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IEEE International Symposium on Personal, Indoor and Mobile Radio Communications

PIMRC 2017

User Association and Bandwidth Allocation for Terrestrial and Aerial Base Stations with Backhaul Considerations

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Outline

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- Introduction
- System model
- Proposed Algorithm
- Performance Evaluation
- Conclusion

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Different Applications of Drones

Military

Agriculture

Aerial Photography

Product Delivery

Recreational Applications

Why Drone Base Stations?

Terrestrial base stations' locations is determined based on the **long term average traffic**.

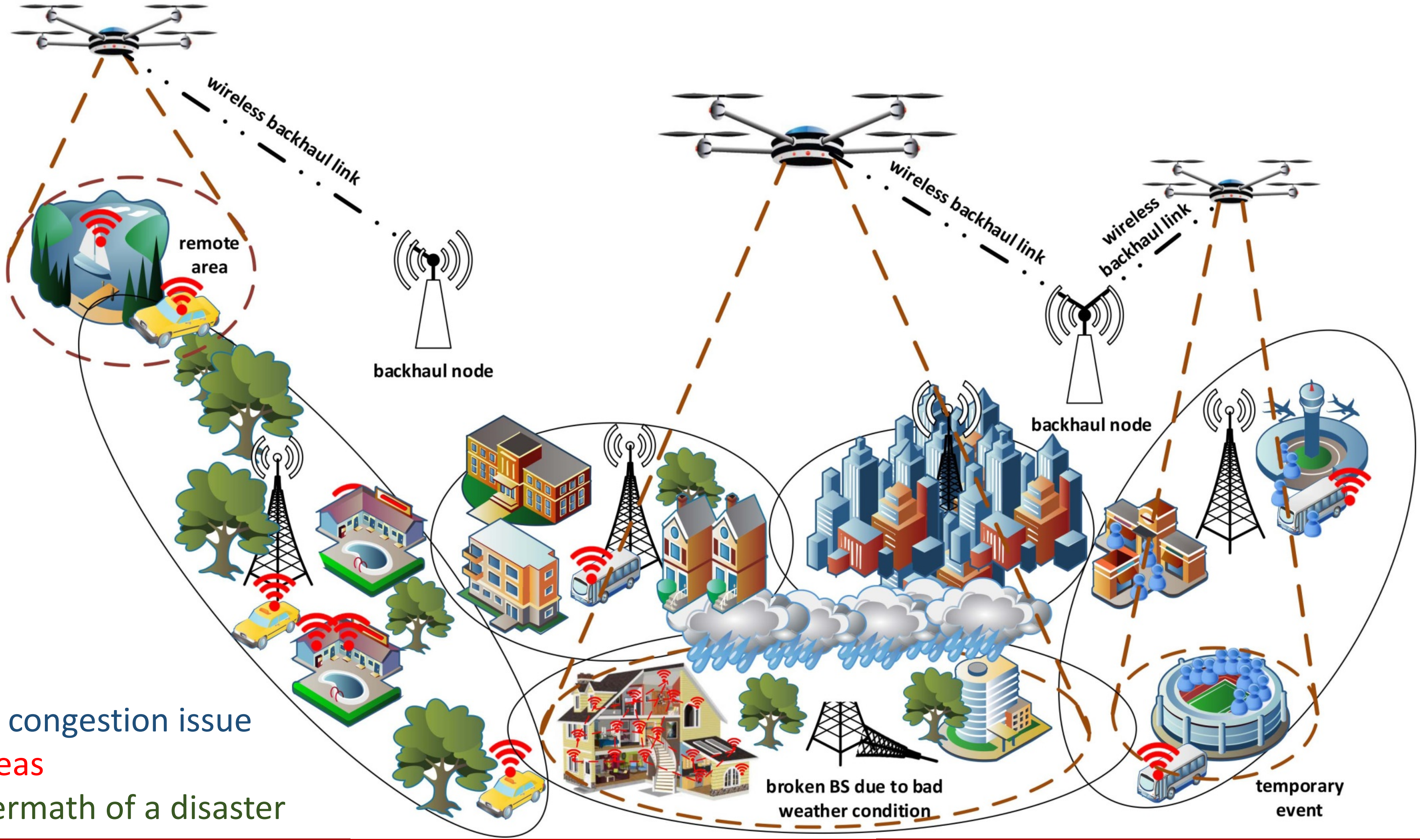
However temporal and spatial variations in user densities and user application rates are expected to result in **difficult-to-predict traffic patterns**.

supply and demand mismatch.

