Backhaul-aware Uplink Communications in Full-Duplex DBS-aided HetNets

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***Abstract*—Drone-mounted base stations (*DBS*s) are promising solutions to provide ubiquitous connections to users and support many applications in the fifth generation of mobile networks while full duplex communications has the potential to improve the spectrum efficiency. In this paper, we have investigated the backhaul-aware uplink communications in a full-duplex DBS-aided HetNet (*BUD*) problem with the objective to maximize the total throughput of the network, and this problem is decomposed into two sub-problems: the DBS Placement problem (including the vertical position and horizontal position) and the joint UE association, power and bandwidth assignment (*Joint-UPB*) problem. Since the BUD problem is NP-hard, we propose approximation algorithms to solve the sub-problems and another, named the AA-BUD algorithm, to solve the BUD problem with guaranteed performance. The performance of the AA-BUD algorithm has been demonstrated via extensive simulations, and results show that the AA-BUD algorithm is superior to two benchmark algorithms.**

***Index Terms*—Drone-mounted base station, heterogeneous networks, wireless backhauling, full-duplex, OFDMA, resource allocation.**

I. Introduction

The fifth generation of mobile technology (*5G*) targets to provide better performance as compared to 4G LTE, i.e., greater throughput, lower latency and ultra-high reliability [1]. Full duplex (*FD*), which facilitates simultaneous transmission and reception over the same frequency spectra, is a promising technology to improve the spectrum efficiency for the next generation of wireless networks to overcome the shortage of spectrum [1], [2]. Drone-mounted base stations (*DBS*s) are able to provide ubiquitous connections to diversified user equipments (*UE*s) because of their flexibility, and efficient and high quality-of-service (*QoS*) provisioning, especially useful for supporting unexpected and temporary events [3], [4].

Many works related to DBS communications, viz., Unmanned Aerial Vehicle Base Station (*UAV-BS*) communications [5]–[7], have been reported. Alzenad *et al.* [5] studied the UAV-BS placement problem with the target to maximize the number of served UEs, and they proposed an exhaustive search algorithm to obtain the the optimal altitude and coverage radius under a given path loss threshold. Bor-Yaliniz *et al.* [6] highlighted the properties of the 3-D DBS placement problem with the objective to maximize the revenue, which is proportional to the number of covered UEs. Lyu *et al.* [7] investigated the UAV-BS placement problem, and the objective is to minimize the number of required DBSs while each UE is at least covered by one DBS. There are also many works about FD communications [8]–[10]. Nam *et al.* [8] maximized the total throughput of all FD-enabled UEs in an FD orthogonal frequency division multiple access (*OFDMA*) network with only one BS. Goyal *et al.* [9] studied the spectral efficiency of a mixed multi-cell network, viz., mixed FD and HD cells while all UEs are half-duplex (*HD*) enabled. Chen *et al.* [10] maximized the total sum-rate of uplink and downlink communications within one FD BS under a heavy workload scenario.

Few works have addressed the uplink communications in the HetNet with IBFD enabled DBSs. In our previous work [11], we investigated the throughput maximization of the downlink communications in a HetNet with in-band full-duplex (*IBFD*) enabled DBSs. In this paper, we study the backhaul-aware uplink communications in a full-duplex DBS-aided HetNet (*BUD*) problem.

The main contributions of this paper are delineated as follows: 1) we have proposed an IBFD-enabled DBS-aided HetNet for uplink communications, and the DBSs can provide dynamic coverage to UEs by adjusting their vertical positions and horizontal positions; 2) the macro-BS (*MBS*) is connected to the core network through free space optics (*FSO*) links, implying that this network can be easily deployed to provide communications to temporary events or fast communications recovery in emergency situations; 3) we propose two approximation algorithms to solve the sub-problems and another one named AA-BUD algorithm to solve the BUD problem. The AA-BUD algorithm with the approximation ratio of $\frac{1}{2}$ is shown capable of acquiring the optimal locations of all DBSs.

The remainder of this paper is organized as follows. The system model in described in Section II and the BUD problem is formulated in Section III. Then, two approximation algorithms are proposed to solve the sub-problems and another one named AA-BUD algorithm is proposed to solve the BUD problem in Section IV. Section V presents the performance of the AA-BUD algorithm and the comparison with two benchmark algorithms. Finally, conclusions are drawn in Section VI.

II. System Model

Fig. 1 shows a DBS-aided HetNet, in which the frequency division duplex (*FDD*) OFDMA framework is adopted [8]. DBS

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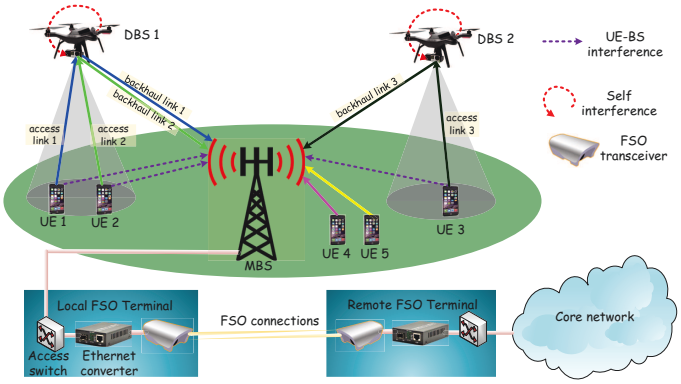

Fig. 1. The IBFD DBS-aided HetNet framework.

