Energy Efficient Positioning of Flying Base Stations via Coulomb's law

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***Abstract*—In this paper, we propose an algorithm for an initial positioning of the unmanned aerial vehicles (UAVs) acting as flying base stations (FlyBSs). We target to maximize the FlyBSs deployment efficiency in terms of the number of users satisfied with an experienced data rate and the energy consumed by the FlyBSs to fly to their initial positions. The required data rates of the users, energy consumption of the FlyBSs, and mutual interference among all base stations and users are represented as electrical forces and the initial positions of the FlyBSs are determined via Coulomb's law. In comparison to the state of the art algorithms, the efficiency of the FlyBS deployment is improved at least 2.5 times and, at the same time, the users' satisfaction with the experienced data rate is increased between 6 to 10 %.**

***Index Terms*—UAV, 6G, positioning, satisfaction, energy**

I. Introduction

The growing demands on communication data rates motivate an exploitation of novel solutions to satisfy the users' requirements. One of the options to increase the capacity of the mobile networks is a deployment of an unmanned aerial vehicle (UAV) acting as a flying base station (FlyBS) [1]. The FlyBS differs from a conventional static base station (SBS) by the possibility to adapt its position according to the users' requirements and the network's condition. However, the deployment of the FlyBSs introduces new challenges, such as finding the positions of the FlyBSs, association of the user equipments (UEs) [2], determining the FlyBSs coverage area [3], an allocation of the FlyBS's transmission power [4], providing a sufficient quality of the FlyBSs' backhaul [5], etc.

The determination of the FlyBSs' positions is investigated, for example, in [6], where the authors propose a clustering method for a joint initialization of the FlyBSs' positions and the UEs' association to uniformly distribute a communication load among the FlyBSs. In [7], the authors determine positions of the FlyBSs based on a simple majority rule, i.e., the FlyBSs move to the positions with the highest UE concentration. The FlyBSs are positioned to maximize the average data rate of the UEs and the probability of a successful data transmission. However, neither [6] nor [7] consider any SBSs deployed in the area served by the FlyBSs. The SBS is considered in [22], where the the objective is to maximize the energy efficiency (bits per Joule), but the SBS operates on a separate bandwidth. Therefore, no mutual interference is considered, but the interference influences the deployment of the FlyBSs as shown, for example, in [8] with FlyBSs acting as relays.

A solution for deployment of the FlyBSs in a scenario with a single SBS is provided in [9], where the authors propose an algorithm for the positioning of the FlyBSs in order to offload the traffic from the SBS. The solution is based on Coulomb's law with the objective to minimize the number of deployed FlyBSs while satisfying a minimum signal to noise ratio (SNR) for all UEs. However, the authors assume that each SBS and FlyBS operate in separated frequency bands and do not mutually interfere with each other. The FlyBS deployment with interference consideration is shown in [10]. The authors exploit antenna tilting to minimize the interference. The interference is also considered by the authors in [11], where one FlyBS flies cyclically along the cell edge, i.e., in the area with a low interference from nearby SBSs, and opportunistically offloads the traffic from the cell edge UEs in a periodic intervals, when the FlyBS flies above the cell edge UEs. However, the UE data rate requirements are taken into account neither in [10] nor [11].

Deployment of the SBSs together with the guaranteed minimum UEs' data rate is considered in [12]. The authors exploit Gaussian Mixture Model (GMM) and weighted GMM (W-GMM) to create models of the UEs' spatial distribution and a time-spatial distribution of data rate requirements of the UEs, respectively. In the W-GMM, the data rate requirements of the UEs represent the weights. The number of FlyBSs that should be deployed is determined iteratively, by increasing the number of the FlyBSs until the ratio of an intra-cluster distances (from UEs to FlyBSs) to an inter-cluster distances (among FlyBSs) is minimized. This work is extended in [13] by a framework covering four stages of the FlyBSs deployment. The first stage (learning) serves to estimate a distribution of the UEs and a traffic demands. In the second stage (association), the overloaded SBS requests service of the FlyBSs. Within the third stage (movement), the FlyBSs move to a determined locations. The last stage (service) is understood as the stage when the FlyBSs provide connectivity to the UEs. The authors also consider the energy consumption of the FlyBSs to maximize the utility of the deployed FlyBS.