To increase the agility and flexibility of the network, DRONES can be integrated into the wireless network as flying base stations.

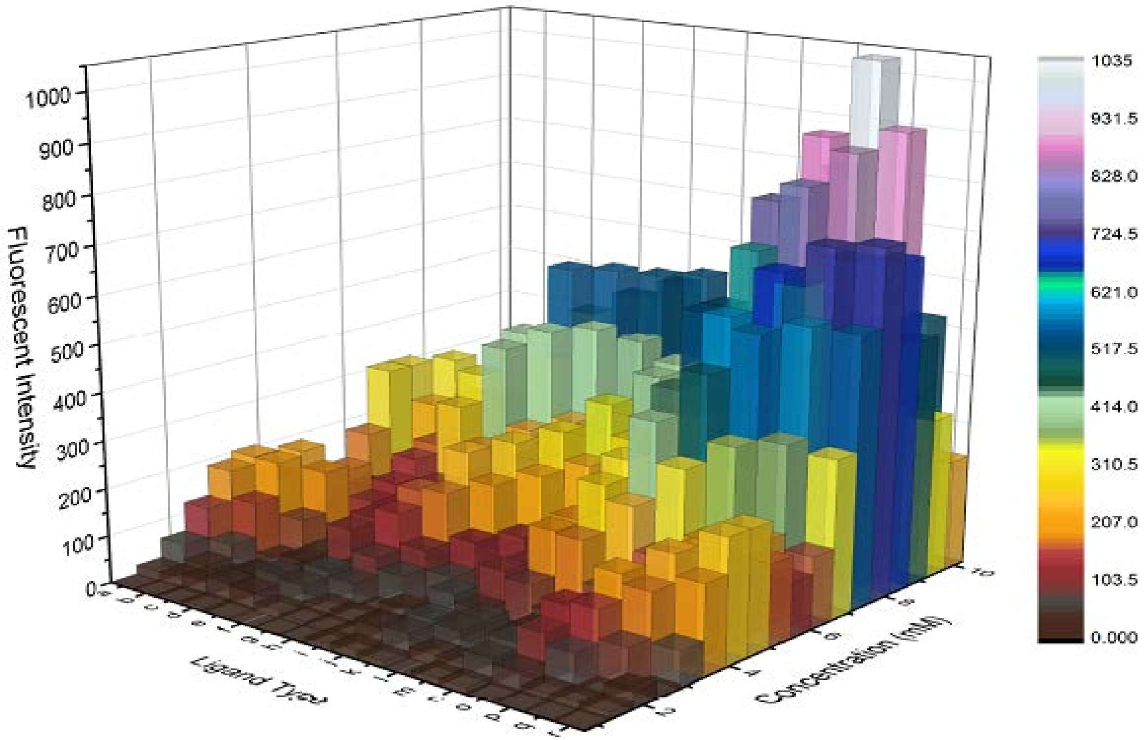
➔ **Bring supply wherever and whenever the demand is.**

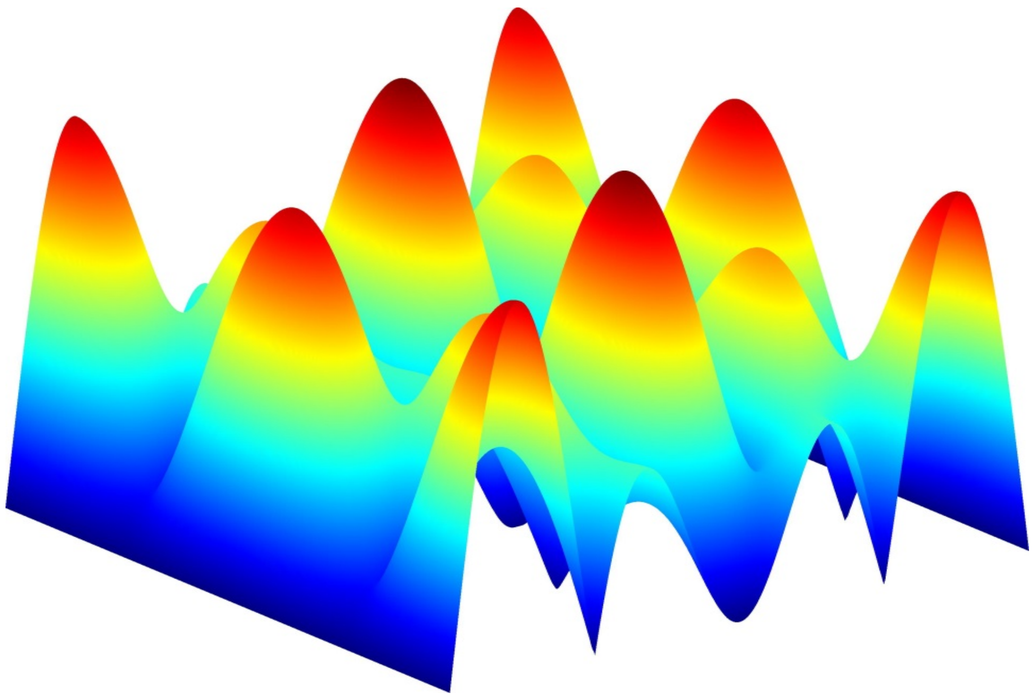
Various Use Cases for Integration of Drone-BSs in Cellular Networks



