Aerial Base Station Placement Leveraging Radio Tomographic Maps

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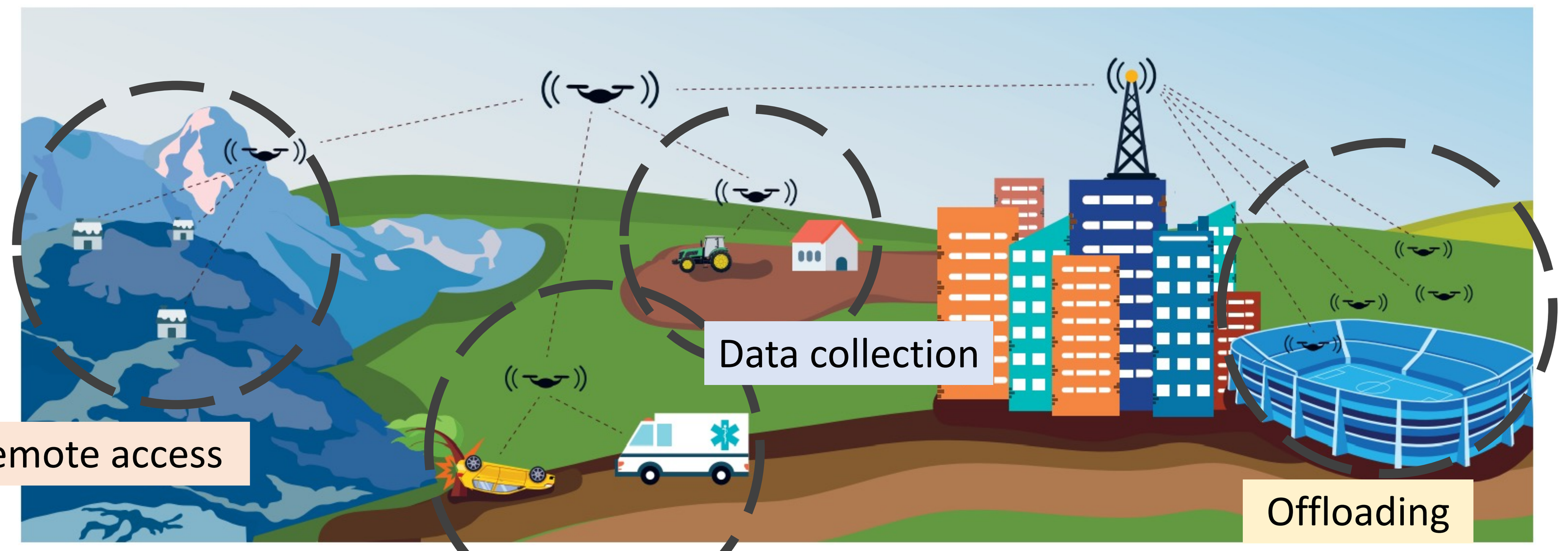
Aerial Base Station Placement - Applications

Romero et al. 2019



Contribution Relative to Prior Art

- 2D aerial base station (ABS) placement
  - Stochastic optimization [Romero et al. 2019]
  - Sparse recovery [Huang et al. 2020]
- 3D ABS placement
  - Particle swarm optimization (PSO) + gradient descent [Kim et al. 2018]
  - Heuristic algorithm [Kalantari et al. 2016]
  - K-means + game theory [Hammouti et al. 2019]
  - PSO [Perabathini et al. 2019]
  - Reinforcement learning [Liu et al. 2019]
  - The genetic algorithm [Shehzad et al. 2021]
  - Reinforcement learning [Qiu et al. 2020]
  - A geometry-based greedy algorithm [Sabzehali et al. 2021]

Free-space propagation (Romero et al. 2019 – Kim et al. 2018); Empirical channel model (Kalantari et al. 2016 – Shehzad et al. 2021); 3D city models (Qiu et al. 2020 – Sabzehali et al. 2021)

Contribution: 3D ABS placement
- Channel-aware → radio tomographic maps
- Convex optimization placement criterion
  - Can accommodate no-fly zones
  - Linear complexity solver

