Power Allocation, Channel Reuse, and Positioning of Flying Base Stations with Realistic Backhaul

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***Abstract*—While an integration of flying base stations (FlyBSs) into future mobile networks has received plenty of attention, a backhaul link (i.e., the link between a static base station and the FlyBS) is often either fully disregarded or oversimplified. However, the backhaul link and an access link between the FlyBS and users should be managed together to exploit radio resources efficiently. Thus, we introduce a novel framework considering the FlyBSs with a realistic backhaul to maximize the sum capacity of the users. First, we propose a scheme for an association of the users and a transmission power allocation. Thus, we derive a closed-form expression for the optimal allocation of the FlyBSs' transmission power to individual users to utilize the radio resources at the backhaul and access links in an efficient way. Second, we develop an algorithm for a re-positioning of the FlyBSs and a re-allocation of the FlyBSs' transmission power to further improve the overall sum capacity. Third, we design a scheme reusing the access links by multiple users in the coalitions to reduce the FlyBSs' transmission power. The reduced transmission power allows to further increase the sum capacity of the users via an additional re-positioning of the FlyBSs. Alternatively, the reduced transmission power also lowers the level of interference experienced by the underlying devices not communicating via the FlyBSs. Our proposal increases the sum capacity of the users by up to 60% while suppresses the interference to the underlying devices by up to 7.7 dB compared to the state-of-the-art schemes.**

***Index Terms*—Flying base station, power allocation, association of users, positioning, backhaul, coalitions, channel reuse**

I. Introduction

The integration of the flying base stations (FlyBSs) into mobile networks is a feasible way to cope with the high density of users and dynamicity of the network [1]. The FlyBS acts as a relay between a conventional terrestrial static base station (SBS) and a user equipment (UE). In such a scenario, the UEs receive/transmit data from/to the FlyBS over an access link and the FlyBS relays the UEs' data to/from the SBS via a backhaul link.

The incorporation of the FlyBSs into future mobile networks introduces many challenges [2] spanning over a coverage maximization by the FlyBSs [3][4], a deployment of the FlyBSs [5]-[8], a UEs' association [9]-[12], or various radio resource management problems, such as power control or resource allocation [13]-[16]. A majority of the existing works, however, *neglect the backhaul link* between the FlyBSs and the SBSs. Still, the backhaul link significantly influences a performance of the solutions developed for the above-mentioned challenges.

The maximization of the communication capacity by means of the FlyBS's positioning while considering the backhaul with a limited capacity is addressed in [17] and [18]. Nevertheless, both [17] and [18] assume the backhaul with a predefined fixed capacity, which is independent of the FlyBS's position. Unfortunately, such an assumption is not realistic as the capacity of the backhaul directly depends on an allocated bandwidth and the backhaul's channel quality. Hence, the backhaul capacity should naturally be a function of the FlyBS's position.

The backhaul using out-band frequencies is considered in [19]-[22]. In [19], the authors provide a novel mathematical framework capturing essential features of a millimeter-wave (mmWave) backhaul in an urban environment. The mmWave backhaul is also considered in [20], where an integrated satellite-drone network is exploited. An analysis of several out-band types of the backhaul using 3.5 GHz and 60 GHz spectrum is presented in [21]. An investigation of the backhaul exploiting an optical spectrum for emergency situations is performed in [22]. In general, the out-band frequencies for the backhaul of the FlyBSs lead to less efficient exploitation of the spectrum (lower spectrum reuse factor). Moreover, the out-band frequencies might not be under the direct control of the mobile operators and it can be hard to guarantee a sufficient backhaul capacity. Besides, both mmWaves and optical waves are highly susceptible to abrupt channel fluctuations.

The backhaul links facilitated by the in-band frequencies are assumed in [23]-[33]. In [23], the authors optimize the 3D trajectory and antenna pattern of a single FlyBS moving between two points. Although the paper assumes the backhaul between the FlyBS and the SBS is limited, it does not optimize the backhaul capacity in any way. In [24], bandwidth allocation, power allocation, and trajectory of the single FlyBS are optimized in order to maximize the minimum capacity among all users to guarantee fairness. Similarly as in [23], the backhaul limitation is considered only as a constraint while no optimization with respect to the access links is pursued in [24]. The optimization of the single FlyBS's trajectory is also addressed in [25]. The authors determine the optimal duration of uplink and downlink transmissions and allocate the transmission power. Then, the authors solve a partial computation offloading and transmission power optimization related to the FlyBS and the SBS. Finally, the FlyBS trajectory is found by successive convex optimization.

In [26], the authors focus on joint optimization of the FlyBS's position and the bandwidth allocation to the UEs. The authors assume the backhaul is implemented over the radio

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resources not consumed by the UEs. Thus, the SBS may have no resources available for the FlyBSs if the network load is high and all resources are consumed by the UEs associated directly to the SBS. The paper also does not address the association of the UEs, since only one FlyBS is assumed and all UEs are associated to this particular FlyBS. The paper [27] studies jointly the placement of FlyBSs, the users' association, and the bandwidth allocation. The association of users and the placement of FlyBSs are done depending on the users' classification into two groups; i) delay sensitive users and ii) delay tolerant users. The objective, then, is to solve the above problem while minimizing the total transmission power at the FlyBSs. Although the backhaul link is considered to be limited, the backhaul capacity is only a constraint and the authors do not optimize the access and backhaul links together. The paper [28] proposes the positioning of a single FlyBS, the bandwidth allocation, and the transmission power allocation for full duplex FlyBS exploiting non-orthogonal multiple access (NOMA). Similarly as in [27], the main objective is to minimize the transmission power of the FlyBS while guaranteeing the minimum capacity of the users.

In order to efficiently reuse radio resources at the backhaul and the access links of the FlyBSs, an integrated access and backhaul (IAB) concept, proposed by 3GPP [29], is considered in [30]-[33]. In [30], the main objective is to minimize the transmission power of the single FlyBS while meeting the rate requirements of the UEs. The objective is achieved by a placement of the FlyBS and an allocation of the transmission power at the backhaul and access links. The FlyBSs placement, the UEs association, and the bandwidth allocation are proposed in [31]. The paper, however, disregards the transmission power allocation, which is crucial in IAB, where the access and backhaul links reuse the same resources. The main objective of [32][33] is to manage the interference among the access and backhaul links by the association of the UEs, the power control at the backhaul and access links, and the positioning of the FlyBSs. Nevertheless, if the backhaul quality is below a threshold (defined by signal to noise plus interference ratio, SINR), no transmission at the access link is allowed and the FlyBS is not exploited at all.

None of the papers assuming the limited/constrained backhaul [17]-[33], however, guarantees that the access and backhaul links are of an equal capacity. Thus, the resources either at the access or backhaul links are not utilized efficiently. The goal to ensure the same capacity at the access and backhaul links is considered in [34], where the authors maximize the capacity of indoor users with poor channel conditions to the SBSs. The UEs' uplink transmission power is optimally split between the transmissions to the SBS and to the FlyBS in a way that one part is used for the users' transmission to the SBS and the second part is used for the users' transmission to the FlyBS. Then, the position of the FlyBS is optimized with respect to the access channels and considering the optimal power setting at the UEs. The paper assumes only one FlyBS, thus, it addresses neither the association of UEs to the FlyBSs nor the reuse of the access channels.

Main contributions: In this paper, we propose a *backhaul-aware* framework for the association of the UEs, the power allocation at the FlyBSs, the positioning of the FlyBSs, and the reuse of the access links by multiple UEs with an overall objective to maximize the sum capacity of the UEs. Unlike [17][18], we assume a realistic case, where the backhaul capacity depends on the FlyBS's position. Also, all works considering the limited backhaul of the FlyBSs [17]-[33] do not consider the backhaul and access links fully jointly. Consequently, the resources at the backhaul and access links are still exploited inefficiently and either the backhaul or the access link is underutilized and acts as a bottleneck. The backhaul and access links are optimized jointly in [34], however, the paper is focused on the uplink and optimizes the transmission power of the UEs and the position of the FlyBS with respect to the access channels only. Moreover, as the paper assumes only single FlyBS, the association of the UEs to the multiple FlyBSs and the reuse of the access links are not addressed in [34]. In addition, the works adopting the IAB concept [30]-[33] assume that the FlyBSs always reuse all access links, thus, generate a significant interference. With respect to this approach, we reuse the access links in a controlled way only if the reuse is of benefit for the individual UEs. Consequently, the interference introduced by the FlyBSs is significantly suppressed.

The contributions of the paper are summarized as follows:

- We derive a closed-form expression for the optimal transmission power allocation at the FlyBSs ensuring the same capacity at the backhaul and access links. Further, we formulate the association of the UEs to the FlyBSs as a matching problem and we propose a greedy algorithm to solve it. We show that the proposed greedy algorithm reaches optimum or close-to-optimum performance.
- We propose a re-positioning of the FlyBSs to further boost the sum capacity provided by these FlyBSs. First, we solve the re-positioning problem by the high complexity Nelder-Mead simplex algorithm to show the upper bound performance. Then, we propose a low complexity algorithm suitable even for an urban environment, as the trajectory of the FlyBS considers various obstacles, such as buildings.
- We propose a scheme reusing the access links among the UEs by means of a coalition structure generation to decrease the allocated transmission power at the FlyBS. The reduced transmission power facilitates either a further increase in the sum capacity of the UEs (via an additional re-positioning of the FlyBSs) or a decrease in interference generated to the various underlying devices not exploiting the FlyBSs. We solve the problem of the coalition structure generation optimally by the dynamic programming and, subsequently, we also propose a low complexity algorithm suitable for practical applications.
- Via extensive simulations, we demonstrate that the proposed scheme outperforms all competitive schemes by up to 60% in terms of the sum UE capacity and reduces the transmission power of the FlyBSs by up to 64% resulting in a suppression of interference by up to 7.7 dB.

This paper is an extension of our prior work [35], where only a basic idea of the novel concept is presented.

The rest of the paper is organized as follows. The next section introduces the system model and formulates the problem. Section III describes the proposed optimal power allocation and the association of the UEs at the FlyBSs. The re-positioning of the FlyBSs and the re-allocation of their transmission power is outlined in Section IV. Section V focuses on the reuse of the access links through the coalitions creation. The simulation scenario and a discussion of the simulation results are delivered in Section VI and Section VII, respectively. Section VIII concludes the paper and contemplates possible future research directions.

II. System Model and Problem Formulation

In this section, we outline the system model and formulate the problem.

A. System model

We consider a multicell scenario with K+1 SBSs, where a reference serving cell is surrounded by K adjacent interfering cells (see Fig. 1). Thus, we define the set of SBSs as $\mathcal{K} = \{k_0, k_1, \ldots, k_K\}$, where k_0 is the serving SBS while the rest represent the adjacent interfering SBSs. The serving SBS is further supported by M FlyBSs defined by the set $\mathcal{M} = \{m_1, m_2, \ldots, m_M\}$. The positions of the FlyBSs are denoted as $\boldsymbol{V} = \{\boldsymbol{v_1}, \boldsymbol{v_2}, \ldots, \boldsymbol{v_M}\}$, where $\boldsymbol{v_m} \in \mathbb{R}^3$ represents the position of the m-th FlyBS. Then, N UEs in the set $\mathcal{N} = \{n_1, n_2, \ldots, n_N\}$ are associated with either the SBS or one of the FlyBSs.

The SBS splits the whole bandwidth B into N channels so that n-th UE is assigned with one channel of a bandwidth B_n. Note that the bandwidth allocation is not in the scope of this paper and our proposed solution is suitable for any arbitrary bandwidth allocation. Thus, we do not specify any concrete splitting of B into the channels in the system model.