- Temporary congestion issue
- Remote areas
- During aftermath of a disaster

When Supply and Demand Do Not Match in Space and Time





Can we store (in time) and/or transfer (in space) the supply?

If difficult, then more heterogeneous + more unpredictable → more problems

When Supply and Demand Do Not Match in Space and Time

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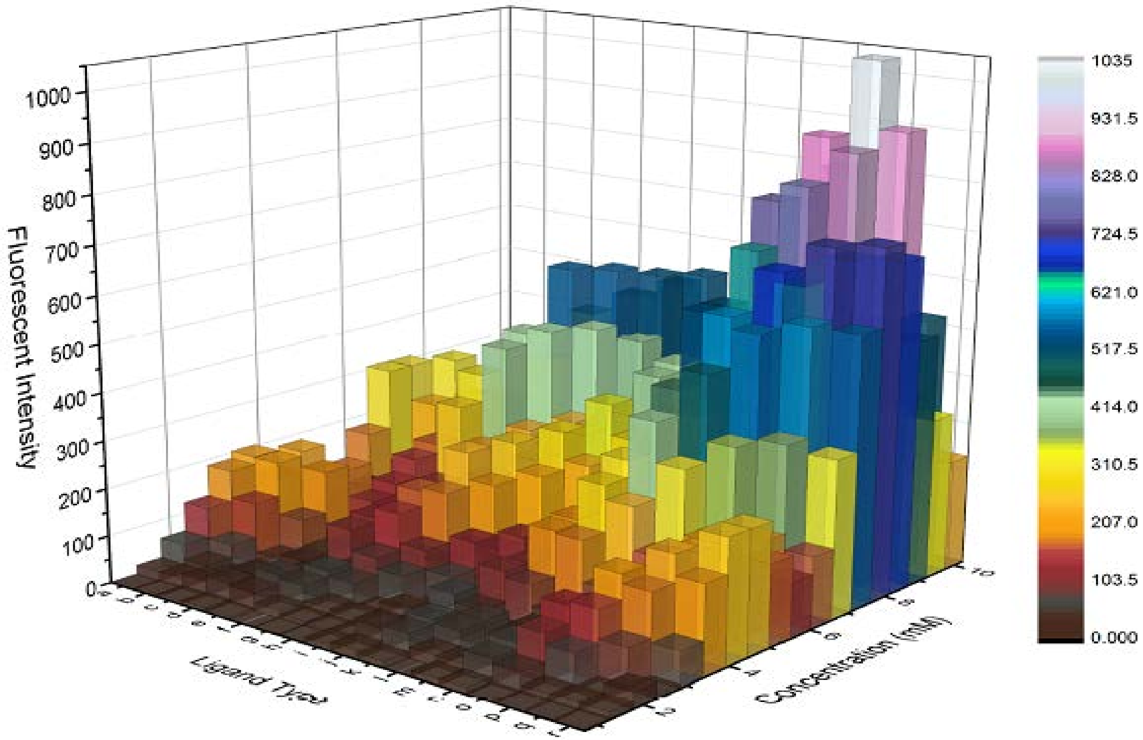
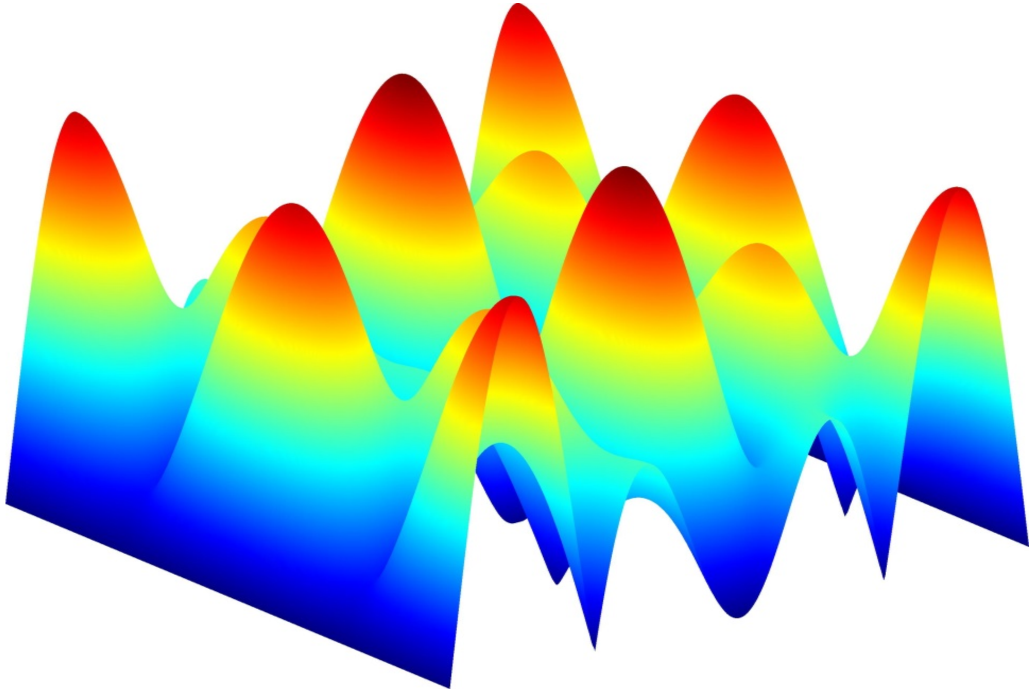




