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

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Outline

- Introduction
- System Model and Problem Formulation
- Problem Analysis and Solutions
- Conclusions

Number of mobile-connected devices:
7.9 billion in 2016
8.6 billion in 2017
12.3 billion in 2022

Smartphones (including phablets) represented only 51 percent of total mobile devices and connections in 2017, but represented 88 percent of total mobile traffic.

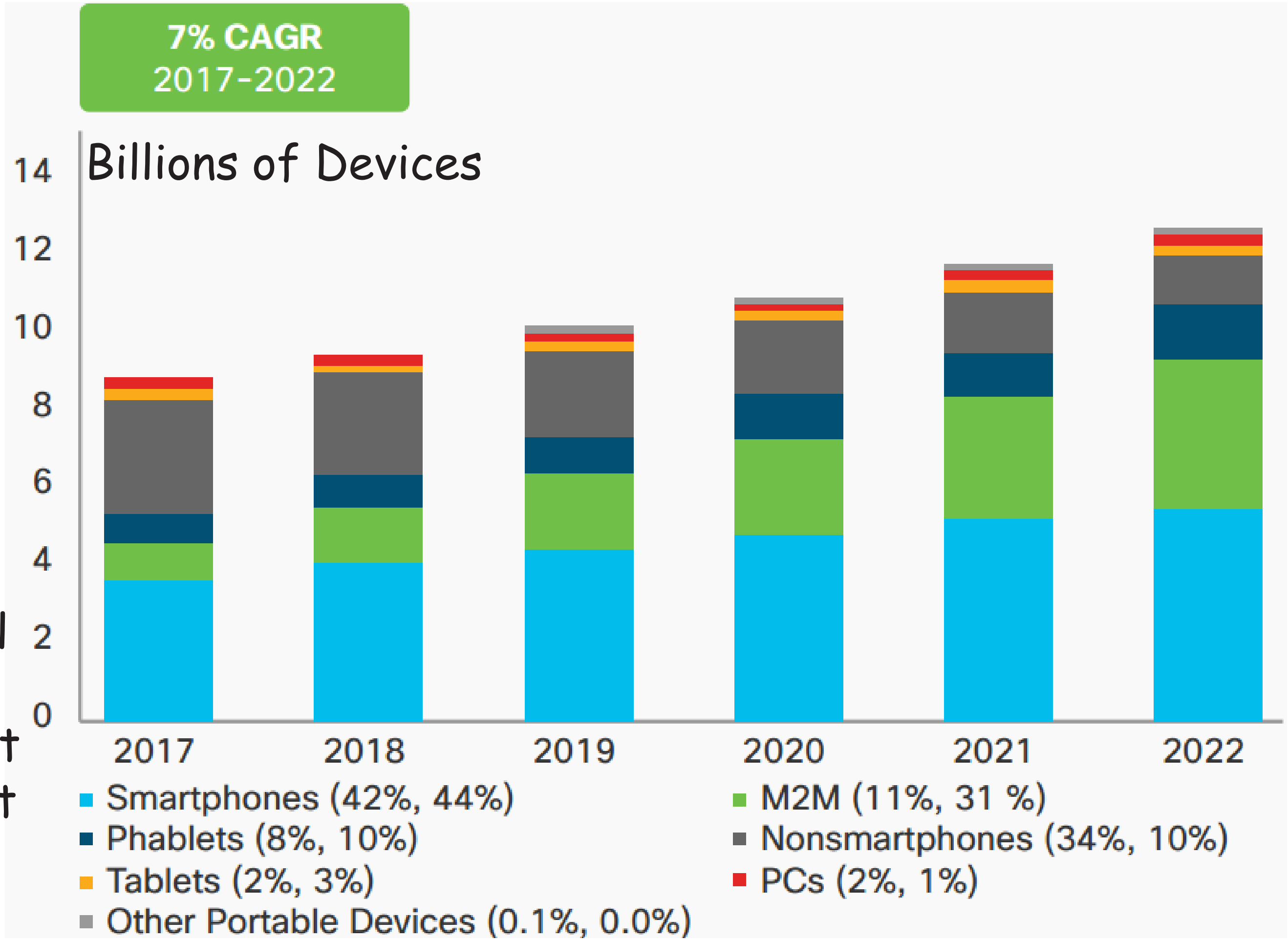
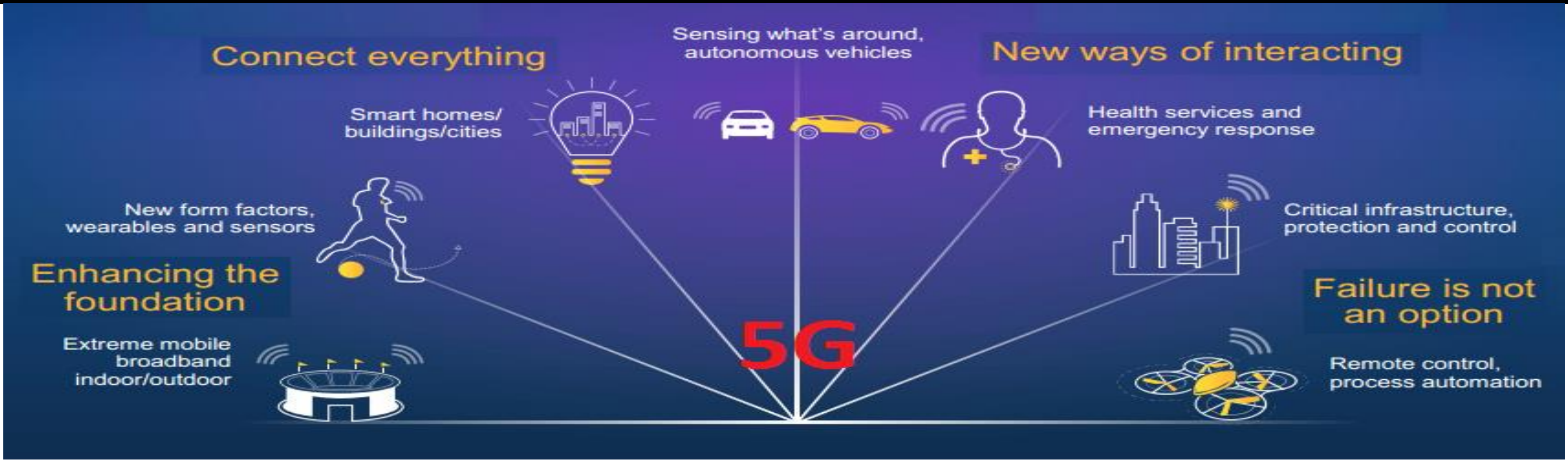
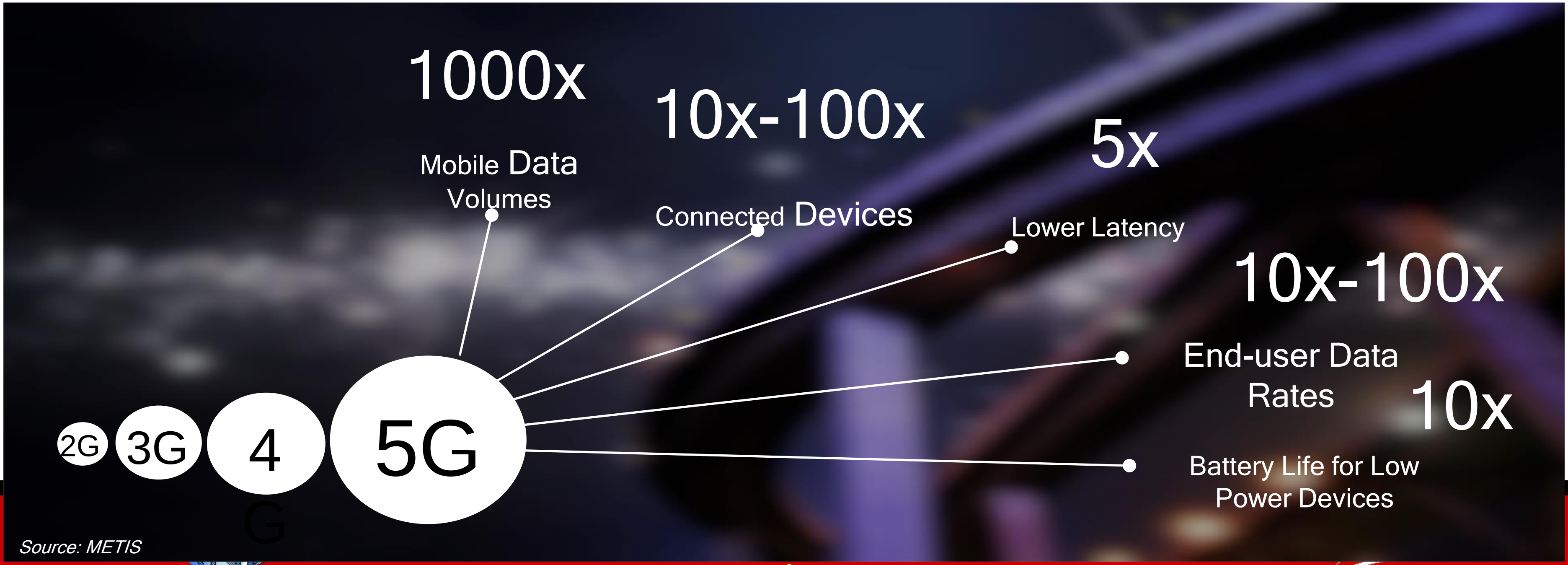