We focus on the downlink communication, where the communication capacity of the n-th UE served directly by the serving SBS is expressed as:

$$C^D_{k_0,n} = B_n log_2 \left(1 + \frac{p_{k_0,n} g_{k_0,n}}{B_n \sigma + \sum\limits_{\mathcal{K} \setminus \{k_0\}} p_k g_{k,n}}\right) \quad (1)$$

where $p_{k_0,n}$ is the transmission power of the serving SBS to the n-th UE, p_k is the transmission power of the k-th neighboring SBS interfering the n-th UE, $g_{k_0,n}$ represents the channel gain between the serving SBS and the n-th UE, σ corresponds to the noise spectral density, and $g_{k,n}$ is the channel gain between the k-th neighboring SBS and the n-th UE.

Due to a scarcity of the available radio spectrum, no channel(s) are dedicated exclusively for either the backhaul link (between the SBS and the FlyBS) or the access link (between the FlyBS and the UEs) as considered, e.g., in [26]. Instead, both the backhaul and access links are facilitated by the channels that are initially assigned to the UEs by the SBS to increase the spectrum reuse. If the n-th UE is associated with the m-th FlyBS, the m-th FlyBS relays data for the n-th UE solely over the n-th channel (see Fig. 1). Similarly as in many research papers (e.g., [30][31][36]), we assume

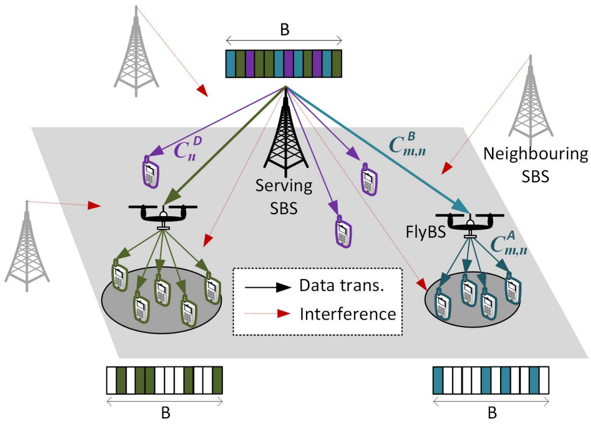


Fig. 1: Illustrative example of the system model.

the FlyBSs work in the full duplex mode. However, we also discuss modifications required to be made in our proposal if the half duplex FlyBSs are adopted. In addition, we analyze the performance of both full and half duplex FlyBSs via the simulations.

The backhaul channel capacity between the SBS and the m-th FlyBS serving the n-th UEs via the n-th channel is determined as:

$$C^B_{m,n} = B_n log_2 \left(1 + \frac{p_{k_0,m} g_{k_0,m}}{B_n \sigma + \sum\limits_{\mathcal{K} \setminus \{k_0\}} p_k g_{k,m}}\right) \quad (2)$$

where $p_{k_0,m}$ is the transmission power of the serving SBS allocated to the m-th FlyBS, $g_{k_0,m}$ stands for the channel gain between the serving SBS and the m-th FlyBS, and $g_{k,m}$ is the channel gain between the k-th neighboring SBS and the m-th FlyBS. Similarly, the capacity at the access channel between the m-th FlyBS and the n-th UE is expressed as:

$$C^A_{m,n} = B_n log_2 \left(1 + \frac{p_{m,n} g_{m,n}}{B_n \sigma + \sum\limits_{\mathcal{K}} p_k g_{k,n}}\right) \quad (3)$$

where $p_{m,n}$ is the transmission power allocated by the m-th FlyBS for the transmission of data to the n-th UE and $g_{m,n}$ represents the channel gain between the m-th FlyBS and the n-th UE. When compared to the backhaul link, the access link is interfered also by the SBS, since the SBS transmits at the same channels as the FlyBS (see Fig. 1).

The relaying gain experienced by the n-th UE exploiting the m-th FlyBS instead of the SBS is defined as:

$$G_{m,n} = \min(C^B_{m,n}, C^A_{m,n}) - C^D_{k_0,n} \quad (4)$$

The relaying gain is the function of $\min(C^B_{m,n}, C^A_{m,n})$, since either the backhaul or the access link acts as a bottleneck whenever $C^B_{m,n} \neq C^A_{m,n}$. To indicate whether the UEs are associated directly with the SBS or with one of the FlyBSs, we introduce a binary association control variable $x_{m,n} \in \{0, 1\}$. If $x_{m,n} = 1$, the n-th UE is associated with the m-th FlyBS, however, if $x_{m,n} = 0$, the n-th UE is not associated with the m-th FlyBS.

B. Problem formulation

The objective of the paper is to maximize the sum capacity of the UEs via the transmission power allocation at the FlyBSs $\boldsymbol{P}^*$, the association of the UEs to either the FlyBSs or the SBS $\boldsymbol{X}^*$, and the subsequent re-positioning of the FlyBSs $\boldsymbol{V}^*$, while both the backhaul and access links are taken into account. The objective is formulated as:

$$\begin{aligned} \boldsymbol{P}^*, \boldsymbol{X}^*, \boldsymbol{V}^* = \quad & \underset{\boldsymbol{P},\boldsymbol{X},\boldsymbol{V}}{\text{argmax}} \sum_n (C^D_{k_0,n} + \sum_m x_{m,n} G_{m,n}) \\ \text{s.t.} \quad & \text{(5a)} \sum_n x_{m,n} p_{m,n} \leq P_{max}, \forall m \\ & \text{(5b)} \sum_m x_{m,n} \leq 1, \forall n \\ & \text{(5c)}\ x_{m,n} C^A_{m,n} \leq x_{m,n} C^B_{m,n}, \forall m, n \\ & \text{(5d)}\ C_n \geq C^D_{k_0,n}, \forall n \end{aligned} \tag{5}$$

where (5a) guarantees that the sum transmission power allocated to all UEs connected to the same FlyBS does not exceed the maximum power budget P_{max} available at each FlyBS, (5b) ensures that each UE can be associated only with either one of the FlyBSs or the SBS, (5c) assures that the capacity at the access channel does not exceed the backhaul channel capacity, as the FlyBS may not, in principle, send more data over the access channels than the volume of data received over the backhaul channel, and (5d) guarantees that the capacity of the n-th UE (C_n) is not lower than the capacity provided initially by the serving SBS (i.e., $C^D_{k_0,n}$). Note that the reuse of the access channels by means of the coalitions is not included in the overall problem formulation. The reason is that the reuse is just a part of the solution that enables a further improvement in the sum capacity via a reduction of the FlyBSs transmission powers to enable a further re-positioning of the FlyBSs to increase the sum capacity (see Section V for more detail).

The problem defined in (5) is a mixed integer programming that is hard to be solved jointly. To that end, we divide the problem into several subproblems and solve each sequentially. First, we derive the optimal power allocation at the FlyBSs (Section III-A) and formulate the optimal matching to associate the UEs with the FlyBSs exploiting the derived optimal transmission power allocation (Section III-B). Second, the capacity of the UEs associated with the FlyBS is maximized by the re-positioning of the FlyBSs and the optimal re-allocation of the transmission power (Section IV). Third, the coalitions among the UEs are created to enable the reuse of the access links and, consequently, to decrease the transmission power of the FlyBSs (Section V). Finally, the FlyBSs may be re-positioned again, using the algorithm proposed in Section IV after the coalitions are created, to further boost the capacity of the UEs.

III. Power allocation and association of the UEs

This section first defines the subproblem of the FlyBS's power allocation and solves this subproblem optimally. Then, the optimal power allocation is exploited for solving the association problem of the UEs with the FlyBSs.

A. Optimal power allocation at the FlyBS

The objective of the power allocation is to maximize the relaying gain $G_{m,n}$ introduced by the m-th FlyBS's forwarding data of the n-th UE. The problem of the relaying gain maximization is defined as:

$$\begin{aligned} \boldsymbol{P}^{**} = \quad & \underset{\boldsymbol{P}}{\text{argmax}}\ x_{m,n} G_{m,n} \\ \text{s.t.} \quad & \text{(6a)}\ x_{m,n} p_{m,n} \leq P_{max}, \forall m, n \\ & \text{(6b)}\ x_{m,n} C^A_{m,n} \leq x_{m,n} C^B_{m,n}, \forall m, n \end{aligned} \tag{6}$$

The relaying gain is limited either by the backhaul or the access link (see term $\min(C^B_{m,n}, C^A_{m,n})$ in (4)). Thus, whenever $C^B_{m,n} \neq C^A_{m,n}$, the resources are not used efficiently as one of the links is underutilized. Since the capacity at the backhaul is given by the transmission power of the SBS and the bandwidth of the corresponding channel to the FlyBS, the FlyBS is not able to affect the backhaul capacity at its current position. However, the transmission power allocation at the FlyBS influences the capacity at the access link. Thus, we define the optimal transmission power allocation of the m-th FlyBS in closed-form by Lemma 1 below.

Lemma 1. *The optimal transmission power allocated by the m-th FlyBS for the communication with the n-th UE is:*

$$p_{m,n} = \begin{cases} \frac{(2^{\frac{C^B_{m,n}}{B_n}} - 1)(B_n \sigma + \sum_{\mathcal{K}} p_k g_{k,n})}{g_{m,n}}, & \textit{if (6a) is met} \\ 0 & \textit{otherwise} \end{cases} \tag{7}$$

Proof. To optimize the capacity of the n-th UE associated with the m-th FlyBS, the transmission power $p_{m,n}$ should be set to such value that the capacity at the access link is the same as the capacity at the backhaul link (i.e., the constraint (6b) is set as $C^A_{m,n} = C^B_{m,n}$). If $p_{m,n}$ would be set to a lower level, the access link is the bottleneck decreasing the achievable association gain. If $p_{m,n}$ would be set to a higher level, the backhaul becomes the bottleneck and the FlyBS wastes its transmission power (and, thus, also increases interference unnecessarily). To obtain the optimal $p_{m,n}$ for which $C^A_{m,n} = C^B_{m,n}$, we substitute $C^A_{m,n}$ by $C^B_{m,n}$ in (3). Thus, (3) is rewritten as:

$$C^B_{m,n} = B_n log_2 \left(1 + \frac{p_{m,n} g_{m,n}}{B_n \sigma + \sum_{\mathcal{K}} p_k g_{k,n}}\right) \tag{8}$$

Then, after several math operations, (8) is rewritten as:

$$2^{\frac{C^B_{m,n}}{B_n}} - 1 = \frac{p_{m,n} g_{m,n}}{B_n \sigma + \sum_{\mathcal{K}} p_k g_{k,n}} \tag{9}$$

After few simple math operations, the transmission power $p_{m,n}$ of the m-th FlyBS for the n-th UE is expressed from (9) directly in the form as in (7). This concludes the proof. ■

Remark 1: The derivation of the optimal power allocation for the half duplex FlyBSs is analogous to the full duplex with the following variations: i) the half duplex requires to guarantee $TC^B_{m,n} = (1-T)C^A_{m,n}$, where T is the duration of the transmission over the backhaul channel and ii) the UE is not interfered at the access channel from the serving SBS. Then, $p_{m,n}$ for the half duplex is expressed as:

$$p_{m,n} = \begin{cases} \frac{\left(2^{\frac{TC^B_{m,n}}{(1-T)B_n}} - 1\right)\left(B_n\sigma + \sum\limits_{\mathcal{K}\setminus k_0} p_k g_{k,n}\right)}{g_{m,n}}, & \text{if (6a) is met} \\ 0 & \text{otherwise} \end{cases} \quad (10)$$

B. Association of the UEs

The objective of our paper is to maximize the system capacity. Thus, each UE should be associated with the BS (either the SBS or one of the FlyBSs) providing the highest capacity. To decide whether the UEs should be associated with the SBS or with one of the FlyBSs, the relaying gain $G_{m,n}$ calculated in (4) should be adopted. If $G_{m,n} \leq 0$, the n-th UE remains associated with the SBS. Contrary, the n-th UE should be associated with the m-th FlyBS if $G_{m,n}$ is positive and if associating the n-th UE with the m-th FlyBS increases the capacity. Nevertheless, considering only $G_{m,n}$ does not necessarily maximize the sum capacity if the backhaul is considered, because the transmission power allocation, as derived in (7), is not taken into account. For example, the UEs with a low channel quality to the SBS should be always associated preferentially to the FlyBSs as these UEs experience a significant relaying gain due to their low $C^D_{k_0,n}$ (see (4)). Nevertheless, if these particular UEs have also the channels to the FlyBSs of a low quality (reflected by a low channel gain $g_{m,n}$), a significant amount of the FlyBSs' transmission power is required to serve these UEs (see (7)). Consequently, only a limited number of the UEs would be served by the FlyBSs and the overall gain introduced by the FlyBSs would be also limited.

