Traffic-aware Gateway Placement for High-capacity Flying Networks

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Abstract—The ability to operate virtually anywhere and carry payload, make Unmanned Aerial Vehicles (UAVs) perfect platforms to carry communications nodes, including Wi-Fi Access Points (APs) and cellular Base Stations (BSs). This is paving the way to the deployment of Flying Networks (FNs) that enable communications to ground users anywhere, anytime. Still, FNs impose significant challenges in order to meet the Quality of Experience expectations. State of the art works addressed these challenges, but have been focused on routing and the placement of the UAVs as APs and BSs serving the users on the ground, overlooking the backhaul network design. The main contribution of this paper is a centralized traffic-aware Gateway UAV Placement (GWP) algorithm for FNs with controlled topology. GWP takes advantage of the knowledge of the offered traffic and the future topologies of the FN to enable backhaul communications paths with high enough capacity. The performance achieved using the GWP algorithm is evaluated using ns-3 simulations. The obtained results demonstrate significant gains regarding aggregate throughput and end-to-end delay.

Index Terms—Unmanned Aerial Vehicles, Flying Networks, Aerial Networks, Gateway Placement, Relay Placement.

I. INTRODUCTION

In the recent years the usage of Unmanned Aerial Vehicles (UAVs) has emerged to provide communications in areas without network infrastructure and to enhance the capacity of existing networks in temporary crowded events [1], [2]. The ability to operate virtually anywhere, as well as their hovering, mobility, and on-board payload capabilities make UAVs perfect platforms to carry communications nodes, including Wi-Fi Access Points (APs) and cellular Base Stations (BSs) [3]. This is paving the way to the deployment of Flying Networks (FNs) that enable communications to ground users anywhere, anytime. A reference example is the WISE project [4], which proposes a novel communications solution based on Flying Mesh Access Points (FMAPs) that position themselves according to the traffic demand of the users on the ground, as depicted in Fig. 1.

Still, FNs impose significant routing challenges. Firstly, radio link disruptions may occur, due to the high-mobility of UAVs, especially when the FN’s topology is being reconfigured. On the other hand, there is inter-flow interference between neighboring UAVs that need to be close to each other to establish high capacity air-air radio links and meet the traffic demand of the users in crowded scenarios. The first problem was addressed in [5], where we have proposed RedeFINE, a centralized routing solution that defines in advance the forwarding tables and the instants they shall be updated in the UAVs, enabling uninterruptible communications. The second problem was tackled in [6], where we proposed a novel routing metric, named I2R, which enables the definition of paths that minimize the inter-flow interference in the FN.

When it comes to the UAV placement problem, state of the art works have been focused on the UAVs acting as APs and BSs according to the users’ traffic demand [1], [2]. Even though users are directly affected by the Quality of Service (QoS) and Quality of Experience (QoE) provided by the Radio Access Network (RAN), the backhaul network, including the gateway (GW) placement, needs to be carefully designed in order to meet the variable traffic demand of the RAN. This aspect has been overlooked in the state of the art.

The main contribution of this paper is a centralized traffic-aware GW UAV Placement (GWP) algorithm for FNs with controlled topology. GWP takes advantage of both the knowledge of the offered traffic and the future topologies of the FN to enable backhaul communications paths with high enough capacity, and accommodate the traffic demand from the ground users. The performance achieved using GWP was evaluated using ns-3, allowing to demonstrate significant gains regarding aggregate throughput and end-to-end delay.

The rest of the paper is organized as follows. Section II presents the state of the art on GW placement approaches in wireless networks in general. Section III defines the system model. Section IV formulates the problem. Section V presents the GWP algorithm, including its rationale and a numerical analysis for a simple scenario. Section VI addresses the performance evaluation, including the simulation setup,
the simulation scenarios, the performance metrics, and the simulation results. Finally, Section [VII] points out the main conclusions and directions for future work.