Figure: Global Mobile Devices and Connections Growth

Source: Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022 White Paper. [Online] https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white-paper-c11-738429.html

5G is a Fully Mobile Connected Society



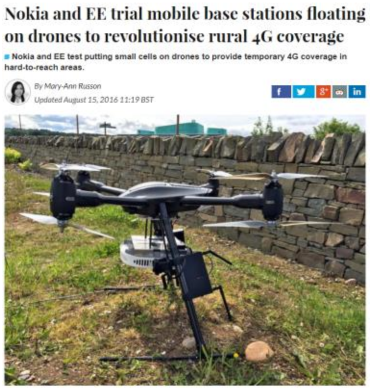


Prototype of DBS and IBFD

- Nokia had developed a 4G base station weighing only 2Kg in 2016, which was successfully mounted on a commercial quad-copter to provide coverage over a remote area in Scotland.

- An IBFD WiFi radio communication prototype has been demonstrated, and it can also be used for the 2.3GHz and 2.5GHz LTE bands.

- Several projects by the industry have already been initiated, such as Project Aquila by Facebook, Cell on Wings (COW) by ATT, and Google projects such as SKYBENDER that are designed for drone-based internet services.



Source: I. B. Times, "Nokia and EE trial mobile base stations floating on drones to revolutionise rural 4G coverage," url: http://www. ibtimes.co.uk/nokia-ee-trial-mobile-base-stations-floatingdrones-revolutionise-rural-4g-coverage-1575795, 2016.
Source: D. Bharadia, E. McMilin, and S. Katti, "Full duplex radios," in Proc. *ACM SIGCOMM*, pp. 375–386, Aug. 2013.

Main Contributions

- 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 dimension and horizontal dimensions.

- The MBS is connected to the core network through FSO links, implying that this network can be easily deployed to provide communications to temporary events or fast communications recovery for emergency situations.

- We have proposed approximation algorithms to solve the proposed problem with determined deviations to the optimal solution, and the optimal locations of all DBS are achieved.

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Network Architecture

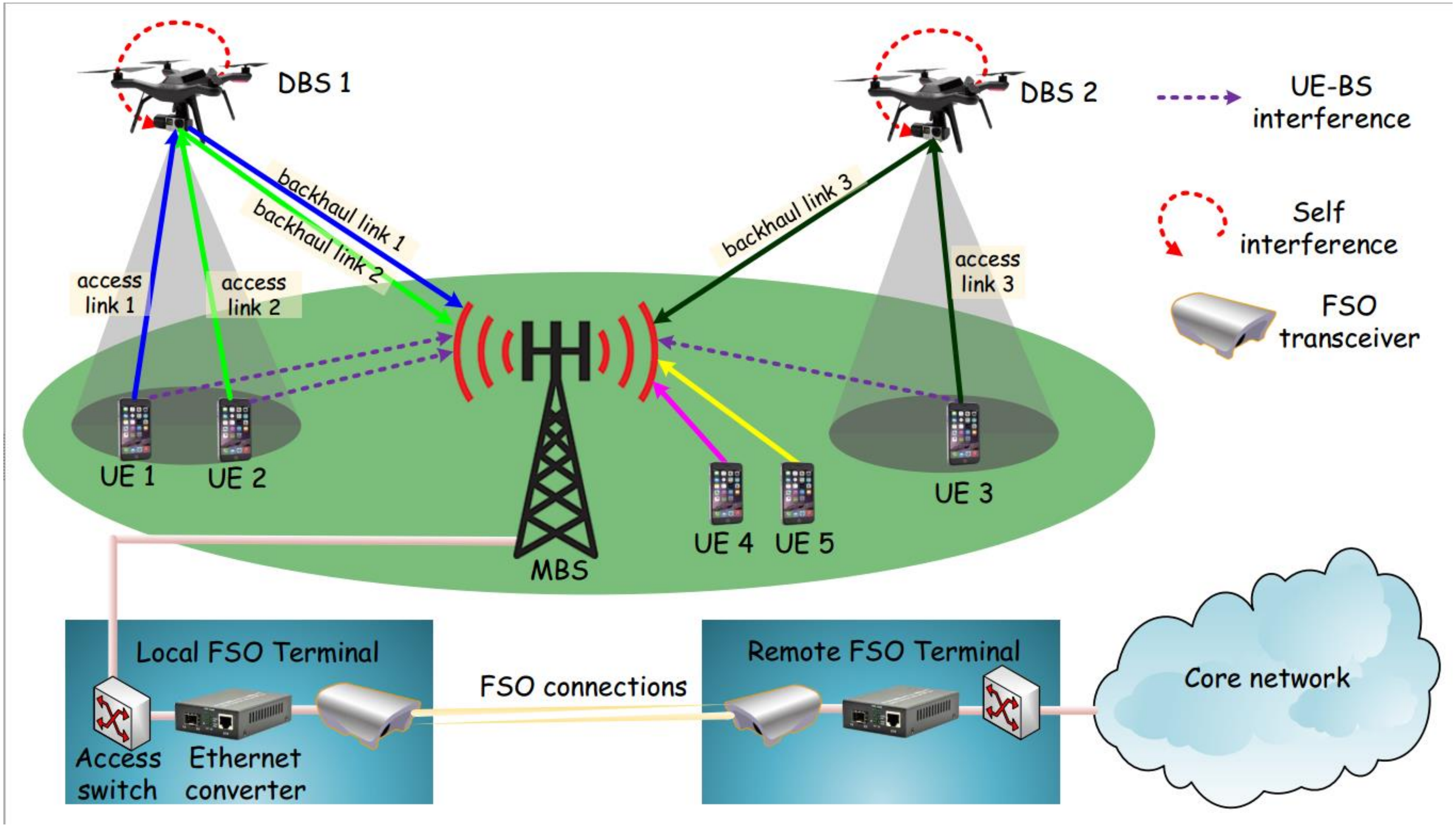


Fig. 4. The IBFD DBS-aided HetNet framework.