Nevertheless, neither mutual interference among the FlyBSs nor between the FlyBSs and the SBSs is considered in any of [9], [11]–[13]. The interference, however, plays a key role in

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the deployment of the FlyBSs as it leads to a channel quality degradation of the UEs, which are served by the SBSs or by other FlyBSs. In [9], [11]–[13], the interference cannot be directly considered, due to the design of the proposed algorithms as the consideration of the interference would significantly change the problem and the related solutions.

Therefore, we propose a novel solution that maximizes an efficiency of the FlyBSs deployment, i.e., maximizes the number of UEs satisfied with the provided data rate while considering the energy consumed by the FlyBSs to reach their initial positions. The proposed solution determines the initial positions of the FlyBSs via the Coulomb's law to meet the UEs' data rate requirements and to minimize interference to other UEs. With respect to the existing works, we assume all BSs (including both SBSs and FlyBSs) operate at the same frequency, thus, interfering with each other. Moreover, we also consider the UEs' data rate requirements to maximize the ratio of the UEs satisfied with their experienced data rates.

The rest of the paper is organized as follows. In Section II, we outline a system model and define the problem. In Section III, a novel solution for the FlyBS positioning is described. In Section IV we compare the proposed algorithm with the state of the art works and conclude the paper in Section V.

II. System model and problem formulation

In this section, we describe the system model and formulate the problem addressed in this paper.

A. System model

We consider a set $\mathbb{K}^s$ consisting of N^s SBSs. Together with the SBSs, a set $\mathbb{K}^f$ consisting of N^f FlyBSs is deployed. The sets of SBSs and FlyBSs form a set of all base stations (BSs) $\mathbb{K}^a = \mathbb{K}^s \cup \mathbb{K}^f$ with the cardinality N^a. The positions of all BSs in 3D space are defined by a set $\mathbb{L}^{\mathrm{BS}}$, where the BS $k \in \mathbb{K}^a$ is located at (x_k, y_k, z_k). When not deployed, the FlyBSs are "parked" at the base camp positions denoted as $\mathbb{L}^{\mathrm{FlyBS}}$. The BSs provide a downlink connectivity to a set $\mathbb{U}$ consisting of N^u UEs. The positions of the UEs in 3D space are defined as a set $\mathbb{L}^{\mathrm{UE}}$, where the UE $u \in \mathbb{U}$ is located at (x_u, y_u, z_u). The UE u requires the communication data rate c_u^{req}. The communication bandwidth $b_{uk} \in \langle 0, B_k^{\max} \rangle$, where $B_k^{\max}$ is the bandwidth available at the BS k, is allocated to the UE u at the BS k. The UE u is associated to the BS k if $b_{uk} > 0$. The data rate of the UE u is calculated as:

$$c_u = \sum_{k \in \mathbb{K}^a} b_{uk} log_2 \left(1 + \frac{P_k^{\mathrm{tx}} h_{uk}\left(l_u^{UE}, l_k^{\mathrm{BS}}\right)}{\sum_{l \in \mathbb{K}^a, l \neq k} P_l^{\mathrm{tx}} h_{ul}\left(h_{ul}\right) + \sigma^2} \right) = \sum_{k \in \mathbb{K}^a} b_{uk} log_2 \left(1 + \gamma_{uk}\left(l_u^{UE}, l_k^{\mathrm{BS}}\right)\right) \quad (1)$$

where P_k^{tx} is the transmission power of the BS k, $h_{uk}\left(l_u^{UE}, l_k^{\mathrm{BS}}\right)$ denotes the channel gain between the UE u and the BS k at their respective positions l_u^{UE} and l_k^{BS}, σ^2 denotes the power of the additive white Gaussian noise, and $\gamma_{uk}\left(l_u^{UE}, l_k^{\mathrm{BS}}\right)$ is Signal to Interference plus Noise (SINR) observed by the UE u served by the BS k for the given UEs and BSs positions. Furthermore, we define the number of UEs satisfied with their data rate in a case when the FlyBSs are deployed as:

$$\phi^{FlyBS} = \sum_{u \in U} \left[c_u \geq c_u^{\mathrm{req}}\right] \quad (2)$$

where the operator [.] is equal to 1 if $c_u \geq c_u^{\mathrm{req}}$, otherwise it is equal to 0. In similar way, we define the number of UEs satisfied with their data rates if only SBS are deployed:

$$\phi^{SBS} = \sum_{u \in U} \left[c_u^{\mathrm{SBS}} \geq c_u^{\mathrm{req}}\right] \quad (3)$$

where c_u^{SBS} is the data rate of the UE u only with the SBSs deployed ($\mathbb{K}^f$ is empty) .

