Fair Multiple Subchannel Assignment and 3-D UAV-BS Placement in UAV-Enabled Networks

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***Abstract*—This paper focuses on multiple subchannel assignment for ground users in an unmanned aerial vehicle (UAV) enabled network. The main objective is to ensure fair service to the users by maximizing the rate of the worst-off user. To this end, we jointly optimize the three-dimensional (3-D) placements of the UAV-BSs, the multiple subchannel assignment to each user, and the transmit power of each subchannel. The presented problem is non-convex in nature. In order to solve this problem, we propose to divide it into three tractable subproblems: user clustering, multiple subchannel assignment, and joint altitude and power optimization. The first subproblem is solved by using the modified K-means algorithm. A novel algorithm based on the Hungarian-based dynamic many–many matching (HD4M) algorithm is proposed to solve the second subproblem. To solve the third subproblem, three methods based on sequential quadratic programming (SQP), including our proposed iterative method, are investigated. The simulation results show that our proposed iterative method provides a higher worst-off user rate and fairness than the other two methods.**

***Index Terms*—3-D Placement, Multiple Subchannel Assignment, Unmanned Aerial Vehicles (UAVs), User Clustering**

I. Introduction

Unmanned aerial vehicles (UAVs) have seen considerable growth in their popularity in recent times. They have been employed in a wide variety of applications such as weather monitoring, forest fire detection, traffic control, cargo transportation, emergency search and rescue, among several others. Among the plethora of new applications enabled by UAVs, the use of UAVs for achieving high-speed wireless communications is expected to play an important role in the next generation of communications systems [1]. UAV-enabled networks confer several advantages over their traditional counterparts that largely rely on ground base stations. For example, when dealing with large numbers of users distributed over a wide area, ground base stations may be unable to cover all users effectively. In contrast, UAV mounted with remote radio heads (RRHs), known as UAV-base stations (UAV-BSs), can provide the desired QoS (Quality Of Service) to all the users in a cost-effective manner [2].

Since these UAV-BSs are mobile, we need to determine their precise three-dimensional (3-D) locations. Furthermore, we also need to make efficient use of the limited power and frequency resources through an appropriate resource allocation scheme. In [3], the 3-D placement and resource allocation of multiple UAV-BS in an uplink IoT network are studied in the presence of interference. In [4], the 3-D UAV-BS placement that maximizes the number of covered users with different QoS requirements using the minimum power is studied. In [5] the trajectory control and subchannel assignment for UAV-based wireless networks are studied with the objective to optimize the max-min rate of the users. In [6], a distributed algorithm is proposed that allows UAV-BSs to learn their optimal 3-D locations and associate with ground users while maximizing the network's sum rate. In [7], the 3-D UAV-BS placement and user association problem for a multi-UAV system is considered. However, [3] and [6] have overlooked the determination of the number of UAV-BSs. Moreover, in [3] and [7], each user is assigned only one subchannel.

In this work, we have considered a UAV-enabled network where multiple UAV-BSs are deployed to transmit data to ground users considering the equitable distribution of users to UAV-BSs along with a limited number of subchannels, and the presence of interference between users. We focus on jointly optimizing the 3-D UAV-BS placement, multiple subchannel assignment, transmit power of each subchannel, and user association to maximize the minimum rate among all the users. Maximizing the minimum rate ensures that the fairness of the network is not compromised. Unlike the prior works, we consider that a user can be assigned more than one subchannel. The main contributions of our work can be summarized as follows:

- We propose a fair 3-D UAV-BS placement and multiple subchannel assignment framework for a UAV-enabled wireless network. The main objective is to maximize the minimum rate among all the users while optimizing the 3-D placements of UAV-BSs, multiple subchannel assignment, transmit power of each subchannel, and user association.
- The above problem is non-convex in nature. Hence, we divide it into three subproblems. In the first subproblem, we determine the user associations. To accomplish this,

