Energy Efficient Resource Allocation in UAV-based Heterogeneous Networks

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***Abstract*—Recently, the deployment of unmanned aerial vehicles (UAVs) in the wireless networks has gained attention to achieve a better quality of service (QoS) for the mobile nodes. This paper studies the use of UAV network to assist the terrestrial network to meet the QoS requirements of the mobile nodes. However, such cellular traffic offloading to the energy constrained UAVs is not trivial. Therefore, we propose a weighted power allocation scheme in the UAV assisted heterogeneous networks (UAV-HetNets) where both UAV and terrestrial networks are efficiently utilized to meet the QoS requirements of the mobile nodes. For that purpose, the weighted energy minimization problem is formulated under the QoS constraints of the mobile node. Simulation results are drawn to show the significance of the proposed energy efficient resource allocation scheme.**

***Index Terms*—Energy Efficiency, Resource Allocation, Unmanned Aerial Vehicles**

I. Introduction

INITIALLY proposed for the military applications to avoid the human involvement in hazardous operations, the use of *unmanned aerial vehicles (UAVs)* is extended to other applications like navigation, surveillance, agriculture and disaster situations during the past decade. Currently, the trends of utilizing the UAVs in wireless networks have gained interests to get the benefits of boost in network capacity, a better quality of service (QoS), and improved user experience [1]. Therefore, UAVs are involved in many recent proposals of wireless networks to play a role as: 1) a back-haul network hub to connect the front-haul with the core network, 2) a flying base-station [2] to enhance the capacity of cellular networks and, 3) a regular mobile node. In addition, UAV-based schemes of computation and caching have also been proposed recently [3].

Indeed, the deployment of UAVs to assist the terrestrial wireless networks can contribute well by utilizing the promising UAV features e.g., flexibility, easy deployment at the required location, automation, and the direct communication link with the ground users. Moreover, UAVs can prove to be an economic and energy efficient substitute of the prevailing terrestrial base-stations in hazardous locations and emergency situations. Therefore, UAV flying base-station is advised to be a strong candidate to assist the underlay heterogeneous networks (HetNets).

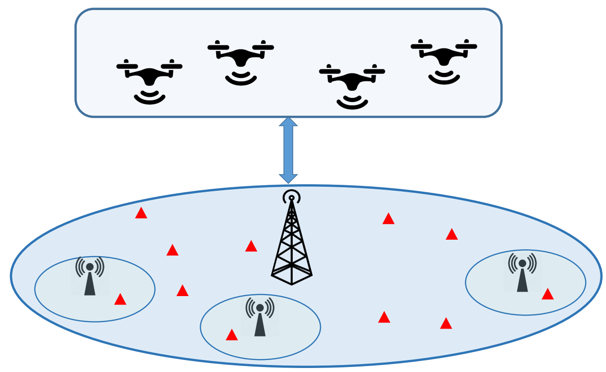

Fig. 1: System model of UAV-based heterogeneous network. The UAV pool is deployed over the terrestrial network consisting of MBS and TBSs. The small red triangles represent the mobile nodes uniformly deployed in the area.

However, the application of UAVs to assist the HetNets faces certain challenges. The most significant challenge in UAV-HetNets is the efficient utilization of the on-board energy of UAVs to serve the ground users. To address this challenge, we propose a weighted power allocation scheme where both UAV and terrestrial networks strive to meet the QoS requirements of the ground users with minimum energy spent. To do this, we formulate the weighted optimization problem to minimize the overall energy consumption of the base-stations while satisfying the QoS constraints. The weights of the consumed energy are adjusted among the UAVs and terrestrial networks. These weights are determined using a heuristic approach which is based on the received signal to interference and noise ratio (SINR) at the mobile node from the neighboring UAV base-station (UAV-BS) or *terrestrial base-station* (TBS). The more weight is assigned to the BS with better SINR level. As a result, the QoS requirement is fulfilled with comparatively less amount of the consumed energy. After the computation of the wighted contribution of the participating BSs, the power allocation is performed to meet the QoS requirements of the mobile nodes.

Recently, different approaches of the resource allocation in various 5G technologies like HetNets [4], device-device

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(D2D) communication [5], wireless network virtualization, non-orthogonal multiple access (NOMA) [6], LTE-unlicensed (LTE-U) [7], [8], ultra-reliable and low-latncy communication (URLLC) [9], and data security in IoT [10] have been proposed to enhance the network capacity and user experience. However, the limitations of flexible base-station deployments, and the lack of automation restrain the scope of such techniques. To fill this gap, UAV-HetNets are proposed where the wireless network traffic is offloaded to the coexisting UAV networks which use the UAVs as flying base-stations [11]–[14]. UAV-based solution is proposed in [11] to provide the communication services in the disaster recovery scenarios. An efficient UAV path planning scheme is proposed in [12]. Furthermore, traffic offloading scheme is proposed for the mobile nodes by utilizing the UAV based networks to assist the ground network in [13]. Moreover, an efficient UAV positioning scheme is proposed in [14] to enhance the user association at dense locations. However, the aforementioned works did not utilize both the UAV networks and the terrestrial networks to serve a single network user.