Taking both the relaying gain and the required transmission power allocated at the FlyBS into account in the association decision, we define a power-efficiency metric as:

$$\eta_{m,n} = \begin{cases} \frac{G_{m,n}}{p_{m,n}} & \text{if } G_{m,n} > 0 \ \& \ p_{m,n} > 0 \\ 0 & \text{Otherwise} \end{cases} \quad (11)$$

where $\eta_{m,n}$ is set to 0 if $G_{m,n} \leq 0$ to ensure that the n-th UE always benefits from the association with the m-th FlyBS, thus satisfying the constraint (5d). Moreover, $\eta_{m,n}$ is also set to 0 if $p_{m,n}$, derived in line with Lemma 1, is 0 (i.e., if the m-th FlyBS does not have enough transmission power to serve the n-th UE). Note that setting $\eta_{m,n} = 0$ indicates that the n-th UE cannot be associated with the m-th FlyBS The subproblem of the UEs' association is formulated as:

$$\begin{aligned} \boldsymbol{X}^{**} = \ & \underset{\boldsymbol{X}}{\text{argmax}} \sum_m \sum_n x_{m,n}\eta_{m,n} \\ \text{s.t.} \ & \text{(12a)} \ \sum_n x_{m,n}p_{m,n} \leq P_{max}, \forall m \\ & \text{(12b)} \ \sum_m x_{m,n} \leq 1, \forall n \end{aligned} \quad (12)$$

The problem defined in (12) represents a many-to-one matching problem, as multiple UEs can be associated with the same FlyBS while each UE can be associated with only one FlyBS (given by (12b)). At the same time, the matching of the UEs with the FlyBSs is constrained by P_{max} at each FlyBS (defined by (12a)). Thus, (12) is a mixed integer programming problem that is, generally, hard to be solved optimally. One way of finding the optimal association is to employ a high-complexity full search, which tests all possible matching combinations and selects the one yielding the maximum performance. The full search, however, cannot be solved in a polynomial time. To decrease the complexity of the full search, only a subset of all possible combinations can be checked, as each UE can be matched with just one FlyBS. For our specific problem, we can eliminate all combinations, where the UE would be matched with two or more FlyBSs simultaneously. This, then leads to the knapsack problem, as we maximize $\sum_n x_{m,n}\eta_{m,n}$ for each FlyBS separately while guaranteeing (12a). Nevertheless, even the knapsack problem is NP-complete and not solvable in a polynomial time. Thus, we propose a low-complexity greedy algorithm to solve the association problem and we also discuss its optimality.

The UEs' association is described in Algorithm 1. At the beginning, we derive the optimal $p_{m,n}$ for all m and n exploiting Lemma 1 (see line 1 in Algorithm 1). Then, $\eta_{m,n}$ is obtained for all UEs and all FlyBSs and, subsequently, all $\eta_{m,n}$ are inserted into the matrix $\boldsymbol{\eta}$ (line 2). Afterward, $x_{m,n}$ is set to 0 for all m and n to indicate that, initially, no UE is associated with any FlyBS (line 3). Next, the maximum value in $\boldsymbol{\eta}$ is found and this value represents the highest ratio between the relaying gain and the power required to serve the UEs by the given FlyBS (see line 5). The algorithm then checks if the sum transmission power for all served UEs (including the n-th UE currently being associated) does not exceed the transmission power budget of the m-th FlyBS. If the m-th FlyBS has enough transmission power to serve this UE (i.e., if $\sum_n x_{m,n}p_{m,n} + p_{m,n} \leq P_{max}$) the n-th UE is associated with the m-th FlyBS and this fact is indicated by setting $x_{m,n} = 1$ (line 7). Then, all $\eta_{m,n}$ in the n-th row of $\boldsymbol{\eta}$ are set to 0, as this particular UE cannot be associated with any other FlyBS (line 8). If the m-th FlyBS, however, does not have enough transmission power to serve the n-th UE, this particular UE is not associated with the FlyBS and only $\eta_{m,n}$

Algorithm 1 The greedy algorithm for UEs' association

1: Derive optimal $p_{m,n}, \forall m, n$, using Lemma 1
2: Calculate $\eta_{m,n}, \forall m, n$, using (11), create matrix $\boldsymbol{\eta}$
3: Set $x_{m,n} = 0, \forall m, n$
4: **while** $\max(\eta_{m,n} \in \boldsymbol{\eta}) > 0$ **do**
5: $\quad$ $\{m, n\} \leftarrow \max(\eta_{m,n} \in \boldsymbol{\eta})$
6: $\quad$ **if** $\sum_n x_{m,n}p_{m,n} + p_{m,n} \leq P_{max}$ **then**
7: $\quad\quad$ $x_{m,n} = 1$ (n-th UE associated with m-th FlyBS)
8: $\quad\quad$ set n-th row in $\boldsymbol{\eta}$ to 0
9: $\quad$ **else**
10: $\quad\quad$ $\eta_{m,n} = 0$
11: $\quad$ **end if**
12: **end while**

is set to 0. The lines 4-12 in Algorithm 1 are repeated as long as there is at least one positive entry in $\boldsymbol{\eta}$. When $\boldsymbol{\eta}$ contains no positive entry, Algorithm 1 is completed as there is no UE that can be further associated with any FlyBS. Note that the UEs that cannot be served by any FlyBS remain associated with the serving SBS.

The proposed greedy algorithm is optimal as long as the algorithm selects the highest $\eta_{m,n}$ for each UE that benefits from the association with at least one FlyBS (i.e., those UEs having at least one positive entry in the initially created $\boldsymbol{\eta}$). This happens if $\sum_n x_{m,n}p_{m,n} + p_{m,n} \leq P_{max}$ (i.e., if the condition in line 6 of Algorithm 1 is fulfilled), since (12a) does not impose any constraint on the association problem and the objective function in (12) is maximized. In fact, the greedy algorithm is always optimal for a lower number of UEs as long as the total transmission power allocated at all FlyBSs is well below P_{max}.

Even in the cases when the greedy association would not be optimal, it still gives a close-to-optimal performance for the following reason. The entries (UEs) in $\boldsymbol{\eta}$ with a high value of $\eta_{n,m}$ are selected preferentially by Algorithm 1 and these entries (UEs) require only a very low $p_{m,n}$ allocated at the FlyBSs (see (11)). Thus, these also contribute most significantly into the maximization of the objective function in (12) while keeping a low requirement on the transmission power allocated to the UEs associated with the FlyBSs. Consequently, the entries with the high value in $\boldsymbol{\eta}$ are selected both by the optimal and proposed greedy algorithms. Then, the difference between the optimal and greedy associations can appear only for the UEs having a small $\eta_{n,m}$. However, these UEs contribute only marginally to the overall objective function, since $\eta_{n,m} \ll \sum_m \sum_n x_{m,n}\eta_{m,n}$. Thus, the gap between the optimal and greedy associations is very small. Note that we show the optimal association in the simulation results and demonstrate that even for 100 UEs, the greedy algorithm is still optimal.

The complexity of Algorithm 1 is equal to $\mathcal{O}(M\sum\limits_{n=1}^{N} n) = \mathcal{O}(M\frac{N(N-1)}{2})$. Since there are usually only few FlyBSs with which the UEs can be associated, the complexity of Algorithm 1 can be considered as $\mathcal{O}(N(N-1) = \mathcal{O}(N^2)$. As assumed in many recent papers (see, e.g., [27][38][39], Algorithm 1 is executed centrally by the SBS to avoid computation/processing burden of the FlyBSs, which are constrained with a limited energy. Hence, the SBS decides which UEs should stay connected to the SBS and which UEs should be associated with one of the FlyBSs. Note that the FlyBSs are anyway expected to exchange signaling with the SBS to manage radio resources efficiently. Thus, such centralized approach does not lead to any significant increase in the signaling overhead. Moreover, the algorithm itself can be executed also in a distributed manner provided that all FlyBSs obtain $\boldsymbol{\eta}$, e.g., from the SBS). Then, all FlyBSs can perform the algorithm and choose the UEs simultaneously, since all FlyBSs reach the same association result and the UEs are associated with the FlyBS most profitable for each individual UE.

IV. Re-positioning of FlyBSs and Re-allocation of Transmission Power

After the optimal power allocation at the FlyBSs and the association of the UEs to them, the capacity can be further increased by a re-positioning of the FlyBSs provided that the transmission power of the FlyBSs is below P_{max}. Note that the capacity of the UEs cannot be increased by a sole increase in the transmission power of the FlyBSs as the backhaul links between the FlyBSs and the SBS would still pose a bottleneck. Hence, the capacity of the UEs can be increased only if the backhaul link quality is improved as well. Since the transmission power of the SBS is assumed to be fixed, the only option to increase the backhaul capacity of the UEs associated to any FlyBS is to move the FlyBS "closer" to the SBS. Of course, if the FlyBS is re-positioned, the power allocation for all its associated UEs must be updated since: i) the backhaul channel capacity changes with the changing position of the FlyBS and ii) the quality of the access links to the UEs changes as well if the FlyBS moves away from its original position. Consequently, we should continuously ensure the optimal power allocation in line with Lemma 1.

The subproblem of the re-positioning is formulated as:

$$\begin{aligned} \boldsymbol{V}^{**} = \; & \underset{\boldsymbol{V}}{\operatorname{argmax}} \sum_m \sum_n x_{m,n} G_{m,n} \\ \text{s.t.} \quad & \text{(13a)} \; \sum_n x_{m,n} p_{m,n} \leq P_{max}, \forall m \end{aligned} \tag{13}$$

The location of the FlyBS is optimal if the sum capacity of the UEs served by the FlyBS is maximized and, at the same time, if (13a) is not violated. As shown in Fig. 2, the optimal position v_m^* should be always within the area, where the distance to the SBS is shortened compared to its initial

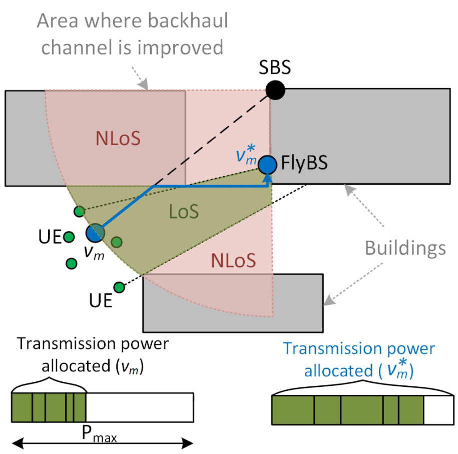


Fig. 2: Illustrative example of the optimal FlyBS's position while keeping the total transmission power at the FlyBS below P_{max}. The red sector of the circle represents the area, where the FlyBS decreases its distance to the SBS with respect to the initial position v_m. The green area further represents the FlyBS's position ensuring LoS for all UEs attached to it. The blue curve is an example of the moving trajectory according to Algorithm 2.

v_m position (determined, e.g., by K-means [37]), see the red sector of the circle in Fig. 2. The shortening of the distance to the SBS results in an increase in the backhaul capacity and, subsequently, in an increase in the relaying gain $G_{m,n}$.

