Drone-mounted Base-stations Communications with Spectrum Sharing in 5G networks

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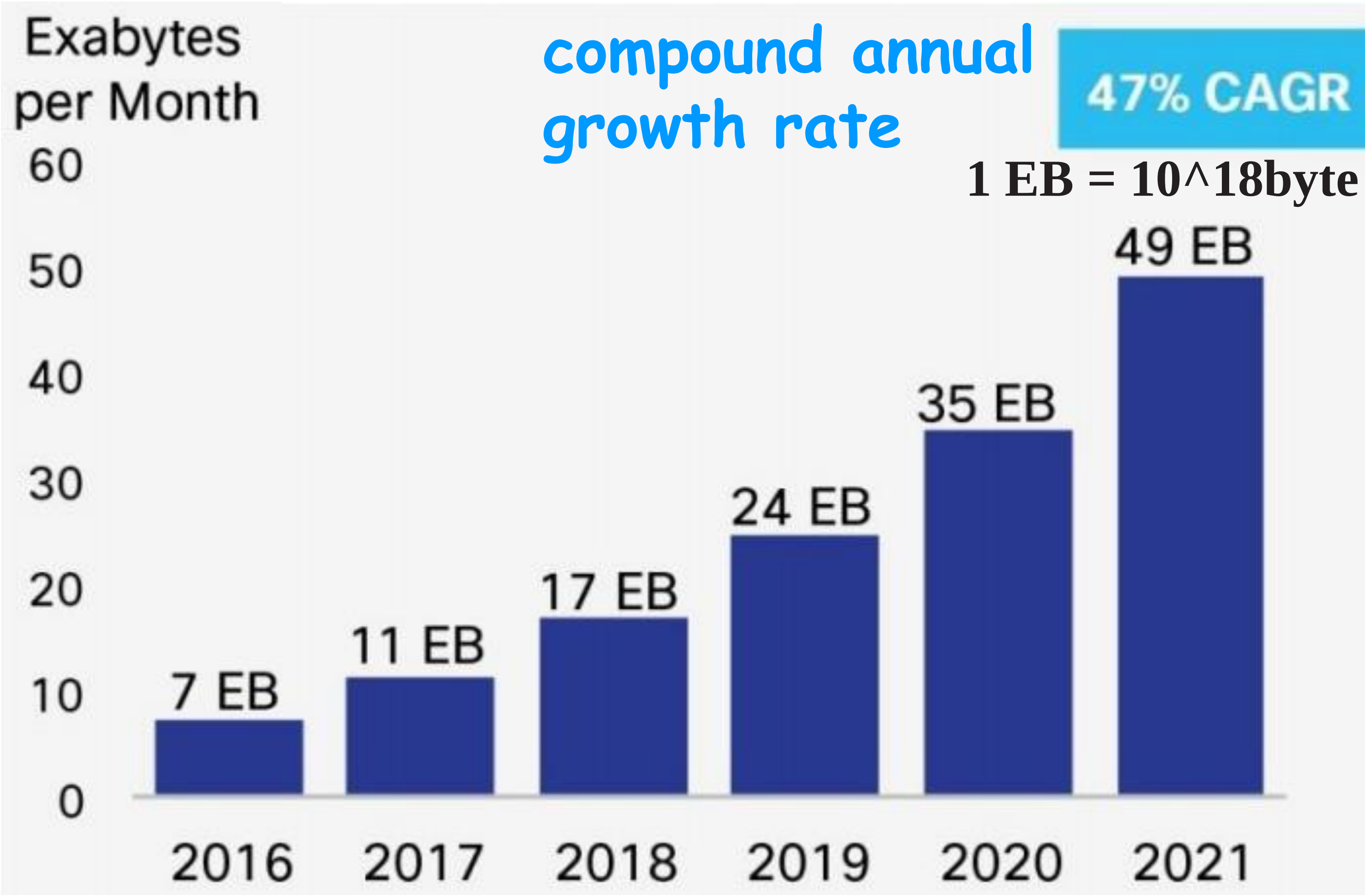
3-D Drone-Base-Station Placement with In-Band Full-Duplex Communications

Outline

- Introduction
- System Model
- Problem Formulation
- Algorithm and Analysis
- Performance Evaluation

Global Mobile Data Traffic from 2016 to 2021



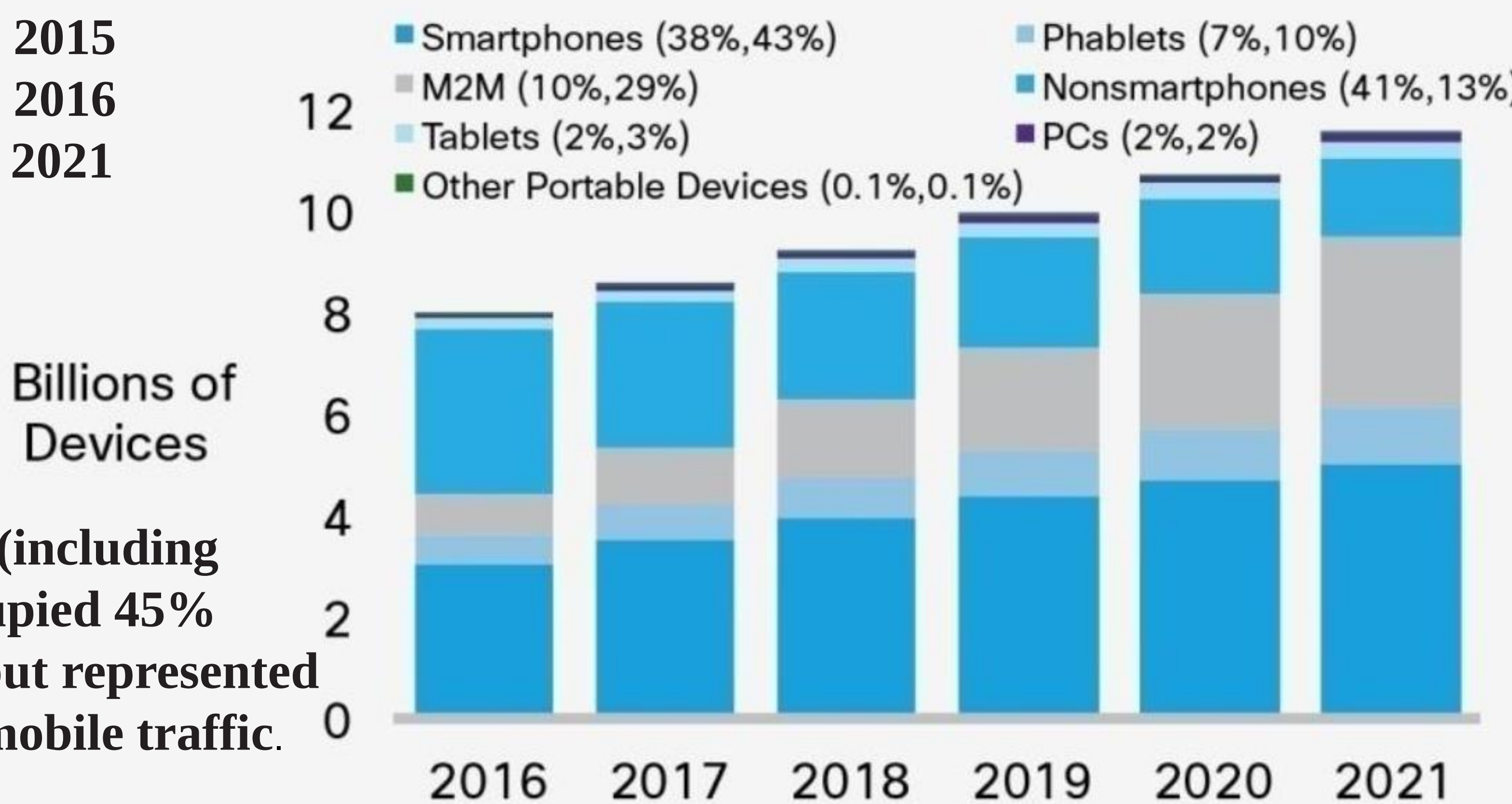
Source: Cisco VNI Mobile, 2017

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021, [Online]https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

7.6 billion in 2015
8 billion in 2016
11.6 billion in 2021

8% CAGR 2016-2021

Smartphones (including phablets) occupied 45% connections, but represented 81% of total mobile traffic.