1 and DBS 2 are FD-enabled, and the MBS and all UEs are HD-enabled. The MBS is connected to the core network through the local FSO terminal and the remote FSO terminal. Both the local FSO terminal and the remote FSO terminal include an access switch, an Ethernet converter (Ethernet/FSO signal conversion) and an FSO transceiver. The distance between the local FSO terminal and the remote FSO terminal can be a few kilometers while a high data rate transmission can still be achieved [12]. For example, Sarkar *et al.* [13] designed a 64-QAM FSO transceiver for one hop transmission, and the transceiver demonstrates a 120 Gb/s reliable communication data rate over a 1 km link. An access link is the link from a UE to a BS (DBS), and a backhaul link is the link from a DBS to the MBS.

As shown in Fig. 1, different UEs utilize different frequency spectra for communication, no matter whether the UEs are associated with the DBS (UE 1 and UE 2) or the MBS (UE 4 and UE 5); different DBSs are assigned with different frequency spectra (UE 1, UE2 and UE 3); the backhaul link of a DBS reuses the frequency spectra of its access link (access link 1 and backhaul link 1). In this work, we focus on the uplink communications. In other words, we focus on data transmission from a UE to the MBS directly or via a FD-enabled DBS. For the uplink communications, the basic (minimum) unit of the frequency spectrum is one subcarrier (*SC*); one UE can be provisioned by one or multiple SCs while one subcarrier can only be assigned to one UE in order to avoid UE-UE interference.

A. Path Loss Model

For the path loss of the proposed framework in Fig. 1, we consider air-to-ground (*A2G*) path loss (DBS-MBS) and ground-to-air (*G2A*) path loss (UE-DBS). For both A2G and G2A path loss, we consider line-of-sight (*LoS*) and none-line-of-sight (*NLoS*) path loss [11], [14], [15]. Denote $\psi_{i,j}^L$ and $\psi_{i,j}^N$ as the probability of a LoS and NLoS connection of an A2G (G2A) link, as shown in Eq. (1). Here, a and b are environment constants (i.e., suburban, urban or dense urban); $\theta_{i,j} = arctan(\frac{h_j}{d_{i,j}})$ is the elevation angle; h_j ($j > 1$) is the altitude of the jth DBS and $d_{i,j}$ ($j > 1$) is the 3-D distance between the ith UE and the jth DBS [5], [14].

$$\begin{cases} \psi_{i,j}^L = [1 + a \cdot exp(-b(\frac{180\theta_{i,j}}{\pi} - a))]^{-1}, \\ \psi_{i,j}^N = 1 - \psi_{i,j}^L. \end{cases} \tag{1}$$

Let $\eta_{i,j}$ be the path loss between the ith UE and the jth DBS, as described in Eq. (2). Here, ζ^L and ζ^N are the additional path loss of LoS and NLoS, respectively; f_0 is the carrier frequency and c_0 is the transmission speed of light. The first item is the excessive path loss of LoS, the second item is the excessive path loss of NLoS, and the third item is the mean free-space path loss (including LoS and NLoS free-space path loss).

$$\eta_{i,j} = \psi_{i,j}^L \zeta^L + \psi_{i,j}^N \zeta^N + 20log(4\pi f_0 d_{i,j}/c_0). \tag{2}$$

After substituting Eq. (1) into Eq. (2), we have

$$\eta_{i,j} = \psi_{i,j}^L (\zeta^L - \zeta^N) + 20log(4\pi f_0 d_{i,j}/c_0) + \zeta^N. \tag{3}$$

B. Communications Model

Let $s_{i,j}^1$ and $s_{i,j}^2$ ($j > 1$) be the signal to interference plus noise ratio (*SINR*) of the access link and the backhaul link from the ith UE to the MBS via the jth DBS, as expressed in Eqs. (4)-(5). Here, $j = 1$ implies that the UE connects to the MBS directly; P_U is the transmission power of a UE; $\sigma_j^2 = \tau_0 b_{i,j} N_0$ is the thermal noise power, τ_0 is the bandwidth of one SC, $b_{i,j}$ is the assigned bandwidth for the ith UE to the jth BS in terms of SCs, and N_0 is the thermal noise power spectral density; $\alpha_{i,j} = p_{i,j}/\tau^{SI}$ is the self interference (*SI*) at the jth DBS incurred by the FD communications, $p_{i,j}$ is the assigned power by the jth DBS for the backhaul link (the jth DBS to the MBS) in provisioning the ith UE, and τ^{SI} is the SI cancellation capability [16].

$$s_{i,j}^1 = \begin{cases} \frac{P_U \Gamma_{i,j}}{\sigma_{i,j}^2}, & \forall i \in \mathcal{U}, j \in \mathscr{B}, j = 1, \\ \frac{P_U \eta_{i,j}}{\alpha_{i,j} + \sigma_{i,j}^2}, & \forall i \in \mathcal{U}, j \in \widetilde{\mathscr{B}}. \end{cases} \tag{4}$$