The subproblem of finding the optimal position of the FlyBSs defined in (13) cannot be solved analytically, as the derivative of the objective function with respect to V is not known due to the complexity and variation of general path loss model. Nevertheless, we can adopt a derivative-free numerical optimization approach to solve it. One of the well-known derivative-free optimization numerical approaches is the Nelder-Mead simplex algorithm. However, the algorithm is designed for the unconstrained optimization problems. Thus, we first transform the constrained problem (13) into an unconstraint one and, then, we apply the simplex algorithm. To this end, the problem in (13) is rewritten as:

$$\boldsymbol{V}^{**} = \underset{\boldsymbol{V}}{\text{argmax}} \sum_{m}\sum_{n} x_{m,n}G_{m,n} - \\ - \rho \sum_{m} \max(0, \sum_{n} x_{m,n}p_{m,n} - P_{max}) \quad (14)$$

where ρ is the penalty for breaking the constraint (13a). If the constraint is satisfied, the second term in (14) is always 0 and no penalty is applied. In the opposite case, a negative penalty is added to the $\sum_m \sum_n x_{m,n}G_{m,n}$ and, thus, the value of the objective function in (14) decreases. Consequently, the simplex algorithm finds the position, where the constraint (13a) is guaranteed (i.e., no penalty is applied) while maximizing the objective function in (14).

The numerical solution based on the Nelder-Mead simplex algorithm is not suitable for real networks due to its high complexity. To that end, we propose the re-positioning of the FlyBSs that can be used in practice, depicted in Algorithm 2. The algorithm itself is described for a single FlyBS, as multiple FlyBSs can update their positions simultaneously. At the beginning, the movement indicator i_m is set to 1 indicating that the m-th FlyBS can be re-positioned (see line 1 in Algorithm 2). As long as $i_m = 1$, the following steps are performed. First, the FlyBS moves continuously to the new position in a straight direction to the SBS (line 4) while the transmission powers allocated to all UEs served by the m-th FlyBS are progressively updated (line 5). If the FlyBS is able to serve all these UEs, that is, if $\sum_n p_{m,n} < P_{max}$, the FlyBS is allowed to keep moving in the same direction towards the SBS. However, if the transmission power of the FlyBS reaches the maximal limit (i.e., $\sum_n p_{m,n} = P_{max}$), the FlyBS is forced to stop and sets i_m to 0 (line 6).

If the transmission power limit would be exceeded (i.e., if $\sum_n p_{m,n} \geq P_{max}$), the FlyBS goes back to the last position, where the condition $\sum_n p_{m,n} \leq P_{max}$ holds (line 9) and decides whether there is another eligible direction for the movement of the FlyBS or not (line 10). The eligible direction is understood as the direction, where the LoS communication between the UEs and the FlyBS is likely and the distance between the FlyBS and the SBS is shortened. Thus, if the FlyBS reaches a building's boundary its movement direction is adjusted so that the FlyBS starts moving along the edge of this building (line 11). If there is no possible way to move the FlyBS closer to the SBS and while keeping LoS communication to all served UEs, i_m is set to 0 and the m-th FlyBS is not allowed to move any further (line 12). The example of the moving trajectory of the FlyBS is shown in Fig. 2.

Algorithm 2 FlyBS re-positioning and power re-allocation

1: Set $i_m = 1$
2: **while** $i_m = 1$ **do**
3:     Move to new position
4:     Update $\sum_n p_{m,n}$
5:     **if** $\sum_n p_{m,n} = P_{max}$ **then**
6:         Stop moving and set $i_m = 0$
7:     **end if**
8:     **if** $\sum_n p_{m,n} > P_{max}$ **then**
9:         Go back to previous position
10:         **if** Any eligible new moving direction? **then**
11:             Adjust moving direction
12:         **else** Set $i_m = 0$
13:         **end if**
14:     **end if**
15: **end while**

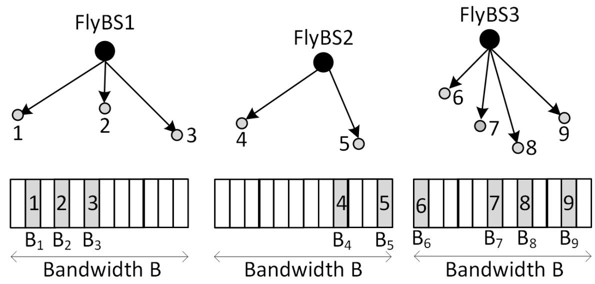
V. Reuse of access channels through coalitions

So far we have assumed that the FlyBSs relay data to their UEs on the dedicated orthogonal access channels for each UE. This section elaborates the reuse of the access channels by means of the coalitions. First, we describe the basic principle of the access channel's reuse and define the problem. Then, we solve the problem optimally via the dynamic programming and we also propose a sub-optimal, but low-complexity greedy algorithm.

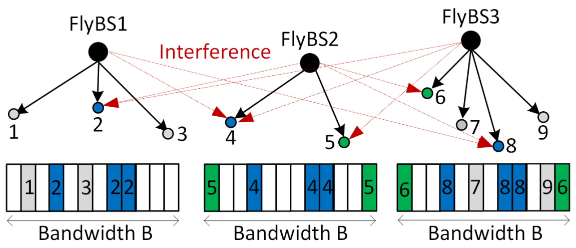
A. Principle and problem formulation

If the access channels are not reused, there is no interference to the UEs from the adjacent FlyBSs, but the spectrum efficiency can be degraded (see Fig. 3a). To improve the spectrum efficiency, some of the access channels can be, in fact, reused by the multiple UEs. Thus, we propose to reuse the access channels by means of the coalitions in a way that the coalitions *significantly increase the channel bandwidth* for the individual UEs in the coalitions while *the interference* from other FlyBSs *is increased only negligibly*. Thus, if the UEs are in the same z-th coalition, the respective FlyBSs serve the UEs via the channel $B^z = \sum_{n \in \boldsymbol{u_z}} B_n$ aggregating the access channels of all individual UEs in the z-th coalition (see Fig. 3b), where $\boldsymbol{u_z}$ is the set of the UEs in the z-th coalition. The set of the FlyBSs serving these UEs is denoted as $\boldsymbol{f_z}$.

Whenever the n-th UE is in the z-th coalition, the n-th UE is inevitably interfered, even if only lightly, by the FlyBSs in $\boldsymbol{f_z}$ serving other UEs in the z-th coalition. Hence, the optimal transmission power allocation defined by Lemma 1 (see (7)) is modified and the closed-form expression for the transmission



(a) Allocations of the access channels before the coalitions creation.



(b) Allocations of the access channels if two coalitions are created: $\boldsymbol{u_1} = \{2,4,8\}$ ($\boldsymbol{f_1} = \{1,2,3\}$) and $\boldsymbol{u_2} = \{5,6\}$ ($\boldsymbol{f_2} = \{2,3\}$) with channel bandwidth $B^1 = B_2 + B_4 + B_8$ and $B^2 = B_5 + B_6$, respectively.

Fig. 3: Example of the reuse of the access link channels by multiple UEs via created coalitions of the UEs to increase channel bandwidth of individual users while keeping low interference.

power allocated by the FlyBS to any UE in the coalition is defined by the following lemma.

Lemma 2. *The optimal transmission power allocated by the m-th FlyBS to serve the n-th UE within the z-th coalition is:*

$$p^z_{m,n} = \begin{cases} a^z_{m,n}\left(b^z_{m,n} + c^z_{m,n}\right), & \text{if } p^z_{m,n} \leq P_{max} \\ 0 & \text{otherwise} \end{cases} \tag{15}$$

where:

$$a^z_{m,n} = \frac{2^{\frac{C^B_{m,n}}{B^z}} - 1}{g_{m,n}}, \tag{16}$$

$$b^z_{m,n} = B^z\sigma + \sum_{\mathcal{K}} p^z_k g_{k,n}, \tag{17}$$

$$c^z_{m,n} = \sum_{m' \in \boldsymbol{f_z} \setminus m} \sum_{n' \in \boldsymbol{u_z} \setminus n} p^z_{m',n'} g_{m',n} \tag{18}$$

where p^z_k stands for the transmission power of the k-th neighboring SBS over the coalition channel bandwidth B^z and $p^z_{m',n'}$ represents the transmission power of the m'-th FlyBS allocated to the n'-th UE in the z-th coalition, and $c^z_{m,n}$ is the interference at the n-th UE from the FlyBSs serving the other UEs in the z-th coalition.

Proof. Similarly as in the case without the coalitions, the objective is to allocate the transmission power of the m-th FlyBS so that $C^B_{m,n} = C^A_{m,n}$. At the access link, the n-th UE is interfered by the FlyBSs serving the UEs in the same coalition (i.e., z-th coalition); thus, (3) is rewritten as:

$$C^A_{m,n} = B^z log_2\left(1 + \frac{p^z_{m,n} g_{m,n}}{b^z_{m,n} + c^z_{m,n}}\right) \tag{19}$$

Then, considering $C^B_{m,n} = C^A_{m,n}$ and after several math operations similar as in Lemma 1, (19) is rewritten into the form presented in (15). This concludes the proof. ■

Remark 2: If the half duplex FlyBSs are considered, $a^z_{m,n}$ and $b^z_{m,n}$ are modified as follows:

$$a^z_{m,n} = \frac{2^{\frac{TC^B_{m,n}}{(1-T)B^z}} - 1}{g_{m,n}}, \tag{20}$$

$$b^z_{m,n} = B^z\sigma + \sum_{\mathcal{K}\setminus k_0} p^z_k g_{k,n}, \tag{21}$$

for the reasons already explained in Remark 1.

As indicated in (15), whenever the transmission power allocation of any FlyBS changes, all UEs within the same coalition are affected and the transmission power allocated to these UEs should be updated by all FlyBSs accordingly. However, this is expected even in the case without the coalitions, as the UEs are interfered from the adjacent cells no matter whether the coalitions are created or not. The reason is that the interference from the adjacent cells can change frequently depending on the allocation of resources in these cells (like channels/resource blocks and power allocation). Still, this is in line with the radio resource management, interference management, or scheduling in 5G and beyond mobile networks, where these procedures are supposed to take place frequently (e.g., each transmission time interval with a duration of 1 ms or even less).