All BSs (SBSs and FlyBSs) communicate with the UEs in the same band to maximize the frequency reuse. Therefore, the transmissions of the BSs interfere with each other. Such situation represents the most challenging scenario in terms of interference. The UE is associated to the BS with the highest SINR (assumed in [14]). All FlyBSs provide line of sight communication [2] as the coverage area provided by the FlyBS is small and FlyBSs operate outdoor [15]. The UE is allocated bandwidth to meet its data rate requirements. The bandwidth allocation starts with the UE that experiences the highest SINR and ends when the BS does not have enough bandwidth to satisfy the next UE or does not have any bandwidth left.

The initial energy available for the FlyBS k is denoted as E_k and the energy consumed by the FlyBS k to move from the position l_k^{BS} to a new position l_k^{FlyBS} is denoted as $e_k\left(l_k^{BS}, l_k^{\mathrm{FlyBS}}\right)$. In this paper, we follow a FlyBS energy consumption model defined in [16] assuming that the FlyBS flies with a constant speed corresponding to a maximum endurance to minimize the energy consumption during the FlyBS movement in line with [13], [16] and [17].

B. Problem formulation

The objective of this paper is to maximize the FlyBSs deployment efficiency, i.e. the number of UEs additionally satisfied with data rates thanks to the deployed FlyBSs with respect to the energy spent by the FlyBSs to reach the initial position, where service is provided. We determine the initial positions of the FlyBSs $\mathbb{L}^{FlyBS^*}$ by searching over all possible positions $\mathbb{L}$. The problem is, then, formulated as:

$$\mathbb{L}^{\mathrm{FlyBS}^*} = \underset{\mathbb{L}}{\operatorname{argmax}} \left(\phi^{FlyBS} - \phi^{SBS}\right) \sum_{k \in \mathbb{K}^f} \frac{E^k}{e_k\left(l_k^{BS}, l_k^{\mathrm{FlyBS}}\right)} \quad (4)$$

$$\text{s. t.} \sum_{u \in U} b_{uk} \leq B_k, \forall k \in \mathbb{K}^a, \quad (5)$$

$$b_{uk} \in \langle 0, B_k \rangle, \quad (6)$$

$$e_k\left(l_k^{BS}, l_k^{\mathrm{FlyBS}}\right) \leq E^k, \forall k \in \mathbb{K}^f, \quad (7)$$

The constraint (5) limits the allocated bandwidth to the maximum available bandwidth at each BS, (6) provides the bounds for the amount of bandwidth allocated to individual UEs, and (7) limits the energy that can be consumed by the FlyBS to reach its initial position.

III. Proposed solution

In this section, we describe the proposed solution that finds the initial positions of the FlyBSs to maximize the efficiency of the FlyBSs deployment. With respect to existing works, we consider interference experienced by the UEs from all FlyBSs and SBSs (except the serving BS). The extension of the existing work to consider the interference is not directly possible, as it significantly changes the system model either by requiring different forces and convergence criteria in [9] or by different approach in case of W-GMM [13]. Our proposed solution is based on the Coulomb's law. In the next subsection, we describe the determination of the target UEs for each FlyBS (i.e., the set of UEs to be served by the given FlyBS). Afterwards, we explain the proposed initial positioning of the FlyBSs via forces. Last, we integrate both parts (target UEs determination and initial positioning) into a single algorithm.

A. Determination of the set of UEs served by each FlyBS

For each FlyBS it is necessary to determine a set $\mathbb{U}_k^{FlyBS}$ of the target UEs to be served by the given FlyBS. Without this set, the FlyBS would be attracted to all unsatisfied UEs even though only a part of these UEs can be served due to signal propagation path loss and interference. The set of target UEs is created by clustering the unsatisfied UEs based on their density without apriori knowledge of the number of the clusters. The number of available FlyBSs can be exploited to set the number of clusters, as it is done in [13]. However, the deployment of all FlyBSs is not always necessary as the unsatisfied UEs can be, sometimes, served by a lower number of FlyBSs or not all UEs can be satisfied by the FlyBSs anyway due to interference.