For Eq. (5), $\tilde{\eta}_{1,j}$ is the channel gain from the jth DBS to the MBS; $\Gamma_{i,1}$ is the channel gain from the ith UE to the MBS; $\sigma_{i,1}^2$ is the thermal noise power at the MBS owing to the transmission of the ith UE.

$$s_{i,j}^2 = \frac{p_{i,j} \tilde{\eta}_{1,j}}{P_U \Gamma_{i,1} + \sigma_{i,1}^2}, \quad \forall i \in \mathcal{U}, j \in \widetilde{\mathscr{B}}. \tag{5}$$

Let $\beta_{i,j}$ be the data rate of the ith UE towards the jth BS. Then, $\beta_{i,j}$ can be calculated by Eq. (6). Here, $\beta_{i,j}^1$ is the data rate of the access link (UE-BS) and $\beta_{i,j}^2$ is the data rate of the backhaul link (DBS-BS), as expressed in Eq. (7).

$$\beta_{i,j} = \begin{cases} \beta_{i,j}^1, & \forall i \in \mathcal{U}, j \in \mathscr{B}, j = 1, \\ \min(\beta_{i,j}^1, \beta_{i,j}^2), & \forall i \in \mathcal{U}, j \in \widetilde{\mathscr{B}}. \end{cases} \tag{6}$$

$$\begin{cases} \beta_{i,j}^1 = \tau_0 b_{i,j} log_2(1 + s_{i,j}^1), & \forall i \in \mathcal{U}, j \in \mathscr{B}, \\ \beta_{i,j}^2 = \tau_0 b_{i,j} log_2(1 + s_{i,j}^2)], & \forall i \in \mathcal{U}, j \in \widetilde{\mathscr{B}}. \end{cases} \tag{7}$$

TABLE I
NOTATIONS AND VARIABLES

Symbol	Definition
$\mathscr{B}$	The set of BSs (including the MDBS and DBSs).
$\widetilde{\mathscr{B}}$	The set of DBSs.
$\mathscr{U}$	The set of UEs.
$\mathscr{V}_1$	The set of horizontal candidate locations.
$\mathscr{V}_2$	The set of vertical candidate locations.
τ_0	The bandwidth of one SC.
r_i	The data rate requirement of the ith UE.
f^{max}	The total available bandwidth of all BSs in terms of SCs.
f_j^{max}	The total available bandwidth for the jth BS in term of SCs.
P_D	The power capacity of the jth BS.
P_U	The power capacity of the ith UE.
κ_j	The power spectral density of the jth DBS, $j \in \widetilde{\mathscr{B}}$.
$d_{i,j}$	The 3-D distance between the ith UE and the jth DBS.
$\eta_{i,j}$	The path loss between the ith UE and the jth DBS.
$\tau_{i,j}^{SI}$	The SI power at the jth DBS for provisioning the ith UE.
$x_{i,j}$	The UE-BS association indicator.
$\beta_{i,j}$	The achieved data rate of the ith UE towards the jth BS.
$b_{i,j}$	The assigned SCs by the jth BS towards the ith UE.
$p_{i,j}$	The assigned power by the jth DBS for the DBS-MBS transmission (backhaul data transmission for the ith UE).
γ_j	The horizontal position of the jth BS, $\gamma_j \in \mathscr{V}_1$.
h_j	The vertical position of the jth BS, $h_j \in \mathscr{V}_2$.

III. PROBLEM FORMULATION

We focus on uplink communications in an FD DBS-aided HetNet, and each UE is provisioned by one BS. Notations and variables are listed in Table I.

$$\mathscr{P}_0: \quad \max_{x_{i,j},p_{i,j},b_{i,j},\gamma_j,h_j} \quad \sum_i \sum_j x_{i,j} r_i$$

$$s.t.:$$

$$C1: \sum_j x_{i,j} \le 1, \quad \forall i \in \mathscr{U},$$

$$C2: \sum_i x_{i,j} b_{i,j} \le f_j^{max}, \quad \forall j \in \mathscr{B},$$

$$C3: \sum_i x_{i,j} p_{i,j} \le P_D, \quad \forall j \in \widetilde{\mathscr{B}},$$

$$C4: x_{i,j} r_i \le \beta_{i,j}, \quad \forall i \in \mathscr{U}, j \in \mathscr{B},$$

$$C5: \gamma_j \in \mathscr{V}_1, \quad \forall j \in \widetilde{\mathscr{B}},$$

$$C6: h_j \in \mathscr{V}_2, \quad \forall j \in \widetilde{\mathscr{B}},$$

$$C7: x_{i,j} \in \{0,1\}, \quad \forall i \in \mathscr{U}, j \in \mathscr{B}. \tag{8}$$

The BUD problem is formulated as follows. The objective is to maximize the total throughput of the network for the uplink communications, as expressed in Eq. (8). C1 and C7 are the UE provisioning constraints, which impose one UE to be provisioned by at most one BS. C2 is the bandwidth capacity constraint for each BS and imposes the assigned bandwidth by a BS to its associated UEs not to exceed the BS' bandwidth capacity. C3 is the power capacity constraint of each DBS for the backhaul link, and it imposes the total power used by a DBS not to exceed its power capacity. C4 is the data rate requirement constraint of each UE, implying that the achieved data rate of a UE is equal or larger than the required data rate. C5–C6 are the DBS placement constraints, and they impose all DBSs to be placed on the candidate dimensions in the horizontal plane and vertical plane.