To find the transmission power allocation within the coalition, we form a linear system of equations with multiple variables, where each variable represents the transmission power allocation of individual FlyBSs serving the UEs in the same coalition. Taking the example from Fig. 3b with the coalition $\boldsymbol{u_1} = \{2,4,8\}$ and applying Lemma 2, the following system of equations is obtained:

$$\begin{aligned} p^z_{1,2} &= a^z_{1,2}b^z_{1,2} + a^z_{1,2}p^z_{2,4}g_{2,2} + a^z_{1,2}p^z_{3,8}g_{3,2} \\ p^z_{2,4} &= a^z_{2,4}b^z_{2,4} + a^z_{2,4}p^z_{1,2}g_{1,4} + a^z_{2,4}p^z_{3,8}g_{3,4} \\ p^z_{3,8} &= a^z_{3,8}b^z_{3,8} + a^z_{3,8}p^z_{1,2}g_{1,8} + a^z_{3,8}p^z_{2,4}g_{2,8} \end{aligned} \tag{22}$$

Then, (22) is rewritten into a matrix representation as:

$$\begin{bmatrix} 1 & -a^z_{1,2}g_{2,2} & -a^z_{1,2}g_{3,2} \\ -a^z_{2,4}g_{1,4} & 1 & -a^z_{2,4}g_{3,4} \\ -a^z_{3,8}g_{1,8} & -a^z_{3,8}g_{2,8} & 1 \end{bmatrix} = \begin{bmatrix} a^z_{1,2}b^z_{1,2} \\ a^z_{2,4}b^z_{2,4} \\ a^z_{3,8}b^z_{3,8} \end{bmatrix} \tag{23}$$

After that, the transmission power allocation is found by applying the Cramer's rule (or any other solver for the system of linear equations). Note that, in some cases, the solution to the system of equations would require an allocation of negative transmission powers. This phenomenon occurs if the

UEs in the coalition are strongly interfered by the FlyBSs and, thus, this coalition is not profitable. Consequently, the UEs are in the same coalition only if all transmission powers (i.e., $p^z_{1,2}$, $p^z_{2,4}$, and $p^z_{3,8}$) are positive.

To determine which UEs should be in the coalitions, we formulate the coalition creation problem as a constrained coalition structure generation [40]. For any set of players, the coalition structure is understood as a set of coalitions $\boldsymbol{\mathcal{U}}= \{\boldsymbol{u_1}, \boldsymbol{u_2}, \dots, \boldsymbol{u_Z}\}$ such that each element $\boldsymbol{u_z} \in \boldsymbol{\mathcal{U}}$ is the set of players (i.e., the set of UEs) composing one coalition. Note that each player belongs only to a single coalition. The problem is defined as a constrained one, since the UEs attached to the same FlyBS cannot be in the same coalition. The reason is that we assume simple FlyBSs that are not able to serve multiple UEs at the same resources. Consequently, only the UEs attached to the different FlyBSs can belong to the same coalitions. The objective is, then, to find such coalition structure ($\boldsymbol{\mathcal{U}}^*$) that minimizes the sum transmission power over all access channels and over the FlyBSs, i.e.,:

$$\begin{aligned} \boldsymbol{\mathcal{U}}^* &= \underset{\boldsymbol{\mathcal{U}}}{\text{argmin}} \sum_m \sum_n x_{m,n} p^z_{m,n} \\ \text{s.t.} &\quad \text{(24a) } 0 < p^z_{m,n} < p_{m,n}, \forall m \in \mathcal{M}, \forall n \in \mathcal{N} \\ &\quad \text{(24b) } m \neq m', \forall m, m' \in \boldsymbol{f_z}, \forall z \end{aligned} \tag{24}$$

where the constraint (24a) guarantees that the transmission power allocated by all FlyBSs is not increased by any coalition and the constraint (24b) ensures that the UEs attached to the same FlyBSs cannot be in the same coalition.

The following subsection first describes the solution for the optimal coalition structure based on the dynamic programming. Then, we outline a low-complexity greedy algorithm.

B. Optimal coalitions creation

To find the optimal solution for the problem defined in (24) and to determine the optimal structure of the coalitions, the dynamic programming [40] is a suitable option. The problem defined in (24) is, however, different from the conventional coalition structure generation problems due to both constraints. Hence, the dynamic programming is modified as explained below.

The dynamic programming is an iterative two-phases process. In the first phase, a gain function is calculated for all coalitions with a size of 1 (i.e., one UE in each coalition), a size of 2 (two UEs in the coalitions), up to the coalition with a size of N_f, where N_f is the number of UEs connected to the FlyBSs. Note that the UEs attached directly to the SBS cannot be in any coalition as their channel cannot be reused by the FlyBSs. Then, the gain function for each created coalition with the sizes of $1, 2, \dots, N_f$ is determined as:

$$f(\boldsymbol{u_z}) = \begin{cases} \sum_{n \in \boldsymbol{u_z}} \left(p_{m,n} - p^z_{m,n}\right) & \text{if (24a), (24b) are met} \\ -\infty & \text{otherwise} \end{cases} \tag{25}$$

The definition of $f(\boldsymbol{u_z})$ reflects the fact that the goal of the coalitions creation is to reduce the total transmission power at the FlyBSs. Hence, the coalition is profitable only if all FlyBSs serving the UEs in the same coalition decrease their transmission power. If (24a) or (24b) is not met, $f(\boldsymbol{u_z})$ is set to $-\infty$ to ensure that this coalition is not selected. Note that we set $f(\boldsymbol{u_z})$ to $-\infty$ instead of to 0 to distinguish between the coalition that is not allowed and the case when the UE is in the coalition with the size 1, where the gain for such case is 0 by default, since the FlyBS is not able to decrease its transmission power. Besides the calculation of the gain function for all coalitions with the sizes $1, 2, \dots, N_f$, the dynamic programming also calculates the gain functions if the coalition of the size 2 or higher are split into smaller coalitions. These gain functions are again enumerated via (25).

Then, in the second phase, the dynamic programming finds the optimal coalition structure recursively. That is, at the beginning, the coalition with the size of N_f is assumed to be the optimal one. Then, the dynamic programming iteratively checks if the gain can be increased by separating the UEs in one larger coalition into two smaller coalitions exploiting the gain functions already calculated in the first phase. If the gain would be increased by the splitting of some UEs, these UEs are not allowed to be in the same coalitions. Otherwise, the UEs are assumed to be in the same coalition.

The dynamic programming-based solution is of a very high complexity equal to $\mathcal{O}(3^{N_f})$. Hence, such solution is not practical for the real networks and we propose a low-complexity greedy algorithm in the next subsection to solve the coalitions' creation problem.

C. Low-complexity greedy algorithm for coalitions creation

As explained in the previous subsection, the dynamic programming is not suitable for the derivation of the coalitions for a high number of the UEs due to its high complexity. Thus, in this section, we propose the greedy algorithm for the creation of the coalitions.

The proposed greedy algorithm for the coalitions' creation is described in Algorithm 3. In the first step, the gains of any two UEs potentially creating the coalition are calculated according to (25), see line 1 in Algorithm 3. In the next step, the matrix $\boldsymbol{U}$ with a size of NxN is created as (line 2):

$$\boldsymbol{U} = \begin{bmatrix} 0 & U_{1,2} & \dots & U_{1,N} \\ 0 & 0 & \dots & U_{2,N} \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & U_{N-1,N} \\ 0 & 0 & \dots & 0 \end{bmatrix} \tag{26}$$

The diagonal values of $\boldsymbol{U}$ are set to 0, as the UE cannot be in the coalition with itself. The matrix $\boldsymbol{U}$ is symmetric, since $U_{n,n'} = U_{n',n}$ and, thus, all values below the diagonal are also zeroed out. In the next step, the maximal value in $\boldsymbol{U}$ is found (line 4) and the corresponding n-th and n'-th UEs create the coalition (line 5). Then, $U_{n,n'}$ entry in $\boldsymbol{U}$ is set to 0 (line 6). Moreover, all positive entries in the n-th row and the n'-th column of $\boldsymbol{U}$ are updated (lines 7-8). The reasons for this update of the positive values in $\boldsymbol{U}$ are as follows. First, the n-th UE can no longer be in the same coalition with any UE attached to the same FlyBS, since the n'-th UE and vice versa, to guarantee (24b). Thus, all positive entries in the n-

Algorithm 3 Greedy algorithm for coalition creation

1: Calculate $U_{n,n'}, \forall n, n' \in \mathcal{N}$ acc. to (25)
2: Create matrix $\mathbf{U}$
3: **while** $\max(U_{n,n'}) > 0$ **do**
4: $\quad \{n, n'\} \leftarrow \max(U_{n,n'})$
5: $\quad$ Add n-th and n'-th UEs into the same coalition
6: $\quad$ Set $U_{n,n'}$ to 0
7: $\quad$ Update all positive values in n-th row of $\mathbf{U}$
8: $\quad$ Update all positive values in n'-th column of $\mathbf{U}$
9: **end while**

th row and the n'-th column are set to 0. Second, if the n-th UE is inserted to the coalition with the n'-th UE while at least one of these UEs is already in another coalition with another UE(s), all positive entries in the n-th row and the n'-th column should be updated, as the gain calculated initially in $\boldsymbol{U}$ is only for two UEs (n and n'). Note that the new gain is calculated according to (25) and the transmission powers of the FlyBSs are derived via (15). This way, we determine whether the coalition composing more than two UEs is of a benefit (indicated by a positive value in the n-th row and the n'-th column). Otherwise, this entry is set also to 0. After that, the maximum value in $\boldsymbol{U}$ is found again and the whole process (i.e., lines 3-9) is repeated as long as there is at least one positive entry in $\boldsymbol{U}$.

The complexity of the proposes greedy algorithm is $\mathcal{O}(N_f^2 log N_f)$, as N_f^2 entries are sorted from the highest to the lowest.

D. Re-positioning after the coalitions are created

Even though the UEs in the same coalition are served over a wider access channel, the backhaul channels are still of the same bandwidth. Thus, the UEs' benefit from the coalitions cannot be directly translated to their capacity gains, as the capacity of the backhaul links remains unchanged and act as a bottleneck (see (4)). Nevertheless, the created coalitions decrease the transmission power allocated at the FlyBSs while the same capacity at the access links is kept. Hence, the FlyBSs can be further re-positioned in the direction to the SBS to increase the capacity at the backhaul links.

The re-positioning described in Section IV is applicable also for the case with the coalitions already created. Nevertheless, $p_{m,n}$ for all UEs in the coalitions should always be positive. Note that $p_{m,n}$ for the UEs in the coalitions is derived by solving linear equations, where the found solution may not be feasible, because $p_{m,n}$ can be negative (as described in Section V-A). Thus, (13) should include an additional constraint ensuring that $p_{m,n} \geq 0$ for all m and n. Then, to adopt the Nelder-Mead simplex algorithm, the optimization problem is transformed into the unconstrained one as:

$$\boldsymbol{V}^{**} = \underset{\boldsymbol{V}}{\operatorname{argmax}} \sum_m \sum_n x_{m,n} G_{m,n} - \\ - \rho \sum_m \max(0, \sum_n x_{m,n} p_{m,n} - P_{max}) - \\ - \rho \sum_m \sum_n \max(0, -p_{m,n}) \quad (27)$$

where the penalty ρ is applied if $p_{m,n} < 0$. After that, the Nelder-Mead simplex algorithm is exploited in the same way as described in Section IV. Similarly, Algorithm 2 proposed for the re-positioning requires also a minor change. More specifically, the condition in line 8 in Algorithm 2 should include the additional constraint on $p_{m,n}$. Thus, if $p_{m,n} < 0$ for any n-th UE in the coalition, the FlyBS should go back to its previous position.

VI. Simulation Scenario, Parameters, and Competitive Schemes

This section describes the simulation scenario, the simulation parameters, and outlines the competitive schemes to which our proposal is compared. The performance of the proposed scheme is evaluated in MATLAB. We consider a

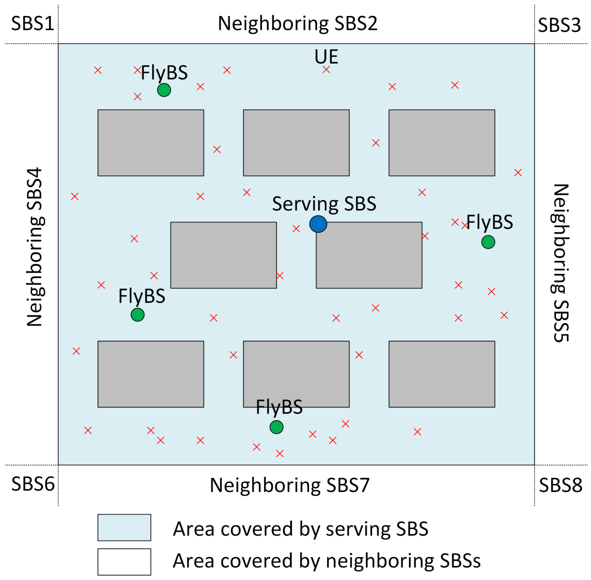


Fig. 4: Illustrative simulation scenario in Urban area with building blocks.

