Resource Allocation and UAVs Placement in Cell-free Wireless Networks

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***Abstract*—This paper investigates the use of cell-free unmanned aerial vehicles (UAVs)-assisted wireless networks and optimizes the number of deployed UAVs under quality of service and coverage constraints. The formulated problem tackles the user-UAVs association, UAVs placement, channel assignment and transmit power allocation while considering both access and backhaul networks. Since the problem is a non-convex and non-linear mixed-integer programming, low-complexity efficient greedy-based algorithmic solutions are proposed. The first one finds the UAVs' best positions and allocates resource whereas the second one guarantees the problem feasibility (i.e., all users can be satisfied) by removing the worst users. For comparison purposes, a meta-heuristic solution based on the Particle Swarm Optimization technique is proposed. Simulation results illustrate the efficiency of the proposed algorithms in terms of the number of deployed UAVs in cell-free wireless networks.**

Keywords*—*Cell-free networks, UAV-assisted wireless networks, Particle Swarm Optimisation.

I. Introduction

In recent years, the use of unmanned aerial vehicles (UAVs) in mobile wireless communications has been vastly investigated. Because of its mobility, flexibility and line-of-sight (LoS) channels, UAVs can be deployed as aerial base stations (BSs) to provide larger coverage or as relays to connect multiple nodes over long distances providing significant throughput gains [1], [2]. The joint problem of resource allocation and UAVs placement in UAV-assisted wireless networks has received recently considerable attention in the literature.

The authors in [3] studied the power allocation in UAV-assisted networks and proposed two algorithms. The first is a decoupling-based placement algorithm to obtain the optimal UAVs location when the transmit power is equal for all users. The second is a successive convex approximation-based algorithm for the general case. The objective of [4] is to maximize the number of users by optimizing the UAVs' positions. The results of the two proposed meta-heuristic solutions, genetic (GA) and Particle Swarm Optimization (PSO) algorithms, were shown. Similarly, the work in [5] compared different algorithms, including PSO and GA and artificial bee colony algorithms, to solve the problem of UAVs placement in a post-disaster area where the objective is to maximize the network throughput. In [6], the authors investigated a multi-population GA to find the optimal UAVs positions that maximize the number of satisfied users with different QoS requirements. With the objective of minimizing the number of deployed UAVs in wireless systems, an efficient PSO algorithm was proposed in [7] to find the optimal 3D UAV positions so that the system spectral efficiency respects a given threshold. The authors in [8] proposed a 3D deployment scheme for a similar problem where the different QoS requirements of all users are satisfied. To achieve that, the relationship between the UAV altitude and the coverage was studied then a heuristic algorithm was proposed. In [9], the UAVs placement problem was studied in uneven terrain to provide the network coverage and connectivity services. To solve the formulated problem, which belong to $\mathcal{NP}$-hard, they proposed an efficient PSO algorithm. The authors in [10] proposed a mathematical model to optimize the number of required UAVs and their optimal positions while satisfying users' rate requirements. In [11], the authors proposed a heuristic algorithm to minimize the number of UAVs required to satisfy the users' coverage ratio. In [12], the optimization objective was to minimize the power consumption in an ultra-dense cellular network under transmit power, access network capacity, and QoS constraints. The number and the position of the deployed UAVs were jointly optimized using the PSO method. In [13], the objective was to maximize the coverage radius of each UAV while maximizing the coverage lifetime of the deploying UAVs. This goal was achieved using circle packing theory to determine the locations of UAVs as well as the minimum number of UAVs needed to guarantee a target coverage probability. The problem of minimizing the number of deployed UAVs was also studied in sensor networks with delay constraints using graph theory in [14]. In this scenario, the freshness of the data is essential, so the UAVs' flying time and data collection time must be less than the given thresholds.

This paper proposes efficient heuristic and PSO-based solutions that jointly optimize the horizontal coordinates of multiple UAVs, the transmit power and the user-UAVs association in order to minimize the number of deployed UAVs. To achieve that, we consider a cell-free wireless network where a user can be associated with more than one UAV. Hence, the potential of UAVs to provide effective coverage can be better exploited [5].