Communication Model

- Channel gain: $\gamma_m(\boldsymbol{x}^{\text{ABS}}) = 20\log_{10}\left(\frac{\lambda}{4\pi\|\boldsymbol{x}_m^{\text{GT}} - \boldsymbol{x}^{\text{ABS}}\|}\right) - \xi(\boldsymbol{x}_m^{\text{GT}}, \boldsymbol{x}^{\text{ABS}})[\text{dB}]$
  - Wavelength: λ
  - ABS position: $\boldsymbol{x}^{\text{ABS}} \in \mathcal{F} \subset \mathbb{R}^3$
  - Ground terminal (GT) position: $\boldsymbol{x}_m^{\text{GT}} \in \mathcal{X} \subset \mathbb{R}^3$
  - Shadowing: $\xi(\boldsymbol{x}_m^{\text{GT}}, \boldsymbol{x}^{\text{ABS}})$
- Capacity: $C_m(\boldsymbol{x}^{\text{ABS}}) = W\log_2\left(1 + P_{\text{TX}}10^{\gamma_m(\boldsymbol{x}^{\text{ABS}})/10}/\sigma^2\right)$
  - Bandwidth: W
  - Transmit power: P_{TX}
  - Noise power: σ^2
- Assumptions:
  - Known: $\lambda, W, P_{\text{TX}}, \sigma^2$
  - Unlimited backhaul

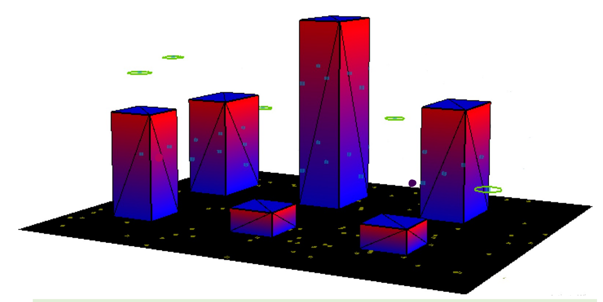
Problem Formulation

Given:
- Positions of ground terminals $\{\boldsymbol{x}_1^{\text{GT}}, \dots, \boldsymbol{x}_M^{\text{GT}}\} \subset \mathcal{X} \subset \mathbb{R}^3$
- Minimum rate $r_{\min}$

Optimization problem:

$$\underset{N, \{\boldsymbol{x}_n^{\text{ABS}}\}_{n=1}^N}{\text{minimize}} \quad N$$
$$\text{s.t.} \quad \textstyle\sum_n C_m(\boldsymbol{x}_n^{\text{ABS}}) \geq r_{\min},\ m = 1, \dots, M,$$
$$\boldsymbol{x}_n^{\text{ABS}} \in \mathcal{F},\ n = 1, \dots, N.$$

The number of ABSs: N. Allowed flying zone: $\mathcal{F}$.

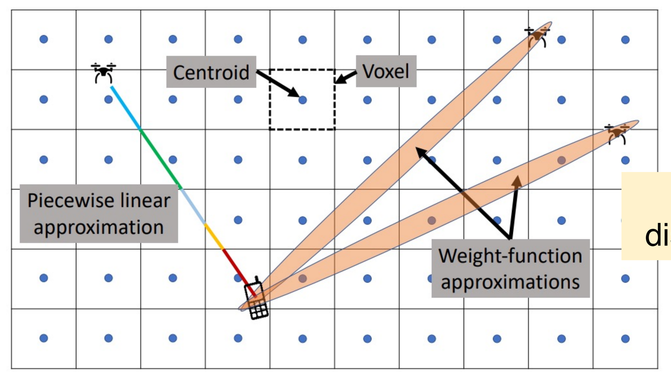


markers on the ground: GTs
green circles: ABS positions

Challenge: unknown $\xi(\boldsymbol{x}_m^{\text{GT}}, \boldsymbol{x}^{\text{ABS}})$ ⇒ unknown $C_m(\boldsymbol{x}^{\text{ABS}})$