Source: Cisco VNI Mobile, 2017

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016–2021, [Online]https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/mobile-white-paper-c11-520862.html

Why We Need Drone-mounted Base-stations (DBSs)?

- Drone-mounted base-stations(DBSs) have several advantages:
  i) it can fly across a hazardous area,
  ii) it can be easily mobilized (high mobility),
  iii) it can change its altitude to provide guaranteed QoS based on UE intensity [2].

- Sample use cases of using DBSs for communication:

temporary large-scale or unexpected events such as Olympic games, football games, concerts, and some other application scenarios [3].

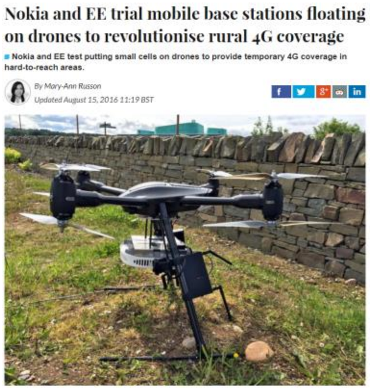
[2] S. Sekander, H. Tabassum, and E. Hossain, "Multi-Tier Drone Architecture for 5G/B5G Cellular Networks: Challenges, Trends, and Prospects," *IEEE Communications Magazine*, vol. 56, no. 3, pp. 96–103, Mar. 2018.
[3] I. Bucaille, S. Hethuin, A. Munari, R. Hermenier, T. Rasheed, and S. Allsopp, "Rapidly deployable network for tactical applications: Aerial base station with opportunistic links for unattended and temporary events absolute example," in *IEEE Military Communications Conference*, Nov. 2013.

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 [4].

- An IBFD WiFi radio communication prototype is demonstated in [5], 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.


Nokia and EE trial mobile base stations floating on drones to revolutionise rural 4G coverage
Nokia and EE test putting small cells on drones to provide temporary 4G coverage in hard-to-reach areas.
By Mary-Ann Russon
Updated August 15, 2016 11:19 BST

[4] 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.
[5] D. Bharadia, E. McMilin, and S. Katti, “Full duplex radios,” in Proc. *ACM SIGCOMM*, pp. 375–386, Aug. 2013.

DBS with IBFD Communications

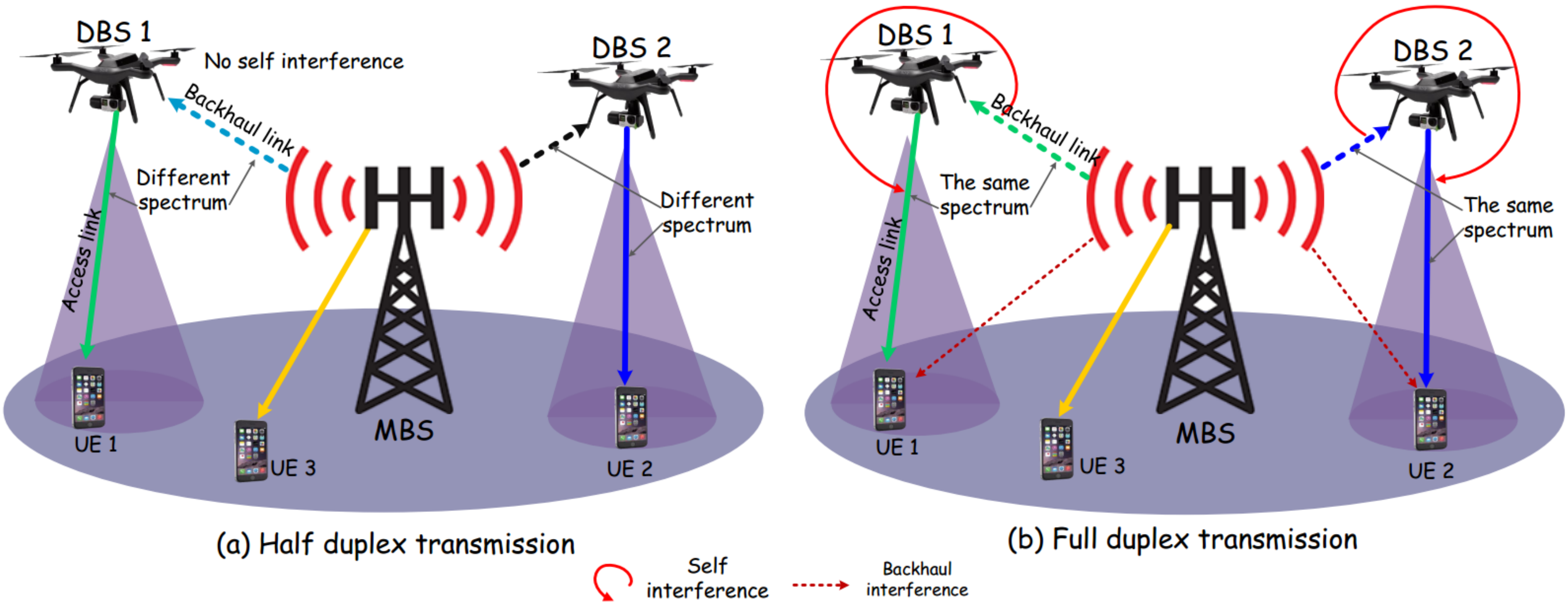


Fig. 4. Full duplex and half duplex communications with DBSs.