The rest of the paper is organized as follows. Section describes the system model. Section III formulates the optimization problem as a non-convex and non-linear mixed-integer programming. The efficient proposed heuristic solutions are described in Sections IV and V. Simulation results are presented in Section VI and Section VII concludes this paper.

II. System Model

This paper considers a wireless communication system deploying UAVs as aerial BSs to serve U ground users. The

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backhaul network is composed of a single ground BS that communicates wirelessly with UAVs. Let $\mathcal{V} = \{1, \ldots, V\}$ and $\mathcal{U} = \{1, \ldots, U\}$ denote the set of UAVs and the set of users, respectively. The coordinates of the ground BS, of UAV v, and of user u are denoted by $(x_{BS}, y_{BS}, 0)$, (x_v, y_v, H) and $(x_u, y_u, 0)$, respectively, where H is the UAVs' height. Each user can be served by multiple UAVs, and each UAV can serve simultaneously multiple users using C_a orthogonal access channels. The backhaul bandwidth B_{BS} is assumed to be equally divided into C_b orthogonal backhaul channels that are orthogonal to the C_a access channels. We assume that C_b is simply equal to the number of deployed UAVs.

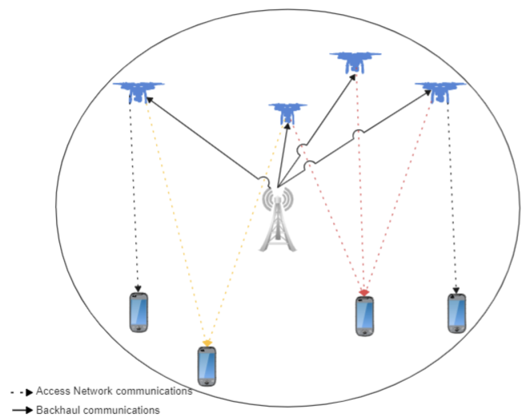

Figure 1 – System model.

A. UAV-user transmissions

Down-link links between UAVs and users are modeled as air-to-ground links [15]. The probability of LoS communication between UAV v and user u is expressed as in [15]:

$$\mathbb{P}_{LoS}^{v,u} = \frac{1}{1 + a\ exp(-b(\theta_{v,u} - a))}, \tag{1}$$

where a and b are constants that depend on the environment. $\theta_{v,u}$ is the elevation angle which is given by:

$$\theta_{v,u} = \frac{180}{\pi} \arcsin\left(\frac{H}{d_{v,u}^{H}}\right), \tag{2}$$

where $d_{v,u}^{H} = \sqrt{(x_v - x_u)^2 + (y_v - y_u)^2}$ is the horizontal distance between UAV v and user u. The channel gain between UAV v and user u is modelled as:

$$g_{v,u} = \left(\frac{\nu}{4\pi f}\right)^2 \frac{1}{d_{v,u}^{\alpha}\left(\mathbb{P}_{LoS}^{v,u}\mu_{LoS} + \mathbb{P}_{NLoS}^{v,u}\mu_{NLoS}\right)}, \tag{3}$$

where $d_{v,u}$ is the euclidean distance between UAV v and user u, $\mathbb{P}_{NLoS}^{v,u} = 1 - \mathbb{P}_{LoS}^{v,u}$ is the probability of non-LoS (NLoS) links, μ_{LoS} and μ_{NLoS} are the mean additional path-loss for LoS and NLoS, α is the path-loss exponent, f is the carrier frequency, and finally ν is the speed of light.