The UE clustering is done via a density based clustering algorithm, in our case MeanShift clustering algorithm [18], as the UEs in the same cluster should be close to each other to be served by a single FlyBS. The MeanShift algorithm determines the sets of UEs' clusters $\{\mathbb{U}_1^{\text{clust}}, \mathbb{U}_2^{\text{clust}}, \dots, \mathbb{U}_{N^{\text{clust}}}^{\text{clust}}\}$, where N^{clust} is an apriori unknown number of clusters. For each cluster, a metric m, consisting of ratio between sum of the data rate requirements in the cluster to ratio of energy to total FlyBS energy consumed to reach the cluster is calculated. The metric represents energy efficiency of deploying a FlyBS (similar to (4)) to the cluster center, and is calculated as follows:

$$m_i = \frac{E^k \sum_{u \in \mathbb{U}_i^{\text{clust}}} c_u^{\text{req}}}{e_k\left(l_i^{BS}, l_k^{\text{FlyBS}}\right)} \tag{8}$$

where $i \in \{1, \dots, N^{\text{clust}}\}$, and l_i^{BS} is the gravity center of the i-th cluster derived according to [1].

Then, the cluster i^* with the highest metric is selected and served first:

$$i^* = \underset{i \in \{1,\dots,N^{\text{clust}}\}, m_i > \epsilon}{\operatorname{argmax}} \; m_i \tag{9}$$

Note that the clusters with m_i below ϵ are not considered to be served, to avoid the deployment of FlyBS to the places, where (4) is too low or (7) is not met. The set of target UEs is then created as $\mathbb{U}_k^{FlyBS} = \mathbb{U}_{i^*}^{\text{clust}}$.

B. Positioning of the FlyBS via forces

The proposed solution for positioning of the FlyBSs is based on the Coulomb's law, which describes forces between electrically charged particles. The particles, based on their electrical charge, either attract (opposite sign of the electrical charges) or repulse (same sign of electrical charges) each other. The force between the particles 1 and 2 at positions r_1 and r_2 is defined as:

$$\overrightarrow{F_{12}} = \alpha^c \frac{q_1 q_2 \bar{r}_{21}}{|\overrightarrow{r}_{21}|^2} \tag{10}$$

where α^{c} is the Coulomb's constant, q_1 and q_2 are the electrical charges of the particles, $\overrightarrow{r}_{21} = r_1 - r_2$ is the vector between the particles, and $\bar{r}_{21} = \frac{\overrightarrow{r}_{21}}{|\overrightarrow{r}_{21}|}$ is a unit vector.

The Coulomb's law for the positioning of the FlyBSs is applied by transforming the objective function (4) and constraints into the forces. The UEs with the data rate lower than the required data rate, i.e., $c_u < c_u^{\text{req}}$, attract the FlyBSs. The attractive force does not directly translate to the UE being served by the FlyBS, as the FlyBS is positioned to maximize (4). The attraction force of the FlyBS k to the UE u is calculated as:

$$\overrightarrow{F}_{uk}^{\text{a}} = \alpha^{\text{a}} c_u^{\text{req}} |\overrightarrow{r}_{ku}| \tag{11}$$

where α^{a} is the multiplicative constant to normalize the force, $\overrightarrow{r}_{ku} = l_k^{\text{FlyBS}} - l_u^{\text{UE}}$ is the vector between the FlyBS k at the position l_k^{FlyBS} and the UE u at the position l_u^{UE}. Note the inverse dependency on the distance in comparison to the Coulomb's law, to avoid the force reaching infinity for a close UE.

To reflect the energy consumed for flying, the FlyBS is attracted to its base camp position l_k^{FlyBS} with:

$$\overrightarrow{F}_k^{\text{e}} = \alpha^{\text{e}} |\overrightarrow{r}_k^{\text{init}}| \tag{12}$$

where α_{e} is the multiplicative constant to normalize the force, $\overrightarrow{r}_k^{\text{init}} = l_k^{BS} - l_k^{\text{FlyBS}}$ is the vector between the FlyBS k at position l_k^{BS} and its base camp position l_k^{FlyBS}. Note that $\overrightarrow{F}_k^{\text{e}}$ increases with the distance of the FlyBS from its base camp.