Can we store (in time) and/or transfer (in space) the supply?

If difficult, then more heterogeneous + more unpredictable → more problems

Ultra-Agile Infrastructure for Wireless Super-Connectivity

Previous work in VTC 2016

- Find the minimum number of drone-BSs and their 3D placement so that users with high data rates are served. *

$$\min_{x_j, y_j, h_j} \sum_{j=1}^{N_{BS}} \epsilon_j$$

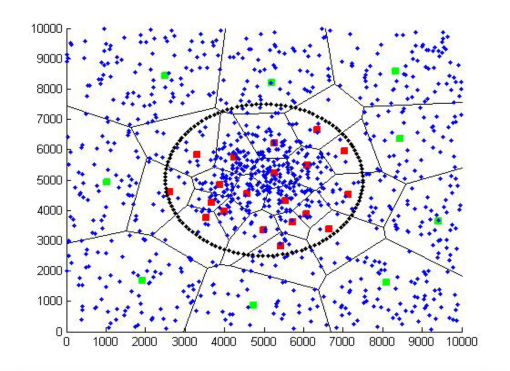
Subject to:

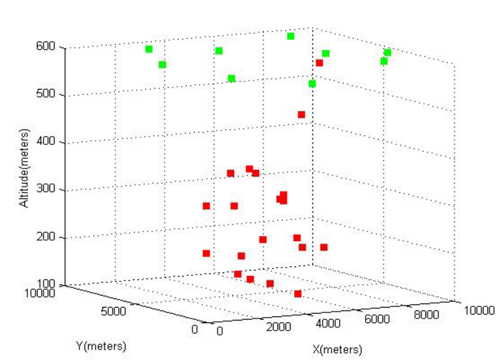
$$\sum_{j=1}^{N_{BS}} N_{U_{BS}} \rho_{j,k} \geq D_k S_k, \forall k = 1, \ldots, N_{subarea}$$