The received data rate at user u connected to UAV v using access channel c is given by:

$$r_{v,u,c}^{access} = B_{v,u} \log_2\left(1 + \frac{p_{v,u,c}\ g_{v,u}}{\sigma^2 B_{v,u} + I_{v,u,c}}\right), \tag{4}$$

where $B_{v,u} = B_v / C_a$ is the allocated bandwidth to user u, B_v is the available bandwidth at UAV v, $p_{v,u,c}$ is the power allocated by UAV v to user u, σ^2 is the power spectral density of the additive white Gaussian noise (AWGN) and $I_{v,u,c}$ is the interference received by user u. $I_{v,u,c}$ is calculated as follows:

$$I_{v,u,c} = \sum_{v' \in \mathcal{V}\setminus\{v\}} \sum_{u' \in \mathcal{U}\setminus\{u\}} p_{v',u',c}\ g_{v',u}\ \gamma_{v',u',c}, \tag{5}$$

where $\gamma_{v,u,c}$ is a binary variable that takes 1 if user u is associated to UAV v using channel c and it takes 0 otherwise.

B. BS-UAV transmissions

To model the backhaul channels, we assume that all links are LoS. Indeed, the propagation environment in the sky can be assimilated to free space. Let $d_{BS,v}$ be the distance between UAV v and the ground BS. The channel gain between the BS and UAV v is given by [16]:

$$g_{BS,v} = \beta_0 / d_{BS,v}^2, \tag{6}$$

where β_0 is the channel gain at the reference distance d_0. The data rate received at UAV v can be given by:

$$r_{BS,v}^{backhaul} = B_{BS,v} \log_2\left(1 + \frac{p_{BS,v}\ g_{BS,v}}{\sigma^2\ B_{BS,v}}\right), \tag{7}$$

where $B_{BS,v} = B_{BS}/C_b$ is the allocated bandwidth between the BS and UAV v, and $p_{BS,v}$ is the BS transmit power to v.

III. Problem Formulation

The objective of the formulated problem is to minimize the number of deployed UAVs while respecting the required data rate by served users. The optimisation variables are the $V \times U \times C$ matrices: $\mathbf{P} = [p_{v,u,c}]$ and $\mathbf{\Gamma} = [\gamma_{v,u,c}]$, and the two V-size vectors: $\mathbf{P'} = [p_{BS,v}]$ and $\mathbf{\Delta} = [(x_v, y_v)]$. To define the optimization problem mathematically, the two following binary variables are introduced:

$$\eta_v = \begin{cases} 1, & \text{if UAV } v \text{ is deployed} \\ 0, & \text{otherwise} \end{cases}, \tag{8}$$

and

$$\mu_{u,c} = \begin{cases} 1, & \text{if user } u \text{ is associated to channel } c \\ 0, & \text{otherwise} \end{cases}. \tag{9}$$

The problem constraints are detailed in the following. Constraints (10) ensure that all users are within the target area which is a circular area represented by its radius R:

$$\sqrt{x_u^2 + y_u^2} \leq R, \quad \forall u \in \mathcal{U}. \tag{10}$$

Constraints (11) guarantee a minimum access data rate requirement denoted by r_{min}:

$$\sum_{v \in \mathcal{V}} \sum_{c \in \mathcal{C}_a} r_{v,u,c}^{access}\ \gamma_{v,u,c} \geq r_{min}, \quad \forall u \in \mathcal{U}. \tag{11}$$

Constraints (12) guarantee that the backhaul rate is at least the sum of users' access rates:

$$r_{b,v}^{backhaul} \geq \sum_{u \in \mathcal{U}} \sum_{c \in \mathcal{C}_a} r_{v,u,c}^{access}\ \gamma_{v,u,c}, \quad \forall v \in \mathcal{V}. \tag{12}$$

Constraints (13) ensures that η_v, $\gamma_{v,u,c}$ and $\mu_{u,c}$ are binary variables:

$$\eta_v, \gamma^c_{v,u}, \mu_{u,c} \in \{0,1\}, \quad \forall u \in \mathcal{U}, \forall v \in \mathcal{V}, \forall c \in \mathcal{C}_a. \tag{13}$$

Constraints (14) indicate that each user can be served by more than one UAV and constraints (15) ensure that each channel is allocated to at most one user:

$$\sum_{v \in \mathcal{V}} \sum_{c \in \mathcal{C}_a} \gamma_{v,u,c} \geq 1, \quad \forall u \in \mathcal{U}, \tag{14}$$

$$\sum_{u \in \mathcal{U}} \gamma_{v,u,c} \leq 1, \quad \forall v \in \mathcal{V}, \forall c \in \mathcal{C}. \tag{15}$$