To solve the energy efficiency problems in the UAV-based communication networks, various schemes have been proposed [15]–[17]. In [15], a distributed approach for the energy efficiency is proposed by formulating a non-cooperative game between the participating UAVs. In [16], an energy efficiency scheme to collect data from the IoT devices is proposed by developing a UAV based system model. However, most of the existing works consider single BS association of a mobile node which can limit the energy efficiency of network. To address this problem, we propose an energy efficient scheme to meet the QoS requirements of the mobile node by developing a weighted power allocation framework among the UAV and terrestrial networks. The main contributions of the paper are summarized as follows:

- First, we formulate a wighted optimization problem to minimize the total energy of UAV-BSs and TBSs in the network while meeting the QoS requirements of the mobile nodes.
- To solve the problem, a heuristic approach is used which utilizes the received SINR level at the mobile node from the closest UAV-BS and TBS. Based on the SINR level, the proportional weights for the UAV-BS and TBS are computed.
- After the optimal weight computation, the weighted power allocation is performed to meet the QoS demand of the mobile nodes.
- Finally, the numerical results are presented which show that the proposed scheme contributes well to perform the energy efficient power allocation in the UAV-based HetNets.

II. System Model and Problem Formulation

In the system model, we consider a dense UAV network consisting of a set of U number of UAV base-stations (UAV-BS) denoted by $\mathcal{U} = \{1, \ldots, U\}$. This UAV network is coexisting with the terrestrial heterogeneous network (HetNet) which is consisting of a single macro base-station and S number of terrestrial small-cell base-stations compositely denoted by $\mathcal{S} = \{0, 1, 2, \ldots, S\}$, where 0 denotes the index of MBS. Every UAV $u \in \mathcal{U}$ location is denoted by $r_u = (x_u, y_u, h_u)$, where h_u represents the height of the UAV. This network of UAV-based HetNet is serving N number of ground users denoted by the set $\mathcal{N} = \{1, \ldots, N\}$ for the downlink communication. These N number of ground users are deployed uniformly in a geographical area at the locations denoted by $r_n = (x_n, y_n, 0)$. It can be seen in the Fig. 1 that a mobile node $n \in \mathcal{N}$ can be served by a UAV-BS $u \in \mathcal{U}$ and TBS $s \in \mathcal{S}$.

As the communication link from UAV-BS and TBS to the mobile node experience different scattering, fading and reflections, we consider different path loss models these links. Moreover, the LoS feature of UAV-BS deliver better channel quality to the ground user.

The generalized SINR level from any BS $j \in \mathcal{J}$, where $\mathcal{J} = \{\mathcal{U} \cup \mathcal{S}\}$ is given as follows:

$$SINR_{jn} = \frac{P_{jn} h_{jn}}{1 + \sum_{j' \in \mathcal{J} \setminus \{j\}} P_{j'n} h_{j'n} + W\sigma}, \tag{1}$$

where, P_{jn} represents the transmitted power from any BS to the user n, h_{jn} denotes the channel gain, W denotes the allocated channel bandwidth, and σ denotes the noise.

The generalized achievable rate from any BS $j \in \{\mathcal{U} \cup \mathcal{S}\}$ to the mobile node

$$R_{jn} = W \log\left(1 + SINR_{jn}\right). \tag{2}$$

We analyze the UAV-based HetNet for a time duration which is long enough to compute and allocate the power to the mobile nodes and short enough that the topology of the network is not significantly changed. During this time, the total energy consumption E_U by all the UAV-BSs, and the energy consumed E_S by all the TBSs in order to provide communication services to the mobile nodes is given as follows:

$$E_U = \sum_{u \in \mathcal{U}} \sum_{n \in \mathcal{N}} P_{un} \times \tau, \tag{3}$$

$$E_S = \sum_{s \in \mathcal{S}} \sum_{n \in \mathcal{N}} P_{sn} \times \tau, \tag{4}$$

where, τ denotes the time duration for single LTE frame of downlink communication.