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Path Loss Model

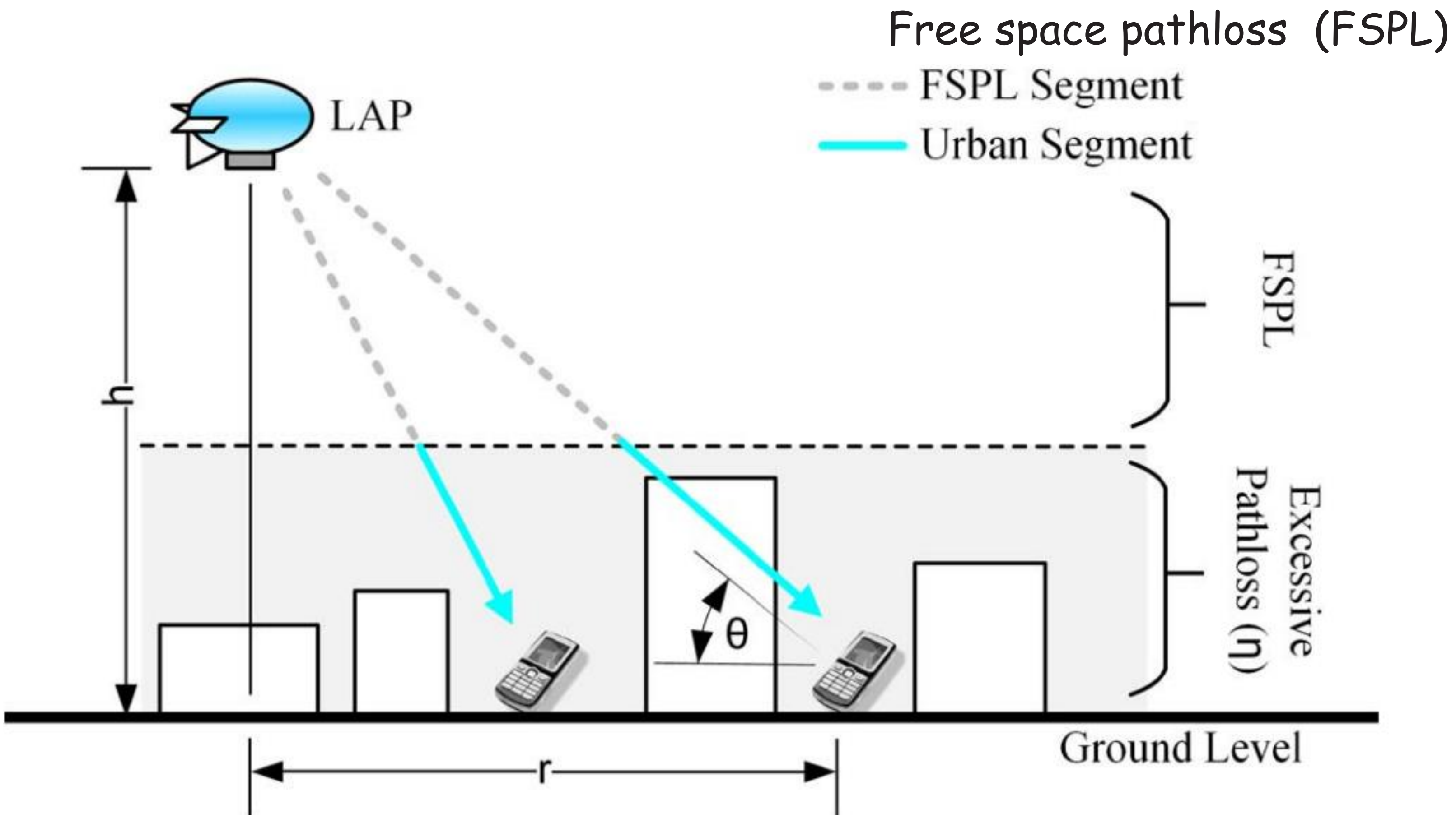

Fig. 5. Low Altitude Platforms radio propagation in urban environment [6].

[6] A. Al-Hourani, S. Kandeepan, and S. Lardner, "Optimal LAP altitude for maximum coverage," *IEEE Wireless Communications Letters*, vol. 3, no. 6, pp. 569–572, Dec. 2014.

Path Loss Model

- Probabilities of a LoS (Ψ_L) and NLoS (Ψ_N) transmission between a transmitter and a receiver.

$$\begin{cases} \Psi_L = \left(1 + a\exp\left(-b\left(\frac{180}{\pi}\theta - a\right)\right)\right)^{-1} \\ \Psi_N = 1 - \Psi_L \end{cases} \quad (1)$$

Here, *a* and *b* are constants depending on the environment (rural, urban, etc.), $\theta = \arctan\left(\frac{h}{r}\right)$ is the elevation angle, *h* is the altitude of a DBS, and *r* is the horizontal distance, respectively [4], [11].

- The mean path loss Γ is used.

$$\mathbf{\Gamma} = \eta_L \Psi_L + \eta_N \Psi_N + 20\log(4\pi f_c d/c) \quad (2)$$

f_c is the carrier frequency, *c* is the speed of light, *d* stands for the distance between a drone-BS and a user ($d = \sqrt{h^2 + r^2}$). η_L and η_N are the average additional losses for LoS and NLoS connections.

$$\mathbf{\Gamma} = \frac{\eta_L - \eta_N}{1 + a\exp(-b(\frac{180}{\pi}\theta - a))} + 20\log(4\pi f_c d/c) + \eta_N \quad (3)$$

Communication Model

- Let $s_{i,j}$ as the signal to interference plus noise ratio (SINR) of the ith UE towards the jth BS.

$$s_{i,j} = \begin{cases} \frac{p_{i,j}|h|_{i,j}^2}{\sigma^2}, & j = 1 \\ \frac{p_{i,j}\boldsymbol{\Gamma}_{i,j}}{p_{i,j'}|h|_{i,j'}^2 + \sigma^2}, & j > 1, j' = 1 \end{cases} \quad (4)$$

- Let $\phi_{i,j}$ be the data rate of the ith UE from the jth BS.

$$\phi_{i,j} = b_{i,j} log_2(1 + s_{i,j}) \quad (5)$$

- The data rate of the backhaul f_j is formulated as:

$$f_j = \beta_B log_2\left(1 + \frac{P_{1,j}\boldsymbol{\Gamma}_{1,j}}{I_{SI+}\sigma_j^2}\right), \quad j > 1 \quad (6)$$

β_B is the total backhaul bandwidth for a DBS, $P_{1,j}$ is the transmission power from the MBS to the jth DBS, $I_{SI} = \sum_i p_{i,j} / C_{SI}$ is the residual SI experienced at the DBS.

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Notations and Variables

- N: the number of DBS.
- x_i^{ue}, y_i^{ue}: the location of the ith UE.
- P_M: the maximum transmission power of a MBS.
- P_D: the maximum transmission power of a DBS.
- d_{min}: the minimum data rate for each UE.
- ζ_j: the power spectral density of the jth BS.
- $P_{j,j'}(j' > 1)$: the transmission power of the MBS towards the jth DBS.

- $\omega_{i,j}$: binary variable: 1 if the ith UE is associated with the jth BS.
- $b_{i,j}$: the bandwidth of the jth BS allocated to the ith UE.
- $p_{i,j}$: the transmission power of the jth BS allocated to the ith UE.
- $\{x_j, y_j, h_j\}$: 3-D co-ordinates of the jth DBS; h_j is the altitude.
- P_j: the total transmission power of the jth DBS towards its associated UEs.
- Φ_j: the total throughput of the jth BS, Φ_j=$\sum_i \phi_{i,j}$.

Problem Formulation

$$\max_{x_j, y_j, h_j, \omega_{i,j}, b_{i,j}} \sum_j \Phi_j \quad (7)$$

$p_{i,j} = b_{i,j} * \zeta_j$

$s.t.:$

The objective is to maximize the total throughput of the network.

$$\sum_j \omega_{i,j} = 1, \quad \forall i \in \mathcal{U} \quad (8)$$

$$\omega_{i,j^*} = 1, j^* = arg_j(\max s_{i,j}), \quad \forall i \in \mathcal{U} \quad (9)$$

provisioning constraint

$$\sum_i \phi_{i,j} \leq f_j, \quad \forall j \in \mathcal{B}' \quad (10)$$

backhaul data rate constraints

$$P_j \leq P_D, \quad \forall j \in \mathcal{B}' \quad (11)$$

$$\sum_i b_{i,j'} * \zeta_{j'} + \sum_{j, j \neq j'} P_{j',j} \leq P_M, \quad \forall j, j' = 1 \quad (12)$$

power capacity constraints

$$\phi_{i,j} \geq \omega_{i,j} * d_{min}, \quad \forall i \in \mathcal{U}, j \in \mathcal{B} \quad (13)$$

