In order to reach the GW UAV, FMAP 0 uses as relay nodes FMAP 1 until $t = 60$ s and FMAP 2 from $t = 60$ s to $t = 130$ s. The path with the highest capacity at each instant is highlighted by the circle symbol.

Conversely, in the logarithmic scale the distance (cf. right Y-axis) is only the same for equal relative changes. Thus, while in the linear scale the difference between, for instance, 100 m and 50 m is the same as the difference between 150 m and 100 m, in the logarithmic scale the difference between these values is not equal. On the other hand, in the logarithmic scale the difference between, for instance, 200 m and 100 m is the same as between 100 m and 50 m. Therefore, the linear scale is preferable to be used as routing metric, in order to characterize the link quality based on the distance.

B. Analysis of a Reference Case

In order to demonstrate the RedeFINE concept and perform a preliminary evaluation, an analysis of a reference case is presented herein. For the sake of simplicity, we consider the scenario depicted in Fig. 3. It is formed by: 1) a GW UAV, at the highest altitude; 2) two relay FMAPs, FMAP 1 and FMAP 2, at the intermediate tier; 3) a moving FMAP, FMAP 0, which is placed at the lowest altitude and is following a straight line at 0.5 m/s in the direction from FMAP 1 to FMAP 2, between $t = 0$ s and $t = 130$ s. The initial position of UAV i is represented by $X_i(0)$ and the constant velocity is denoted by v_i. The initial cost of the wireless link between UAV i and UAV j is represented by $w_{i,j}(0)$, which is the linear Euclidean distance between both UAVs for the initial positions. The wireless link availability is restricted by a 5 dB SNR threshold, that is $S \approx 3.16$ (cf. (1)). The SNR is derived from the Friis propagation model (cf. (2)). We assume that the maximum capacity for the wireless links is given by the Shannon-Hartley theorem (cf. (3)). The maximum capacity of a wireless link is computed considering an average noise power equal to −85 dBm. In turn, the capacity of a path is restricted by the link with lower capacity among the set of links forming the path. Additionally, we consider the transmission power equal to 0 dBm, the carrier frequency equal to 5250 MHz, and the channel bandwidth equal to 160 MHz, which are values compatible with the IEEE 802.11ac standard.

Based on these assumptions, the theoretical maximum capacity values for the paths between FMAP 0 and the GW UAV are plotted in Fig. 4. With RedeFINE, in order to reach the GW UAV, FMAP 0 uses as relay nodes FMAP 1 until $t = 60$ s and FMAP 2 from $t = 60$ s to $t = 130$ s. These are the highest-capacity paths, which are highlighted by the circle symbol in Fig. 4.

Considering as baseline the static routing configuration that uses FMAP 1 as relay node for the communications between FMAP 0 and the GW UAV during 130 s, RedeFINE allows a gain of $\approx 20\%$ regarding the total amount of bits received in the GW UAV. The areas under the curves in Fig. 4 give the total amount of bits carried by the respective path. We compute the amount of information received on each case (static and RedeFINE) as $\sum_{k=0}^{130} R_0(t_k) \times \Delta t$, considering $\Delta t = 1$ s. In this analysis, FMAP 1 and FMAP 2 do not generate traffic; they only forward traffic received from FMAP 0.

VI. Performance Evaluation

The methodology followed for the performance evaluation of RedeFINE is presented in this section, including the simulation setup, the simulation scenarios, and the performance metrics.

A. Simulation Setup

In order to evaluate the performance of RedeFINE in more complex networking scenarios, the ns-3 simulator was used. The FMN consisted of 1 GW UAV in the first tier, 16 FMAPs in the second tier, and 4 FMAPs in the third tier generating traffic, respectively in descending order of altitude. The FMAPs in the third tier were moving according to the

TABLE I
SUMMARY OF THE NS-3 SIMULATION PARAMETERS.