Constraints (16) and (17) guarantee that each user is served via the same access channel by all associated UAVs.

$$\sum_{c \in \mathcal{C}_a} \mu_{u,c} \leq 1, \quad \forall u \in \mathcal{U}, \tag{16}$$

$$\mu_{u,c} - \gamma_{v,u,c} \geq 0, \quad \forall u \in \mathcal{U}, \forall v \in \mathcal{V}, \forall c \in \mathcal{C}_a. \tag{17}$$

Let p_v and p_{BS} be the available transmit power at UAV v and the ground BS, the power constraints are:

$$\sum_{u \in \mathcal{U}} p_{v,u} \gamma_{v,u,c} \leq p_v, \quad \forall v \in \mathcal{V}, \tag{18}$$

$$p_{v,u} \ \gamma_{v,u,c} \geq 0, \quad \forall v \in \mathcal{V}, \forall u \in \mathcal{U}, \forall c \in \mathcal{C}_a, \tag{19}$$

$$\sum_{v \in \mathcal{V}} p_{BS,v} \leq p_{BS}, \tag{20}$$

$$p_{BS,v} \geq 0, \quad \forall v \in \mathcal{V}. \tag{21}$$

Hence, the problem is formulated mathematically as follows:

$$\underset{\mathbf{P}, \mathbf{P'}, \mathbf{\Gamma}, \mathbf{\Delta}}{\text{minimize}} \quad \sum_{v=1}^{V} \eta_v, \tag{P1a}$$

$$\text{s.t} \quad (11), (12), (13), (14), (15), (16), (17), (18), (19), (20), (21).$$

Problem (P1) is a non-convex and non-linear mixed integer programming problem which cannot be solved by traditional optimization methods in a reasonable time. Hence, in the next section, we propose a heuristic solution to minimize the number of deployed UAVs when the problem is feasible. Next, when the problem is infeasible, we propose a heuristic user selection algorithm to reduce the number of users to satisfy.

Algorithm 1 Greedy UAVs Placement Algorithm (GUPA)

INPUT: User locations, $\mathcal{U}$
Sort users according to distance that separates them
$NSU \leftarrow 0$, $\mathcal{DV} \leftarrow \emptyset$
while $NSU < U$ **and** $DV \leq V$ **do**
  for $u \in \mathcal{U}$ **do**
    if u is not satisfied **then**
      for $v \in \mathcal{DV}$ **do**
        if first time associating u **then**
          if v has enough channels and power **then**
            Choose channel c with minimum power
            $\gamma_{v,u,c} \leftarrow 1$
            $\mu_{u,c} \leftarrow 1$
          end if
        else if v has enough power **then**
          if u already associated to v **then**
            Update $p_{v,u,c}$
          else if channel c is not used **then**
            $\gamma_{v,u,c} \leftarrow 1$
          end if
        end if
      end for
    end if
    calculate $r^{access}_{v,u,c}$
    while u is not satisfied **and** $DV \leq V$ **and** (12) **do**
      $\mathcal{DV} \leftarrow \mathcal{DV} \cup \{v\}$
      sort positions according to $d_{v,u}$
      for the N_{pos} closest positions to u **do**
        if first time associating u **then**
          choose the position and the channel that minimize the allocated power
          $\gamma_{v,u,c} \leftarrow 1$
          $\mu_{u,c} \leftarrow 1$
        else
          choose position that minimizes the allocated power using channel c
          $\gamma_{v,u,c} \leftarrow 1$
        end if
      end for
      update $r^{access}_{v,u,c}$
    end while
  end for
  $NSU \leftarrow NSU + 1$
end while
return DV, NSU

IV. Proposed heuristic Solution

A. Greedy UAVs placement Algorithm

This section assumes that the formulated problem has feasible solutions. Hence, we propose a heuristic algorithm to solve it efficiently. The idea of the proposed algorithm is to find the best positions for deploying UAVs that minimize the necessary transmit power to be used in access links to satisfy the data rate requirement of users. Hence, this reduces the number of deployed UAVs. The pseudo-code of the proposed algorithm is given in Algorithm 1, and it is named Greedy UAVs placement Algorithm (GUPA).