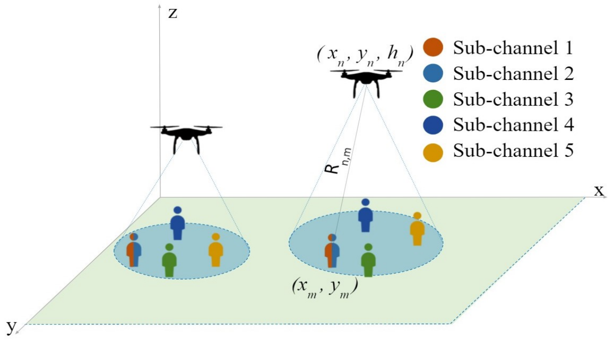

Fig. 1. Network Model

we use the modified K-means algorithm. Then, in the second subproblem, we perform multiple subchannel assignment via a novel algorithm based on the HD4M algorithm. Finally, in the third subproblem, the joint optimization of power assignment and UAV-BS altitude is solved using three methods based on sequential quadratic programming (SQP), including our proposed iterative optimization method. Moreover, we also determine the number of UAV-BS required via the elbow method.

- We have compared the performance of the above methods in terms of rate, fairness, and computation time. It is shown that the iterative optimization method results in a higher minimum rate and fairness.

The rest of the paper is organized as follows: We present the network model and problem formulation in Section II. Next, we divide our problem into three subproblems and solve them in Section III. Simulation results are presented in Section IV. Finally, the paper is concluded in Section V.

II. Network Model and Problem Formulation

A. Network Model

As shown in Fig. 1, we consider a downlink scenario where a group of ground users receives data from multiple hovering UAV-BSs. There are M users and N UAV-BSs in the network, whose index sets are denoted as $\mathcal{M} = \{1, 2, 3, ..., M\}$ and $\mathcal{N} = \{1, 2, 3, ..., N\}$, respectively. All users must be served and each user can be served by only one UAV-BS. Each UAV-BS must be associated with an approximately equal number of users. The two-dimensional (2-D) location of the m^{th} user is given by $X_m = (x_m, y_m)$ and the n^{th} UAV-BS is located at $u_n = (x_n, y_n, h_n)$. Each UAV-BS is allotted K orthogonal subchannels. We assume that K is the same for all UAV-BSs and $K \geq \lceil \frac{M}{N} \rceil$. This means that users may be assigned multiple subchannels, as shown in Fig. 1. We define the set $\{S_{n,m,k}\}$ to indicate the association between UAV-BSs and users, and the subchannel assignment of the users. If UAV-BS n serves user m on subchannel k, then $S_{n,m,k}$ is set to 1. Otherwise, it is set to 0. The users not associated to the same UAV-BS but served on the same subchannel will experience interference while users assigned to the same UAV-BS will not experience any interference as the subchannels are orthogonal. In the following paragraph, we will discuss the air to ground channel model [9].

a) Channel Model: We have included both line-of-sight (LoS) and non-line-of-sight (NLoS) links in our analysis. We use a probabilistic model, where the probability of an LoS link depends on the altitudes of the UAV-BS. As described in [3], the probability of the LoS link between user m and UAV-BS n is given by:

$$P_{n,m}^{LoS} = \frac{1}{1 + ae^{-b(\theta_{n,m} - a)}}, \tag{1}$$

where a and b are the constants encoding information about the environmental conditions and the carrier frequency, respectively [8]. $\theta_{n,m}$ denotes the elevation angle in degrees from UAV-BS n to its associated user m. It is computed by $\theta_{n,m} = (\frac{180}{\pi}) tan^{-1}(\frac{h_n}{r_{n,m}})$ with the altitude of UAV-BS n denoted by h_n and the horizontal distance from UAV-BS n to user m denoted as $r_{n,m} = \sqrt{(x_n - x_m)^2 + (y_n - y_m)^2}$. Correspondingly, the NLoS probability is $P_{NLoS} = 1 - P_{LoS}$. Once we have the probabilities of the LoS and NLoS paths, we can compute the path loss as described in [9]:

$$L_{n,m}^{LoS} = \left(\frac{4\pi f_c d_{n,m}}{c}\right)^{\beta} \eta_{LoS}, \tag{2}$$

$$L_{n,m}^{NLoS} = \left(\frac{4\pi f_c d_{n,m}}{c}\right)^{\beta} \eta_{NLoS}, \tag{3}$$

where β is the path loss exponent and $d_{n,m}$ is the distance between the n^{th} UAV-BS and the m^{th} user. It is given by $d_{n,m} = \sqrt{r_{n,m}^2 + h_n^2}$. η_{LoS} and η_{NLoS} are the path loss coefficients for LoS and NLoS paths respectively. Using this model, the path loss is a bernoulli random variable. We compute its expected value as:

$$\begin{aligned} \mathbb{E}(L_{m,n}) &= P_{n,m}^{LoS} L_{n,m}^{LoS} + P_{n,m}^{NLoS} L_{n,m}^{NLoS} \\ &= P_{n,m}^{LoS} \left(\frac{4\pi f_c d_{n,m}}{c}\right)^{\beta} \eta_{LoS} \\ &+ (1 - P_{n,m}^{LoS}) \left(\frac{4\pi f_c d_{n,m}}{c}\right)^{\beta} \eta_{NLoS}, \end{aligned} \tag{4}$$

where $\mathbb{E}(.)$ is the expectation operator. The average gain between the n^{th} UAV-BS and the m^{th} user is defined as $G_{n,m} = \frac{1}{\mathbb{E}(L_{n,m})}$. Now, we discuss the effect of interference in our network.

b) Interference: Due to the UAV-BSs sharing the same frequency spectrum, multiple users operate on the same subchannel, which leads to interference. Each user can be allotted multiple subchannels. For users allotted multiple subchannels, we compute the interference independently for each subchannel. Let $P_{n,k}$ where $n \in \mathcal{N}$ and $k \in \{1, 2, ...K\}$ be the transmission power on the k^{th} subchannel of the n^{th} UAV-BS. The interference experienced by the k^{th} subchannel of UAV-BS n that serves user m is given by:

$$I_{n,m,k} = \sum_{\substack{i=1 \\ i \neq n}}^{N} \sum_{j=1}^{M} S_{i,j,k} P_{i,k} G_{i,j}. \tag{5}$$

Based on this, the signal-to-interference and noise ratio (SINR) $\xi_{n,m,k}$ for the k^{th} subchannel of the n^{th} UAV-BS can be computed as:

$$\xi_{n,m,k} = \frac{P_{n,k} G_{n,m}}{I_{n,m,k} + \sigma^2}, \quad (6)$$

where σ^2 is the variance of additive white Gaussian noise (AWGN). We have computed the SINR of the subchannels for all the UAV-BSs. From the channel capacity theorem [5], we can obtain the maximum rate at which information can be transmitted for each subchannel at a given SINR. However, in our network, multiple subchannels can be assigned to one user. Hence, the maximum achievable rate for a user is equal to the sum of the capacity of all the subchannels assigned to it. Let the rate for the m^{th} user be R_m where $m \in \mathcal{M}$:

$$R_m = \sum_{k=1}^{K} \log_2 \left(1 + \sum_{n=1}^{N} \xi_{n,m,k} S_{n,m,k} \right). \quad (7)$$