minimum data rate constraints

$$0 \leq x_j \leq x_{max}, \quad \forall j \in \mathcal{B}' \quad (14)$$

$$0 \leq y_j \leq y_{max}, \quad \forall j \in \mathcal{B}' \quad (15)$$

$$h_{min} \leq h_j \leq h_{max}, \quad \forall j \in \mathcal{B}' \quad (16)$$

DBS placement constraints

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Heuristic Algorithm

Algorithm 1: Dynamic-DSP Algorithm

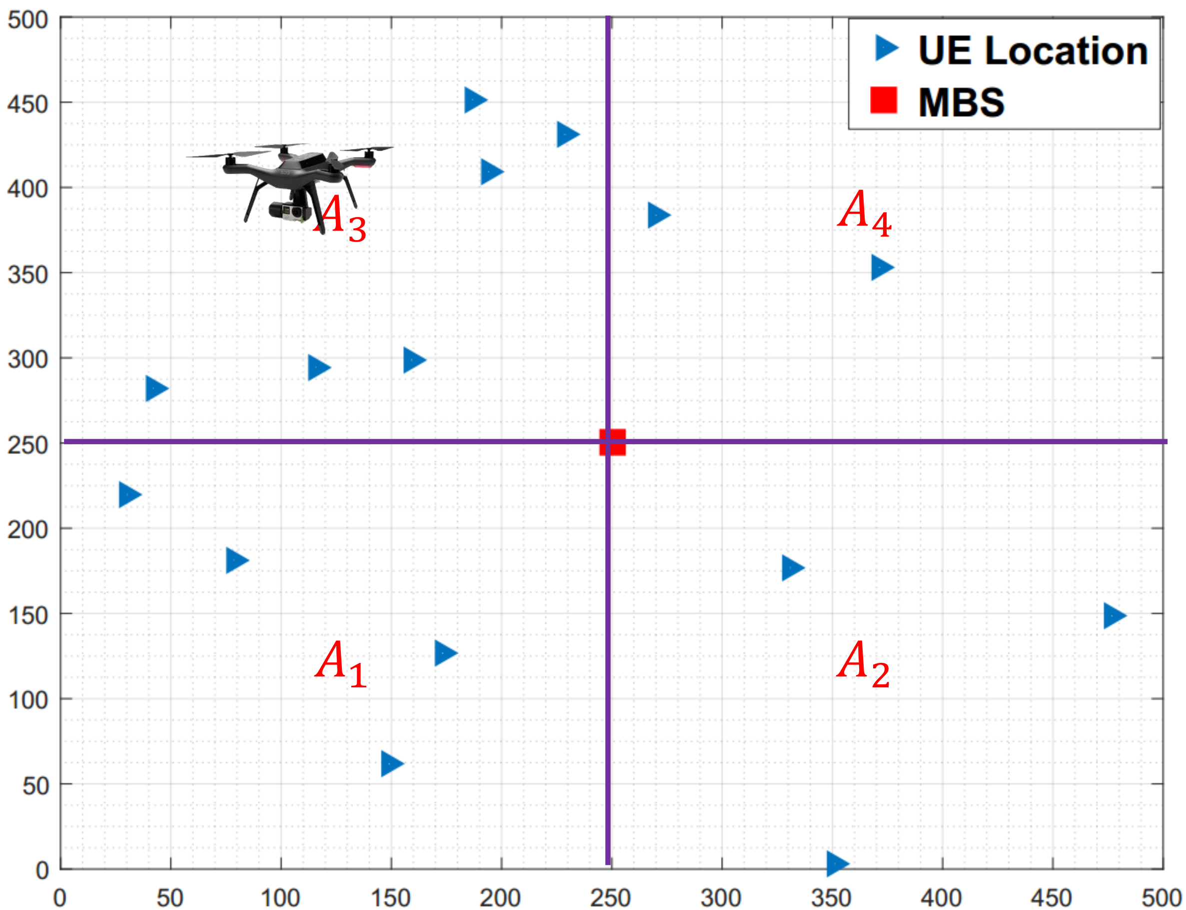
Input : (x_i^{ue}, y_i^{ue}) and other parameters in Table I;
Output: $\{x_j, y_j, h_j\}$, $\omega_{i,j}$, $b_{i,j}$;

for $j \in \mathcal{B}'$ **do**
  calculate the weight of UEs in C_j by Eq. (17);
  get x_j and y_j with the highest weight;
  remove UEs in the coverage of the jth DBS;
calculate SINR of all UEs and all BSs;
get h_j with the best average SINR of all UEs;
calculate the UE association based on the best SINR;
allocate the bandwidth and power to UEs in MBS according to Eq. (13);
assign the redundant bandwidth and power to the UE which has the best SINR in MBS;
$L = 0$, $D = 1$, $D_j = 1$, $P_j^L = P_D/2^{L+1}, \forall j$;
while $D > 0$ & $L < L_{max}$ **do**
  set maximum available power $P_j^{max} = \sum P_j^L, \forall j$;
  for $j \in \mathcal{B}'$ **do**
    allocate the bandwidth and power to UEs by Eq. (13);
    assign the remaining bandwidth and power to the UE which has the best SINR;
    if $|(\sum_i \phi_{i,j} - f_j)/f_j| < \varepsilon$ **then**
      $D_j = 0$, and $D = \sum_j D_j$;
      continue;
    if $\sum_i \phi_{i,j} \geq f_j$ **then**
      set $P_j^{L+1} = P_D/2^{(L+1)+1}$;
    else
      set $P_j^{L+1} = -P_D/2^{(L+1)+1}$;
  $L = L + 1$, and $D = \sum_j D_j$;
update $b_{i,j} = p_{i,j}/\zeta_j$, $\omega_{i,j}$, and P_j;

- The complexity of the Dynamic-DSP algorithm is:

$$O\left(\frac{C_m}{C_j}|U||B| + \frac{h_{max}-h_{min}}{\Delta h}|B| + |U|^{|B|} + L_{max}|B|(|U| + log(|U|))\right).$$

Example of Finds a Horizontal Location for a DBS



- $W(A_k) = \sum_{i \in A_k} \xi_i$
  $\xi_i = 1$

- $W(A_1) = 4,$
- $W(A_2) = 3,$
- $W(A_3) = 6,$
- $W(A_4) = 2.$

- $$\xi_i = 1 + \frac{1}{1 + \sqrt{(x_i^{ue} - x_j)^2 + (y_i^{ue} - y_j)^2}} \quad (17)$$

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Simulation Settings

- We consider three DBSs and one MBS (|B'| =3) in an urban area (i.e., the coverage area of the MBS is 500 ∗ 500 m2). The other parameters are listed in Table I.

Table I: Simulation Parameters

a, environment constant	9.61
b, environment constant	0.16
η_L, additional mean loss of LoS	1 dB
η_N, additional mean loss of NLoS	20 dB
C_m, MBS cell coverage	$500 * 500\ m^2$
C_j, coverage of a DBS (used for DBS placement)	$70 * 70\ m^2$
h_{min}, the minimum altitude of a DBS	60 m
h_{max}, the maximum altitude of a DBS	200 m
path loss of MBS-UE	$34.5 + 35 * log_{10}(d[m])$ [12]
Shadow fading of MBS-UE	$N(0, 8^2)$ dB
N_0, thermal noise power spectral density	−174 dBm/Hz
C_{SI}, SI cancellation value	130 dB [8]
β_M, the total bandwidth capacity of the MBS	20 MHz
β_B, the total backhaul bandwidth of a DBS	3.3 MHz
P_M, the maximum transmission power of a MBS	4 W
P_D, the maximum transmission power of a DBS	1 W
$\lvert\mathcal{U}\rvert$, the number of UEs	$\{100, 120, \cdots, 220\}$
The minimal data rate	500 kbps
L_{max}, the maximum loop number	60
ε, deviation of throughput and backhaul data rate	0.0002