Let NSU be the number of satisfied users, DV be the number of deployed UAVs, and $\mathcal{DV}$ be the set of deployed UAVs. The input of GUPA includes the set of users in the network and their coordinates. It stops when all users are satisfied. First, GUPA places several UAVs around each user until all the constraints of (P1) are satisfied. We denote by N_{pos} the number of available UAV positions around a user. N_{pos} is chosen much smaller than the total number of positions. The algorithm runs iteratively by choosing one user to satisfy at a time. To improve the efficiency, the users are chosen according to their Euclidean distance from each other. In other words, the first user is chosen randomly, but the second user to be served is the closest to the first one and so on. Indeed, the closest user has a higher probability of being satisfied with the already deployed UAVs since it is closer. In lines 5–19, each user tests the associations with already deployed UAVs and associates with the UAVs that may satisfy its data rate constraint. The first time of associating a user, there is no constraints on the channel to be associated with. In this case, the algorithm selects the channel that ensures the minimum allocated power (lines 8–12). Otherwise, the user will add its allocated power from the channel of the UAVs it is already associated with or associate with another UAV on the same channel (lines 13–22). If the deployed UAVs don't allow the user to satisfy its required data rate, a new UAV will be deployed by choosing a position among N_{pos} around that user (lines 21–35) until the constraint (11) is met. The algorithm returns the total number of deployed UAVs, DV. The complexity of GUPA is related to the number of users in the system and the number of UAVs. So the complexity is $O(U \times V \times N_{pos})$.

B. Greedy User Selection Algorithm

Depending on r_{min} and U, the problem might be infeasible. To overcome this, we propose to relax some constraints of (P1), more precisely the constraints (14). In other words, the objective becomes to satisfy the maximum number of users. An iterative user selection algorithm is proposed as a heuristic solution. The pseudo-code of the proposed algorithm is given in Algorithm 2, and it is named Greedy User Selection Algorithm (GUSA).

The algorithm starts by removing the worst user. The worst user can be defined as the user causing the most interference to others or the user associated to the highest number of UAVs. Simulations show in Section VI that defining the worst user as the one causing the most interference provides better performance. Indeed, removing it decreases the interference, and thus more users can be satisfied. At each iteration, The set of users $\mathcal{U}$ is updated by the removal of the worst user and the problem is solved using GUPA with the updated set of users. If all users in $\mathcal{U}$ are satisfied, then it's feasible, and the algorithm stops. Otherwise, GUSA removes the next worst user until the problem becomes feasible.

Algorithm 2 Greedy User Selection Algorithm (GUSA)

```
feasible ← False
while U ≠ ∅ and feasible = False do
    U ← U \ {worst user}
    Execute Algorithm 1
    if U = NSU then
        feasible ← True
    end if
end while
return U, DV
```

V. Particle Swarm Optimization

In PSO, particles move in the search space of the optimization problem, with each particle's position representing a candidate solution. By adjusting its velocity, each particle searches for a better position in the search space. The meta-heuristic PSO is applied to (P1) as follows. A particle i is represented by a matrix X_i with $|V \times C_a|$ rows and two columns. These columns represent the index of the users and the assigned position for each UAV. Hence, X_i represents the association between users and UAVs, and the UAV position.