B. Problem Formulation

The objective of our optimization problem is to maximize the minimum rate among all the users. We introduce a binary variable, $C_{n,m}$ to indicate whether a user is associated to a UAV-BS or not. $C_{n,m}$ will be '1' if $\sum_{k=1}^{K} S_{n,m,k} \geq 1$, indicating user m is associated to UAV-BS n. $C_{n,m}$ will be '0' otherwise. The optimization problem is formulated as follows:

$$\max_{\substack{P_{n,k}, u_n \\ S_{n,m,k}, C_{n,m}}} \quad \min(R_m) \quad (8a)$$

$$\text{s.t} \sum_{k=1}^{K} S_{n,m,k} - (C_{n,m} - 1) Q \geq 1, \forall n \in \mathcal{N}, \ \forall m \in \mathcal{M}, \ \forall k \in \mathcal{K}, \quad (8b)$$

$$\left\lfloor \frac{M}{N} \right\rfloor \leq \sum_{m=1}^{M} C_{n,m} \leq \left\lceil \frac{M}{N} \right\rceil, \quad \forall n \in \mathcal{N}, \quad (8c)$$

$$\sum_{n=1}^{N} C_{n,m} = 1, \quad \forall m \in \mathcal{M}, \quad (8d)$$

$$\sum_{m=1}^{M} \sum_{k=1}^{K} S_{n,m,k} = K, \quad \forall n \in \mathcal{N}, \quad (8e)$$

$$C_{n,m} \in \{0,1\}, \ \forall n \in \mathcal{N}, \ \forall m \in \mathcal{M}, \quad (8f)$$

$$S_{n,m,k} \in \{0,1\}, \ \forall n \in \mathcal{N}, \ \forall m \in \mathcal{M}, \ \forall k \in \mathcal{K}, \quad (8g)$$

$$0 \leq \sum_{k=1}^{K} P_{n,k} \leq P_{total}, \ \forall n \in \mathcal{N}, \quad (8h)$$

$$h_{min} \leq h_n \leq h_{max}. \quad (8i)$$

Constraint (8b) guarantees that $C_{n,m}$ is set to '1' if $\sum_{k=1}^{K} S_{n,m,k} \geq 1$ or '0' otherwise [10] where $Q >> K$ is a large constant. Constraint (8c) is applied to make sure that each UAV-BS provides service to an approximately equal number of users. Constraint (8d) indicates that all users in the network are served by exactly one UAV-BS. Constraint (8e) indicates that each UAV-BS utilizes K subchannels. Constraints (8f) and (8g) indicate that $C_{n,m}$ and $S_{n,m,k}$ are binary, respectively. Constraint (8h) indicates that P_{max} is the maximum power available to each UAV-BS, which is distributed across K subchannels. Constraint (8i) indicates that the altitudes of the UAV-BSs lie between h_{min} and h_{max}.

III. Problem Solution

Problem (8a)-(8j) is a non-convex mixed-integer programming (MIP) problem. From (1)-(4), we can see the path gains are non-convex functions. This accounts for the non-convexity of the problem. As a result, finding the global optimum of this problem is non-trivial. In order to obtain a suboptimal solution of (8a), we propose to divide the problem into three sub-parts and then solve them separately. First, N is decided, and the association between UAV-BSs and users is determined. Moreover, the 2-D placements of the UAV-BSs are also obtained in this step. Next, the number of subchannels to be assigned to each user is fixed, and the subchannel assignment is done in a manner that minimizes interference. Finally, the altitudes of the UAV-BSs and the powers allocated to each subchannel are jointly optimized iteratively.

A. User Clustering

In this subproblem, the sum of the Euclidean distances between the users and their associated UAV-BS is the cost function. This cost function is to be minimized with respect to the associations between UAV-BSs and users the 2-D placement of the UAV-BSs. We minimize this cost function as shorter horizontal distances imply higher gains, which in turn result in better rates for the users [11]. We formulate this subproblem as follows:

$$\min_{\substack{u_n \\ C_{n,m}}} \quad \sum_{n=1}^{N} \sum_{m=1}^{M} C_{n,m} r_{n,m}^2 \quad (9a)$$

s.t (8b)-(8d), (8f)

We perform clustering of users such that the sum of Euclidean distances between the UAV-BSs and their associated users is minimized. To do this, we use the user clustering algorithm described in [3]. The user clustering algorithm returns the association between users and UAV-BSs, and the 2-D placements of the UAV-BSs for a given value of N. We utilize the modified K-means clustering algorithm [3] so that each cluster has approximately the same number of users, satisfying constraint (8c) while minimizing the cost function (9a).