System Model

- The probability of a LoS and NLoS connection of an air-to-ground (ground-to-air) link:

$$\begin{cases} \psi_{i,j}^{L} = \left(1 + a\exp\left(-b\left(\frac{180\theta_{i,j}}{\pi} - a\right)\right)\right)^{-1} \\ \psi_{i,j}^{N} = 1 - \psi_{i,j}^{L} \end{cases} \quad (1)$$

- The path loss between the ith UE and the jth DBS is:

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

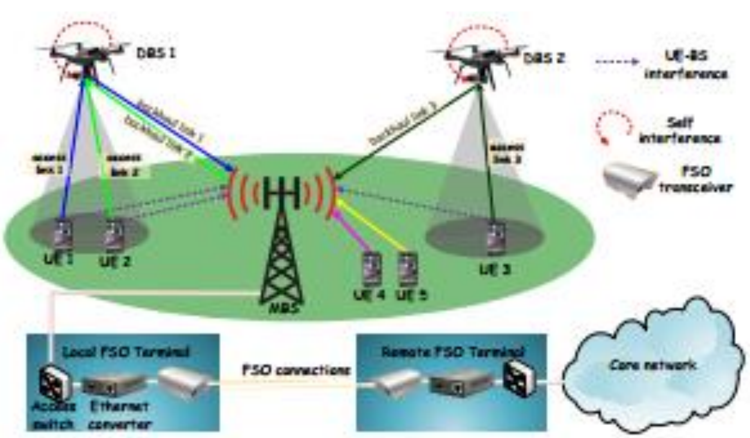
$$\eta_{i,j} = \psi_{i,j}^{L}(\zeta^{L} - \zeta^{N}) + 20log\left(4\pi f_0 d_{i,j}/c_0\right) + \zeta^{N} \quad (3)$$

- The SINR of the access link and the backhaul link.

$$s_{i,j}^{1} = \begin{cases} \frac{P_U \Gamma_{i,j}}{\sigma_{i,j}^{2}}, & j = 1 \\ \frac{P_U \eta_{i,j}}{\alpha_{i,j} + \sigma_{i,j}^{2}}, & j > 1, \end{cases} \quad (4)$$

$$\sigma_j^2 = \tau_0 b_{i,j} N_0, \alpha_{i,j} = \sum_i p_{i,j} / \tau^{SI}$$

$$s_{i,j}^{2} = \frac{p_{i,j}\eta_{i,j}'}{P_U \Gamma_{i,1} + \sigma_{i,1}^{2}} \quad (5)$$



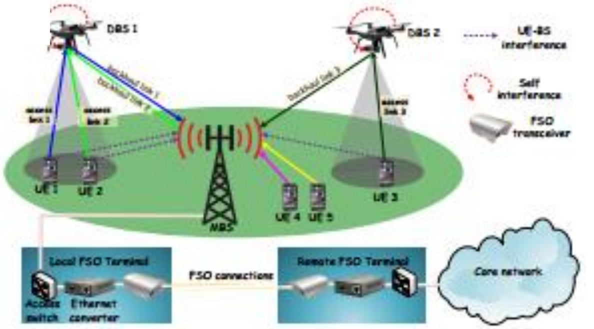
System Model (Cont'd)

- Data rate of a UE.

$\beta_{i,j}$ is the data rate of the ith UE towards the jth BS, $\beta_{i,j}^1$ 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).

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

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



Notations and Variables

- B: the set of all BSs, including the MBS and DBSs.
- U: the set of UEs.
- V_1: the set of candidate areas for placing DBSs in the horizontal plane.
- V_2: the set of candidate altitudes for placing DBSs in the vertical plane.
- 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 BS.
- $d_{i,j}$: 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 assignment indicator.
- $\beta_{i,j}$: the achieved data rate of the ith UE via the jth DBS.
- $b_{i,j}$: 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.
- γ_j: the horizontal position of the jth BS, $\gamma_j \in V_1$.
- h_j: the vertical position of the jth BS, $h_j \in V_2$.

Problem Formulation

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

The objective is to maximize the total throughput of all UEs.

$s.t.:$

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

Provisioning Constraint

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

Bandwidth Capacity Constraint

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

Power Capacity Constraints

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

Data Rate Constraints

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

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

DBS Placement Constraints

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

Provisioning Constraint

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Solving the BUD Problem

- Any instance of the Max-Generalized Assignment Problem (*Max-GAP*) problem [A3] can be reduced into the BUD problem for a given number of DBSs, and the BUD problem is NP-hard because the Max-GAP problem is a well-known NP-hard problem.