Shadowing Maps via Radio Tomography

Unknown shadowing → Learn a shadowing map from measurements → Radio tomographic model [Patwari et al. 2008]



$$\xi(\boldsymbol{x}_1, \boldsymbol{x}_2) = \frac{1}{\|\boldsymbol{x}_1 - \boldsymbol{x}_2\|_2^{1/2}} \int_{\boldsymbol{x}_1}^{\boldsymbol{x}_2} l(\boldsymbol{x}) d\boldsymbol{x},$$

Spatial loss field: $l(\boldsymbol{x})$

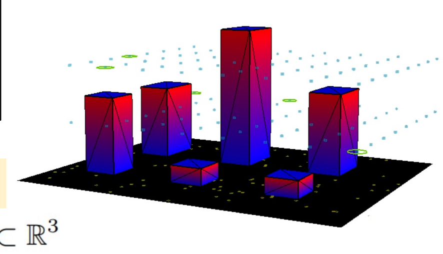
Integral discretization →
- conventional weight-function approximation
- proposed approximation
  - continuous
  - can be used with large grid point spacing
  - linear complexity $\mathcal{O}(Q)$

N. Patwari and P. Agrawal, "NeSh: A joint shadowing model for links in a multi-hop network," in Proc. IEEE Int. Conf. Acoust., Speech, Signal Process., Las Vegas, NV, Mar. 2008, pp. 2873–2876.

Placement with Min-Rate Guarantees

Proposed approach

$$\underset{N, \{\boldsymbol{x}_n^{\text{ABS}}\}_{n=1}^N}{\text{minimize}} \quad N \quad \text{s.t.} \quad \textstyle\sum_n C_m(\boldsymbol{x}_n^{\text{ABS}}) \geq r_{\min},\ m = 1, \dots, M, \quad \boldsymbol{x}_n^{\text{ABS}} \in \mathcal{F},\ n = 1, \dots, N.$$



Region discretization: $\bar{\mathcal{F}} := \{\boldsymbol{x}_1^{\bar{\mathcal{F}}}, \dots, \boldsymbol{x}_G^{\bar{\mathcal{F}}}\} \subset \mathcal{F} \subset \mathbb{R}^3$

$$\underset{\boldsymbol{\alpha} \in \{0,1\}^G}{\text{minimize}} \quad \textstyle\sum_g \alpha_g \quad \text{s.t.} \quad \textstyle\sum_g \alpha_g \boldsymbol{c}_g \geq r_{\min}\boldsymbol{1},$$

$$\alpha_g = \begin{cases} 1, & \exists \text{ an ABS at } \boldsymbol{x}_g^{\bar{\mathcal{F}}} \\ 0, & \text{otherwise} \end{cases} \qquad \boldsymbol{c}_g := [C_1(\boldsymbol{x}_g^{\bar{\mathcal{F}}}), \dots, C_M(\boldsymbol{x}_g^{\bar{\mathcal{F}}})]^\top$$

$\alpha_g \boldsymbol{c}_g \to \boldsymbol{r}_g$

$$\mathbb{I}[\bullet] = \begin{cases} 1, & \bullet \text{ is true} \\ 0, & \text{otherwise} \end{cases} \qquad \boldsymbol{R} := [\boldsymbol{r}_1, \dots, \boldsymbol{r}_G]$$

$$\underset{\boldsymbol{R} \in \mathbb{R}^{M \times G}}{\text{minimize}} \quad \textstyle\sum_{g=1}^G \mathbb{I}[\boldsymbol{r}_g \neq \boldsymbol{0}] \quad \text{s.t.} \quad \textstyle\sum_{g=1}^G \boldsymbol{r}_g \geq r_{\min}\boldsymbol{1}, \quad \boldsymbol{r}_g \in \{\boldsymbol{0}, \boldsymbol{c}_g\},\ g = 1, \dots, G,$$

$$\textstyle\sum_{g=1}^G \mathbb{I}[\boldsymbol{r}_g \neq \boldsymbol{0}] = \sum_{g=1}^G \mathbb{I}[\|\boldsymbol{r}_g\|_\infty \neq \boldsymbol{0}] = \|[\|\boldsymbol{r}_1\|_\infty, \dots, \|\boldsymbol{r}_G\|_\infty]^\top\|_0 \xrightarrow{\text{Relax}} \sum_g w_g \|\boldsymbol{r}_g\|_\infty$$

$$\underset{\boldsymbol{R} \in \mathbb{R}^{M \times G}}{\text{minimize}} \quad \textstyle\sum_g w_g \|\boldsymbol{r}_g\|_\infty \quad \text{s.t.} \quad \boldsymbol{R}\boldsymbol{1} = r_{\min}\boldsymbol{1},\ \boldsymbol{0} \leq \boldsymbol{R} \leq \boldsymbol{C},$$