The FlyBSs are repulsed by the UEs, which are satisfied with the provided data rate, i.e., $c_u \geq c_u^{\text{req}}$, because the new FlyBS deployed close to these UEs would increase interference in the area. The repulsion force is defined as:

$$\overrightarrow{F}_{uk}^{\text{r}} = \alpha^{\text{r}} \frac{c_u^{\text{req}}}{|\overrightarrow{r}_{ku}|} \tag{13}$$

where α^{r} is the multiplicative constant to normalize the force, and $\bar{r}_{ku} = \frac{\overrightarrow{r}_{ku}}{|\overrightarrow{r}_{ku}|}$ is a unit vector. The repulsion force, increases with a decreasing distance, as a lower distance leads to a higher interference to other UEs.

The FlyBSs also repulse each other as their close distance to each other causes additional interference to the UEs. The repulse force on the FlyBS k is expressed as:

$$\overrightarrow{F}_k^{\text{o}} = \alpha^{\text{o}} \sum_{j \in K^f, j \neq k} \frac{\sum_{u \in \mathbb{U}_j^{\text{FlyBS}}} c_u^{\text{req}}}{|\overrightarrow{r}_{kj}|} \tag{14}$$

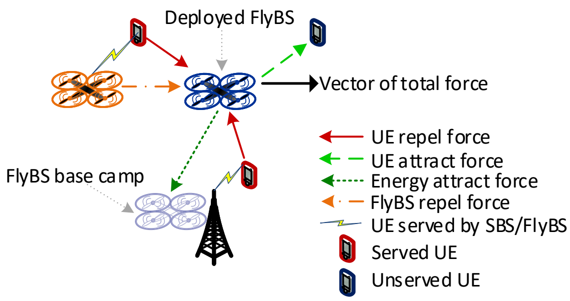

Fig. 1. Minor forces forming the total force on the deployed FlyBS.

where α^{o} is the multiplicative constant to normalize the force, $\overrightarrow{r}_{kj}$ is the vector between the FlyBSs j and k positions.

The total force applied to the FlyBS k is then calculated as:

$$\overrightarrow{F}_k = \overrightarrow{F}^{\mathrm{e}}_k + \sum_{u \in \mathbb{U}_k^{FlyBS}} \overrightarrow{F}^{\mathrm{a}}_{uk} + \sum_{u \in \mathbb{U} \setminus \mathbb{U}_k^{FlyBS}} \overrightarrow{F}^{\mathrm{r}}_{uk} + \overrightarrow{F}^{\mathrm{o}}_k \quad (15)$$

All the forces affecting the FlyBS are shown in Figure 1. In this figure, the FlyBS determines, where to position itself based on the forces exerted from the UEs, other FlyBSs, and the FlyBS base camp.

C. Proposed algorithm for FlyBS deployment

The proposed algorithm for determination of the initial position of the FlyBSs based on the Coulomb's law is described in Algorithm 1. In the first step, the algorithm checks if there exists at least one UE that is not satisfied (line 1). If there is at least one unsatisfied UE, the initial positions of the FlyBSs are determined. First, variables j, representing an index of the FlyBS to deploy, and α_j^f, controlling a magnitude of the total force, i.e., how far is the FlyBS "pushed" by the force, are initialized. Then the FlyBSs positions are determined by the algorithm (loop lines 3 to 33).

The position of the FlyBS is updated if α_k^f is non zero (line 5), otherwise, the FlyBS is kept at the same position. If the FlyBS is at its base camp (line 6), the set of the target UEs for the FlyBS is determined (line 7). If the target set is empty (lines 8 to 10), the FlyBS is not deployed and the algorithm ends, otherwise the FlyBS is positioned to the gravity center of the set $\mathbb{U}_k^{FlyBS}$ (line 11) and previous total force of the FlyBS $\overrightarrow{F}^{\mathrm{prev}}_k$, used later to improve convergence of the algorithm, is initialized (line 12).

The total force applied to the FlyBS is determined via (15) (line 14). Then, to improve the convergence of the algorithm, we check whether the angle β between the total force and the previous total force is higher than $\frac{\pi}{2}$ (lines 15 to 20). If $\beta > \frac{\pi}{2}$, the FlyBS is close to its targeted initial position and α_k^f is divided by a constant ϵ_{f} (line 18). The convergence is achieved, as the vector of the total force near the FlyBS initial position changes angle to opposite direction.