Simulation time	(30 s initialization +) 130 s
Wi-Fi standard	IEEE 802.11ac
Channel	50 (5250 MHz)
Channel bandwidth	160 MHz
Guard Interval	800 ns
TX power	0 dBm
Propagation delay model	Constant speed
Propagation loss model	Friis path loss
Remote station manager	IdealWifiManager
Wi-Fi mode	Ad Hoc
Mobility model	Constant velocity
Third tier's FMAPs speed	0.5 m/s
Traffic type	UDP Poisson
Packet size	1400 bytes

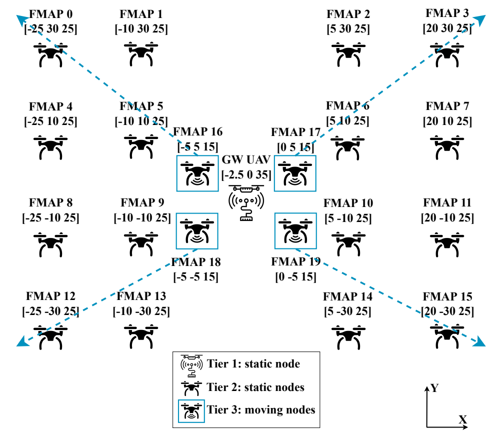
ConstantVelocityMobilityModel at 0.5 m/s during 130 s. The GW UAV and the FMAPs in the second tier are static. A Network Interface Card (NIC) on each UAV was configured in Ad Hoc mode, using the IEEE 802.11ac standard in channel 50, with 160 MHz channel bandwidth, and 800 ns Guard Interval. The wireless links between UAVs are modeled by Friis path loss; only links with SNR above 5 dB were considered as usable. The transmission power of the NICs was set to 0 dBm and the UAVs positions were defined in order to guarantee, at least, $\approx 15\,\mathrm{dB}$ of SNR for the links between neighbors in their initial positions.

One spatial stream was used for all inter-UAV IEEE 802.11ac links. With 1 spatial stream, the data rate corresponding to the maximum Modulation and Coding Scheme (MCS) index is 780 Mbit/s. Since the FMN is organized in three tiers, the GW UAV and the 4 FMAPs in the third tier are 2 hops away; this results in $\frac{\frac{780}{4}}{2} = 97.5\,\mathrm{Mbit/s}$ for the maximum achievable data rate per flow. Based on that, the maximum offered load for each scenario was set to: $\lambda_1 = 0.25 \times 97.5 \approx 24\,\mathrm{Mbit/s}$, and $\lambda_2 = 0.75 \times 97.5 \approx 73\,\mathrm{Mbit/s}$. The traffic generated was UDP, for a constant packet size of 1400 bytes with arrival process modeled as Poisson. The IEEE 802.11ac data rate was automatically defined by the *IdealWifiManager* mechanism. The traffic generation and the FMAPs movement were only triggered after 30 s of simulation, in order to ensure a stable state.

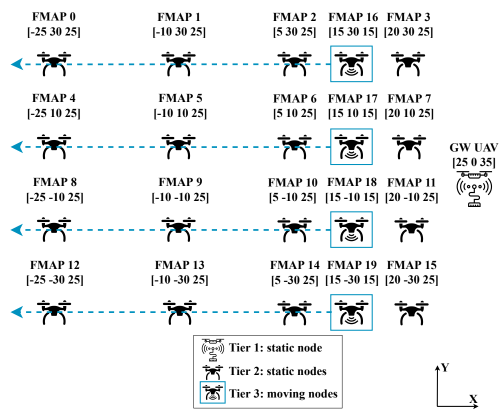
A summary of the ns-3 simulation parameters considered is presented in Table I.

B. Simulation Scenarios

Two simulation scenarios were defined to evaluate the performance of RedeFINE in typical crowded events (e.g., music festivals). Scenario A (cf. Fig. 5a) considered the movement away from a central point, in order to reproduce the dispersion of people from a central point to different points of interest in the event. Scenario B (cf. Fig. 5b) considered a linear movement along the event venue, in order to exemplify the movement of people between two stages.



(a) Scenario A: movement away from a central point.



(b) Scenario B: linear movement along the event venue.

Fig. 5. Simulation scenarios considered for the RedeFINE evaluation.

C. Performance Metrics

RedeFINE was evaluated in simulation environment against two state of the art distributed routing protocols representative of the reactive and proactive routing paradigms – Ad Hoc On-Demand Distance Vector (AODV) and Optimized Link State Routing Protocol (OLSR), respectively – and static routing, for which the forwarding tables are maintained throughout the whole simulation time.