II. STATE OF THE ART

In the literature, GW placement in wireless networks is a common problem. Over the years, different studies have been carried out [7, 8, 9, 10, 11]. However, the majority of them aim at minimizing the number of GWs while optimizing their placement, in order to meet some QoS metrics, including throughput and delay, and reducing the energy consumption. In [12], the authors show how the GW placement and the transmission power have a significant impact on the network throughput. For that purpose, they evaluate the performance of different heuristic methods. However, they do not consider the communications nodes’ traffic demand. Similarly, the work presented in [13] aims at determining the optimal placement for an Evolved Packet Core (EPC), amongst a set of BSs in a self-deployed cellular network. Nevertheless, they do not have control over the mobility of the EPC and assume that the communications nodes have the same traffic demand. In [14], the authors show how the placement of a UAV performing the role of network relay between two ground nodes affects the communications’ performance; however, they do not take into account the traffic demand of the ground nodes.

An analogy between the GW placement and the sink placement in the context of Wireless Sensor Networks (WSNs) can be made, since both are in charge of receiving all the traffic generated within a network. In [15], the authors describe different sink placement approaches and explore their advantages and disadvantages. However, in WSNs the traffic demand is significantly lower and it is not generated continuously over time. In addition, the sink placement in this type of networks aims at minimizing the energy consumption or the end-to-end delay, and increase the network lifetime, rather than enabling high-capacity paths, which is a key-requirement in FNs providing Internet access.

Overall, state of the art works have been focused on routing and the placement of the UAVs as APs and BSs serving the users on the ground, overlooking the backhaul network design. Even though users are directly affected by the QoS and QoE provided by the RAN, the backhaul network, including the GW placement, needs to be carefully designed in order to meet the variable traffic demand of the RAN. This paper introduces a differentiating factor since it aims at defining the position of a flying GW taking advantage of the controlled mobility over the communications nodes being served.

III. SYSTEM MODEL

The network, hereafter named FN, consists of N UAVs that are controlled by a CS. Two types of UAVs are assumed to compose the network, as depicted in Fig. [1] 1) FMAPs, which provide Internet access to users on the ground and forward traffic; 2) a GW UAV, which connects the FN to the Internet. The CS, which is not represented in Fig. [1] can be deployed anywhere on the Internet. The CS is in charge of 1) defining the positions of the FMAPs by running the NetPlan algorithm [1], so that the FMAPs meet the traffic demand of the users on the ground, 2) calculating the forwarding tables to be used by the FMAPs, by running RedeFINE [3], and 3) determining the GW UAV placement, in order to enable links that accommodate the FMAPs’ traffic demand. The CS benefits from a holistic view of the network, including the FMAPs’ geographical coordinates and their traffic demand, which are provided by the NetPlan algorithm. This information is used to calculate the forwarding tables and the position of the GW UAV.

IV. PROBLEM FORMULATION

In the following, we formulate the problem addressed in this paper. At time $t_k = k \cdot \Delta t, k \in N_0$ and $\Delta t \in \mathbb{R}$, the FN is represented by a directed graph $G(t_k) = (V, E(t_k))$, where $V = \{0, ..., N - 1\}$ is the set of UAVs $i$ positioned at $P_i = (x_i, y_i, z_i)$, $E(t_k) \subseteq V \times V$ is the set of directional links between UAVs $i$ and $j$ at $t_k$, $i, j \in V$, and $(i, j) \in E(t_k)$. The wireless channel between two UAVs is modeled by the Free-space path loss model, since a strong Line of Sight (LoS) component dominates the links between UAVs flying dozens of meters above the ground. We define $C_{i,j}(t_k)$ as the capacity, in bit/s, of the wireless channel available from $UAV_i$ to $UAV_j$ at time $t_k$, considering a constant channel bandwidth $B$ in Hz. The Shannon-Hartley theorem is used for this purpose, as given by (1), where $P_{R_{i,j}(t_k)}$ is the average power received at $UAV_i$ transmitted from $UAV_j$ at $t_k$ and $N_i$ is the noise floor power at $UAV_i$, which is assumed to be constant.