Throughput Performance

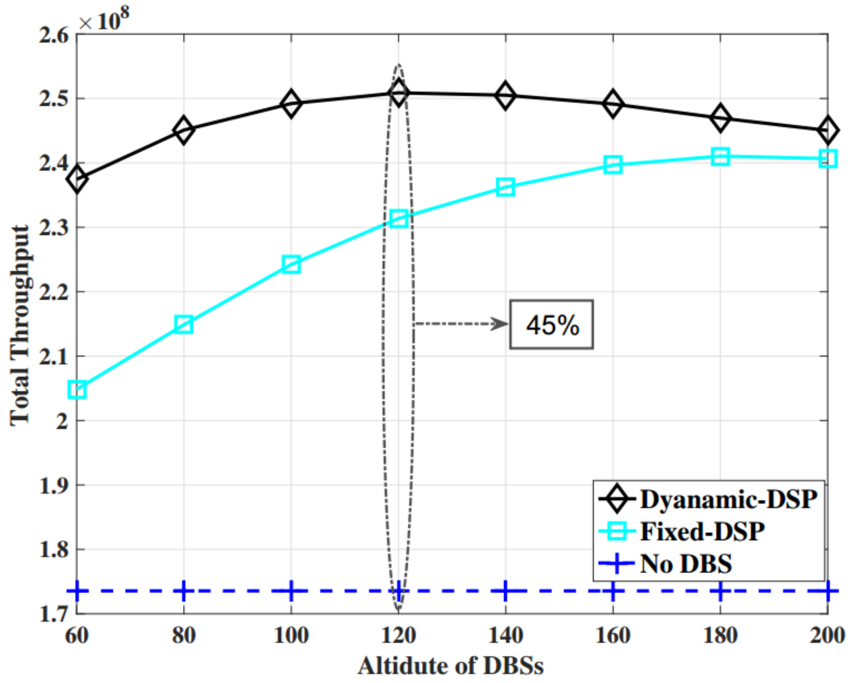

Fig. 6. Throughput versus altitude.

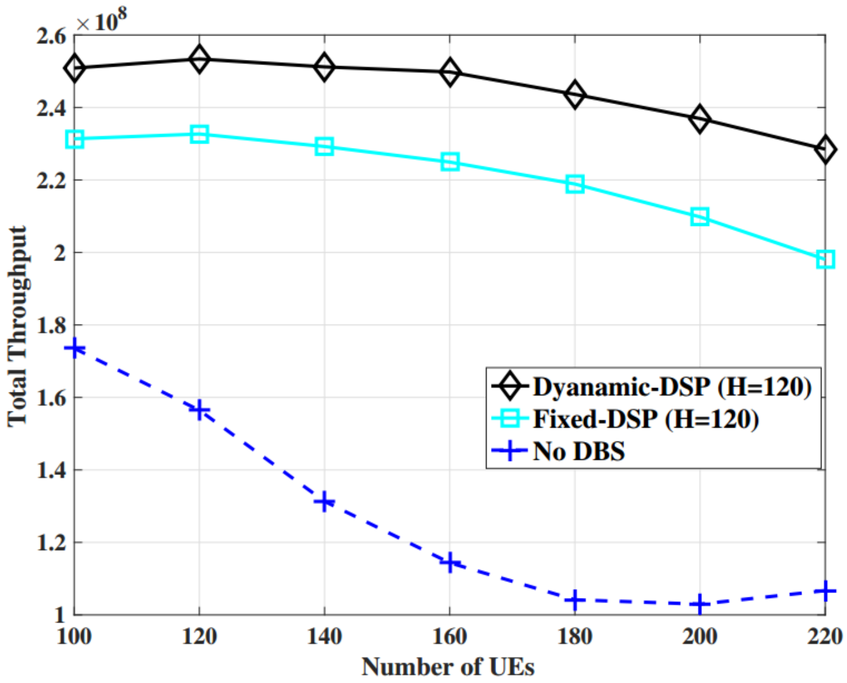

Fig. 7. Throughput versus the number of UEs.

- The throughput achieved by the Dynamic-DSP strategy has been increased by 45% and 8% as compared to the strategy without DBS and the Fixed-DSP strategy, respectively.

DBS Placement

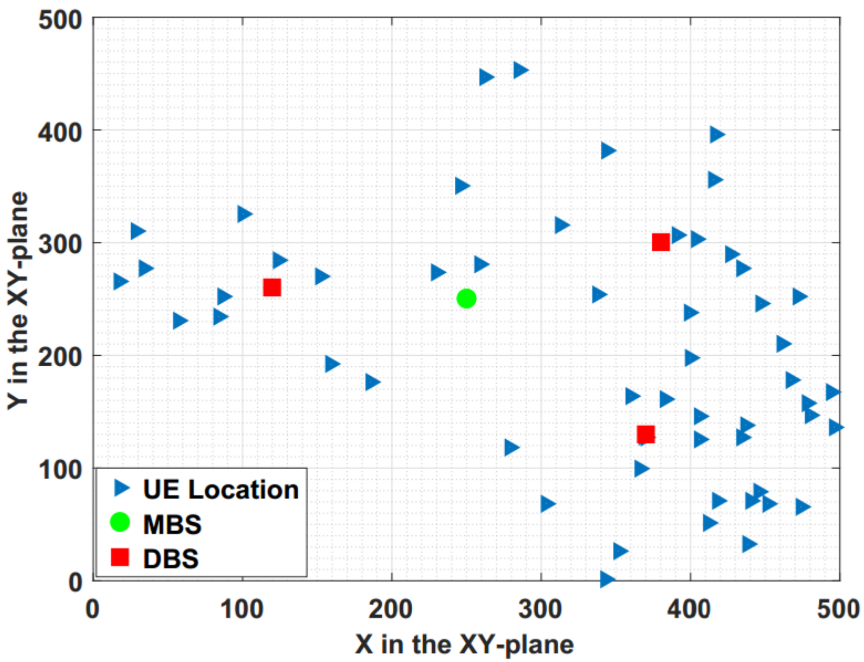

Fig. 8. DBS placement by Dynamic-DSP.

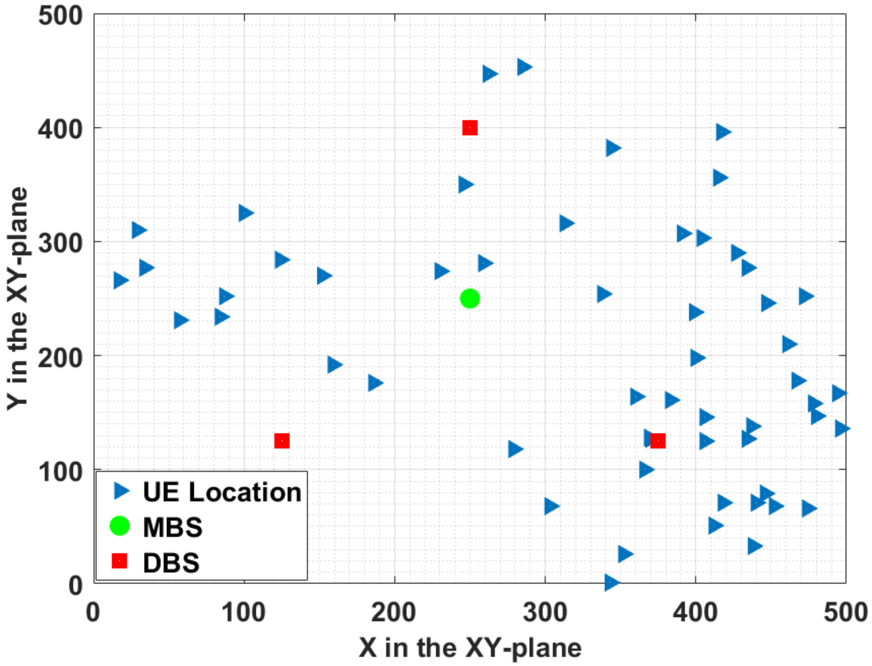

Fig. 9. DBS placement by Fixed-DSP.