TABLE I: The simulation parameters

Parameter	Value
Carrier frequency	2 GHz
Simulation area of the reference cell	500x500 m
Number of the adjacent SBSs (K)	8
Number of FlyBSs (M)	4-10
Number of UEs in the reference cell (N)	10-200
Bandwidth available at the SBS in downlink (B)	20 MHz
Channel bandwidth initially allocated to the UE	B/N MHz
Max. trans. power of the SBS and the FlyBSs	20-30 dBm
Noise spectral density (σ_0)	-174 dBm/Hz
Height of the SBS/FlyBSs/UEs antenna	30/30/1 m
Number of the simulation drops	1000

reference cell with a size of 500x500 m and several buildings to emulate an urban environment (see Fig. 4). The serving SBS is deployed at a fixed position at the left upper corner of the building close to the cell center, as indicated in Fig. 4. The height of each building is generated randomly between 25 m and 29 m. Moreover, eight neighboring areas (cells) with the same building's distribution as in the reference cell surround this reference cell. Each neighboring area is under the coverage of one neighboring SBS mounted on top of the building at the same position as the serving SBS in the reference cell. The neighboring SBSs represent the sources of inter-cell interference to the reference cell.

In the reference cell, N UEs are uniformly deployed in the outdoor areas. We assume, without loss of generality, that the SBS splits the available bandwidth equally among all UEs, i.e., each channel is of a bandwidth $B_n = B/N$ (as in [30]). The UEs are then associated either to the serving SBS or to one of M FlyBS deployed in the area. The initial positions of the FlyBSs are determined with respect to the location of the UEs by K-means, as in [37]. The channel gains between the FlyBSs and the UEs, between the SBS and the UEs, and between the SBS and the FlyBSs are modeled in line with the respective path loss models from [41] considering 2 GHz carrier frequency. While the SBS always communicates with the FlyBSs via LoS (as both the SBS and the FlyBSs are above the buildings), the communication path between the SBS/FlyBSs and the UEs can be obstructed by one or several buildings, each attenuating the signal by additional 20 dB. The simulation is repeated 1000 times with random positions of the UEs and corresponding FlyBSs positions. The simulation results are then averaged out over all these drops. The simulation parameters are summarized in Table I.

The proposal is confronted with the following schemes:

- *K-means*: The association of the UEs and the positions of the FlyBSs is done optimally with respect to the distance between the FlyBSs and the UEs while the reuse of the access channels is not considered [37].
- *w/o BA*: The positions of the FlyBSs are optimized only with respect to the quality of the access links while neither a backhaul awareness nor the reuse of the access channels is assumed as, e.g., in [5]).
- *IAB*: The FlyBSs reuse the whole bandwidth at both the backhaul and the access links based on [30]-[33] considering IAB concept.

We do not compare our proposal with other "backhaul-aware" schemes as these limit the backhaul capacity in a simple way [17][18], consider out-band frequencies for the backhaul [19]-[22], or address a completely different problem [23]-[28][34] and, thus, the comparison is not feasible.

We show also a theoretical upper bound of our proposal with the power allocation at the FlyBSs, the association of the UEs, and the coalitions creation being optimal while the positions of the FlyBSs are found numerically by the Nelder-Mead simplex algorithm. Note that the performance of the optimal coalitions is shown only for up to 20 UEs, as the results for larger numbers of the UEs cannot be derived due to a very high complexity of dynamic programming.

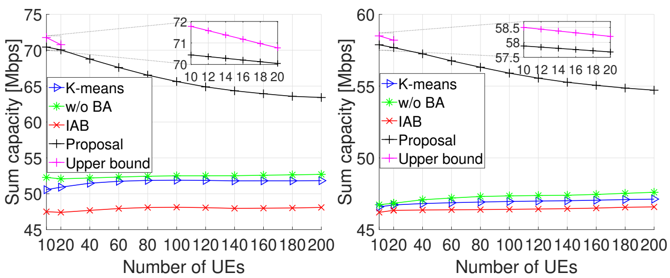
VII. Simulation results

This section presents and discusses the simulation results and compares the performance of the proposal with respect to the competitive schemes. We also analyze the contribution of the individual steps of the proposal to the overall performance. Last, we study the amount of interference generated by the FlyBSs to the underlying devices utilizing the same spectrum in order to demonstrate the benefits resulting from the proposal.

A. Performance evaluation and comparison with state-of-the-art schemes

Fig. 5 illustrates the performance of the individual schemes for a varying number of the UEs in the simulation area considering the full duplex (Fig. 5a) and the half duplex (Fig. 5b). The proposed scheme significantly outperforms all competitive solutions. The sum capacity achieved by the proposal initially decreases with an increasing number of the UEs. This is due to the fact that more deployed UEs share individual FlyBSs and, hence, the FlyBSs have less degree of freedom during the re-positioning step. Consequently, the FlyBSs stay further from the SBS resulting in a lower backhaul capacity that also impacts the sum capacity of UEs attached to the FlyBSs. However, the sum capacity saturates and its decrease becomes marginal when more than 140 UEs are deployed. The saturation of the sum capacity results from a compensation of the initial decrease in the capacity (due to less degree of freedom of the FlyBSs during re-positioning) by the fact that generally more UEs benefit from the FlyBSs deployment.

In case of the full duplex, the proposal increases the sum capacity of the UEs by between 22.4 % and 39.3 %, between 20.3 % and 34.8 %, and between 31.9 % and 48.3 % compared to K-means, w/o BA, and IAB schemes, respectively (see Fig. 5a). The reason why K-means and w/o BA schemes are significantly outperformed by the proposal is that the FlyBSs are positioned close to the UEs by these schemes and the backhaul links act as a bottleneck. The unsatisfactory performance of the IAB-based scheme is mainly due to a high interference among the FlyBSs that reuse the same bandwidth. Hence, it is more efficient to share only a part of the bandwidth as accomplished by the proposed coalition



(a) Full duplex (b) Half duplex

Fig. 5: Sum capacity of the UEs achieved by the proposal and the competitive algorithms over the number of UEs (P_{max} = 27 dBm, $M = 4$).

structure instead of reusing the whole bandwidth by the FlyBSs. The relative improvement in the sum capacity of the proposal with respect to all competitive schemes is slightly decreased for the half duplex when compared to the full duplex, since a lower number of the UEs profit from the relaying in the half duplex. The reason is that the backhaul capacity is decreased, as the FlyBSs receive data in the half duplex from the serving SBS. Nevertheless, even in case of the half duplex, the proposal significantly outperforms K-means, w/o BA, and IAB schemes by up to 23.5%, 23.1%, and 24.5%, respectively.

Fig. 5 also demonstrates that the proposed solution is close to the upper bound in terms of the sum capacity. Specifically, the gap between the proposal and the upper bound is only up to 1.9% and up to 1.1% in the case of the full duplex (Fig. 5a) and the half duplex (Fig. 5b), respectively.

Fig. 6 shows the total transmission power allocated at the FlyBSs depending on the number of UEs. The competitive schemes always allocate and exploit the whole available transmission power P_{max} disregarding the number of the UEs. Consequently, the total power allocated at the FlyBSs by all competitive schemes is constant and is equal to roughly 2 W (four FlyBSs are considered, each with $P_{max} = 27$ dBm ≈ 0.5 W) in this figure. In case of the proposal, the total transmission power allocated at the FlyBSs slightly increases if the number of the UEs increases up to 20. The reason for this phenomenon is that some FlyBSs may not be exploited at all for some simulation drops with a low number of the UEs and the average total transmission power is decreased. Then, the total transmission power starts decreasing with more of the UEs in the area (above 20). Still, the total transmission power starts slightly increasing again for more than 80 UEs (and more than 120 UEs in case of the half duplex). The reasons for this behavior are two opposite trends: i) the total transmission power *increases* with the number of the UEs, since the FlyBSs serve more UEs in average (i.e., more UEs are associated with each FlyBS) and ii) the total transmission power *decreases* if more UEs are attached to the FlyBSs, since the FlyBSs are not able to move so close to the serving SBS in order to still guarantee high quality communication access channels for all of, or at least most of, the UEs. While the second trend is more significant for 20 to 80 UEs in case of the full duplex and for 20 to 120 UEs in case of the half duplex, the first trend becomes more significant for higher number of the UEs.

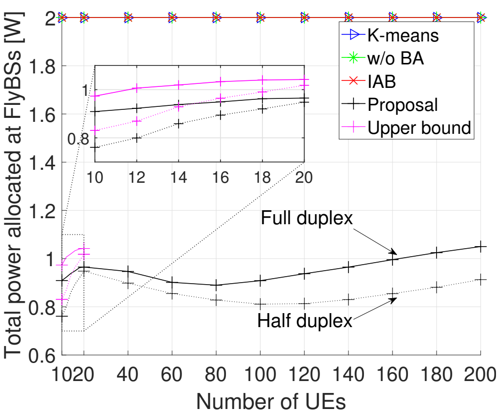
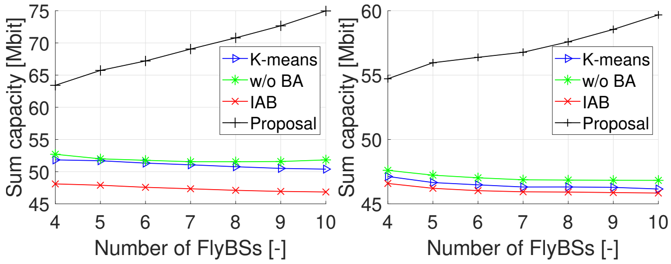


Fig. 6: Total transmission power allocated at all FlyBSs by the proposal and the competitive algorithms (P_{max} = 27 dBm, M = 4). Note: the competitive schemes allocate the same total power (roughly 2 W) at the FlyBSs for both the full and half duplex as these optimize only access links.



(a) Full duplex (b) Half duplex

Fig. 7: Sum capacity reached by the proposal and the competitive algorithms over the number of FlyBSs ($P_{max} = 27$ dBm, $N = 200$).

Fig. 6 demonstrates the proposal decreases the total transmission power to about one half of the transmission power allocated by the competitive schemes. The main reason for this significant decrease in the transmission power is that if the backahul links are of a lower quality than the access links, the transmission power at the FlyBSs is decreased to keep the same capacity at the access and backhaul links. If the half duplex is applied, up to 14% of the total power is saved at the FlyBSs compared to the full duplex since: i) the number of the UEs served by the FlyBSs in the half duplex is lower compared to the full duplex and ii) the UEs are not interfered by the serving SBS and, thus, a lower power is allocated to the UEs to ensure $C^A_{m,n} = C^B_{m,n}$ (see Remark 1 in Section III-A).

Fig. 6 also shows the total allocated power in the case of the upper bound is by up to 9% (in case of the full duplex) and up to 9.2% (for the half duplex) higher than the power allocated by the proposed solution. The reason for this phenomenon is that the numerical positioning of the FlyBSs, which is part of the upper bound and which maximizes the sum capacity, finds the positions for the FlyBSs closer to the SBS than the proposed solution. Consequently, the FlyBSs allocate more transmission power to the UEs, since: i) slightly more data is transmitted to the UEs (as shown in Fig. 5) and ii) the quality of the access channels is worsen, as the FlyBSs are farther from the UEs and more power should be allocated to them.