A. Problem Formulation

The optimization problem is formulated to minimize the overall energy consumption of both UAV-based HetNet while satisfying the QoS requirements, η_n of mobile nodes. The problem formulation is given as:

$$\min_{\boldsymbol{\theta}, \boldsymbol{P}} \quad \sum_{n \in \mathcal{N}} \theta_n E_U + (1 - \theta_n) E_S, \tag{5}$$

$$\text{s.t.} \quad R_{un} + R_{sn} \geq \eta_n, \quad \forall n \in \mathcal{N}, u \in \mathcal{U}, s \in \mathcal{S}, \tag{5a}$$

$$P_{un} \geq 0, P_{sn} \geq 0, \quad \forall n \in \mathcal{N}, u \in \mathcal{U}, s \in \mathcal{S}, \tag{5b}$$

$$\theta_n \in [0, 1], \quad \forall n \in \mathcal{N}. \tag{5c}$$

The objective is to minimize the overall energy consumption of the UAV-based HetNet by optimizing the power allocation

$\boldsymbol{P}$ and weights $\boldsymbol{\theta}$. The decision variable θ_n given in the objective function in (5) denotes the contribution of the UAV network to serve the mobile node n. Conversely, the factor $1-\theta_n$ denotes the contribution of the terrestrial network. The constraint in (5a) ensures that the sum of the rate R_{un} offered by the UAV u and the rate R_{sn} by the TBS s is satisfying the QoS threshold η_n of the mobile node n. (5b) and (5c) are the bounds of the decision variables.

III. Proportional Power Allocation Scheme:

To solve the optimization problem, we use a heuristic approach of the proportional power allocation. For that purpose, the optimal proportion θ_n of the contribution of the UAV-BS $u \in \mathcal{U}$ and the TBS $s \in \mathcal{S}$ is determined. This optimal proportion is calculated by using the received SINR level from the closest UAV-BS and TBS as follows:

$$\theta_n^* = \frac{SINR_{un}}{SINR_{un} + SINR_{sn}}, \quad \forall n \in \mathcal{N}. \tag{6}$$

It can be seen that the proportional weight assignment captures the SINR level, therefore, the BS giving better SINR is preferred to serve the mobile node. Based on the optimal weight θ_n^*, the QoS requirement of the mobile node n can be divided into two parts as follows:

$$R_{un} + R_{sn} \leq \eta_{un} + \eta_{sn}, \tag{7}$$

where, $\eta_{un} = \theta_n \eta_n$ and $\eta_{sn} = (1-\theta_n)\eta_n$ denote the proportional QoS demand of the mobile node n to be fulfilled by the UAV u and TBS s respectively. This means that each contributing BS will have to meet certain QoS requirement for the mobile node n according to the assigned weight θ_n. This is expressed in the following optimization problem:

$$\min_{\boldsymbol{P}} \quad \sum_{n\in\mathcal{N}} \theta_n^* E_U + (1-\theta_n^*)E_S, \tag{8}$$

$$\text{s.t.} \quad R_{un} \geq \eta_{un}, \quad \forall n \in \mathcal{N}, u \in \mathcal{U}, \tag{8a}$$

$$R_{sn} \geq \eta_{sn}, \quad \forall n \in \mathcal{N}, s \in \mathcal{S}, \tag{8b}$$

$$P_{un} \geq 0, P_{sn} \geq 0, \quad \forall n \in \mathcal{N}, u \in \mathcal{U}, s \in \mathcal{S}. \tag{8c}$$

The given problem is upper constrained minimization problem, therefore, we get the boundary solution for the optimal power allocation P_{un}^* and P_{sn}^* as follows:

$$P_{un}^* = \frac{2^{\left(\frac{\eta_{un}}{W}-1\right)} \times \left(1 + \sum_{j'\in\mathcal{J}\setminus\{u\}} P_{j'n} h_{j'n} + WN\right)}{g_{un}}, \tag{9}$$

$$P_{sn}^* = \frac{2^{\left(\frac{\eta_{sn}}{W}-1\right)} \times \left(1 + \sum_{j'\in\mathcal{J}\setminus\{s\}} P_{j'n} h_{j'n} + WN\right)}{g_{sn}}. \tag{10}$$

Algorithm 1 explains the details of weighted power allocation scheme. In the input of the algorithm, the sets containing the number of UAVs U, the number of TBSs S, the number of mobile nodes in the network N, the SINR level from every BS to the mobile node $\boldsymbol{SINR}$, and the QoS requirement $\boldsymbol{\eta_n}$ are provided. In the first step, each mobile node selects single UAV and single TBS which are giving the best SINR level. After that, the weight contribution θ_n is computed for every mobile node using the received SINR level. Next, the weighted QoS requirement for the selected UAV-BS and TBS is computed. In the second step, the power allocation is performed according to the weighted QoS requirement.