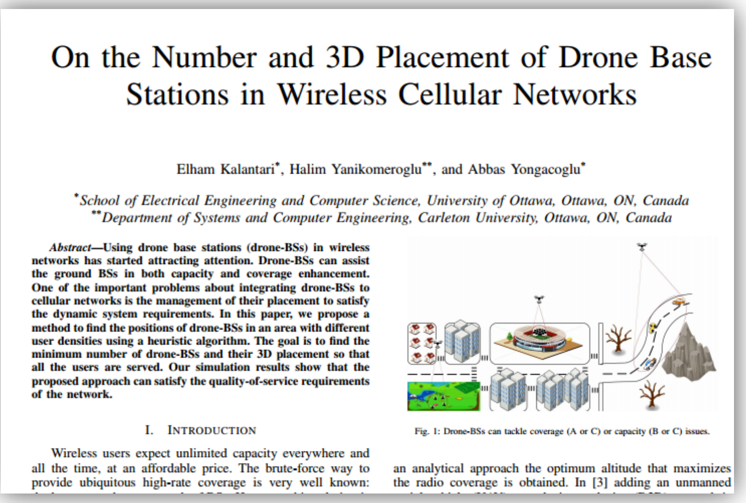
$$\sum_{i=1}^{N_U} \gamma_i \geq \zeta N_U$$

$$\frac{1}{\mathsf{E}\{\frac{1}{\eta_i}\}} \geq \eta$$

$$\epsilon_j = \begin{cases} 1, & \text{if drone-BS } j \text{ is used,} \\ 0, & \text{if drone-BS } j \text{ is redundant.} \end{cases}$$







On the Number and 3D Placement of Drone Base Stations in Wireless Cellular Networks

Elham Kalantari*, Halim Yanikomeroglu**, and Abbas Yongacoglu*

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**Department of Systems and Computer Engineering, Carleton University, Ottawa, ON, Canada

Abstract—Using drone base stations (drone-BSs) in wireless networks has started attracting attention. Drone-BSs can assist the ground BSs in both capacity and coverage enhancement. One of the important problems about integrating drone-BSs to cellular networks is the management of their placement to satisfy the dynamic system requirements. In this paper, we propose a method to find the positions of drone-BSs in an area with different user densities using a heuristic algorithm. The goal is to find the minimum number of drone-BSs and their 3D placement so that all the users are served. Our simulation results show that the proposed approach can satisfy the quality-of-service requirements of the network.

Fig. 1: Drone-BSs can tackle coverage (A or C) or capacity (B or C) issues.

I. Introduction

Wireless users expect unlimited capacity everywhere and all the time, at an affordable price. The brute-force way to provide ubiquitous high-rate coverage is very well known:

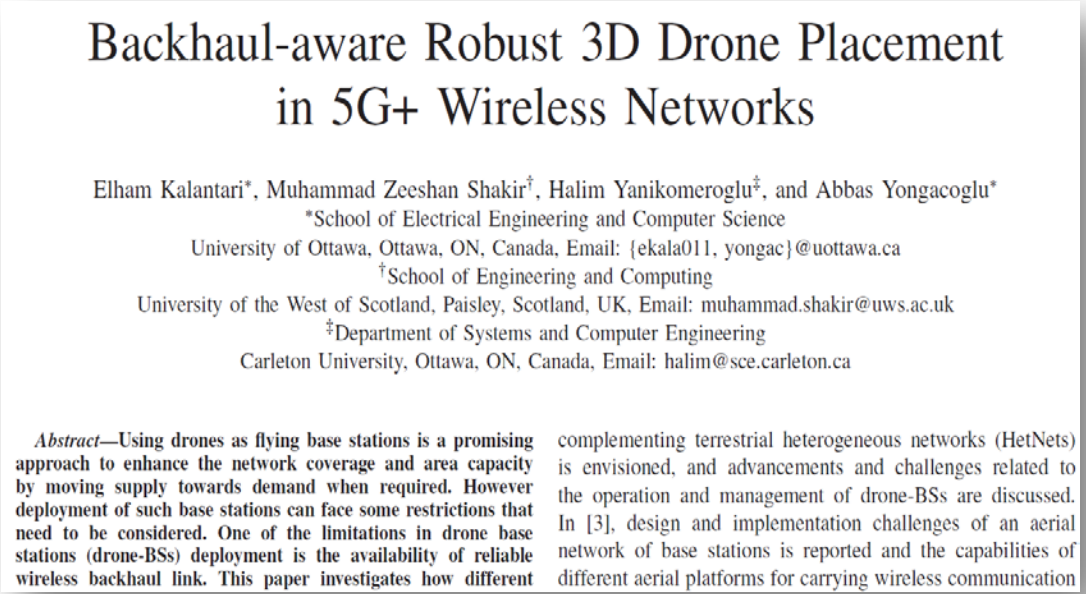
an analytical approach the optimum altitude that maximizes the radio coverage is obtained. In [3] adding an unmanned

- Drone-BSs can change their altitudes in order to tackle coverage and capacity issues. A drone-BS decreases its altitude in a dense area to reduce interference to the users that are not served by it and increases its altitude to cover a large area in a low density region.