$$C_{i,j}(t_k) = B \times \log_2 \left(1 + \frac{P_{R_{i,j}(t_k)}}{N_i}\right)$$  

Let us assume that $UAV_i, i \in \{1, ..., N - 1\}$, performs the role of FMAP and transmits a traffic flow of bitrate $T_i(t_k)$ bit/s during time slot $t_k$ towards $UAV_0$ which performs the role of GW UAV. In this case, we have a tree $T(V, E_T)$ that is a subgraph of $G$, where $E_T \subset E$ is the set of direct links between $UAV_i$ and $UAV_0$. This tree defines the FN active topology. The flow $F_{0,i}$ is received at $UAV_0$ from $UAV_i$ with bitrate $R_{i}(t_k)$ bit/s. The wireless medium is shared and we assume that every $UAV_i$ can listen to any other $UAV_j$, including $UAV_0$. The Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism is employed for Medium Access Control (MAC).

Considering the throughput $R_i(t_k)$ as the bitrate of the flow $F_{0,i}$ at time $t_k$, and $N - 1$ UAVs generating traffic towards $UAV_0$, we aim at determining at any time instant $t_k$ the position of $UAV_0$, $P_0 = (x_0, y_0, z_0)$, and the transmission power of the UAVs, $P_T$, such that the aggregate throughput, $R(t_k) = \sum_{i=1}^{N-1} R_i(t_k)$ is maximized. Our objective function
is defined in (2a).

\[
\begin{align*}
\text{maximize} & \quad R(t_k) = \sum_{i=1}^{N-1} R_i(t_k) \\
\text{subject to:} & \quad (0, i), (i, 0) \in E(t_k), i \in \{1, \ldots, N-1\} \\
& \quad T_i(k) > 0, i \in \{1, \ldots, N-1\} \\
& \quad z_i \geq 0, i \in \{0, \ldots, N-1\} \\
& \quad (x_0, y_0, z_0) \neq (x_i, y_i, z_i), i \in \{1, \ldots, N-1\}
\end{align*}
\]

V. TRAFFIC-AWARE GATEWAY UAV PLACEMENT ALGORITHM

The traffic-aware Gateway UAV Placement (GWP) algorithm is presented in this section, including its rationale and a numerical analysis for a simple scenario.

A. Rationale

The GWP algorithm takes advantage of the centralized view of the FN available at the CS. For the sake of simplicity we omit \( t_k \) in what follows. Considering the future positions of \( UAV_i \) and the bitrate of the traffic flow \( F_{0,i}, T_i \), we aim at guaranteeing that a wireless link towards \( UAV_0 \) (GW UAV) has a minimum SNR, \( SNR_i \), which enables the usage of a Modulation and Coding Scheme (MCS) index, \( MCS_i \), capable of transmitting \( T_i \) bit/s. Conceptually, if \( MCS_i \) is ensured by the network, then \( R_i \approx T_i \) and \( R_i \) is maximized; this is according to the objective function defined in (2a).

The minimum \( SNR_i \) required for using \( MCS_i \) imposes a minimum received power \( P_{R_{0,i}} \). Then, if the transmission power \( P_{T_i} \) is known, we can calculate the maximum distance \( d_{max,i} \), between \( UAV_i \) and \( UAV_0 \), using the Free-space path loss model defined in (3).

\[
P_{R_{0,i}} = \left( \frac{c}{4 \pi d_{max,i} f_i} \right)^2
\]

In the three-Dimensional (3D) space, \( d_{max,i} \) corresponds to the radius of a sphere, centered at \( UAV_i \), inside which \( UAV_0 \) should be placed. Considering \( N - 1 \) UAVs, the placement subspace for positioning \( UAV_0 \) is defined by the intersection of the corresponding spheres \( i \in \{1, \ldots, N-1\} \); we refer to this subspace as the Gateway Placement Subspace, \( S_G \), as depicted in Fig. 2. In order to simplify the process of calculating \( S_G \), we follow Algorithm A, which iteratively enables us to obtain the point \( P_0 = (x_0, y_0, z_0) \) for positioning \( UAV_0 \) and the transmission power \( P_T \) which we assume to be the same for all UAVs.