- The BUD problem can be decomposed into two sub-problems:
  1) the DBS placement problem and
  2) the joint UE association, power and bandwidth assignment problem

     ——— the (Joint-UPB) problem.

[A3] L. Fleischer et al., "Tight approximation algorithms for maximum general assignment problems," in Proceedings of the 17th Annual ACMSIAM Symposium on Discrete Algorithms, Jan. 2006, pp. 611–620.

Solving the Joint-UPB Problem

- For analytical tractability, we assume $p_{i,j} = b_{i,j}\kappa_j$, where κ_j is the power-spectral density of the jth BS.
- The required bandwidth to provision the ith UE by the jth BS can be calculated as $\hat{b}_{i,j} = \underset{b_{i,j}}{\operatorname{argmin}} \left(\beta_{i,j} - x_{i,j} r_i \geq 0\right)$.
- For given locations of all DBSs, P_0 can be re-written as P_2

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

$$s.t.:$$

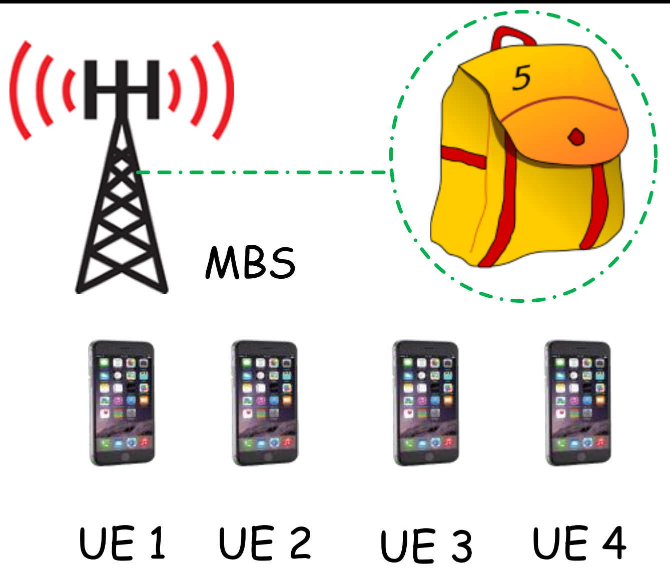
$$C1: \sum_j x_{i,j} \leq 1, \quad \forall i \in \mathscr{U},$$

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

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

- Calculate the weight.

	Data Rate, r_i	Bandwidth, $b_{i,j}$	Weight, $\delta_{i,j}$
UE 1	3	2	1.5
UE 2	2	2	1
UE 3	4	5	0.8
UE 4	1	2	0.5



- Select items by the decreasing weight.

  UE 1, UE2, objective value $f_1 = 5$

- Select items by the maximum value.

  UE3, objective value $f_2 = 4$

- Get maximum value between these two results.

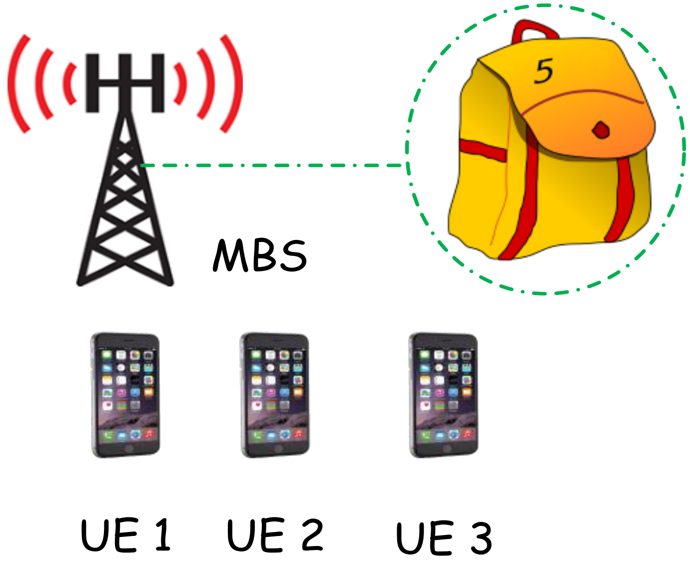
$$f_1 + f_2 > f^*$$

$$f_1 > \frac{1}{2} f^* \quad or \quad f_2 > \frac{1}{2} f^*$$

One More Example of the Approximation Algorithm

- Calculate the weight.

	Data Rate, r_i	Bandwidth, $b_{i,j}$	Weight, $\delta_{i,j}$
UE 1	2	1	2
UE 2	2.5	2	1.25
UE 3	5	5	1



- Select items by the weight.
  UE 1, UE2, objective value f_1=4.5
- Select items by the maximum value.
  UE3, objective value $f_2 = 5$ and $f_2 > f_1$
- Get maximum value between these two results.

$$f_1 + f_2 > f^*$$

$$f_1 > \frac{1}{2} f^* \quad or \quad f_2 > \frac{1}{2} f^*$$

Approximation Algorithm for the joint-UPB problem

- We propose an approximation algorithm to solve problem P_2 as depicted in Algorithm 1, referred to as Approximation Algorithm for the joint-UPB problem (AA-UPB).