- Fig. 8 shows how DBSs are placed by Dynamic-DSP; note that DBSs hover close to regions with higher UE densities but not far away from the MBS.
- DBS locations: $\left(\frac{1}{4}x_{max}, \frac{1}{4}y_{max}\right), \left(\frac{3}{4}x_{max}, \frac{1}{4}y_{max}\right), \left(\frac{1}{2}x_{max}, \frac{4}{5}y_{max}\right).$

On the Number and 3-D Placement of In-Band Full-Duplex Enabled Drone-mounted Base-stations

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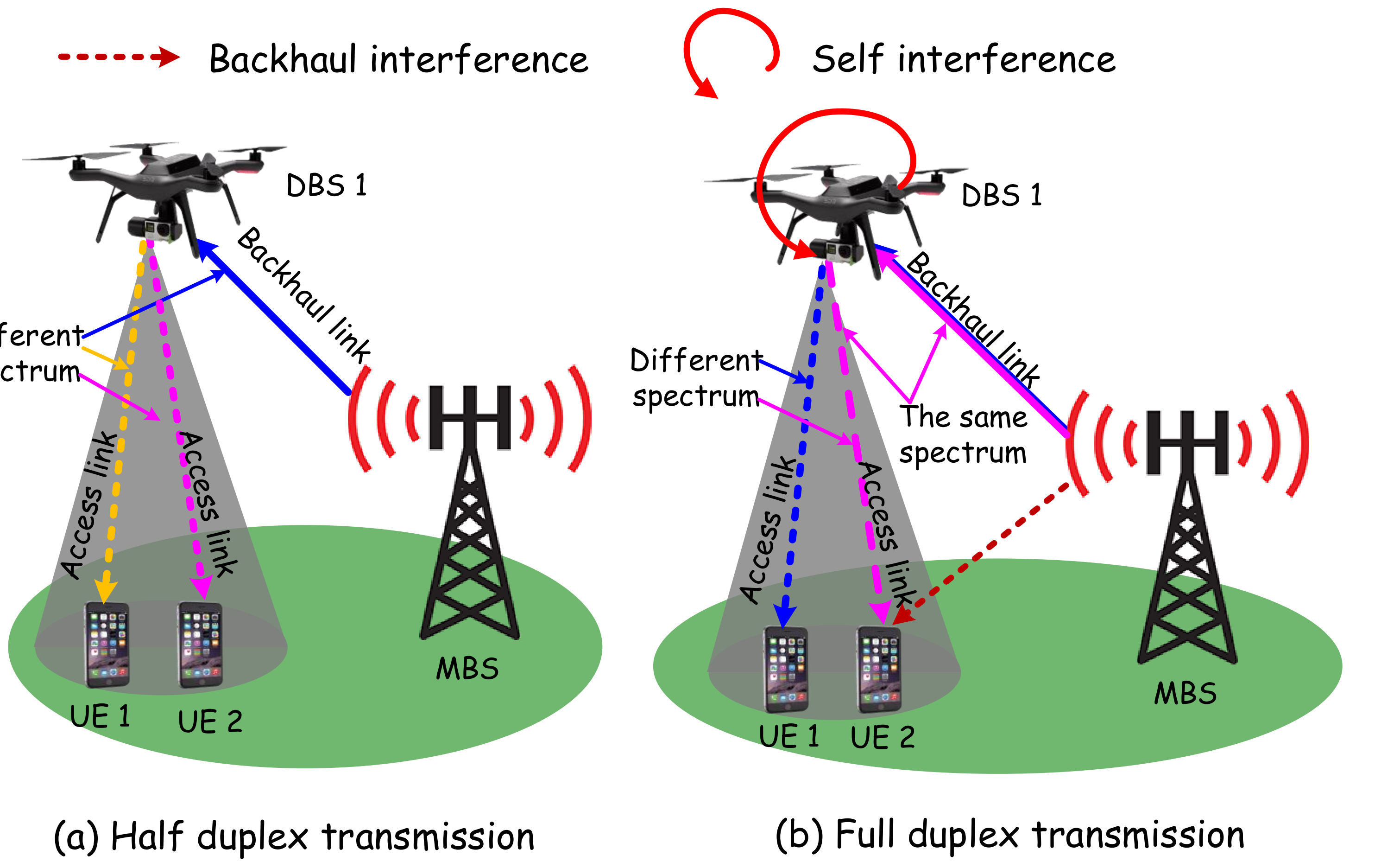

Fig. 1. DBS communications with half duplex and full duplex.

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Notations and Variables

- N_{max}: the maximum number of available BSs.
- $\{x_i^{ue}, y_i^{ue}\}$: the 2-D location information of the ith UE.
- d_i: the data rate requirement of the ith UE.
- Q: the set of candidate locations for DBSs in the horizontal plane.
- P_M: the power capacity of the MBS.
- P_D: the power capacity of a DBS.
- ξ_j: the power spectral density of the jth BS.
- β^M: the total bandwidth capacity of the MBS.
- β_j^B: the backhaul bandwidth towards the jth DBS which is assigned by the MBS.
- $P_{j,1}$: the assigned transmission power from the MBS to the jth DBS (backhaul).

- f_j: a binary variable indicating whether the jth DBS is used ("1" is affirmative).
- $\omega_{i,j}$: a binary variable indicating whether the ith UE is associated with the jth BS.
- $b_{i,j}$: the assigned bandwidth from the jth BS to the ith UE.
- $p_{i,j}$: the assigned power from the jth BS to the ith UE.
- q_j: the location of the jth BS in the horizontal plane, $q_j \in Q$.
- h_j: the height of the jth DBS.
- T_j: the total throughput of the jth BS, $T_j = \sum_i R_{i,j}$.

Problem Formulation

$$\min \sum_j f_j \quad \& \quad \max_{\{f_j, q_j, h_j, \omega_{i,j}, b_{i,j}\}} \sum_j T_j$$

$$p_{i,j} = b_{i,j} * \xi_j$$

The objective is to minimize the number of required DBSs while maximizing the total throughput of the network.

$s.t.:$

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

$$C2: f_j \leq \sum_i \omega_{i,j} \leq f_j * |\mathcal{U}|, \quad \forall j \in \mathcal{B}, j > 1,$$

provisioning constraint

$$C3: q_j \in \mathcal{Q}, \quad \forall j \in \mathcal{B}, j > 1,$$

$$C4: h_{min} \leq h_j \leq h_{max}, \quad \forall j \in \mathcal{B}, j > 1,$$

DBS placement constraints

$$C5: R_{i,j} = \omega_{i,j} * d_i, \quad \forall i \in \mathcal{U}, j \in \mathcal{B},$$

data rate constraints

$$C6: \sum_i R_{i,j} \leq \phi_j, \quad \forall j \in \mathcal{B}, j > 1,$$

backhaul data rate constraints

$$C7: \sum_i \omega_{i,j} * b_{i,j} * \xi_j \leq P_D, \quad \forall j \in \mathcal{B}, j > 1,$$

power capacity constraints

$$C8: \sum_i b_{i,1} * \xi_1 + \sum_{j \in \mathcal{B}, j > 1} P_{j,1} \leq P_M. \tag{8}$$

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Heuristic Algorithm

Algorithm 1: Dynamic droNe-bAse-station-PlacEment (D-NAPE) Algorithm

Input : x_i^{ue},y_i^{ue} and parameters from Table II;

Output: f_j, q_j, h_j, $\omega_{i,j}$, $b_{i,j}$, $p_{i,j}$;