Algorithm 1 Weighted Power Allocation Algorithm

```
Input: U, S, N, SINR, η
Step 1:
for n = 1 to N do
    Select u and s with max. SINR_un and max. SINR_sn
    Compute θ*_n from (6)
    Compute η_un = θ_n η_n and η_sn = (1 − θ_n)η_n
end for
Step 2:
for u = 1 to U do
    Compute optimal power P*_un from (9)
end for
for s = 1 to S do
    Compute optimal power P*_sn from (10)
end for
Output: θ*_n, P*_un, and P*_sn
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IV. Numerical Evaluation

This section presents the simulation results to evaluate the proposed weighted power allocation scheme in UAV-based HetNets. For that purpose, we use python language to build the system model which is consisting of a single MBS, which is located at the center of a geographical area of 1000 m $\times$ 1000 m square. We deployed 5 number of TBSs and 5 number of UAV-BSs uniformly in the area. We simulate the network for multiple runs to get the average results with different number of mobile nodes which are also deployed uniformly in the geographical area.

Fig. 2 shows the plot of the energy consumption level while serving the number of mobile nodes in the network. It can be observed that as the number of mobile nodes are increased, the energy consumption by both the UAV and terrestrial network is increased. It can also be seen that the energy consumption in the UAV network is high as compared to the terrestrial network. This is due to the fact that the UAV has LoS communication with the mobile nodes which deliver better SINR level. Therefore, more proportion of UAV energy is allocated to the mobile node to meet the QoS requirements of the mobile node. This result validates that the UAV network can perform well in serving the mobile nodes as compared to the terrestrial network by better utilizing the LoS direct communication links.

Fig. 3 shows the plot of proportional energy consumption of the UAV and terrestrial network against the increasing value of θ. It can be seen that as the value of θ is increased, the proportional energy consumption in the UAV network is increased as compared to the terrestrial network. This is due to the nature of the objective function of our problem. It can also be seen that the total energy consumption is reduced for the values of θ where both the UAV and terrestrial networks

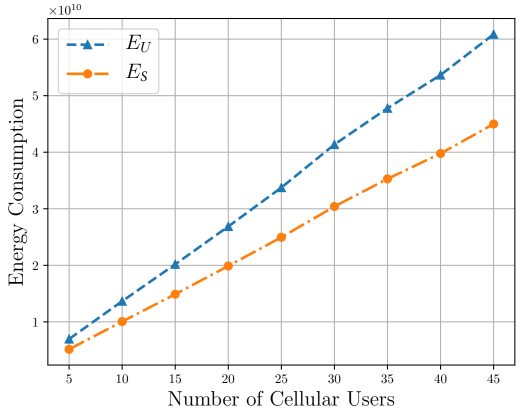

Fig. 2: Plot of the energy consumption vs. the number of mobile nodes in the network.

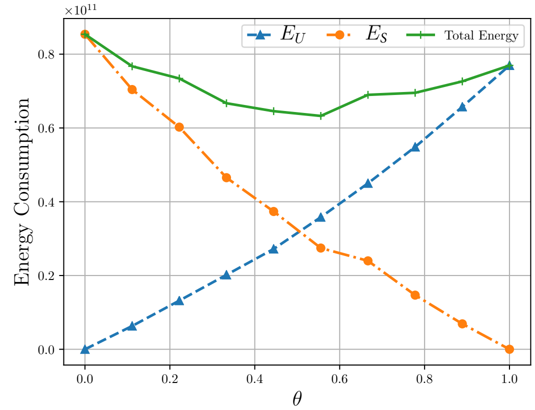

Fig. 3: Plot of the energy consumption vs. θ.

are contributing to serve the mobile nodes as compared to the individual contribution of either UAV or terrestrial network. This result validates our proposed scheme where both the UAV and terrestrial networks contribute to serve the mobile nodes to reduce the overall energy consumption. It can also be seen from Fig. 3 that there is a small difference in the energy consumption level at both peaks around the values of $\theta = 0$, and $\theta = 1$. Specifically, when $\theta = 0$, the energy consumption level is relatively high as compared to the energy consumption at $\theta = 1$. This is due to the fact that, at $\theta = 1$, the cellular traffic is offloaded to the UAV network. The LoS communication link and low path loss in the UAV to the mobile node significantly reduce the amount of energy spent to meet the similar QoS.

V. Conclusion

This paper proposes UAV-based HetNets to offload the cellular traffic to meet the QoS requirements of the network users. For that purpose, a weighted energy minimization problem under the constraint of mobile node's QoS requirements is formulated. First, the optimal weight to offload the cellular traffic to the UAV network is estimated using the proportional SINR level. After that the power allocation is performed to meet the weighted QoS requirement for the UAV and terrestrial network. Simulation results are drawn to show that the proposed weighted allocation scheme performs well in reducing the overall energy consumption of the network.

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