IV. PROBLEM ANALYSIS

Any instance of the Max-Generalized Assignment Problem (*Max-GAP*) problem [17] can be reduced into the BUD problem, and the Max-GAP problem is a well-known NP-hard problem. Thus, the BUD problem is NP-hard. So, we propose to decompose the BUD problem into two sub-problems: the DBS placement problem and the joint UE association, power and bandwidth assignment (*Joint-UPB*) problem. We first solve the sub-problems one by one, and then we solve the BUD problem.

A. Solving the Joint-UPB Problem

For given vertical positions and horizontal positions [18] of all DBSs, i.e., $\hat{\gamma}_j$ and $\hat{h}_j$, $\mathscr{P}_0$ can be transformed into $\mathscr{P}_1$. Let $\Phi(x_{i,j}, p_{i,j}, b_{i,j}, \gamma_j, h_j) = \sum_i \sum_j x_{i,j} r_i$ be the objective function of $\mathscr{P}_0$, and $\Phi_1(x_{i,j}, p_{i,j}, b_{i,j}) = \Phi|_{\gamma_j=\hat{\gamma}_j, h_j=\hat{h}_j}$ be the objective function of $\mathscr{P}_1$.

$$\mathscr{P}_1: \quad \max_{x_{i,j},p_{i,j},b_{i,j}} \quad \sum_i \sum_j x_{i,j} r_i$$

$$s.t.:$$

$$C1, C2, C3, C4, C7 \quad in \quad \mathscr{P}_0 \tag{9}$$

To ensure analytical tractability, we assume the power assignment is proportional to the bandwidth assignment, viz., $p_{i,j} = b_{i,j}\kappa_j$. Note that the MBS does not assign power and bandwidth to the UEs while the DBSs need to assign power and bandwidth to the backhaul links. Then, constraint $C3$ is relaxed. The required bandwidth to provision the ith UE by the jth BS can be calculated as $\hat{b}_{i,j} = \underset{b_{i,j}}{\operatorname{argmin}} (\beta_{i,j} - x_{i,j} r_i \ge 0), x_{i,j} = 1, \forall i \in \mathscr{U}, j \in \mathscr{B}$. Obviously, constraint $C4$ is also relaxed. Then, $\mathscr{P}_1$ can be transformed into $\mathscr{P}_2$.

$$\mathscr{P}_2: \quad \max_{x_{i,j}} \quad \sum_i \sum_j x_{i,j} r_i$$

$$s.t.:$$

$$C1: \sum_j x_{i,j} \le 1, \quad \forall i \in \mathscr{U},$$

$$C2: \sum_i x_{i,j} b_{i,j} \le f_j^{max}, \quad \forall j \in \mathscr{B},$$

$$C3: x_{i,j} \in \{0,1\}, \quad \forall i \in \mathscr{U}, j \in \mathscr{B}. \tag{10}$$

We propose an approximation algorithm to solve problem $\mathscr{P}_2$ as depicted in Algorithm 1, referred to as Approximation Algorithm for the joint-UPB problem (*AA-UPB*). The parameters are initialized in *Step* 1. Let the weight be $z_i = r_i / b_{i,j}$, as calculated by *Steps* $2-6$. Then, the weight is sorted in a decreasing order in *Step* 7 and this new order represents a new UE sequence. One solution of UE association set $\Lambda_1 = \cup\{x_{\tilde{i},\tilde{j}}\}$ is obtained through *Steps* $9-19$. The other solution of UE association set Λ_3, which contains the maximum $|\mathscr{B}|$ UEs, is achieved through *Steps* $20-23$. Finally, the UE association

Algorithm 1: Approximation Algorithm for the joint-UPB problem (*AA-UPB*)

Input : $\mathscr{B}$, $\mathscr{U}$, f_j^{max}, κ_j, r_i, $\hat{\gamma}_j$ and $\hat{h}_j$;
Output: $\tilde{x}_{i,j}$, $\tilde{b}_{i,j}$ and $\tilde{p}_{i,j}$;