The PSO algorithm begins by generating random particle positions in a limited search space: the first column that represents the user-UAVs association is generated randomly, and the position of the UAV is chosen from the set of N_{pos} possible positions around the associated user. The particle that provides the best fitness value in all the iterations is recorded as X^{global}, and the best fitness value that each particle has accomplished so far is X_i^{best}. We iteratively compute the velocity V_i^{l+1} and the position X_i^{l+1} of particle i at iteration $l+1$, according to (22) and (23), until a stopping criterion is reached. The velocity update equations are given by:

$$V_i^{l+1} = w^l \, V_i^l + c_1\phi_1(X^{global} - X_i^l) + c_2\phi_2(X_i^{best} - X_i^l), \quad (22)$$

$$w^l = \frac{1+\beta}{\beta + l}, \quad (23)$$

$$X_i^{l+1} = X_i^l + V_i^{l+1}, \quad (24)$$

where c_1 and c_2 are the acceleration coefficients, ϕ_1 and ϕ_2 are two random positive numbers in $[0,1]$, w^l is the inertia weight parameter at iteration l and β is a random value in $[0,1]$. The weight value decreases as the number of iterations increases. It allows the particle to explore more during the first iterations and then exploit the close solutions when approaching the end.

Whenever a particle violates any constraint of (P1), the algorithm adjusts its position so that it complies with all the constraints. For instance, if a user is associated with different channels on different UAVs, it doesn't respect constraints (16) and (17), if there is a possibility for it to be associated with the correct channels on the same UAVs then the correction is done. Otherwise, the user is disassociated from the UAVs. Moreover, the algorithm allocates to each user the power that ensures the minimum required rate. After these corrections, all constraints are met except for constraint (11). Thus, the algorithm uses the penalty method to handle the (11). The fitness function is defined as: $fitness = \sum_{v \in \mathcal{V}} \eta_v + (\delta \times penalty)$, where the penalty parameter δ is set to $\delta = 10^{-6}$. The penalty is defined as:

$$penalty = \sum_{u \in \mathcal{U}} \max \left(\sum_{v \in \mathcal{V}} \sum_{c \in \mathcal{C}_a} r_{v,u,c}^{access} - r_{min} \, , 0 \right). \quad (25)$$

The algorithm stops when a maximum number of iterations is reached or when the solution stops improving.

VI. Simulation Results

This section presents Monte-Carlo simulation results on the minimum number of UAVs to be deployed. The simulation parameters given in Table I are used, unless otherwise mentioned. The target area to cover is modelled as a circular area whose centre is the BS, and the radius R is set to 200 m. The users are distributed randomly and uniformly within the circle. The maximum number of PSO iterations is set to 200.

First, we study the performance of GUPA by varying the number of users in the target area. Fig. 2 shows the average number of UAVs to be deployed under different r_{min} values. It shows that when r_{min} is higher, the network requires a higher number of UAVs in order to satisfy all users. For instance, for the same number of users ($U = 15$), for $r_{min} = 0.6$ b/s/Hz, only 2 UAVs are needed but for $r_{min} = 1$ b/s/Hz, the average number of deployed UAVs is 27.32. We can also observe the benefit of cell-free networks. Considering $U = 10$ users and $r_{min} = 1.2$ b/s/Hz, each user is associated to more than one UAV. Hence, in a traditional network, 10 users won't be able to meet a required rate higher than 1.2 b/s/Hz, and cell-free networks solve that limitation. We are also notice the exponential increase in deployed UAVs especially for a large number of users due to the interference and the data rate constraints.

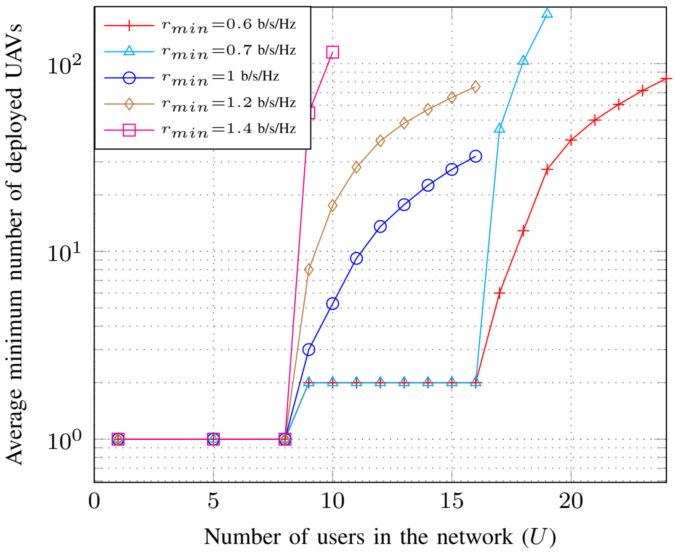

Figure 2 – Number of deployed UAVs for C_a=8.