The GWP algorithm provides the same output whether downlink or uplink traffic is considered, since all the UAVs are configured with the same transmission power and the wireless channel is assumed to be symmetric. This paves the way to the usage of the GWP algorithm in emerging networking scenarios where symmetric traffic applications are growing [16], such as social networks, video streaming, and online gaming.

Algorithm A – GWP Algorithm

1: \( P_T = 0 \) \( \triangleright \) 0 dBm TX power
2: while true do
3: \( P_T = P_T; \quad i \in \{1, \ldots, N-1\} \) \( \triangleright \) Same UAVs’ TX power
4: \( \text{Calculate } (x_0, y_0, z_0) \) \( \triangleright \) System of equations (1)
5: if \( (x_0, y_0, z_0) \neq (x_i, y_i, z_i) \) then
6: return \( P_T = (x_0, y_0, z_0) \) \( \triangleright \) TX power, GW UAV pos.
7: else
8: \( P_T = P_T + 1 \) \( \triangleright \) Increase TX power by 1 dBm
9: end if
10: end while

Fig. 2. Gateway Placement Subspace \((S_G)\) in a two-Dimensional (2D) space, which results from the intersection of the spheres, centered at each UAV, with radius equal to the maximum distance compliant with the minimum SNR.

B. Numerical Analysis for a Simple Scenario

Without loss of generality, we now exemplify the execution of Algorithm A for the simple scenario shown in Fig. 2; the algorithm is generic and may be applied to any traffic demand and number of FMAPs. The scenario of Fig. 2 is composed of two FMAPs, each with a traffic demand equal to 25% of the UAV’s fair share of the wireless channel capacity, and two FMAPs, each with a traffic demand equal to 75% of the UAV’s fair share of the wireless channel capacity. The FMAPs are placed within a square of 30 m sideways, hovering at 10 m altitude. The capacity of the shared wireless medium is assumed to be equal to the maximum MCS index of the IEEE 802.11ac technology, which is 780 Mbit/s, considering one spatial stream, 800 ns Guard Interval (GI), and 160 MHz channel bandwidth (channel 50 at 5250 MHz). Since the wireless medium is shared by four FMAPs generating traffic, and assuming a single hop between the FMAPs and the GW UAV \((UAV_0)\), this results in a fair share \( L = \frac{780}{4} = 195 \) Mbit/s for the capacity of the wireless channel between each \( UAV_i, i \in \{1, 2, 3, 4\} \), and \( UAV_0 \). Accordingly, the FMAPs on the left-side of Fig. 2 transmit at bitrate \( T_1 = T_2 = 0.25 \times 195 \approx 49 \) Mbit/s, and the right-side FMAPs transmit at bitrate \( T_3 = T_4 = 0.75 \times 195 \approx 146 \) Mbit/s.

Taking into account the mapping between SNR, theoretical data rate of the IEEE 802.11ac MCS indexes, and the link capacity for 4 FMAPs sharing the transmission time, from Table 1 we conclude that the target SNR values in dB, considering a −85 dBm noise floor power, are respectively 20 dB.
TABLE I
EXTRACT OF THE MAPPING BETWEEN SNR, DATA RATE OF THE IEEE 802.11AC MCS INDEXES, AND THE LINK CAPACITY VALUES FOR 4 FMAPS SHARING THE TRANSMISSION TIME [18].

| SNR (dB) | MCS data rate (Mbit/s) | Link capacity (Mbit/s) |
|----------|------------------------|------------------------|
| 12       | 58.5                   | $\frac{58.5}{4} \approx 15$ |
| 20       | 234                    | 58                     |
| 25       | 702                    | 176                    |
| 37       | 780                    | 195                    |

for the left-side FMAPs and 35 dB for the right-side FMAPs. Solving the system of equations (4), which is derived from (1) and (3) in logarithmic scale, we conclude that an optimal placement for the GW UAV is $(x_0, y_0, z_0) \approx (23.3, 15.4, 3.3)$ for a transmission power $P_T = 22$ dBm. Note that $P_T$ is the fine tuning parameter in the system of equations (4), so that we can find at least a point $(x_0, y_0, z_0) \in S_G$; otherwise, we may have a system of equations without solution. $P_T$ is initially set to 0 dBm; then, it is iteratively increased by 1 dBm until a valid solution for the GW UAV position is found.