$\tilde{i} = 1$, $f_j^{used} = 0$, $\Lambda_0 = \mathscr{U}$, $\Lambda_1 = \varnothing$, $\forall j \in \mathscr{B}$;
for $i \in \Lambda_0$ **do**
  for $j \in \mathcal{B}$ **do**
    $\hat{b}_{i,j} = \underset{b_{i,j}}{\operatorname{argmin}} (\beta_{i,j} - r_i \geq 0), \forall i \in \mathscr{U}, j \in \mathscr{B}$;
    $\hat{p}_{i,j} = \hat{b}_{i,j}\kappa_j$;
  obtain $\tilde{j} = \underset{j}{\operatorname{argmin}}\, \hat{b}_{i,j}$, $\forall i$;
  get $b_{i,\tilde{j}} = \min(\widehat{b}_{i,j})$ and $z_i = r_i / b_{i,\tilde{j}}$;
put the UEs in a descending order $\tilde{i}$ by z_i;
$\Lambda_2 = \Lambda_0$;
while $f_j^{used} \leq f_j^{max}$ & $\Lambda_2 \neq \varnothing$ **do**
  if $f_j^{used} + b_{\tilde{i},\tilde{j}} \leq f_j^{max}$ **then**
    $x_{\tilde{i},\tilde{j}} = 1$;
    $f_j^{used} = f_j^{used} + b_{\tilde{i},\tilde{j}}$;
    $\Lambda_1 = \Lambda_1 \cup \{x_{\tilde{i},\tilde{j}}\}$;
    $\Lambda_2 = \Lambda_2 \setminus \tilde{i}$;
  else
    $\Lambda_0 = \Lambda_2$;
    go to step 2;
  $\tilde{i} = \tilde{i} + 1$;
$\hat{i} = 1$, $\Lambda_3 = \varnothing$, $\Lambda_4 = \mathscr{U}$;
for $\hat{i} \leq |\mathcal{B}|$ **do**
  $\Lambda_3 = \Lambda_3 \cup \{\hat{x}_{\hat{i},\hat{j}} = \underset{x_{i,j}}{\operatorname{argmax}}\, x_{i,j} r_i\}, \forall i \in \Lambda_4$;
  $\Lambda_4 = \Lambda_4 \setminus \hat{i}$;
return Λ_1 or Λ_3 which produces a higher throughput;
obtain $\tilde{b}_{i,j}$ and $\tilde{p}_{i,j}$.

set (either Λ_1 or Λ_3) which produces a higher throughput is returned, and the corresponding $\tilde{b}_{i,j}$ and $\tilde{p}_{i,j}$ are also returned.

$$\begin{aligned} \mathscr{P}_3: \quad & \max_{x_{i,j}} \quad \sum_i \sum_j x_{i,j} r_i \\ s.t.: \quad & \\ & C1, C2 \quad in \quad \mathscr{P}_2 \\ & C3: 0 \leq x_{i,j} \leq 1, \quad \forall i \in \mathscr{U}, j \in \mathscr{B}. \end{aligned} \tag{11}$$

Theorem 1. *The AA-UPB algorithm is a $\frac{1}{2}$-approximation algorithm of the problem $\mathscr{P}_2$. Especially, this algorithm achieves the optimal throughput when all UEs are provisioned.*

Proof. Note that problem $\mathscr{P}_2$ can be transformed into problem $\mathscr{P}_3$ while $x_{i,j}$ is relaxed to a continuous variable. In order to prove *Theorem* 1, we define $\Phi_2(x_{i,j}) = \Phi_1|_{p_{i,j}=p_{\tilde{i},\tilde{j}}, b_{i,j}=p_{\tilde{i},\tilde{j}}}$ as the objective function of $\mathscr{P}_2$ and $\Phi_3(\bar{x}_{i,j})$ be the objective function of $\mathscr{P}_3$.

1) If all UEs are provisioned, the achieved total throughput of Algorithm 1 is $\max(\Phi_2(\tilde{x}_{\tilde{i},\tilde{j}}), \Phi_2(\hat{x}_{\hat{i},\hat{j}})) = \Phi_2(\tilde{x}_{\tilde{i},\tilde{j}}) = \sum_i \sum_j x_{i,j} r_i = \sum_i (\sum_j x_{i,j}) r_i = \sum_i r_i$; the optimal solutions of $\mathscr{P}_2$ and $\mathscr{P}_3$ are $\Phi_2(x_{i,j}^*) = \sum_i \sum_j x_{i,j}^* r_i = \sum_i r_i$ and $\Phi_3(\bar{x}_{i,j}^*) = \sum_i \sum_j \bar{x}_{i,j}^* r_i = \sum_i r_i$, respectively. Here, $\sum_j x_{i,j} = 1$, $\sum_j x_{i,j}^* = 1$, $\sum_j \bar{x}_{i,j}^* = 1$, $\tilde{x}_{\tilde{i},\tilde{j}} \in \Lambda_1$ and $\hat{x}_{\hat{i},\hat{j}} \in \Lambda_3$. Algorithm 1 produces the results equivalent to the optimal solutions of problem $\mathscr{P}_2$ and $\mathscr{P}_3$.