Based on the derived forces, the position of the FlyBS is updated (line 21) and the previous total force is updated as well (line 22). After the positions of all the FlyBSs are updated, the UEs are allocated with the bandwidth (line 25). As the bandwidth allocation is not the objective of this paper, we follow the allocation proposed in [19]. The algorithm is stopped if all UEs are satisfied (line 26). If there are still unsatisfied UEs, the algorithm continues by deploying additional FlyBSs, if available. In a case when an additional FlyBS is deployed, channel quality of the UEs change due to additional interference and the already deployed FlyBSs are re-positioned to adapt to the changed environment. The additional FlyBS is deployed when α_k^f is zero for all FlyBSs up to FlyBS j (line 29), i.e., all FlyBSs up to j has already converged to their initial positions. Then, index j is increased (line 30), and α_i^f is set to 1 for all indices up to j (line 31).

Algorithm 1 Positioning of the FlyBSs.

1: **if** $\exists u, \sum_{j \in \mathbb{K}^b} c_u < c_u^{\mathrm{req}}$ **then**
2: $\quad j \leftarrow 1$, $\alpha_j^f \leftarrow 1$
3: $\quad$ **while** (true) **do**
4: $\quad\quad$ **for** each k in $\mathbb{K}^f$ **do**
5: $\quad\quad\quad$ **if** $\alpha_k^f > 0$ **then**
6: $\quad\quad\quad\quad$ **if** $l_k^{\mathrm{BS}} = l_k^{\mathrm{FlyBS}}$ **then**
7: $\quad\quad\quad\quad\quad$ Determine $\mathbb{U}_k^{FlyBS}$ via (9)
8: $\quad\quad\quad\quad\quad$ **if** $\mathbb{U}_k^{FlyBS}$ is empty **then**
9: $\quad\quad\quad\quad\quad\quad$ break
10: $\quad\quad\quad\quad\quad$ **end if**
11: $\quad\quad\quad\quad\quad$ $l_k^{\mathrm{BS}} \leftarrow$ gravity center of the cluster [1]
12: $\quad\quad\quad\quad\quad$ $\overrightarrow{F}^{\mathrm{prev}}_k \leftarrow 0$.
13: $\quad\quad\quad\quad$ **end if**
14: $\quad\quad\quad\quad$ Determine $\overrightarrow{F}_k$ applied to the k via (15)
15: $\quad\quad\quad\quad$ **if** $\left|\overrightarrow{F}^{\mathrm{prev}}_k\right| > 0$ **then**
16: $\quad\quad\quad\quad\quad$ $\beta \leftarrow \arccos \frac{\overrightarrow{F}_k \cdot \overrightarrow{F}^{prev}_k}{\left|\overrightarrow{F}_k\right| \cdot \left|\overrightarrow{F}^{\mathrm{prev}}_k\right|}$
17: $\quad\quad\quad\quad\quad$ **if** $\beta \geq \frac{\pi}{2}$ **then**
18: $\quad\quad\quad\quad\quad\quad$ $\alpha_k^{\mathrm{f}} \leftarrow \frac{\alpha_k^{\mathrm{f}}}{\epsilon_{\mathrm{f}}}$
19: $\quad\quad\quad\quad\quad$ **end if**
20: $\quad\quad\quad\quad$ **end if**
21: $\quad\quad\quad\quad$ $l_k^{\mathrm{BS}} \leftarrow l_k^{\mathrm{BS}} + \alpha_k^{\mathrm{f}} \frac{\overrightarrow{F}_j}{|\overrightarrow{F}_j|}$
22: $\quad\quad\quad\quad$ $\overrightarrow{F}^{\mathrm{prev}}_k \leftarrow \overrightarrow{F}_k$
23: $\quad\quad\quad$ **end if**
24: $\quad\quad$ **end for**
25: $\quad\quad$ Allocate bandwidth [19]
26: $\quad\quad$ **if** $\nexists u, \sum_{j \in \mathbb{K}^b} c_u \leq c_u^{\mathrm{req}}$ **then**
27: $\quad\quad\quad$ break
28: $\quad\quad$ **end if**
29: $\quad\quad$ **if** $\nexists \alpha_i^f > 0, i \in \{1, 2, \ldots, j | j < N^f\}$ **then**
30: $\quad\quad\quad$ $j \leftarrow j + 1$
31: $\quad\quad\quad$ $\alpha_i^f \leftarrow 1, i \in \{1, 2, \ldots, j\}$
32: $\quad\quad$ **end if**
33: $\quad$ **end while**
34: **end if**

TABLE I
SIMULATION PARAMETERS.