In the GWP algorithm we assume that the efficiency of the MAC is $\approx 1$ and the overhead of the User Datagram Protocol (UDP), Internet Protocol (IP), and MAC packet headers is negligible; this is compliant with emerging wireless communications technologies, such as IEEE 802.11ax, where Orthogonal Frequency-Division Multiple Access (OFDMA) and frame aggregation mechanisms improve the MAC efficiency [17].

\[
\begin{align*}
(x_0 - 30)^2 + y_0^2 + (z_0 - 10)^2 &\leq 10^{(K + P_T - 25)/20}^2 \\
(x_0 - 30)^2 + (y_0 - 30)^2 + (z_0 - 10)^2 &\leq 10^{(K + P_T - 35)/20}^2 \\
x_0^2 + (y_0 - 30)^2 + (z_0 - 10)^2 &\leq 10^{(K + P_T - 20)/20}^2 \\
x_0^2 + y_0^2 + (z_0 - 10)^2 &\leq 10^{(K + P_T - 29)/20}^2 \\
K &= -20\log_{10} \left( \frac{4\pi}{3 \times 10^8} \right) - 20\log_{10}(5250 \times 10^6) - (-85) \tag{4}
\end{align*}
\]

VI. PERFORMANCE EVALUATION

The FN performance achieved using the GWP algorithm is presented in this section, including the simulation setup, the simulation scenarios, and the performance metrics considered.

A. Simulation Setup

In order to evaluate the FN performance achieved with the GWP algorithm, the ns-3 simulator was used. A Network Interface Card (NIC) was configured on each UAV in Ad Hoc mode, using the IEEE 802.11ac standard in channel 50, with 160 MHz channel bandwidth, and 800 ns Guard Interval. One spatial stream was used for all inter-UAV links. The traffic generated was UDP Poisson for a constant packet size of 1400 bytes. The data rate was automatically defined by the IdealWifiManager mechanism. The traffic generation was only triggered after 30 s of simulation, in order to ensure a stable state, with a total simulation time of 130 s. The Controlled Delay (CoDeL) algorithm [19], which is a Linux-based queuing discipline that considers the time that packets are held in the transmission queue to discard packets, was used; it allows to mitigate the bufferbloat problem. The default parameters of CoDeL in ns-3 were employed [20].

B. Simulation Scenarios

In addition to the optimal GW UAV position, which was obtained using the GWP algorithm, other positions for the GW UAV in the venue depicted in Fig. 2 were evaluated, in order to show the performance gains obtained when using the GWP algorithm; the seven additional positions considered are depicted in Fig. 3 and hereinafter referred to as Scenario A. Position 1 to position 7 were defined to allow an inter-position distance of 7.5 m; they aimed at exploring the vertical and horizontal corridors of the venue. We define as baseline the GW UAV placed in the FMAPs center (i.e., three-coordinates average considering all FMAPs). Position 8 represents the optimal GW UAV placement, which was derived from (4).

In order to evaluate the performance achieved when using the GWP algorithm in a typical crowded event, a more complex scenario, depicted in Fig. 4 and hereafter named Scenario B, was also considered. It represents an FN composed of 10 FMAPs and 1 GW UAV within a box of dimensions 80 m × 80 m × 20 m. The FMAPs were randomly positioned in order to form two zones with different traffic demand, $\lambda_1$ and $\lambda_2$ bit/s, as illustrated in Fig. 4. Since the GWP algorithm relies on knowing in advance the positions of the FMAPs, provided by the NetPlan algorithm in a real-world deployment, instead of generating the random waypoints during the ns-3 simulation we used BonnMotion [21], which is a mobility scenario generation tool. These waypoints were considered to calculate in advance the forwarding tables and the optimal GW UAV position using the GWP algorithm. We considered as baseline the GW UAV placed in the FMAPs center. Finally, the forwarding tables and the GW UAV position along the time, as well as the generated scenarios, were imported to ns-3, with a sampling period of 1 s. The WaypointMobilityModel model of ns-3, which places the UAVs in the positions generated by BonnMotion, was used. Two different traffic demand combinations were considered: a) $\lambda_1 = 0.1 \times L$ and $\lambda_2 = 0.9 \times L$; and b) $\lambda_1 = 0.25 \times L$ and $\lambda_2 = 0.75 \times L$, where $L$ is the capacity of the wireless medium divided by the number of FMAPs.