Alternating-direction method of multipliers (ADMM)

$\bar{\boldsymbol{r}}_m \in \mathbb{R}^G$ m-th column of $\boldsymbol{R}^\top$

Algorithm 1: ABS Placement

```
Data: C ∈ R_+^{M×G}, r_min ∈ R_+, {w_g}_g ⊂ R_+, ρ > 0
Initialize U^1 ∈ R_+^{M×G} and Z^1 ∈ R_+^{M×G}
for k = 1, 2, ... do
    for g = 1, 2, ..., G do
        Bisection: find s_g^{k+1} s.t.
          1^T max(z_g^k − u_g^k − s_g^{k+1} 1, 0) = w_g/ρ
        Set r_g^{k+1} = min(z_g^k − u_g^k, s_g^{k+1} 1)
    for m = 1, 2, ..., M do
        Bisection: find λ s.t.
          1^T max(0, min(c̄_m, r̄_m^{k+1} + ū_m^k − λ1)) = r_min
        Set z̄_m^{k+1} = max(0, min(c̄_m, r̄_m^{k+1} + ū_m^k − λ1))
    Set U^{k+1} = U^k + R^{k+1} − Z^{k+1}
    If convergence( ) then return R^{k+1}
```


E.J. Candes, M.B. Wakin, and S.P. Boyd, "Enhancing sparsity by reweighted l1 minimization," J. Fourier Analysis App., vol. 14, no. 5, pp. 877–905, 2008.

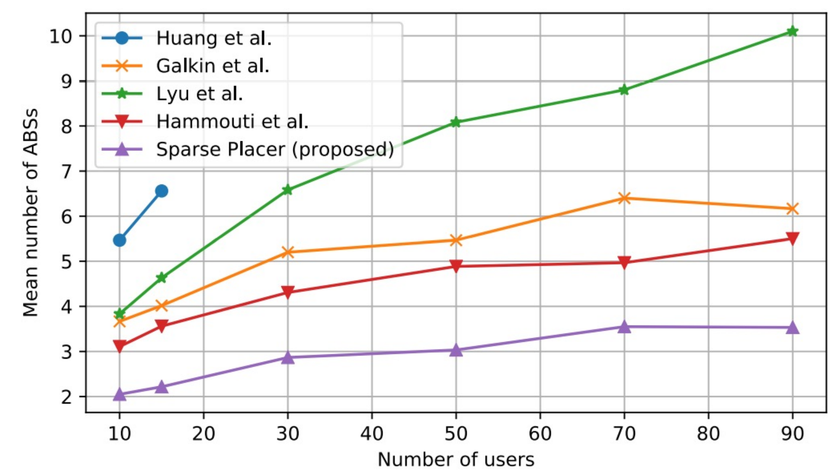
Simulation Experiments

Environment Parameters	Value
Area of interest	500 x 400 m
No. streets in each direction	9
No. rows and columns of buildings	8
Height of buildings	
Flight height	[50; 150] m
Absorption inside the buildings	3 dB/m
Carrier frequency	2.4 GHz
Bandwidth	20 MHz
Transmit power	0.1 Watt
Noise power	-96 dBm