Fig. 3 shows the feasibility limits of GUPA for different r_{min}. As expected, the curve decreases when r_{min} increases. For $r_{min} = 0.2$ b/s/Hz, the maximum number of users that can be satisfied is 58 and the number decreases until it reaches a plateau for $0.8 \leq r_{min} \leq 1.2$ where only 16 users are satisfied. For higher values of r_{min}, the maximum number of users that can be satisfied decreases again until it reaches 8 where the interference value becomes too high for more than one UAV. The 8 users are each associated with a channel of the single deployed UAV. The figure also shows the impact of a limited back-haul on the feasibility limit. The impact of the back-haul resources is noticeable for $r_{min} > 1$ b/s/Hz. The number of users satisfied is smaller when $B_{BS} = 1$ GHz due to the limited back-haul resources. Indeed, to serve more users, more UAVs have to be deployed but the available bandwidth can only support a limited number of UAVs.

Table I – Notations and value parameters

Notations	Parameters	Values
H	Height at which UAVs fly	100 m
C_a	Number of channels per UAV	8
B_v	Bandwidth of the vth UAV	400 MHz
p_v	Maximum power of vth UAV	3 W
α	Path-loss exponent	2
b, a	Path-loss parameters for urban environment	$0.28, 9.6$
f	Frequency	2 GHz
μ_{LoS}	Mean additional path-loss for LoS	1 dB
μ_{NLoS}	Mean additional path-loss for NLoS	20 dB
β_0	Channel gain at reference distance	-60 dB
B_{BS}	Bandwidth of BS	10 GHz
p_{BS}	Maximum Power of BS	10 W
N_0	Spectral density of AWGN	-174 dBm/Hz
d_0	Reference distance	1 m
c_1, c_2	PSO acceleration coefficients	$2, 2$

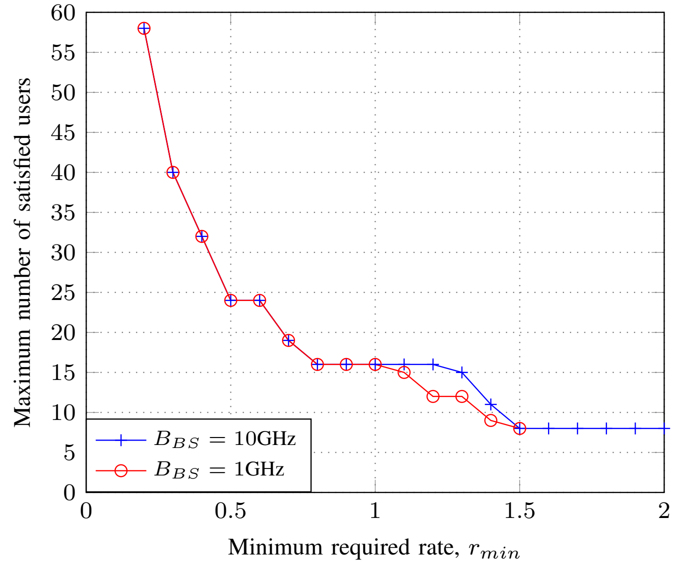

Figure 3 – Feasibility threshold for different values of r_{min}.