Parameter	Value
Simulation area	800 m x 800 m
Carrier frequency	2 GHz
Number of UEs/SBSs/FlyBSs	200/2/3 or 6
Tx power of SBS/FlyBS	23/15 dBm
Bandwidth of SBS/FlyBS	100/100 MHz
SBS/FlyBS/UE height	30/30/1.5 m
$\alpha^{\mathrm{a}}/\alpha^{\mathrm{r}}/\alpha^{\mathrm{o}}/\alpha^{\mathrm{e}}/\epsilon_{\mathrm{f}}$	1/1/1/1/2
FlyBS speed (yielding max. endurance)	10.21 m/s
E_k	2000 J
Number of simulation drops	100 drops

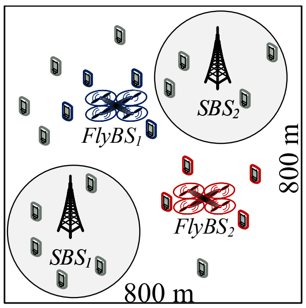

Fig. 2. Simulation area with deployment of the SBSs and FlyBSs and UEs served by each BS.

IV. SIMULATION SCENARIO AND PERFORMANCE EVALUATION

The performance of the proposed solution and the competitive algorithms is evaluated out via simulations in MATLAB.

A. Simulation scenario

The simulation area of 800 x 800 m (Figure 2) includes two SBSs deployed at the positions [200 200, 600 600]. The SBSs are deployed to consider a scenario with an existing infrastructure. The UEs are deployed homogeneously within the whole simulation area. The FlyBS are deployed according to the following algorithms:

- *Proposal* – the proposed algorithm considering UE data rate requirements and interference.
- *W-GMM* according to [13] – for each SBS, the FlyBSs are placed to the centers of the W-GMM.
- *Force3D* according to [9] – FlyBSs are positioned following Coulomb's law, but interference, energy consumption of the FlyBSs, and data rate requirements not considered.
- *no FlyBS* – situation with no FlyBSs.

The major simulations parameters are summarized in Table I. A signal propagation for the SBSs is modeled according to [20] with path loss model $PL = 128.1 + 37.6 log_{10} d$, where d is the Euclidean distance between the SBS and the UE. For the FlyBS, we select commonly used path loss model from [15] with parameters of the Suburban environment from [21]. The energy consumption model of the FlyBSs follows [16] with speed of FlyBSs equal to its maximal endurance speed. The multiplicative constants α^{a}, α^{r}, α^{o}, and α^{e} are set to 1. Note that each can be adapted to a given environment, but such optimization is left for future research.

B. Performance evaluation

In this section, we evaluate performance of the proposed solution in terms of the gain in the UEs' satisfaction, energy consumption, and FlyBS's deployment efficiency (see (4)).

In Figure 3a, we show the UE satisfaction gain in comparison to no FlyBS case with their experienced data rates. The UE is considered as satisfied if $c_u \geq c_u^{req}$ (see (5)). The Force3D algorithm performs even slightly worse than if no FlyBS is deployed and less UEs are satisfied than if no FlyBS is deployed (-0.3 % and -1.3% for 3 and 6 FlyBS) as mutual interference among FlyBSs and UE data rate requirements are not considered. The W-GMM algorithm for c_u^{req} 3 Mbit/s and higher provides a gain with respect to no FlyBS up to 3.4 % and 5.7 % for 3 and 6 FlyBSs, respectively. However, for c_u^{req} below 3 Mbit/s, the UE satisfaction gain is negative (up to -1.1 %), as the interference is not taken into account. The proposed solution provides gain of up to 9.2 % for 3 FlyBSs and up to 15.8 % for 6 FlyBSs. The gain of the proposal increases with c_u^{req}, as there are more unsatisfied UEs that can be satisfied via the FlyBSs deployment. In comparison to the Force3D and W-GMM, the proposed solution improves the UE satisfaction by up to 17 and 10 percent points, respectively.