Since the default implementations of AODV and OLSR in the latest release of ns-3 do not employ a link quality-based routing metric, we used alternative implementations for both protocols, publicly available in [12] and [13], respectively. They use the Expected Transmission Count (ETX) [14]. This enables a fair comparison with RedeFINE. ETX represents the predicted number of transmissions required to send a packet over a link, including retransmissions.

The performance evaluation of RedeFINE considers three performance metrics:

- **Aggregate throughput –** The average number of bits received per second by the GW UAV.
- **Packet Delivery Ratio (PDR) –** The number of packets received by the GW UAV divided by the number of packets generated by the FMAPs, measured at each

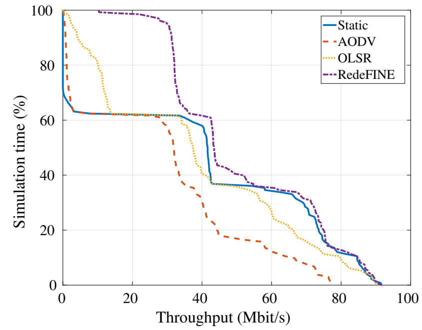
second.

- **End-to-end delay –** Time taken by the packets to reach the application layer of the GW UAV since the instant they were generated, measured at each second; it includes queuing, transmission, and propagation delays.

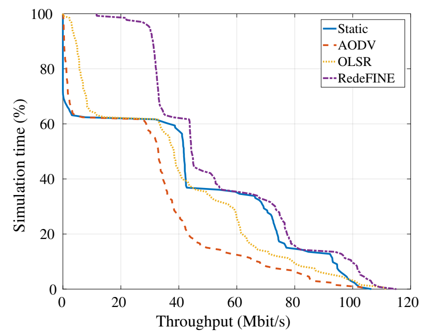
D. Simulation Results

The simulation results obtained for both scenarios are presented in this sub-section. The results were obtained considering 20 simulation runs for each scenario using different seeds. The results are expressed by means of the Cumulative Distribution Function (CDF) for the mean end-to-end delay, and by the Complementary CDF (CCDF) for the aggregate throughput and PDR. The CDF $F(x)$ represents the percentage of simulation time for which the mean end-to-end delay was lower or equal to x, whereas the CCDF $F'(x)$ represents the percentage of simulation time for which the mean aggregate throughput or PDR was higher than x. The mean aggregate throughput measured in the GW UAV versus the simulation time is also presented.

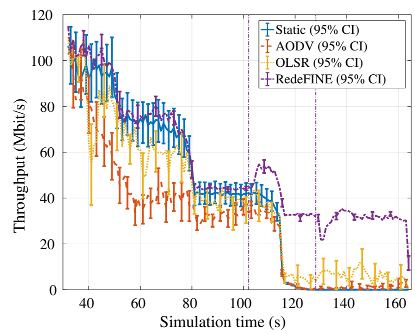
The CCDF representations for the aggregate throughput in the GW UAV (cf. Fig. 6 and Fig. 9), considering different packet generation rates, show that RedeFINE allows higher throughput than its state of the art counterparts. RedeFINE overcomes the state of the art solutions mainly in the last stage of the FMAPs movement; the static route to the GW UAV becomes unusable, while AODV and OLSR switch in short time periods between different relay nodes, which decreases the throughput substantially, as depicted in Fig. 6c and Fig. 9c. RedeFINE enables throughput higher than 10 Mbit/s for the whole simulation time, which demonstrates its superior performance. This is due to the selection of stable paths with minimal length, formed by links with high SNR, high capacity, and low delay. The area under the CCDF curves for the aggregate throughput gives the total of bits received in the GW UAV. For Scenario A, we conclude that RedeFINE increases the number of bits received up to 27%, 47%, and 31% respectively with respect to static routing, AODV, and OLSR. For Scenario B, RedeFINE increases the number of bits received up to 37%, 54%, and 46%, respectively. The CCDF plots for PDR follow the same pattern as the CCDF for the aggregate throughput. Overall, the PDR in Scenario A (cf. Fig. 7) is higher than in Scenario B (cf. Fig. 10). This is justified by the links with higher capacity in Scenario A, due to the lower distances between the FMAPs and the GW UAV. Nevertheless, RedeFINE allows higher PDR than static routing, AODV, and OLSR for both scenarios. Regarding the end-to-end delay, RedeFINE does not achieve the minimum values that its state of the art counterparts do, as depicted in Fig. 8 and Fig. 11. However, this is justified by the higher PDR achieved by RedeFINE. While for static routing, AODV, and OLSR more packets are dropped, with RedeFINE the network is subject to a higher level of congestion; hence, packets are held in the transmission queue longer.