2) Here, we discuss the scenario with one or more blocked UEs. We first find the relationship between the optimal value of problem $\mathscr{P}_3$, $\Phi_2(\Lambda_1)$ and $\Phi_2(\Lambda_3)$. Then, the lower bound of $\max(\Phi_2(\tilde{x}_{\tilde{i},\tilde{j}}), \Phi_2(\hat{x}_{\hat{i},\hat{j}}))$ is determined, which is leveraged to prove the approximation ratio of the AA-UPB algorithm. Note that Algorithm 1 puts all UEs in a sequence by the decreasing order of the weight (defined by the data rate over the required bandwidth to provision a UE), and all UEs are provisioned by this order until the rest of UEs cannot be served by any BS. Let $(y-1)$ be the index of the last UE which is provisioned in Λ_1, i.e., $|\Lambda_1| = y - 1$. $\Phi_3(\bar{x}_{i,j}^*) = \Phi_2(\cup_{\tilde{i}=1}^{y-1} \tilde{x}_{\tilde{i},\tilde{j}}) + \epsilon_{\hat{i}} \Phi_2(\cup_{\hat{i}=y}^{y-1+|\mathcal{B}|} \hat{x}'_{\hat{i},\hat{j}})$. Here, $\Lambda_1 = \cup_{\tilde{i}=1}^{y-1} \tilde{x}_{\tilde{i},\tilde{j}}$, and $\cup_{\tilde{i}=y}^{y-1+|\mathcal{B}|} \hat{x}'_{\tilde{i},\tilde{j}}$ includes $|\mathscr{B}|$ UEs with the maximum data rate requirement among the UEs with the starting index y and the end index $|\mathscr{U}|$; $\epsilon_{\hat{i}} = (f_j^{max} - \sum_{\tilde{i}=1}^{i=\tilde{y}-1} \tilde{x}_{\tilde{i},\tilde{j}} \tilde{b}_{\tilde{i},\tilde{j}}) / (\hat{x}'_{\hat{i},\hat{j}} \hat{b}'_{\hat{i},\hat{j}})$, $0 \leq \epsilon_{\hat{i}} < 1$ and $\hat{x}'_{\hat{i},\hat{j}} = 1$. Note that $\Lambda_3 = \cup_{\hat{i}=1}^{|\mathscr{B}|} \{\hat{x}_{\hat{i},\hat{j}} = \underset{x_{i,j}}{\operatorname{argmax}}\, x_{i,j} r_i\}$, which represents the $|\mathscr{B}|$ UEs with the maximum data rate requirement among all UEs. Thus, the objective value of Λ_3 should be equal or bigger than $\Phi_2(\cup_{\hat{i}=y}^{y-1+|\mathcal{B}|} \hat{x}'_{\hat{i},\hat{j}})$. Then, $\Phi_2(\cup_{\hat{i}=y}^{y-1+|\mathcal{B}|} \hat{x}'_{\hat{i},\hat{j}}) \leq \Phi_2(\Lambda_3)$, and $\epsilon_{\hat{i}} \Phi_2(\cup_{\hat{i}=y}^{y-1+|\mathcal{B}|} \hat{x}'_{\hat{i},\hat{j}}) < \Phi_2(\Lambda_3)$. Therefore, we have $\Phi_3(\bar{x}_{i,j}^*) < \Phi_2(\cup_{\tilde{i}=1}^{y-1} \tilde{x}_{\tilde{i},\tilde{j}}) + \Phi_2(\Lambda_3)$ and $\Phi_3(\bar{x}_{i,j}^*) < \Phi_2(\Lambda_1) + \Phi_2(\Lambda_3)$, implying that the objective values of set Λ_1 and Λ_3 are bigger than that of $\Phi_3(\bar{x}_{i,j}^*)$. Meanwhile, the objective value of the problem $\mathscr{P}_2$ is smaller or equal to that of problem $\mathscr{P}_3$, $\Phi_2(x_{i,j}^*) \leq \Phi_3(\bar{x}_{i,j}^*)$. We have $\Phi_2(x_{i,j}^*) < \Phi_2(\Lambda_1) + \Phi_2(\Lambda_3)$, either $\Phi_2(\Lambda_1) \geq \frac{1}{2}\Phi_2(x_{i,j}^*)$ or $\Phi_2(\Lambda_3) \geq \frac{1}{2}\Phi_2(x_{i,j}^*)$. Thus, $\max(\Phi_2(\tilde{x}_{\tilde{i},\tilde{j}}), \Phi_2(\hat{x}_{\hat{i},\hat{j}})) \geq \frac{1}{2}\Phi_2(x_{i,j}^*)$, which means that the lower bound of the AA-UPB algorithm is bigger than $\frac{1}{2}$ of the optimal value of problem $\mathscr{P}_2$ and the approximation ratio of the AA-UPB algorithm is $\frac{1}{2}$. □

$$\begin{aligned} \mathscr{P}_4: & \max_{\gamma_j, h_j} \quad \sum_i \sum_j x_{i,j} r_i \\ s.t.: \quad & \\ & C1: \gamma_j \in \mathscr{V}_1, \quad \forall j \in \widetilde{\mathscr{B}}, \\ & C2: h_j \in \mathscr{V}_2, \quad \forall j \in \widetilde{\mathscr{B}}. \end{aligned} \tag{12}$$

B. Solving the DBS placement Problem

The UE association, power and bandwidth allocation are determined in the last subsection. Here, we try to find the best positions to place all DBS which can maximize the total throughput of the network. Problem $\mathscr{P}_0$, given $\tilde{x}_{i,j}$, $\tilde{p}_{i,j}$ and $\tilde{b}_{i,j}$, can be transformed into problem $\mathscr{P}_4$. We propose an optimal DBS placement algorithm (*Opt-DBS-Placement*), which utilizes the exhaustive search method [5] to solve the problem $\mathscr{P}_4$, as depicted in Algorithm 2. Here, $\Phi_4(\gamma_j, h_j) = \Phi|_{x_j=\tilde{x}_j, p_{i,j}=\tilde{p}_{i,j}, b_{i,j}=\tilde{b}_{i,j}}$ is the objective function of $\mathscr{P}_4$.