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 $\tilde{p}_{i,j}$;
1 $\bar{i} = 1$, $f_j^{used} = 0$, $\Lambda_0 = \mathscr{U}$, $\Lambda_1 = \varnothing$, $\forall j \in \mathscr{B}$;
2 **for** $i \in \Lambda_0$ **do**
3   **for** $j \in \mathcal{B}$ **do**
4         $\hat{b}_{i,j} = \operatorname{argmin}_{b_{i,j}} (\beta_{i,j} - r_i \geq 0), \forall i \in \mathscr{U}, j \in \mathscr{B}$;
5         $\hat{p}_{i,j} = \hat{b}_{i,j}\kappa_j$;
6   obtain $\tilde{j} = \operatorname{argmin}_{j} \hat{b}_{i,j}, \forall i$;
7   get $b_{i,\tilde{j}} = \min(\widehat{b_{i,j}})$ and $z_i = r_i / b_{i,\tilde{j}}$;
8 put the UEs in a descending order $\bar{i}$ by z_i;
9 $\Lambda_2 = \Lambda_0$;
10 **while** $f_j^{used} \leq f_j^{max}$ & $\Lambda_2 \neq \varnothing$ **do**
11   **if** $f_j^{used} + b_{\bar{i},\tilde{j}} \leq f_j^{max}$ **then**
12         $x_{\bar{i},\tilde{j}} = 1$;
13         $f_j^{used} = f_j^{used} + b_{\bar{i},\tilde{j}}$;
14         $\Lambda_1 = \Lambda_1 \cup \{x_{\bar{i},\tilde{j}}\}$;
15         $\Lambda_2 = \Lambda_2 \setminus \bar{i}$;
16   **else**
17         $\Lambda_0 = \Lambda_2$;
18   go to step 2;
19     $\bar{i} = \bar{i} + 1$;
20 $\hat{i} = 1$, $\Lambda_3 = \varnothing$, $\Lambda_4 = \mathscr{U}$;
21 **for** $\hat{i} \leq |\mathcal{B}|$ **do**
22     $\Lambda_3 = \Lambda_3 \cup \{\hat{x}_{\hat{i},\hat{j}} = \operatorname{argmax}_{x_{i,j}} x_{i,j} r_i\}, \forall i \in \Lambda_4$;
23     $\Lambda_4 = \Lambda_4 \setminus \hat{i}$;
24 return Λ_1 or Λ_3 which produces a higher throughput;
25 obtain $\tilde{b}_{i,j}$ and $\tilde{p}_{i,j}$.

Theorem 1. The AA-UPB algorithm is a $\frac{1}{2}$-approximation algorithm of the problem P_2. Especially, this algorithm achieves the optimal throughput when all UEs are provisioned.

Proof.

1) When all UEs are provisioned, $\Phi_1(\Lambda_1) = (OPT)_{frac} = OPT$. Here, Λ_1 is the solution for Eq. (10), and $(OPT)_{frac}$ is the optimal solution of relaxed variable for problem P_2.

2) When one or more UEs are blocked, implying that not all UEs are provisioned. We use an approximation algorithm for the knapsack problem to prove it.

The DBS Placement Problem

- We try to find the best positions to place all DBS which can maximize the total throughput of the network of problem P_4.
- For the DBS placement, we exhaustively search for the optimal locations of all DBSs that achieve the highest throughput.
- Algorithm 2 is proposed to solve the DBS placement problem.

$$\mathscr{P}_4 : \max_{\gamma_j, h_j} \quad \Phi_4(\gamma_j, h_j)$$

$$s.t. :$$

$$C1 : \gamma_j \in \mathscr{V}_1, \quad \forall j \in \widetilde{\mathscr{B}},$$

$$C2 : h_j \in \mathscr{V}_2, \quad \forall j \in \widetilde{\mathscr{B}}. \quad (12)$$

$$\Phi_4(\gamma_j, h_j) = \Phi\Big|_{x_{i,j}=\tilde{x}_{i,j}, p_{i,j}=\tilde{p}_{i,j}, b_{i,j}=\tilde{b}_{i,j}}$$

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: Let $\Phi_4(\gamma_j, h_j)$ be the objective value of 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 ($\tilde{x}_j$, $\tilde{p}_{i,j}$, $\tilde{b}_{i,j}$). Meanwhile,

$$\Phi_4(\hat{\gamma}_j^*, \hat{h}_j^*) = \Phi\Big|_{\gamma_j=\hat{\tau}_j^*, h_j=\hat{h}_j^*} = \max_{\hat{\gamma}_j, \hat{h}_j} \Phi_4(\hat{\gamma}_j, \hat{h}_j),$$

and $(\hat{\gamma}_j^*, \hat{h}_j^*) = \underset{\hat{\gamma}_j, \hat{h}_j}{\operatorname{argmax}} \Phi_4(\hat{\gamma}_j, \hat{h}_j)$.

Algorithm 2 has checked all candidate horizontal and vertical positions. Thus, the optimal horizontal and vertical positions are achieved by Algorithm 2.