(a) Throughput CCDF for λ=24 Mbit/s.



(b) Throughput CCDF for λ=73 Mbit/s.

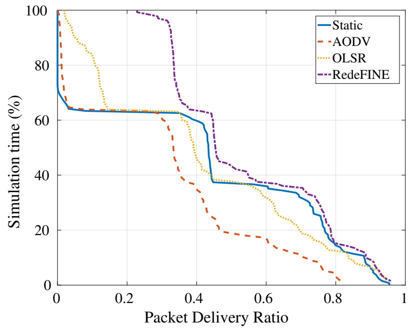


(c) Throughput versus simulation time for λ=73 Mbit/s. The vertical lines represent the path change events defined by RedeFINE.

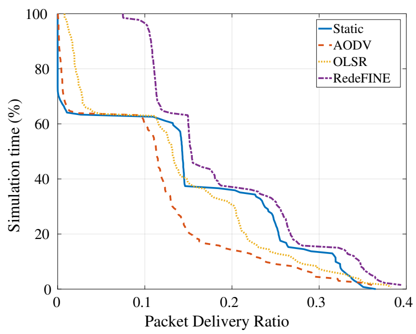
Fig. 6. Scenario A: throughput results.

VII. Discussion

The simulation results show that RedeFINE allows improving the performance of an FMN, especially regarding aggregate throughput and PDR. RedeFINE outperforms AODV and OLSR, even when they use the link quality-based metric ETX. These results are due to the selection of stable paths with minimal length, formed by links with high SNR, and consequently with high capacity and low delay. We believe the results will be even better for scenarios where UAVs move at higher speeds. In those scenarios we argue that the distributed routing protocols will not be able to update the routing tables frequently enough to properly react to the topology changes.



(a) PDR CCDF for λ=24 Mbit/s.



(b) PDR CCDF for λ=73 Mbit/s.

Fig. 7. Scenario A: PDR results.

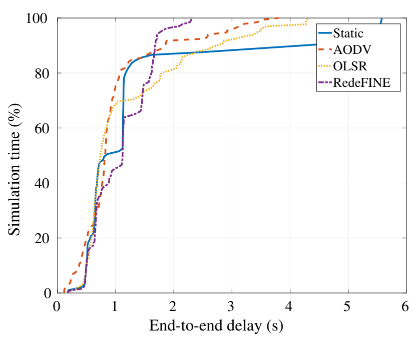
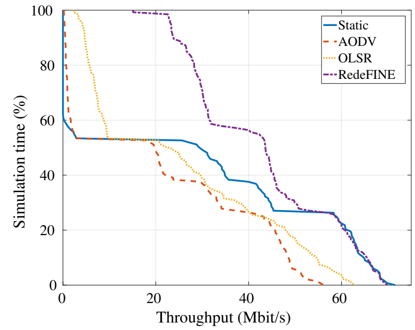
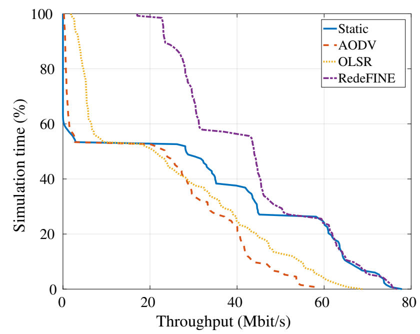


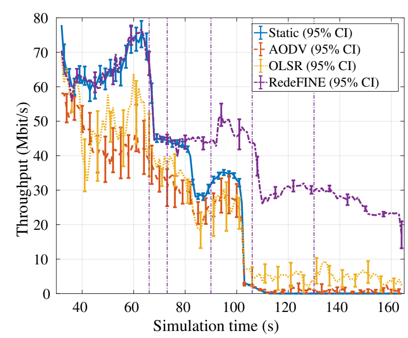
Fig. 8. Scenario A: end-to-end delay CDF for λ=73 Mbit/s.