C. Performance metrics

The performance achieved with the GWP algorithm was evaluated considering two metrics:

- **Aggregate throughput (R)**: The mean number of bits received per second by the GW UAV.
- **End-to-end delay**: The mean time taken by the packets to reach the application layer of the GW UAV since the instant they were generated by the FMAPs, including queuing, transmission, and propagation delays.
D. Simulation results

The simulation results are presented in this section. The results were obtained after 20 simulation runs for each traffic demand combinations that were considered (cf. Section VI-B), under the same networking conditions, using RingSeed = 10 and RingRun = \{1, ..., 20\}. The results are expressed using mean values and they are represented using the Cumulative Distribution Function (CDF) for the end-to-end delay and by the complementary CDF (CCDF) for the aggregate throughput.

The CCDF \( F'(x) \) represents the percentage of time for which the mean aggregate throughput was higher than \( x \), while the CDF \( F(x) \) represents the percentage of time for which the mean end-to-end delay was lower or equal to \( x \).

Regarding Scenario A, when the GW UAV is placed in the optimal position (Position 8 in Fig. 3), the aggregate throughput is improved 24% for the 90th percentile and 21% for the 50th percentile (median), with respect to the baseline (i.e., the GW UAV placed in the FMAPs center). In parallel, the end-to-end delay is decreased 26% for respectively the 90th and 50th percentiles (cf. Fig. 5). The similar results obtained for Position 2 and Position 8, which are depicted in Fig. 5, are justified by the closer distance between these positions; note that Position 2 was obtained by chance, while Position 8 resulted from the GWP algorithm. In order to meet the higher traffic demand of the right-side FMAPs, the GWP algorithm places the GW UAV closer to them, in order to improve the SNR of the communications links and enable the selection of higher MCS indexes. This improves the overall FN performance and the shared medium usage – the packets are held in the transmission queues for shorter time, the transmission delay is decreased, and the throughput is increased.

With respect to Scenario B, when \( \lambda_1 \) and \( \lambda_2 \) are respectively equal to 10% and 90% of the channel capacity, the GWP algorithm allows to improve the aggregate throughput up to 27%, considering the 90th and 50th percentiles, while the end-to-end delay is reduced up to 4% (cf. Fig. 6). When \( \lambda_1 \) and \( \lambda_2 \) are respectively equal to 25% and 75% of the channel capacity, the GWP algorithm also improves the aggregate throughput in 18% with respect to the 90th percentile and 19% for the 50th percentile; the end-to-end delay is reduced 12% for the 90th percentile and 8% for the 50th percentile (cf. Fig. 7). These results validate the effectiveness of the GWP algorithm and corroborate our research hypothesis: the FN performance can be improved by dynamically adjusting the position of the GW UAV, considering both the positions and the offered traffic of the FMAPs.

VII. Conclusions

This paper proposes GWP, a traffic-aware GW UAV placement algorithm for FNs with controlled topology. It takes advantage of the knowledge of the offered traffic and the future topologies of the FN to enable communications paths with
high enough capacity. The FN performance using the GWP algorithm was evaluated using ns-3 simulations. The obtained results demonstrate gains up to 27% in aggregate throughput, while the end-to-end delay is reduced up to 26%.

As future work, we aim at exploring the traffic-aware placement approach proposed in this paper in a more complex FN composed of multiple GW UAVs and UAV relays, which are used to forward the traffic from a RAN to the Internet.

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