Solving the BUD Problem

- We propose an approximate algorithm to solve the BUD problem.

- Algorithm 3 is used to determine the locations of all DBSs; then, the UE association is determined by Algorithm 1 with the determined placement of all DBSs.

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 τ̃_j ∈ Λ_1 do
    for h̃_j ∈ Λ_2 do
        update the locations of all DBSs (γ̂_j, ĥ_j);
        obtain max(Φ_2(x̃_{ĩ,j̃}), Φ_2(x̂_{î,ĵ})) by Algorithm 1;
        update x̃_{i,j}, p̃_{i,j} and b̃_{i,j};
obtain Φ_4(γ̂_j, ĥ_j);
compute (γ̂_j^*, ĥ_j^*) = argmax_{γ̂_j, ĥ_j} Φ_4(γ̂_j, ĥ_j);
calculate x̃_{i,j}, p̃_{i,j} and b̃_{i,j}.
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- **Theorem 3**. The *AA-BUD* algorithm is a $\frac{1}{2}$-approximation algorithm of problem P_0 when not all UEs are provisioned; otherwise, the optimal throughput is achieved.

Simulation Setup

- 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, and all DBS are placed with the same altitude.

Table 2: Simulation Parameters.

$\lvert\mathscr{B}\rvert$	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

Evaluation results

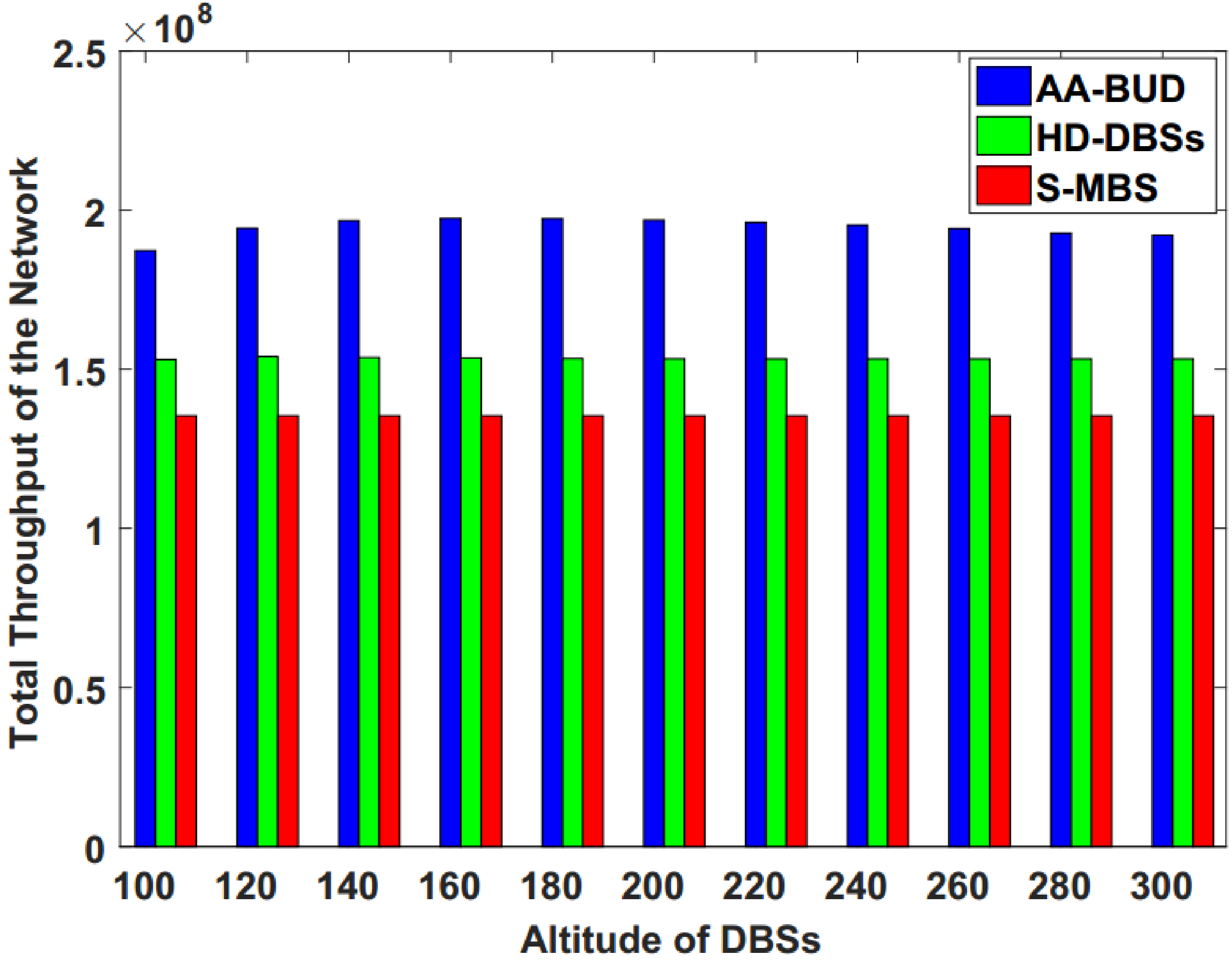

Fig. 5. Throughput versus UEs at a fixed altitude (100m).