(a) Throughput CCDF for λ=24 Mbit/s.



(b) Throughput CCDF for λ=73 Mbit/s.

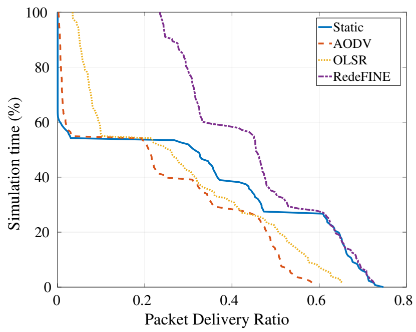


(c) Throughput versus simulation time for λ=73 Mbit/s. The vertical lines represent the path change events defined by RedeFINE.

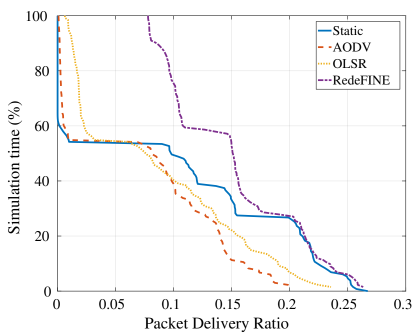
Fig. 9. Scenario B: throughput results.

In its current version, RedeFINE is not suitable for highly dense networks, where the relay nodes can be forwarding traffic from multiple sources, since the load of the nodes is not taken into account. This is an aspect left for future work, where we will take advantage of the information provided by the CS.

The main idea behind RedeFINE is the ability to know in advance the future state of the FMN, based on the topology designed by the CS. In order to achieve similar results using a distributed routing protocol, an option would be to reduce the interval between HELLO packets, so that the routing tables could be updated frequently enough to support high mobility scenarios. However, the price paid would be the reduction of the bandwidth available for data traffic. RedeFINE does not use control packets for neighbor discovery and link sensing, and the routing tables are computed centrally, allowing to reduce the computational power on board of the UAVs; control traffic only consists of the routing tables sent from the CS to the UAVs. Nevertheless, the overhead of the control protocol must be studied in the future, in order to define the optimal periodicity to send the routing tables from the CS to the UAVs; it must guarantee the synchronism of the whole system, but simultaneously weighing the bandwidth wasted. Additionally, RedeFINE must be concerned with the stability of the system, avoiding to change the routing tables on the same UAV in



(a) PDR CCDF for λ=24 Mbit/s.



(b) PDR CCDF for λ=73 Mbit/s.

Fig. 10. Scenario B: PDR results.

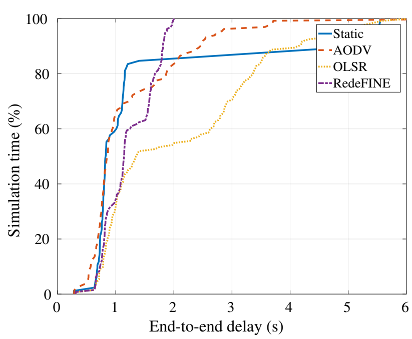


Fig. 11. Scenario B: end-to-end delay CDF for λ=73 Mbit/s.

short time intervals, mainly when no significant gains are anticipated. These aspects will be studied as part of future work, in order to pave the way to deploy RedeFINE in a real system.

VIII. Conclusions

We presented RedeFINE, a centralized routing solution for FMNs enabling high-capacity and uninterruptible communications. RedeFINE takes advantage of the holistic knowledge provided by a CS to predict the future state of the network, in order to perform the routing decisions in advance. Based on an analysis of a reference case and on simulation results for two representative scenarios, we demonstrated the superior performance of RedeFINE when compared to static routing, AODV, and OLSR, regarding throughput and PDR. The results showed gains up to 54%. Regarding end-to-end delay, RedeFINE did not achieve the values obtained for its state of the art counterparts; however, the longer end-to-end delay is justified by the higher PDR of RedeFINE, which increases network congestion and the time packets are held in the transmission queue. As future work, we will evaluate the performance of RedeFINE in other scenarios, considering UAVs moving at higher speeds. Additionally, RedeFINE will be improved in order to take into account the network load of the relay nodes, the overhead of the control protocol, and the stability of the whole system.

Acknowledgments

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