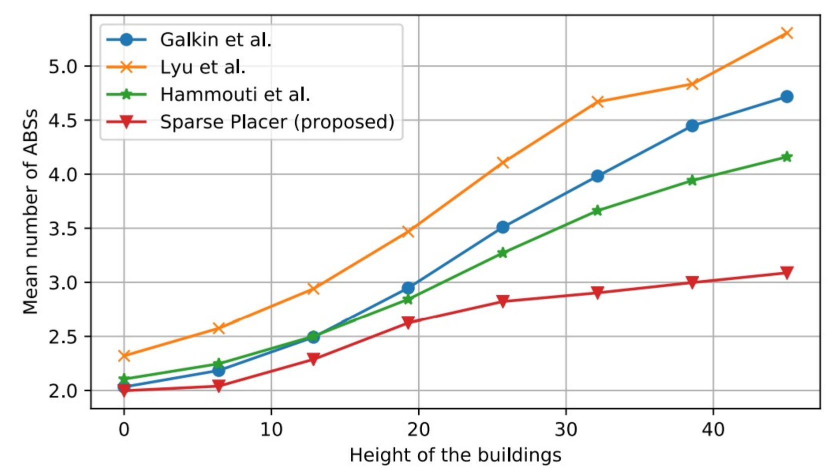
Performance metric: Mean number of ABSs

Compared algorithms

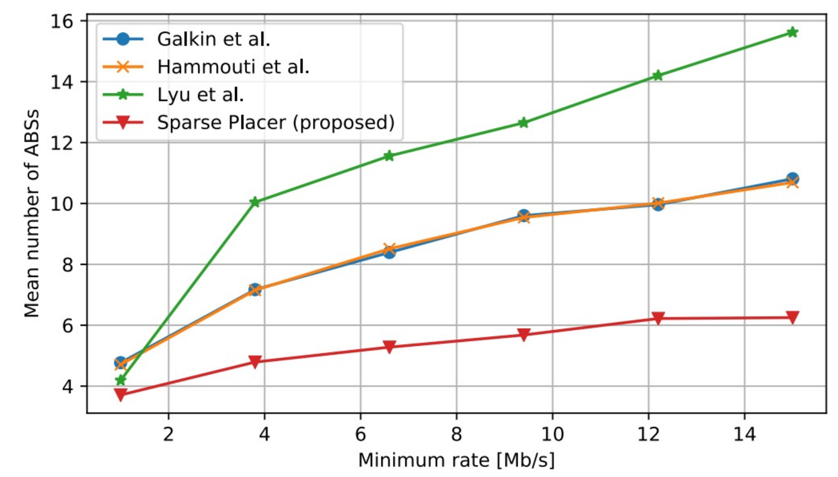
Authors	Approach	Reference
1. Huang et al.	Based on a maximum radius	"UAV-mounted mobile base station placement via sparse recovery," IEEE Access, vol. 8, pp. 71775–71781, 2020.
2. Galkin et al.	Gradually increasing the number of ABSs, starting from 1.	"Deployment of UAV-mounted access points according to spatial user locations in two-tier cellular networks," in Wireless Days. IEEE, 2016, pp. 1–6.
3. Lyu et al.	Based on a maximum radius	"Placement optimization of UAV-mounted mobile base stations," IEEE Commun. Letters, vol. 21, no. 3, pp. 604–607, 2017.
4. Hammouti et al.	Gradually increasing the number of ABSs, starting from 1.	"A distributed mechanism for joint 3D placement and user association in UAV-assisted networks," in IEEE Wireless Commun. Netw. Conf., Marrakech, Morocco, Apr. 2019.



$r_{\min} = 5$ Mb/s, $h = 53$ m, $20 \times 30 \times 5$ SLF grid, $9 \times 9 \times 3$ fly grid.



$r_{\min} = 20$ Mb/s, $h = 53$ m, $20 \times 30 \times 5$ SLF grid, $9 \times 9 \times 3$ fly grid.



$h = 53$ m, $48 \times 40 \times 5$ SLF grid, $9 \times 9 \times 5$ fly grid.

Conclusions

1. Channel-aware ABS placement based on a radio map
2. Optimize ABS locations →
   - minimize the number of ABSs,
   - guarantee a minimum rate to all GTs.
3. Proposed algorithm:
   - Discretization + convex relaxation approach → Low complexity
   - Accommodates flight constraints, e.g. no-fly zones or buildings.
4. Open source simulator: : https://github.com/uiano/abs_placement_via_radio_maps