B. Multiple Subchannel Assignment

After the previous step, we obtain N and fix the association between UAV-BSs and users. However, we still need to decide the number of subchannels to be allotted to the m^{th} user, N_m^{sub}, and the set of users operating on the k^{th} subchannel, V_k. We propose a subchannel assignment strategy aimed at minimizing the interference among different clusters and ensuring fairness in the rates assigned to different users. In the proposed scenario, multiple UAV-BSs transmit data to users through a limited number of subchannels. If two nearby users receive data through the same subchannel, then the signal will experience significant interference. Hence, it must be ensured that users assigned the same subchannel are as far apart from each other as possible. Moreover, the number of subchannels assigned to each user must be decided in a manner that maximizes fairness.

To begin with, we try to assign an approximately equal number of subchannels to all users associated to a particular UAV-BS. We represent the unallocated subchannels of UAV-BS n as $unused\_subchannels_n$. First, we sort all the users associated to a UAV-BS in ascending order of their channel gains. Once the sorting is completed, we assign one subchannel to each user in this order. When the last user is reached, we repeat the process until all the subchannels are utilized, as shown in Algorithm 1. Once the number of subchannels to be assigned to each user is determined, we need to try and minimize interference. The HD4M algorithm described in [3] gives a suboptimal solution for the case when each user is assigned one subchannel. This algorithm is based on matching theory [12]. The algorithm takes as input X_m, $C_{n,m}$ and outputs $S_{n,m,k}$, V_k and N_m^{sub}. To reduce our problem to a form solvable by the HD4M algorithm, we introduce the concept of phantom users. If a user has been assigned N_m^{sub} subchannels, then we treat that user as N_m^{sub} different users in the same location, each assigned a single subchannel. By treating these N_m^{sub} subchannels as N_m^{sub} users, the problem becomes identical to the scenario where each user is assigned one subchannel. To do this, we introduce the variables $X_m^{phantom}$ and $C_{n,m}^{phantom}$. These variables contain the 2-D positions and association of the users, which are repeated N_m^{sub} times for the m^{th} user. Then, we pass these variables to the HD4M algorithm. The HD4M algorithm outputs the matrix $S_{n,m,k}^{phantom}$ which defines the association and subchannel assignment for all the phantom users. Then, we convert $S_{n,m,k}^{phantom}$ to $S_{n,m,k}$ by removing phantom users and assigning subchannels given to these users to the real user.

Algorithm 1: Multiple subchannel Assignment

Input: X_m, $C_{n,m}$
Output: $S_{n,m,k}$,V_k,N_m^{sub}
Initialization: N_n = Number of users assigned to each UAV-BS, $unused\_channels_n$ = K, $N_m^{sub} = 0$, $V_k = []$, $X_m^{phantom} = zeros(N \times K, 2)$, $C_{n,m}^{phantom} = zeros(N \times K, N)$ i=0, j=0
while $i \leq N$ **do**
  while $unused\_channel[i] > 0$ **do**
    if $unused\_channel[i] \geq N_n[i]$ **then**
      Increment N_m^{sub} for all users associated with UAV-BS i by 1
    else
      Sort all users associated with UAV-BS i in ascending order
      of their gains
      Select the first $unused\_channel[i]$ users
      Increment N_m^{sub} of selected users by 1
      Set $unused\_channel[i]$ to 0
  end while
end while
c = 0
while $j \leq M$ **do**
  $X_m^{phantom}$[c : c + N_m^{sub}, :]=$X_m[j,:]$
  $C_{n,m}^{phantom}$[c : c + N_m^{sub}, :]=$C_{n,m}[j,:]$
  c = c + N_m^{sub}
  j = j + 1
end while
Pass $X_m^{phantom}$ and $C_{n,m}^{phantom}$ to HD4M algorithm to get V_k and $S_{n,m,k}^{phantom}$
Convert $S_{n,m,k}^{phantom}$ to $S_{n,m,k}$ by removing phantom users and assigning subchannels given to these users to the real user