The impact of the number of deployed FlyBSs on the sum capacity is depicted in Fig. 7. The sum capacity of K-means and IAB algorithms slightly decreases with more deployed FlyBSs in the area for both the full and half duplex. The reason is that with more FlyBSs in the area, the FlyBSs stay generally "closer" to the UEs, but "farther" from the SBS as the backhaul is ignored. Consequently, the backhaul capacity is degraded and becomes the limiting factor. If the optimization is done solely according to the access links (i.e., w/o BA scheme), the sum capacity starts slightly increasing if seven or more FlyBSs are deployed. In comparison to the competitive schemes, the proposal is able to fully exploit a denser deployment of the FlyBSs and the sum capacity increases almost linearly with the number of FlyBSs. The reason is that with more FlyBSs in the area, a lower number of the UEs is attached to each FlyBS in general. Consequently, the FlyBSs are less restricted in their movement and can be re-positioned closer to the SBS by the proposal resulting in a backhaul of a higher quality. Hence, the proposal with the full duplex FlyBSs significantly increases the sum capacity and gains up to 48.8%, 44.7%, and 60.1% when compared to K-means, w/o BA, and IAB scheme, respectively, if 10 FlyBS are deployed. The sum capacity of all schemes is decreased if the half duplex is considered compared to the full duplex as explained in Fig. 5. Nevertheless, the proposal still outperforms K-means, w/o BA, and IAB schemes significantly up to 29.3%, 27.5%, and 30.2%, respectively.

Fig. 8 shows the impact of the number of deployed FlyBSs on the total transmission power allocated by the FlyBSs. The total transmission power increases linearly with the number of FlyBSs for all competitive schemes as each FlyBS transmits with a fixed transmission power. Also in case of the proposal, the total transmission power is increasing linearly. However, the slope of the increase is much lower compared to the competitive schemes. In fact, the transmission power of a single FlyBS even decreases with the increasing number of the FlyBSs if the proposal is utilized. The main reason is that with more deployed FlyBSs, a lower number of the UEs is served by individual FlyBSs and, thus, less power is allocated by these FlyBSs. Consequently, the proposal is able to reduce the transmission power by 64% compared to all competitive schemes and assuming 10 FlyBSs are being deployed. Moreover, Fig. 8 demonstrates that the proposal exploiting only the half duplex reduces the total power allocated at the FlyBSs by up to 14% with respect to the full duplex.

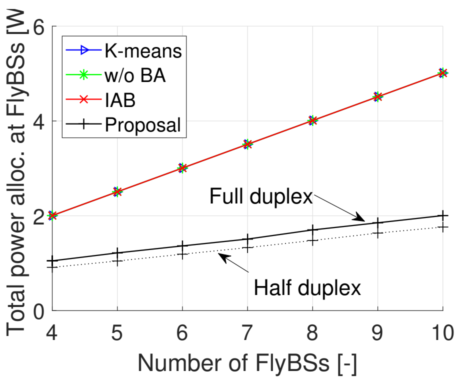


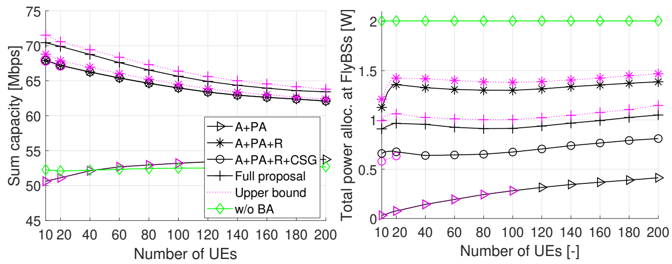
Fig. 8: Total transmission power allocated at all FlyBSs by the proposal and the competitive algorithms (P_{max} = 27 dBm, N = 200).

B. Analysis of gain introduced by individual parts of the proposal

This section analyzes the gain introduced by the individual steps of the proposal for the full duplex. To that end, we evaluate the sum capacity and the total transmission power allocated at the FlyBSs after the following subsequent steps of the proposal: i) the joint association of the UEs to the FlyBSs and the power allocation at the FlyBS via the proposed Algorithm 1 (denoted in figures as "A+PA"), ii) the re-positioning of the FlyBSs according to the proposed Algorithm 2 (denoted as "A+PA+R"), iii) the creation of the coalitions among the UEs (i.e., the coalition structure generation) by the proposed greedy Algorithm 3 (denoted as "A+PA+R+CSG"), and iv) another re-positioning according to Algorithm 2 to further increase the sum capacity (denoted as Full proposal). Note that the Full proposal corresponds to the Proposal scheme in the previous subsection. Besides the individual steps of the proposal, we also depict the best performing competitive scheme, i.e., w/o BA, as a benchmark.

Fig. 9 illustrates the gain of individual steps of the proposal for a varying number of the UEs. After the association and the initial power allocation, the sum capacity of the proposal is similar to the best performing competitive scheme w/o BA (see line "A+PA" in Fig. 9a). Nevertheless, the total transmission power allocated by the proposal at the FlyBSs (Fig. 9b) is notably lower as it varies only between 3.8% and 20.7% of the power allocated by the w/o BA.

The subsequent re-positioning of the FlyBSs leads to a significant increase in the sum capacity with respect to the sole association (by 15.6% and 31.2% for 200 UEs and 20 UEs, respectively, see line "A+PA+R" in Fig. 9a). The gain is achieved due to the improved backhaul capacity as the FlyBSs get closer to the SBS. Although the re-positioning increases also the total power allocated at the FlyBSs to keep the same capacity at the access and the backhaul links (see Lemma 1), the allocated power is still more than 30% lower than the power allocated by the w/o BA scheme disregarding the number of UEs. Note that the trend in the total transmission power is analogous to Fig. 6 for the same reasons. Also note that the FlyBSs are often not able to move to the positions, where the whole power budget can be utilized due to the buildings obstructing the communication path. In other words, if the FlyBS would move to the position where the UEs



(a) (b)

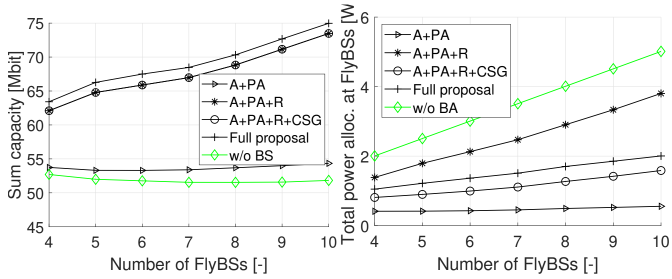
Fig. 9: Gain of individual steps of the proposal over the number of UEs (P_{max} = 27 dBm, M = 4).

become shadowed by the building(s) and the required power to serve the UEs would exceed P_{max}, the FlyBS rather stays at its current position even if the actual allocated power is lower than P_{max}.

The next step, the coalition structure generation, reduces the total transmission power at the FlyBSs significantly (roughly by 50%) with respect to the case without the coalitions. The reason is that the FlyBSs can allocate less power to the UEs in the coalitions and, thus, reduce their total allocated transmission power. As explained in Section V, the formed coalitions by themselves do not improve the sum capacity of the UEs, since the backhaul quality remains the same (see line "A+PA+R+CSG" in Fig. 9a). Still, the created coalitions open a space for further "boost" in the sum capacity as the FlyBSs are again re-positioned closer to the SBS. This further re-positioning boosts the capacity by up to 4.2%. Of course, the re-positioning increases again the total transmission power. However, the total transmission power is still significantly lower compared to the competitive schemes (see Full proposal in Fig. 9b). This indicates a possible trade-off as, in some use-cases, it can be profitable not to apply the re-positioning of the FlyBSs after the coalitions are created and rather keep the transmission power of the FlyBSs low in order to decrease the interference to other underlying devices (we analyze and demonstrate this in Section VII-C).

Fig. 9 also shows the gap between the proposed solution (encompassing proposed Algorithms 1-3) and the upper bound. First, Fig. 9 demonstrates that the proposed Algorithm 1 for the UEs association is optimal for up to 100 UEs (see "A+PA" in Fig. 9). Note that we are not able to show the performance of the full search for more than 100 UEs due to its huge complexity. Second, the gap in the sum capacity between the proposed re-positioning (described in Algorithm 2) and the upper bound found by Nelder-Mead simplex is only negligible as it varies between 1% and 1.5%, as shown in Fig. 9a. Fig. 9b also shows that the upper bound performance of the FlyBSs' re-positioning leads to a higher allocated total transmission power at the FlyBSs (between 5% and 12.1%) when compared to "A+PA+R". This is due to the same reasons as described already above in Fig. 6. Last, Fig. 9b shows that the proposed algorithm for the coalition creations (i.e., "A+PA+R+CSG") decreases the total transmission power nearly the same as the high-complexity optimal dynamic programming-based solution, as the gap between the proposal and the optimum varies only from 3.1% to 7%. Notice the sum capacity is not increased when the coalitions are introduced (see Fig. 9a) as the coalitions decrease the transmission power only, as explained in Section V.

Fig. 10 depicts the gain of individual proposal steps over the number of the deployed FlyBSs. Similarly as in Fig. 9, a notable gain in the sum capacity is achieved by the re-positioning of the FlyBSs in the direction of the SBS with respect to the association and power allocation only (between 15.6% and 35.2%). Then, an additional gain in the sum capacity is observed by the re-positioning of the FlyBSs after the coalitions are created (up to 2.6% as shown in Fig. 10a). Such relatively small gain is due to the fact that the re-positioning of the FlyBSs after the coalitions are created is often restricted by these coalitions. Consequently, the FlyBSs cannot move much closer to the SBS as the FlyBSs serving the UEs in the coalition would interfere to all other UEs. Nevertheless, the formed coalitions significantly decrease the total power allocated at the FlyBSs by up to 58.3% if 10 FlyBSs are deployed (see Fig. 10b). Even after the re-positioning with the created coalitions that slightly increases the total transmission power, the full proposal decreases the total allocated transmission power roughly 2.5 times compared to the state-of-the-art solutions.

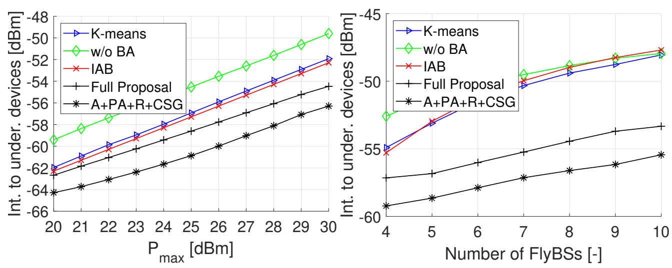


(a) (b)

Fig. 10: Gain of individual steps of the proposal over the number of FlyBSs ($P_{max} = 27$ dBm, $N = 200$).

C. Interference to underlying devices

One concern regarding the adoption of the FlyBSs into the mobile networks is the increased interference from the deployed FlyBSs to the various underlying devices, such as IoT devices, machines, or sensors, exploiting the same spectrum. Our proposal reduces the transmission power as shown in previous subsections and, consequently, mitigates the interference generated by the FlyBSs to these underlying devices. This subsection shows the average interference generated by the FlyBSs to 100 underlying devices deployed uniformly within the reference cell. In case of our proposal, we also show the amount of the interference generated if no re-positioning after the coalitions creation is allowed (i.e., the line "A+PA+R+CSG"). This option is seen as a good trade-off between the minimization of the interference to the underlying devices and the maximization of the sum capacity of the UEs attached to the FlyBSs.