Algorithm 2: The optimal DBS placement algorithm (*Opt-DBS-Placement*)

Input : $\mathscr{B}$, $\mathscr{U}$, $\mathscr{V}_1$, $\mathscr{V}_2$, $\tilde{x}_{i,j}$, $\tilde{p}_{i,j}$ and $\tilde{b}_{i,j}$;
Output: $\hat{\gamma_j}^*$ and $\hat{h}_j^*$;
for $\hat{\gamma}_j \in \mathscr{V}_1$ **do**
  for $\hat{h}_j \in \mathscr{V}_2$ **do**
    update the locations of all DBSs $(\hat{\gamma}_j, \hat{h}_j)$;
    update $\tilde{x}_{i,j}$, $\tilde{p}_{i,j}$ and $\tilde{b}_{i,j}$;
    obtain the objective value, $\Phi_4(\hat{\gamma}_j, \hat{h}_j)$;
calculate $(\hat{\gamma}_j^*, \hat{h}_j^*) = \underset{\hat{\gamma}_j, \hat{h}_j}{\operatorname{argmax}} \Phi_4(\hat{\gamma}_j, \hat{h}_j)$;
return $\hat{\gamma}_j^*$, $\hat{h}_j^*$.

Theorem 2. *The Opt-DBS-Placement algorithm produces the optimal positions of all DBSs in the horizontal and vertical dimensions.*

Proof. Since $\Phi_4(\gamma_j, h_j)$ is the objective value of $\mathscr{P}_4$, $\Phi_4(\hat{\gamma}_j, \hat{h}_j)$ is the total throughput of the network for given locations of all DBSs in the horizontal and vertical dimensions ($\hat{\gamma}_j$ and $\hat{h}_j$), and determined UE association power and bandwidth assignment ($\tilde{x}_j$, $\tilde{p}_{i,j}$ and $\tilde{b}_{i,j}$). Meanwhile, $\Phi_4(\hat{\gamma}_j^*, \hat{h}_j^*) = \Phi\Big|_{\gamma_j=\hat{\gamma}_j^*, h_j=\hat{h}_j^*} = \max_{\hat{\gamma}_j, \hat{h}_j} \Phi_4(\hat{\gamma}_j, \hat{h}_j)$, $(\hat{\gamma}_j^*, \hat{h}_j^*) = \operatorname{argmax}_{\hat{\gamma}_j, \hat{h}_j} \Phi_4(\hat{\gamma}_j, \hat{h}_j)$, Algorithm 2 has checked all candidate horizontal and vertical positions. Thus, the optimal horizontal and vertical positions are achieved by Algorithm 2. □

C. Solving the BUD Problem

Here, we propose an approximation algorithm based on Algorithm 1 and Algorithm 2, which is named Approximation Algorithm for the BUD problem (*AA-BUD*) to solve problem $\mathscr{P}_0$, as depicted in Algorithm 3.

Algorithm 3: Approximation Algorithm for the BUD problem (*AA-BUD*)

Input : $\mathscr{B}$, $\mathscr{U}$, f_j^{max}, κ_j, r_i, $\mathscr{V}_1$ and $\mathscr{V}_2$;
Output: $\tilde{x}_{i,j}$, $\tilde{b}_{i,j}$, $\tilde{p}_{i,j}$, $\hat{\gamma}_j^*$ and $\hat{h}_j^*$;
for $\hat{\gamma}_j \in \mathscr{V}_1$ **do**
  for $\hat{h}_j \in \mathscr{V}_2$ **do**
    update the locations of all DBSs $(\hat{\gamma}_j, \hat{h}_j)$;
    obtain $\max(\Phi_2(\tilde{x}_{\tilde{i},\tilde{j}}), \Phi_2(\hat{x}_{\hat{i},\hat{j}}))$ by *Algorithm* 1;
    update $\tilde{x}_{i,j}$, $\tilde{p}_{i,j}$ and $\tilde{b}_{i,j}$;
obtain $\Phi_4(\hat{\gamma}_j, \hat{h}_j)$;
compute $(\hat{\gamma}_j^*, \hat{h}_j^*) = \underset{\hat{\gamma}_j, \hat{h}_j}{\operatorname{argmax}} \Phi_4(\hat{\gamma}_j, \hat{h}_j)$;
calculate $\tilde{x}_{i,j}$, $\tilde{p}_{i,j}$ and $\tilde{b}_{i,j}$.

Theorem 3. *The AA-BUD algorithm is a $\frac{1}{2}$-approximation algorithm of problem $\mathscr{P}_0$.*

Proof. It is easy to conclude *Theorem* 3 from *Theorem* 1 and *Theorem* 2. In other words, the lower bound of Algorithm 3 is bigger than $\frac{1}{2}$ of the optimal value of problem $\mathscr{P}_2$ and the approximation ratio of the AA-BUD algorithm is $\frac{1}{2}$. □

TABLE II
PARAMETERS FOR SIMULATIONS

$\lvert\mathscr{B}\rvert$	4 BSs (including 3 DBSs)
coverage area of the MBS	$1000m \times 1000m$
f_0	2 GHz
$P_j^{max}, \forall j \in \mathcal{B}$	1 W
$P_j^{max}, \forall j \in \mathcal{B}$	1 W
$\lvert\mathscr{U}\rvert$	$\{100, 110, \cdots, 170\}$
(a, b, ζ^L, ζ^N)	$(4.88, 0.43, 0.1, 21)$ [6]
path loss between a UE and the MBS	$136.8 + 39.1log10(d_{i,j})$, $d_{i,j}$ in km [19]
Rayleigh fading between a UE and the MBS	-8 dB [9]
$\lvert\mathscr{V}_1\rvert$	36
$\mathscr{V}_2$	$\{100, 120, \cdots, 300\}$ m
N_0	-174 dBm/Hz
τ_0	15 kHz
τ^{SI}	130 dB [20]
r_i	$\{0.5, 1, 1.5, 2\}$ Mbps
f^{max}	1200 SCs
f_j^{max}	300