C. UAV-BS Altitude and Power Optimization

In this sub-section, we optimize the altitudes of UAV-BSs (H_n) and the transmission powers of each subchannel ($P_{n,k}$). Previously, we have obtained $S_{n,m,k}$ and u_n. With these values fixed, we write the simplified optimization problem as follows:

$$\max_{P_{n,k},H_n} \quad \min(R_m) \tag{10a}$$
$$\text{s.t} \quad \text{(8h)-(8i)}$$

The above problem is non-convex. The non-convexity arises due to the fact that the rates attained by the users are dependent on the average path gains as shown in (6) and (7), and the average path gain is a non-convex function of H_n according to (2)–(4). The fact that $P_{n,k}$ and H_n are not independent further complicates the problem. To solve the problem (10a), we propose an iterative optimization method to obtain a suboptimal solution. At first, we fix the altitudes of UAV-BSs and optimize $P_{n,k}$. Then, we fix $P_{n,k}$ and optimize the altitudes. We iteratively repeat this process until convergence is reached.

The above-mentioned subproblems are non-linear in nature due to the presence of the logarithm function in rate. Hence, we use SQP to solve these constrained non-linear problems. However, SQP requires the objective function and the constraints to be twice continuously differentiable. In our problem, as we are maximizing the minimum rate, the first derivative of our objective function is only piece-wise continuous. Hence, to use SQP, we need to reformulate the problem such that its first two derivatives are continuous [7]. We introduce a new optimization variable ω. ω represents the lower bound on the rates achieved by the users. We change the objective function to maximizing ω and introduce a constraint that ensures that the rates of all users are greater than ω. Now, we formulate the two above-mentioned sub-problems as follows:

For the case when altitudes are fixed, the problem formulation is:

$$\max_{P_{n,k}} \quad \omega \tag{11a}$$
$$\text{s.t.} \quad \text{(8h)},$$
$$R_m \geq \omega, \quad \forall\, m \in \mathcal{M}. \tag{11b}$$

For the case when $P_{n,k}$ is fixed, the problem formulation is:

$$\max_{H_n} \quad \omega \tag{12a}$$
$$\text{s.t. (11b), (8i).}$$

We iteratively solve these two sub-problems until ω converges. We say that ω has converged when the fractional increase in ω is less than 1%. We summarize this process in Algorithm 2.

Algorithm 2: Iterative Optimization

Input: H_{min},H_{max},P_{total}
Output: $P_{n,k}$,H_n
Initialization: Initialize $P_{n,k}$ to 0 and H_n to H_{min}
Initialize iteration counter cnt to 0
while ω *does not converge* **do**
  Solve problem (11) using SQP and update ω
  Solve problem (12) using SQP and update ω
  cnt=cnt+1
end while

D. Determining N

In a real-world scenario, it may be beneficial to be able to estimate the number of UAVs required to serve a given set of stationary users. In order to get an estimate of the number of UAV-BSs required, we use the elbow method on the cost function (9a), as shown in Algorithm 3. The cost function (9a) is computed repeatedly for increasing values of N. Once $\frac{\Delta(9a)}{\Delta N} \leq \delta$, the corresponding value of N is chosen as the number of UAV-BSs, where $\delta = 0.01$. This provides us with a lower limit to the number of UAV-BSs the network needs. If we further increase the number of UAV-BSs beyond this point, there is only marginal improvement in the cost function. We also define N_{max}, which is the maximum number of UAVs available.