$N_{bs} = 1$, $N_{block} = 1$ and $h = h_{min}$;

for $h \le h_{max}$ **do**

  $h_j = h$;

  while $N_{bs} \le N_{max} \& N_{block} = 1$ **do**

    calculate $S_{i,1}$ of all UEs;

    for $j \in \mathcal{B}$ & $q \in \mathcal{Q}$ **do**

      calculate W_j within C_d through Eqs. (10)-(11);

      get q_j where W_j is maximized;

      remove UEs within coverage q_j;

    get $S_{i,j}$ and calculate $\omega_{i,j}$ by Eq. (9);

    allocate $P_{1,j}$ and β_j^B for backhaul links;

    allocate $b_{i,1}$ and $p_{i,1}$ to MBS' UEs;

    $l = 0$, $N_D = 1$, $N_D^j = 1$, $P_j^l = P_D/2^{l+1}, \forall j$;

    while $N_D > 0 \,\&\, l < l^{max}$ **do**

      set available power $P_j^{max} = \sum P_j^l$;

      for $j \in \mathcal{B}$ **do**

        sort UEs in descending order by SINR;

        allocate $b_{i,j}$ and $p_{i,j}$ to UEs;

        if $|(\sum_i R_{i,j} - \phi_j)/\phi_j| < \varepsilon$ **then**

          $N_D^j = 0$ and $N_D = \sum_j N_D^j$;

          continue;

        if $\sum_i R_{i,j} \ge \phi_j$ **then**

          set $P_j^{l+1} = P_D/2^{(l+1)+1}$

        ;

        else

          set $P_j^{l+1} = -P_D/2^{(l+1)+1}$

        ;

        $l = l + 1$ and $N_D = \sum_j N_D^j$;

    if *all UEs are provisioned* **then**

      $N_{block} = 0$;

    else

      $N_{block} = 1$;

    update f_j;

    $N_{bs} = N_{bs} + 1$;

  calculate throughput $T = \sum_j T_j$ and $h = h + \Delta h$;

  update f_j, q_j, h_j, $\omega_{i,j}$, $b_{i,j}$, $p_{i,j}$ associated with the maximum T.

D-NAPE Algorithm

- The D-NAPE algorithm is illustrated in *Algorithm* 1. D-NAPE provides the vertical coordinates of all DBSs as well as the horizontal locations in the xy-plane.

- The complexity of the D-NAPE algorithm is:

$$O\left(\frac{h_{max}-h_{min}}{\Delta h}|B|((|B||Q|+|B|+1)|U|+|U|^{|B|}+l^{max}|B|(|U|+\log(|U|)))\right).$$

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Simulation Settings

➢ Simulation Parameters are shown in Table II.

Table II: Simulation Parameters

(a, b), environment constants	$(9.61, 0.16)$
(η_L, η_N), additional mean losses of LoS, NLOS	$(1, 20)$ dB
C_m, MBS cell coverage	$500 * 500m^2$
C_d, DBS cell radius (only for DBS placement)	80 m
(h_{min}, h_{max}), the altitude range of a DBS	$(80, 200)$ m
ground to ground (MBS-UE) path loss	$34.5 + 35log_{10}(d[m])$ [12]
Shadow fading of MBS to UE	$N(0, 6^2)$ dB
N_0	-174 dBm/Hz
c_0	130 dB [4]
$\|\mathcal{U}\|$	$\{130, 170, \cdots, 190\}$
d_i	$\{0.5, 0.5, 1, 2\}$ Mbps
P_M	4 W
P_D	0.5 W
β^M	20 MHz
l^{max}	10
ε	0.0002
N_{max}	6

Throughput Performance

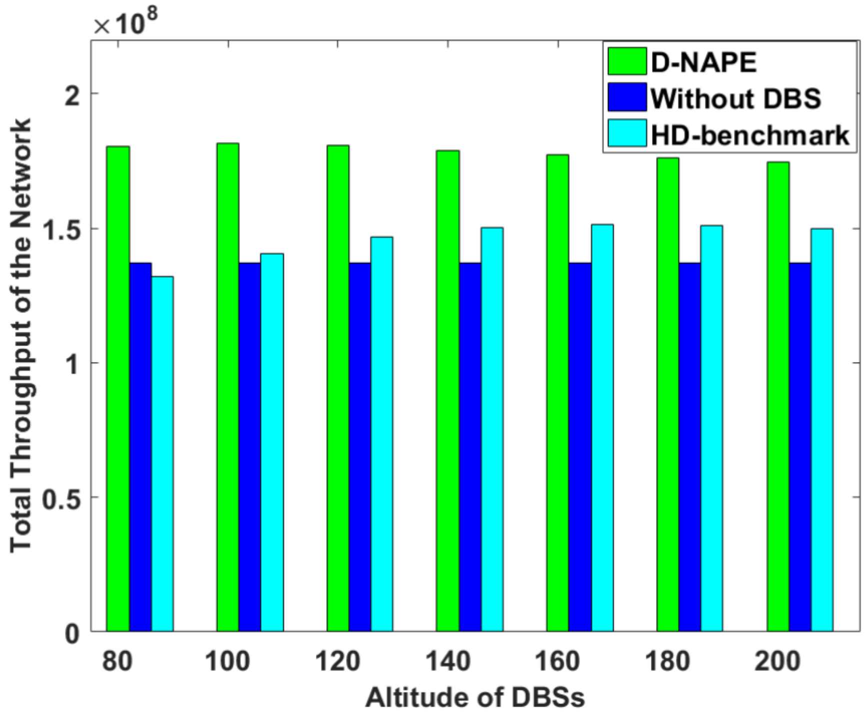

Fig. 2. Throughput versus altitude (|U|=190).

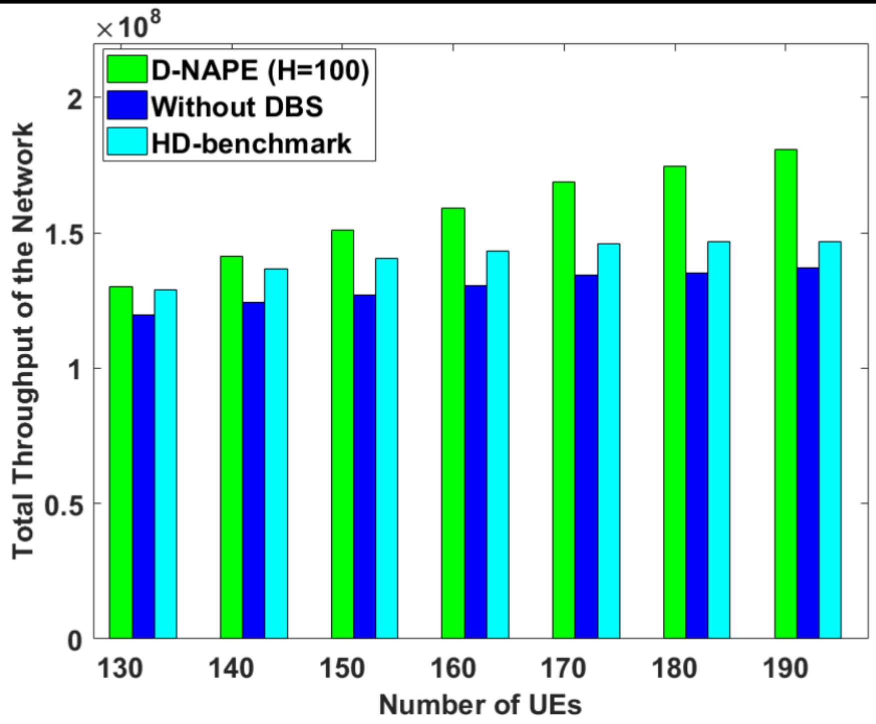

Fig. 3. Throughput versus the number of UEs (H=100).

- For a given altitude such as 100 m, the total network throughput also increases as the number of UE increases, and D-NAPE achieves up to 32% and 23% throughput increase as compared to that of without DBS strategy and HD-benchmark, respectively.