V. PERFORMANCE EVALUATION

MATLAB is used to run the simulations [21], and we run each simulations 200 times to achieve average results. The maximum transmission power of a DBS is set as 40 dBm, and that of a UE is set as 23 dBm. We assume there are three DBSs in the network ($|\widetilde{\mathscr{B}}| = 3$), and all DBS are placed at the same altitude. The locations of UEs are generated through a Matérn cluster process [22]. The simulation parameters are summarized in Table II.

We evaluate the performance of the AA-BUD algorithm with two baseline algorithms. One is the single MBS algorithm without any DBSs (*S-MBS*), and the other algorithm named *HD-DBSs* with half-duplex enabled DBSs. The HD-DBSs algorithm utilizes the same DBS placement strategy, UE association strategy, and the same power and bandwidth assignment strategy as the AA-UPB algorithm.

The total throughput performance versus the altitude with 170 UEs is shown in Fig. 2. The HD-DBSs algorithm obtains the maximum throughput at 120m while the AA-BUD algorithm achieves the maximum throughput at 160m. For the HD-DBSs algorithm, the bottleneck of the uplink communications is the backhaul links (DBS-MBS links) while that of the AA-BUD algorithm is the access links (UE-DBS links or UE-MBS links). This is because the UEs can utilize more frequency spectra when FD-enabled DBSs are operated by the AA-BUD algorithm. For altitude lower than $160m$ of the AA-BUD algorithm, the path loss is dominated by NLoS-path-loss, which decreases as the altitude increases. For altitude higher than $160m$ using the AA-BUD algorithm, the path loss is dominated by LoS-path-loss, which increases as the altitude increases.

The total throughput results versus the workload with 160m altitude are shown in Fig. 3. The AA-BUD algorithm achieves up to 23% and 62% improvement of the total throughput as compared to the S-MBS algorithm and HD-DBSs algorithm, respectively. The total throughput of all algorithms increases as the number of UEs increases. This is because all algorithms

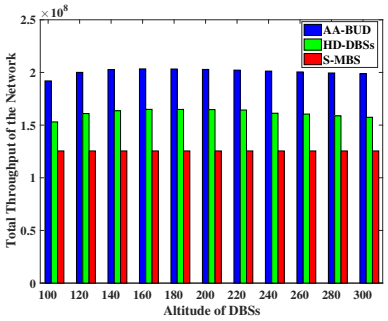

Fig. 2. Total throughput versus altitude with 170 UEs.

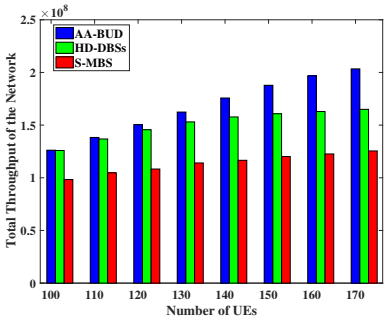

Fig. 3. Total throughput versus the number of UEs at 160m altitude.

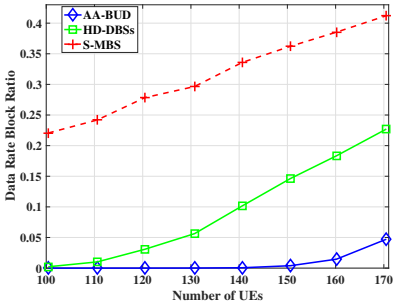

Fig. 4. Data rate block ratio at 160m altitude.

try to serve UEs with better channel conditions first and then provision the remaining UEs. Hence, less radio resources can be used to provision the same number of UEs but with better channel conditions, and then more UEs can be provisioned by the remaining radio resources.

The data rate block ratio versus workload at 160m altitude is shown in Fig. 4. Here, the data rate block ratio is defined as the data rate requirement of provisioned UEs of the uplink communications over the total uplink data rate requirement of all UEs. Obviously, the AA-BUD algorithm exhibits the best performance with the lowest data rate block ratio, and all UEs are provisioned until the number of UEs reaches 150. Evaluation results have demonstrated that the AA-BUD algorithm is superior to the baseline algorithms.

VI. Conclusion

In this paper, we have investigated the backhaul-aware uplink communications in a full-duplex DBS-aided HetNet (*BUD*) problem with the target to maximize the total throughput of the network for the uplink communications. The DBSs are full-duplex enabled, and the MBS and all UEs are half-duplex enabled. Free space optics (*FSO*) terminals are used to connect the MBS to the core network. The proposed AA-BUD algorithm has been proved to be a $\frac{1}{2}$-approximation algorithm that is capable of obtaining the optimal horizontal and vertical dimensions of DBSs. Evaluation results have also demonstrated that the proposed AA-BUD algorithm is superior to the other baseline algorithms with up to 62% improvement of the uplink throughput.

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