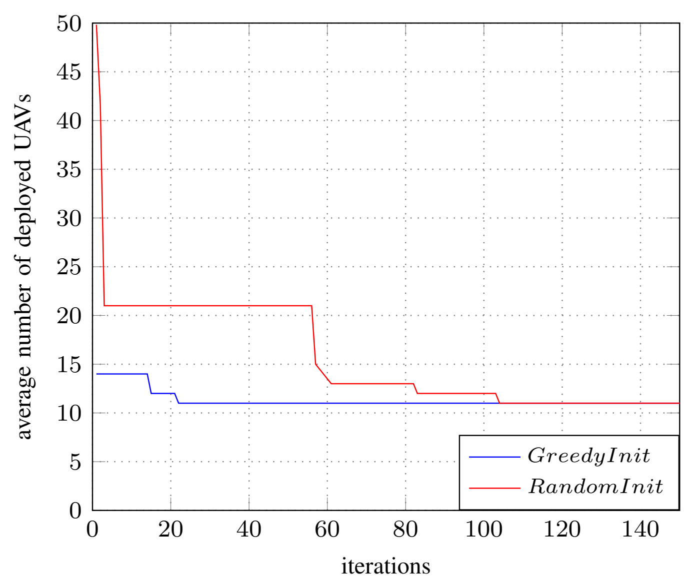

Figure 4 – Convergence of the PSO algorithm ($U = 13$).

Fig 4 shows that the PSO algorithm converges after a certain number of iterations using two initialisation methods. The first considers random initialisation $RandomInit$, and the second uses the greedy algorithm solution for a portion of the initial particles. As expected, $GreedyInit$ converges much faster. This fast convergence shows that the algorithm converges faster when a subset of the initial particle positions is near the optimal positions.

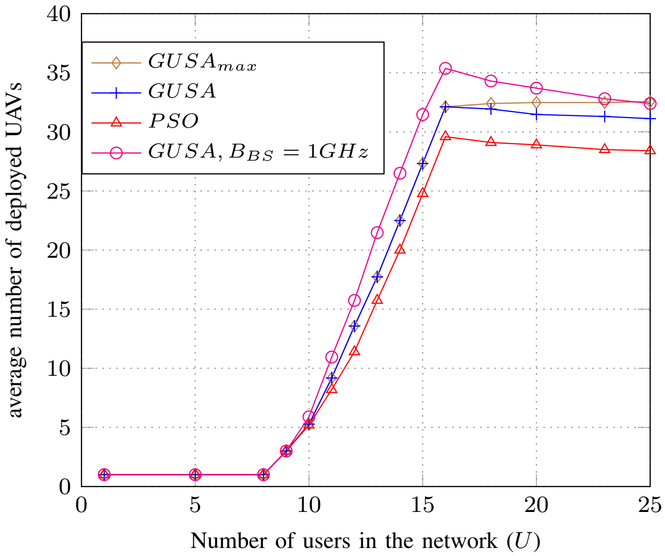

Figure 5 – Number of deployed UAVs for $r_{min} = 1$ b/s/Hz and access bandwidth $B_v = 400$ MHz.

Fig 5 compares the results of two methods to choose the worst user for GUSA and with the PSO algorithm. $GUSA_{max}$ defines the worst user as the user associated with the maximum number of UAVs, and the second variant $GUSA$ defines it as the user causing the most interference. The figure shows that the choice of the worst user made by $GUSA$ decreases the average number of deployed UAVs, compared to $GUSA_{max}$. A comparison between the performances of the GUSA and PSO algorithms is also shown in Fig. 5. The results given by the two algorithms are close, but as expected, the PSO improves the performances for high U. For instance, for $U = 12$, the PSO effectively deploys 16% UAVs less than the heuristic solution. This result shows the efficiency of the heuristic solution.

We can also observe the effect of a limited back-haul on the average number of deployed UAVs. A limited back-haul causes more UAVs to be deployed for the same number of users. That is explained by how the limited back-haul resources affect the positioning of UAVs. To ensure good communication links, the UAVs will be positioned closer to the ground base stations which affects communications between the users and the UAVs. So more UAVs have to be deployed to satisfy all users.

VII. Conclusion

This paper focuses on minimizing the number of deployed UAVs in a wireless cellular network while satisfying the rate requirements of the users. Greedy user association and greedy user selection algorithms are proposed to optimize the position of each UAV in order to deploy a minimal number of UAVs. We also evaluate the performance of the greedy algorithms and compare with a meta-heuristic PSO algorithm. Simulation results show that the performance of greedy algorithms approaches those of the PSO and hence the heuristic algorithm is efficient. In the future, we will propose a reinforcement-learning-based algorithm to solve this problem.

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