Algorithm 3: Elbow Method

Input: M, X_m
Output: N, $C_{n,m}$, u_n $\forall$ n, m
Initialization: $N = 1$, $obj = [\infty]$
while $N <= N_{max}$ **do**
  Run user clustering algorithm [3] for M users and N UAV-BSs
  Update u_n and $C_{n,m}$
  Compute objective function using equation $(9a)$
  Append objective function value to obj
  if $obj[end-1] - obj[end] \leq \delta$ **then**
    return N, $C_{n,m}$, u_n
    break
  end if
end while

IV. Simulation Results

In this section, we present the simulation results of the proposed approach for determining the number of UAV-BSs, the multiple subchannel assignment and the joint optimization of the powers and altitudes of the UAV-BSs. In our simulations, 50 users are uniformly distributed within an area of 1000m×1000m, and evenly served by multiple UAV-BSs with a carrier frequency of 1 GHz. Here, we consider an urban area with a = 11.95 and b = 0.136. The other simulation parameters are listed in Table I.

a) Determining N and User Clustering: In Fig. 2, we plot the cost function (9a) vs the number of UAV-BSs used for different numbers of users. We can observe that for lower values of N, the cost function decreases sharply with increase in the number on UAV-BSs. When we increase N further, there is a much more gradual decrease in the cost function. We choose the number of UAV-BSs as per Algorithm 3. The number of UAV-BSs required as per our method does not increase significantly with an increase in the number of users.

TABLE I
SIMULATION PARAMETERS

Parameter	Description	Value
P_{total}	Total transmission power for each drone	5 W
K	Total number of subchannels	29
N_{max}	Maximum number of UAV-BSs	15
σ^2	Variance of AWGN	-100dBm
β	Path loss exponent	2
η_{LoS}	Path loss for LoS case	3 dB
η_{NLoS}	Path loss for NLoS case	23 dB
h_{min}	Minimum altitude of UAV-BSs	200 m
h_{max}	Maximum altitude of UAV-BSs	500 m

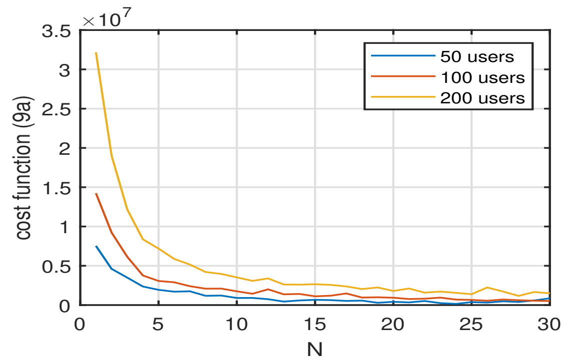

Fig. 2. Cost function (9a) Vs number of UAV-BSs

When the number of users is 50, the average number of UAV-BSs required is 5. When the number of users is increased to 100 and 200, the number of UAV-BSs is 7 and 9, respectively. These values are derived by averaging over 100 different realizations of user locations. In Fig. 3, the users served by the same UAV-BS are assigned the same color. We can also see that each user cluster consists of approximately the same number of users.

b) Multiple Subchannel Assignment: In Fig. 3, the distribution of subchannels among the users is shown. In the figure, 6 UAV-BSs serve 50 users, with each UAV-BS assigned 29 subchannels. The users served by the same UAV-BS are assigned the same color. From the plot, we can see that the multiple subchannel assignment scheme is mostly fair, with each user getting approximately the same number of subchannels. Moreover, it is to be noted that our scheme utilizes 100% of all available frequency resources.

c) UAV-BS Altitude and Power Optimization: In Fig. 4, we present the convergence analysis of our proposed algorithm. The algorithm converges fairly fast, with the difference between iterations falling below our stopping criterion of 1% after 10 iterations. In terms of fairness, the scheme attained Jain's index of 0.945, which means that all users were given roughly the same rate. We compare our scheme with two other optimization methods, as shown in Fig. 5. In the first scheme, we formulate the problem as a joint optimization problem, and we optimize the altitudes and powers simultaneously using SQP. A marginal improvement in fairness is observed, and a significant reduction in computation time is attained. However, the minimum rate achieved is less as compared to our proposed method. We investigated another method where power is optimized using SQP, and the Golden Search method is used to optimize the altitudes [3]. While this method reduces