(a) (b)

Fig. 11: Interference generated to underlying devices by the full duplex FlyBSs.

Fig. 11a shows that the interference level at the underlying devices increases if the FlyBSs are allowed to transmit with a higher power. The proposal causes a lower level of the interference to the underlying devices in vicinity when compared to all competitive schemes. More specifically, the full proposal generates up to 2.55 dBm, 4.87 dBm, and 2.18 dBm less interference with respect to K-means, w/o BA, and IAB scheme, respectively. Moreover, if the minimization of the interference to the underlying devices is of a high priority, the interference can be further decreased by the proposal via disabling the second re-positioning of the FlyBSs after the coalitions are created (denoted in Fig. 11 as "A+PA+R+CSG"). Note that even without the second re-positioning of the FlyBSs, the proposal significantly outperforms all competitive schemes as demonstrated in Fig. 9 and Fig. 10. Thus, without the second re-positioning, the proposal causes up to 4.37 dBm, 6.69 dBm, and 4 dBm less interference when compared to K-means, w/o BA, and IAB scheme, respectively.

Fig. 11b shows that if the number of FlyBSs increases, the interference suppression by the proposal with respect to the competitive schemes is emphasized even more. Hence, the proposal causes up to 5.27 dBm, 5.38 dBm, and 5.64 dBm less interference than K-means, w/o BA, and IAB scheme, respectively, for 10 FlyBSs. Again, if the proposal does not adopt the second re-positioning of the FlyBSs the interference gap with respect to K-means, w/o BA, and IAB scheme increases up to 7.39 dBm, 7.49 dBm, and 7.75 dBm, respectively. These results demonstrate that the proposal is notably more "friendly" to the underlying devices as it suppresses significantly the interference from the deployed FlyBSs.

VIII. Conclusions

In this paper, we have introduced a backhaul-aware framework for the association of the UEs, power allocation of the FlyBSs, their re-positioning, and the access links reuse by means of the coalition structure generation. We have demonstrated that the proposed framework significantly outperforms competitive schemes in terms of capacity (up to 60%) and the transmission power reduction (up to 64%) in a wide range of scenarios and for the varying number of the UEs and the FlyBSs. In addition, due to the proposed reuse of the access links by means of the coalitions creation, the interference to the various underlying devices is significantly decreased (up to 7.7 dB).

The proposed framework can be extended towards joint optimization of the transmission powers of both the FlyBSs and the SBSs. Besides, the mobile users and the related aspects of handover management should further be investigated.

References

[1] Y. Zeng, et al., "Wireless communications with unmanned aerial vehicles: Opportunities and challenges," *IEEE Communications Magazine*, 54(5), pp. 36–42, 2016.

[2] M. Mozaffari, W. Saad, M. Bennis, Y.-H. Nam, and M. Debbah, "A Tutorial on UAVs for Wireless Networks: Applications, Challenges, and Open Problems," *IEEE Communications Surveys and Tutorials*, 21(3), pp. 2334-2360, 2019.

[3] L. Ruan, et al. "Energy-Efficient Multi-UAV Coverage Deployment in UAV Networks: A Game-Theoretic Framework", *China Communications*, 15(10), 2018.

[4] M. Alzenad, A. El-Keyi, and H. Yanikomeroglu, "3-D placement of an unmanned aerial vehicle base station for maximum coverage of users with different QoS requirements," *IEEE Wireless Communication Letters*, 7(1), pp. 38–41, 2018.

[5] X. Zhong, Y. Guo, N. LI, and S. Li, "Deployment Optimization of UAV Relays for Collecting Data From Sensors: A Potential Game Approach," *IEEE Access*, Vol. 7, 2019.

[6] X. Zhong, Y. Guo, N. Li, and Y. Chen, "Joint Optimization of Relay Deployment, Channel Allocation, and Relay Assignment for UAVs-Aided D2D Networks," *IEEE ACM/IEEE Transactions on Networking*, vol. 28, no. 2, pp. 804-817, 2020.

[7] Y. Liu, et al., "UAV Communications Based on Non-Orthogonal Multiple Access," *IEEE Wireless Communications*, 26(1), 2019.

[8] J. Chen and D. Gesbert, "Optimal positioning of flying relays for wireless networks: A LOS map approach," *IEEE ICC*, 2017.

[9] J. Plachy, Z. Becvar, P. Mach, R. Marik, and M. Vondra, "Joint positioning of Flying Base stations and Association of Users: Evolutionary-based approach," *IEEE Access*, pp. 11454–11463, 2019.

[10] H. El Hammouti, M. Benjillali, B. Shihada, and M.-S. Alouini, "Distributed Mechanism for Joint 3D Placement and User Association in UAV-Assisted Networks," *IEEE WCNC*, 2019.

[11] H. El Hammouti, M. Benjillali, B. Shihada, and M.-S. Alouini, "Learn-As-You-Fly: A Distributed Algorithm for Joint 3D Placement and User Association in Multi-UAVs Networks," *IEEE Transactions on Wireless Communications*, 18(12), pp. 5831-5844, 2019.

[12] X. Xi, et al., "Joint User Association and UAV Location Optimization for UAV-Aided Communications," *IEEE Wireless Communications Letters*, 8(6), pp. 1688-1691, 2019.

[13] X. Liu and N. Ansari, "Resource Allocation in UAV-Assisted M2M Communications for Disaster Rescue," *IEEE Wireless Communications Letters*, 8(2), pp. 580-583, 2019.

[14] S. Yan, M. Peng, and X. Cao, "A Game Theory Approach for Joint Access Selection and Resource Allocation in UAV Assisted IoT Communication Networks," *IEEE Internet Things J*, vol.6, no. 2, pp. 1663-1674, 2019.

[15] M. Nikooroo, Z. Becvar, "Optimizing Transmission and Propulsion Powers for Flying Base Stations," *IEEE WCNC 2020*.

[16] J. Cui, Y. Liu, and A. Nallanathan, "Multi-Agent Reinforcement Learning-Based Resource Allocation for UAV Networks," *IEEE Trans. Wireless Commun.*, vol. 19, no. 2, pp. 729-743, 2020.

[17] E. Kalantari, M. Z. Shakir, H. Yanikomeroglu, and A. Yongacoglu, "Backhaul-aware Robust 3D Drone Placement in 5G+ Wireless Networks," *IEEE ICC WKSHP*, 2017.

[18] E. Kalantari, I. Bor-Yaliniz, A. Yongacoglu, and H. Yanikomeroglu, "User association and bandwidth allocation for terrestrial and aerial base stations with backhaul considerations," *IEEE PIMRC*, 2017.

[19] M. Gapeyenko, et al., "Flexible and Reliable UAV-Assisted Backhaul Operation in 5G mmWave Cellular Networks," *IEEE Journal on Selected Areas in Communications*, 31(11), 2018.

[20] Y. Hu, M. Chen, and W. Saad, "Joint Access and Backhaul Resource Management in Satellite-Drone Networks: A Competitive Market Approach," arXiv:1908.11038v1, 2019.

[21] G. Castellanos, M. Deruyck, L. Martens, and W Joseph, "Performance Evaluation of Direct-Link Backhaul for UAV-Aided Emergency Networks," *Sensors*, 19, 2019.

[22] N. Ansari, D. Wu, and X. Sun, "FSO as backhaul and energizer for drone-assisted mobile access networks," *ICT Express*, 6, 2020.

[23] M. M. U. Chowdhury, et al., "3-D Trajectory Optimization in UAV-Assisted Cellular Networks Considering Antenna Radiation Pattern and Backhaul Constraint," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 56, no. 5, pp. 3735 – 3750, 2020.

[24] D. Huang, M. Cui, G. Zhang, X. Chu, and F. Lin, "Trajectory optimization and resource allocation for UAV base stations under in-band backhaul constraint," *EURASIP Journal on Wireless Communications and Networking*, 2020.

[25] G. Feng, et al., "UAV-assisted wireless relay networks for mobile offloading and trajectory optimization," *Peer-to-Peer Networking and Applications*, vol. 12, pp. 1820-1834, 2019.

[26] C. T. Cicek, H. Gultekin, B. Tavli, and H. Yanikomeroglu, "Backhaul-Aware Optimization of UAV Base Station Location and Bandwidth Allocation for Profit Maximization," arXiv:1810.12395v2, 2020.

[27] E. Kalantari, H. Yanikomeroglu, and A. Yongacoglu, "Wireless Networks With Cache-Enabled and Backhaul-Limited Aerial Base Stations," *IEEE Trans. Wireless Commun.*, vol. 19, no. 11, pp. 7363-7376, 2020.

[28] M.-J. Youssef , J. Farah, C. A. Nour, and C. Douillard, "Full-Duplex and Backhaul-Constrained UAV-Enabled Networks Using NOMA," *IEEE Trans. Veh. Technol*, vol. 69, no. 9, pp. 9667-9681, 2020.

[29] Technical Specification Group Radio Access Network, Study on Integrated Access and Backhaul, document 3GPP TR38.874 v16.0.0, Dec. 2018.

[30] M.-J. Youssef, C. A. Nour, J. Farah, and C. Douillard, "Backhaul-Constrained Resource Allocation and 3D Placement for UAV-Enabled Networks," *IEEE VTC-fall*, 2019.

[31] C. Pan, et al., "Joint 3D UAV Placement and Resource Allocation in Software-Defined Cellular Networks With Wireless Backhaul," *IEEE Access*, 7, 2019.

[32] A. Fouda, A. S. Ibrahim, I. Guvenc, and M. Ghosh, "UAV-Based in-band Integrated Access and Backhaul for 5G Communications," *IEEE VTC-fall*, 2018.

[33] A. Fouda, A. S. Ibrahim, I. Guvenc, and M. Ghosh, "Interference Management in UAV-Assisted Integrated Access and Backhaul Cellular Networks," *IEEE Access*, Vol. 7, 2019.

[34] Y. Li, G. Feng, M. Ghasemiahmadi, and L. Cai, "Power Allocation and 3-D Placement for Floating Relay Supporting Indoor Communications," *IEEE Trans. Mobile Comput.*, vol. 18, no. 3, pp. 618-631, 2018.

[35] P. Mach, Z. Becvar, and M. Najla, "Joint Association, Transmission Power Allocation and Positioning of Flying Base Stations Considering Limited Backhaul," accepted in VTC-Fall (Recent Results track), 2020.

[36] H. Wang, et al., "Spectrum Sharing Planning for Full-Duplex UAV Relaying Systems With Underlaid D2D Communications," *IEEE J. Sel. Areas Commun.* , vol. 36, no. 9, pp. 1986-1999, Sept. 2018.

[37] B. Galkin, at al., "Deployment of UAV-mounted access points according to spatial user locations in two-tier cellular networks," *Wireless Days (WD)*, pp. 1–6, 2016.

[38] O. Esrafilian and D. Gesbert, "Simultaneous User Association and Placement in Multi-UAV Enabled Wireless Networks," *In 22nd International ITG Workshop on Smart Antennas*, Bochum, Germany, 2018.

[39] M. Sami, J. N. Daigle, "User Association and Power Control for UAV-Enabled Cellular Networks," *IEEE Wireless Communications Letters*, vol. 9, no. 3, pp. 267-270, 2020.

[40] T. Rahwan et al., "A Coalition Structure Generation: A Survey," *Artificial Intelligence*, 229, pp. 139–174, 2015.

[41] 3GPP: 36.814 - Evolved Universal Terrestrial Radio Access (E-UTRA); Further advancements for E-UTRA physical layer aspects, v 9.2.0, 2017.