Evaluation results

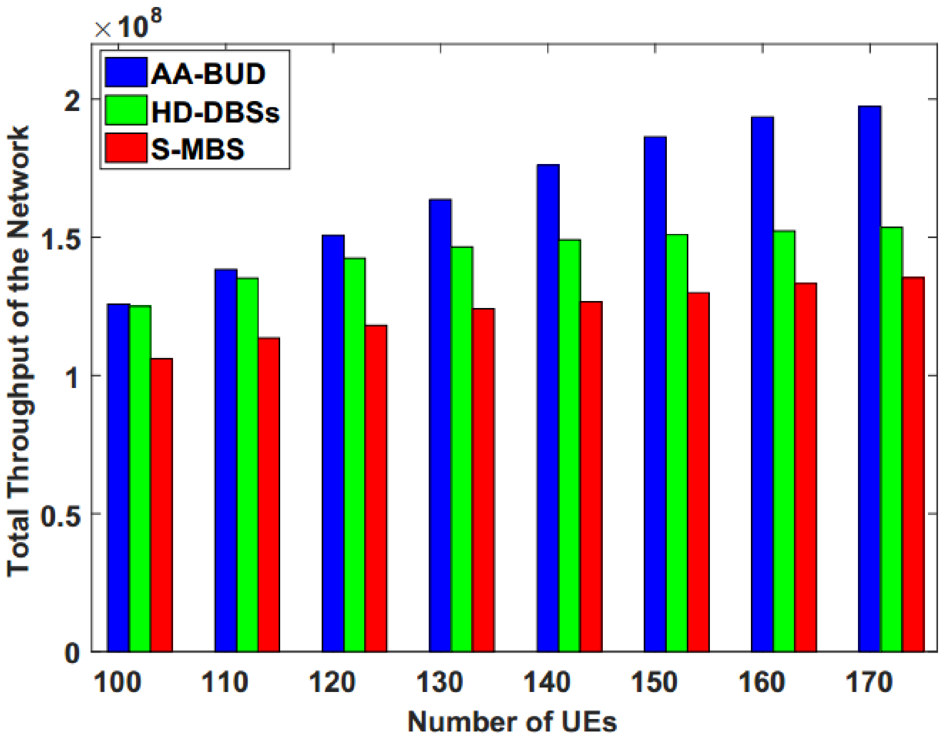

Fig. 6. Total throughput versus the number of UEs at 160m altitude.

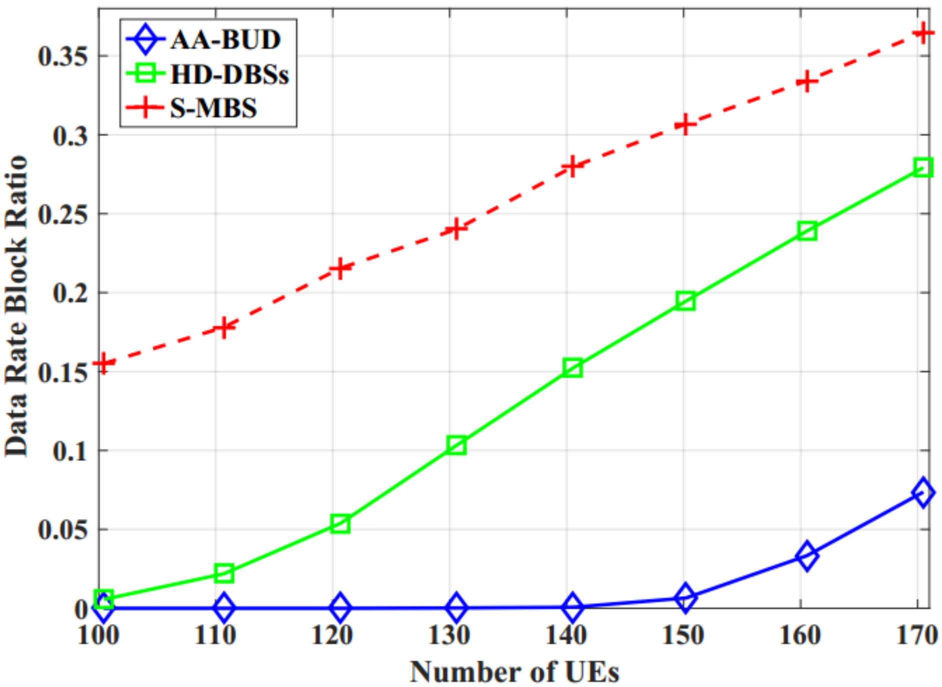

Fig. 7. Data rate block ratio with 160m altitude.

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Conclusions

- 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.

- An approximation algorithm is proposed to solve the BUD problem and proved with determined deviations to the optimal solution.

- Evaluation results show that the proposed algorithm is superior to the baseline algorithms with up to 62% throughput improvement.