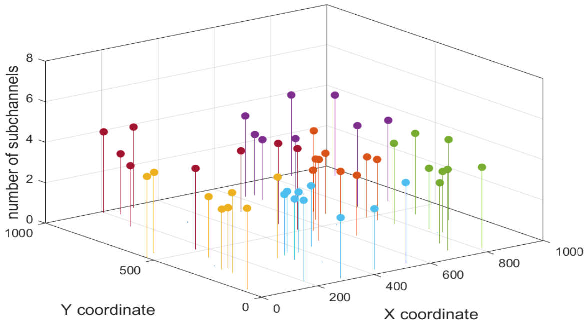

Fig. 3. Number of subchannels assigned to each user. Note the roughly equitable distribution of subchannels

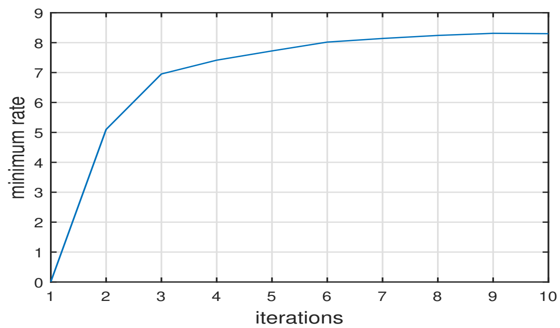

Fig. 4. Convergence of Algorithm 2

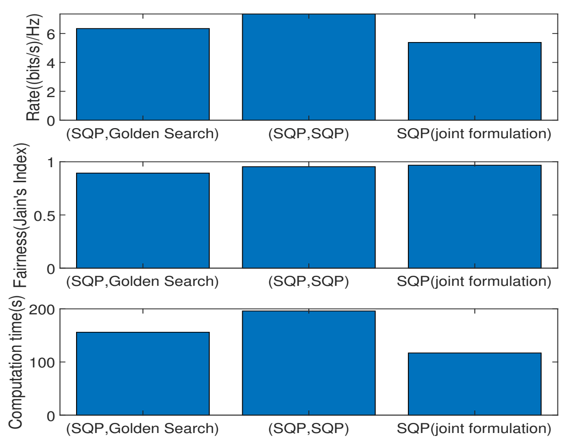

Fig. 5. Comparison of optimization methods for solving the third subproblem

the computation time to some extent, due to the relatively low computational complexity of the Golden Search method, this method performs worse in terms of fairness and minimum rate as compared to our method. Please note that all computation times are reported on an Intel i5 processor running MATLAB R2020a.

V. Conclusion

In this paper, we have put forth a fair 3-D UAV-BS placement and resource allocation framework for UAV-enabled wireless networks. An optimization problem is formulated to maximize the minimum rate among all the users while jointly optimizing the 3D locations of the UAV-BSs and the transmit powers of each subchannel, while also performing multiple subchannel assignment and user association. We have divided the above non-convex problem into three tractable subproblems. In the first subproblem, we have performed user clustering using a modified K-means algorithm that ensures approximately the same number of users in each group. Then, in the second subproblem, we have performed multiple subchannel assignment such that all available subchannels are utilized, giving multiple subchannels to the same user if required while also minimizing interference using the HD4M algorithm. Finally, in the third subproblem, we have jointly optimized the altitudes of the UAV-BSs and the power assigned to each subchannel via the proposed iterative optimization method. We have compared our method against two other methods based on SQP. We showed that the proposed method ensures the highest fairness and minimum rate for a given set of users while also being reasonable in terms of computation time.

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