The ratio of energy consumed by the FlyBSs to reach their designed initial positions, i.e., $\frac{e_k}{E_k}$, is shown in Figure 3b. The Force3D algorithm consumes less than 11 % and 6% of the available energy for 3 FlyBS and 6 FlyBSs, respectively. However, this is at the cost of even a decreased satisfaction (as shown in Figure 3a), i.e., there is no benefit of the FlyBSs' deployment. The W-GMM consumes about 17-18 % of the FlyBS available energy for both 3 and 6 deployed FlyBSs. Nevertheless, the W-GMM provides only minor satisfaction improvement (less than 1.5 percent point) or even decreases the UEs' satisfaction (up to 1 percent point). For both, the Force3D and W-GMM algorithms, the energy consumption is almost constant for all c_u^{req}, as the FlyBSs are placed to very similar positions, because mutual interference among FlyBSs is neglected. The proposed solution consumes less than 28 % of FlyBSs energy for low c_u^{req}. With increasing c_u^{req}, the energy consumed by the proposed solution decreases to 18 and 19 % for 3 and 6 FlyBSs, respectively. The ratio of the consumed energy decreases with an increased number of the deployed FlyBSs for the proposed solution, as there are more unsatisfied UEs closer to the FlyBSs base camps. Note that the energy consumed for the FlyBS can be controlled via (8), but an optimization of this aspect is left for future research.

In Figure 3c, we show the FlyBS deployment efficiency, that expresses how efficiently the FlyBSs spend their energy (similar to [22]), i.e., number of UEs satisfied by the FlyBS (see (2)) to the energy consumed by the FlyBS to reach its initial position, where the UEs are served, as defined in the objective (4). Figure 3c illustrates the relative efficiency of the FlyBSs deployment with respect to the case with no FlyBSs. The figure indicates if is beneficial to deploy the FlyBSs

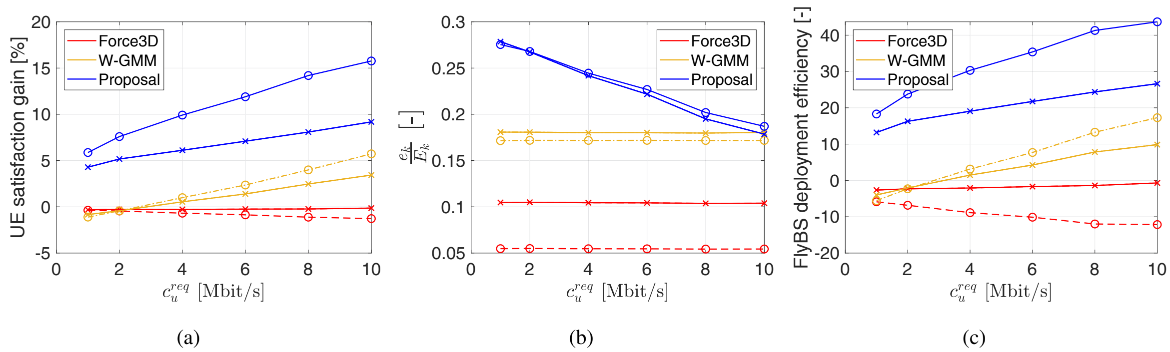

Fig. 3. UE satisfaction gain (a), FlyBS energy consumed ratio (b), objective function (c). Marker "x" denotes 3 FlyBSs, "o" denotes 6 FlyBS.

(positive value) or exploit only SBSs (negative value). The Force 3D reaches a negative objective value, i.e, the energy of the FlyBSs is wasted, as the UEs satisfaction is not improved in comparison to the no FlyBS case. The W-GMM results in a positive value of the objective function for c_u^{req} above 3 Mbit/s, where the W-GMM is able to increase the UE satisfaction in comparison to the no FlyBS case (see Figure 3a). The proposed solution provides at least 2.5 times higher objective value in comparison to the W-GMM, i.e., the energy spent by the FlyBS to serve the unsatisfied UEs is exploited at least 2.5 more efficiently by the proposal. If the number of the FlyBSs is increased from 3 to 6, the objective value for the Force3D algorithm decreases (as interference is not considered), but increases for the W-GMM (due to increased the UEs' satisfaction) and, even more notably, for the proposal due to not deploying FlyBSs when not necessary.

V. Conclusion

In this paper, we have proposed an algorithm for the initial positioning of the FlyBSs to maximize the FlyBSs deployment efficiency, i.e., the ratio of the satisfied UEs to the energy consumed by the FlyBSs. We consider interference among all base stations including the FlyBSs and requirements of the UEs. The proposed solution is based on the Coulomb's law and translates the problem into a relation among repulsion and attraction forces affecting the FlyBSs. The proposed algorithm, in comparison to the state-of-the-art solutions, improves the FlyBSs' deployment efficiency at least 2.5 times and, at the same time, the users' satisfaction with the experienced data rate is increased 6 to 10 %.

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