Throughput Performance

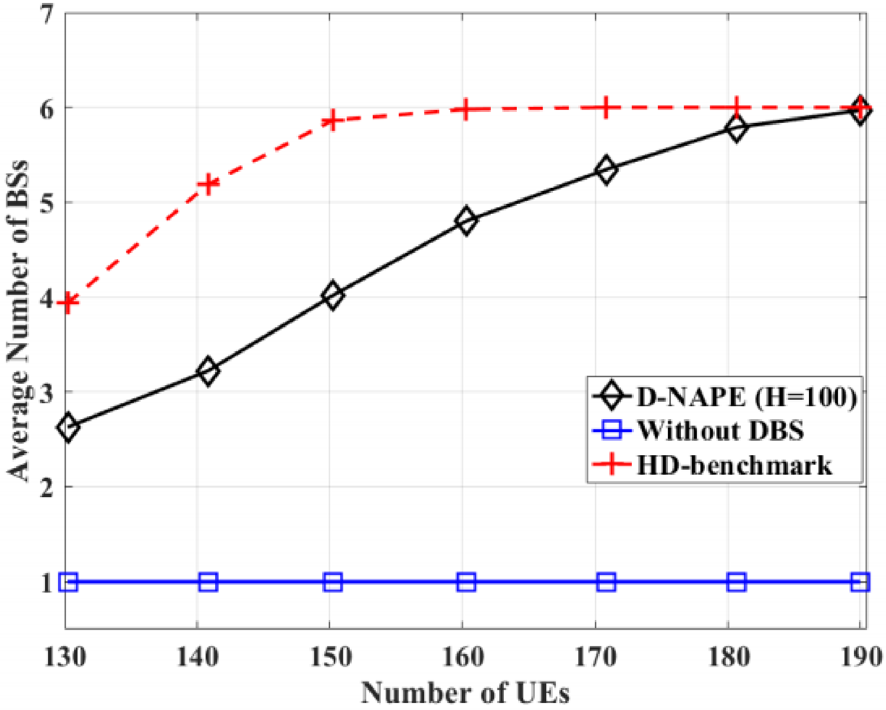

Fig. 4. Required BSs versus UEs.

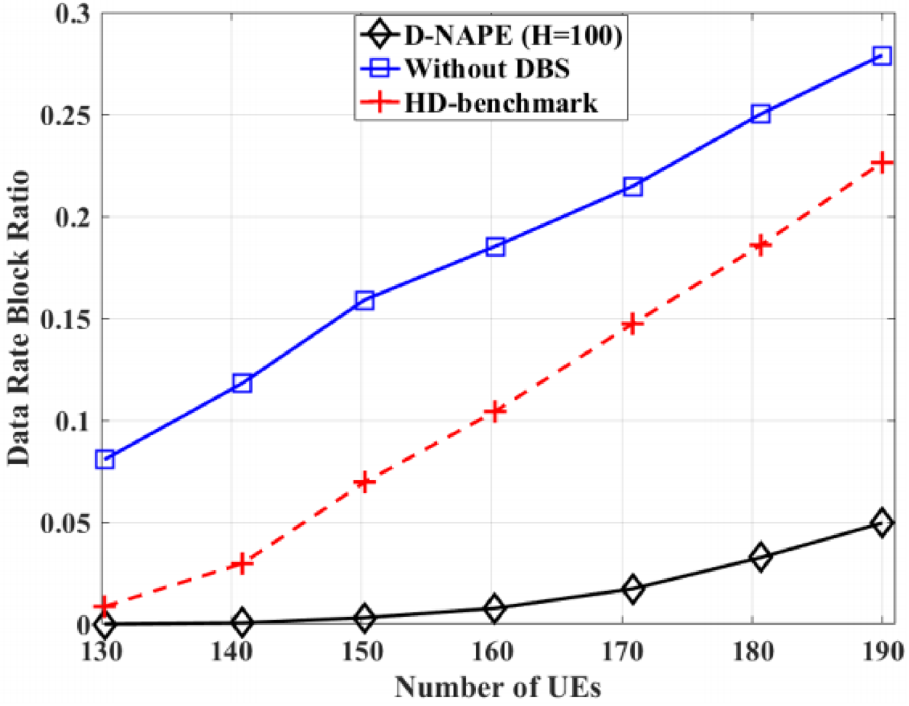

Fig. 5. Data rate block ratio.

- Data rate block ratio is defined as the total bandwidth of blocked UEs over the total required bandwidth of all UEs.

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Conclusions

- We have investigated the Drone-mounted base-Station Placement with In-Band Full-Duplex communication (DSP-IBFD) problem, which includes the DBS placement problem, and the bandwidth and power allocation (in the access link and the backhaul link) problem.

- We have also studied the problem of minimizing the number of required DBSs and maximizing the total throughput of the network in providing services to UEs, while incorporating IBFD-enabled DBSs communications for both access links and backhaul links of DBSs.

Publications

Journal articles:

1. **L. Zhang** and N. Ansari, "A Framework for 5G Networks with In-band Full-duplex Enabled Drone-mounted Base-stations", *IEEE Wireless Communications Magazine*, doi: 10.1109/MWC.2019.1800486, Mar. 2019.
2. **L. Zhang** and N. Ansari, "On the Number and 3-D Placement of In-Band Full-Duplex Enabled Drone-mounted Base-stations," *IEEE Wireless Communications Letters*, vol. 8, no. 1, pp. 221-224, Feb. 2019.
3. **L. Zhang**, Q. Fan and N. Ansari, "3-D Drone-Base-Station Placement with In-Band Full-Duplex Communications," *IEEE Communications Letters*, vol. 22, no. 9, pp. 1902-1905, Sept. 2018.
4. **L. Zhang**, T. Han and N. Ansari, "Energy-Aware Virtual Machine Management in Inter-Datacenter Networks Over Elastic Optical Infrastructure," *IEEE Transactions on Green Communications and Networking*, vol. 2, no. 1, pp. 305-315, Mar. 2018.
5. **L. Zhang**, N. Ansari and A. Khreishah, "Anycast Planning in Space Division Multiplexing Elastic Optical Networks With Multi-Core Fibers," *IEEE Communications Letters*, vol. 20, no. 10, pp. 1983-1986, Oct. 2016.

Conference Papers

1. **L. Zhang**, Y. Luo, N. Ansari, B. Gao, X. Liu and F. Effenberger, "Enhancing Next Generation Passive Optical Network Stage2 (NG-PON2) with Channel Bonding," *International Conference on Networking, Architecture, and Storage*, pp. 1-6, Aug. 2017.
2. **L. Zhang,** Y. Luo, N. Ansari, B. Gao, X. Liu and F. Effenberger, "Channel bonding for Next Generation Passive Optical Network Stage 2 (NG-PON2)," *International Conference on Computer, Information and Telecommunication Systems (CITS)*, pp. 103-107, Jul. 2017.
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4. **L. Zhang**, Y. Luo, B. Gao, X. Liu, F. Effenberger and N. Ansari, "Channel bonding design for 100 Gb/s PON based on FEC codeword alignment," *Optical Fiber Communications Conference and Exhibition (OFC)*, pp. 1-3, Mar. 2017.
5. **L. Zhang**, T. Han and N. Ansari, "Revenue Driven Virtual Machine Management in Green Datacenter Networks Towards Big Data," *IEEE Global Communications Conference (GLOBECOM)*, pp. 1-6, Dec. 2016 (**NSF Travel Grant**).
6. **L. Zhang**, T. Han and N. Ansari, "Renewable Energy-Aware Inter-Datacenter Virtual Machine Migration over Elastic Optical Networks," *IEEE International Conference on Cloud Computing Technology and Science (CloudCom)*, pp. 440-443, Dec. 2015.