* Elham Kalantari, Halim Yanikomeroglu, and Abbas Yongacoglu, "On the number and 3D placement of drone base stations in wireless cellular networks", *IEEE Vehicular Technology Conference* (*VTC2016-Fall*), 18–21 September 2016, Montreal, QC, Canada.

Previous work in ICC 2017

- Backhaul constraint is an important limitation in drone-BSs deployment.
- A drone-BS should have a wireless backhaul; therefore, the peak data rate a drone-BS can support is limited and it may dramatically decrease due to inclement weather conditions especially if the link is based on the FSO or mmWave technology.



Backhaul-aware Robust 3D Drone Placement in 5G+ Wireless Networks

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Abstract—Using drones as flying base stations is a promising approach to enhance the network coverage and area capacity by moving supply towards demand when required. However deployment of such base stations can face some restrictions that need to be considered. One of the limitations in drone base stations (drone-BSs) deployment is the availability of reliable wireless backhaul link. This paper investigates how different

complementing terrestrial heterogeneous networks (HetNets) is envisioned, and advancements and challenges related to the operation and management of drone-BSs are discussed. In [3], design and implementation challenges of an aerial network of base stations is reported and the capabilities of different aerial platforms for carrying wireless communication

- Find the maximum number of weighted users so that the bandwidth, backhaul, and coverage constraints are satisfied for different rate requirements in a clustered user distribution.*

* Elham Kalantari, Muhammad Zeeshan Shakir, Halim Yanikomeroglu, and Abbas Yongacoglu, "Backhaul-aware robust 3D drone placement in 5G+ wireless networks", IEEE International Conference on Communications (ICC) 2017 – Workshop on Flexible Networks (FlexNets), 21 May 2017, Paris, France.

Previous work in ICC 2017

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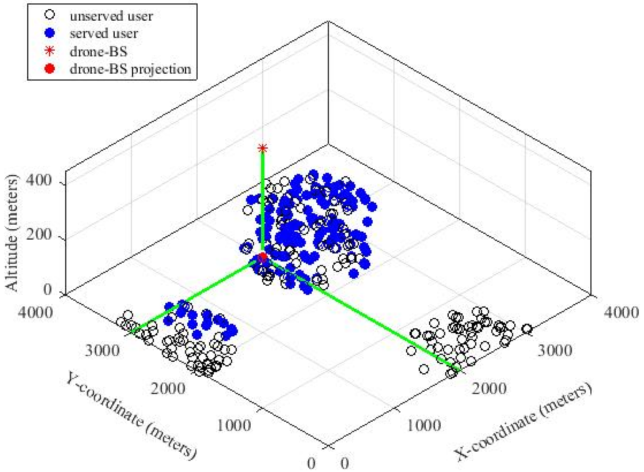
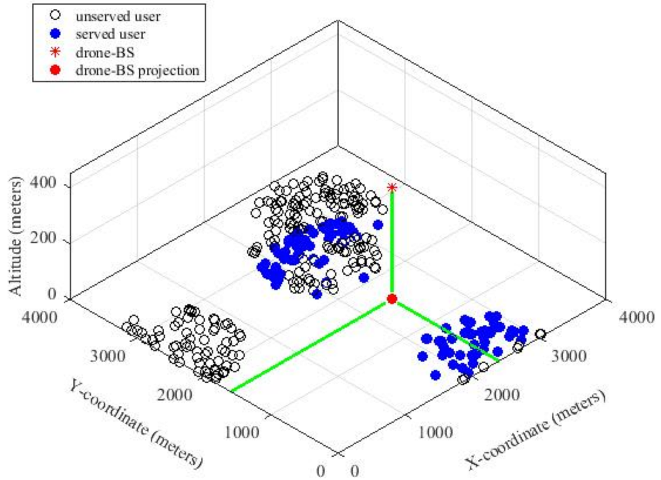
$$\max_{x,y,h,\{I_i\}} \sum_{i=1}^{N_U} \alpha_i \cdot I_i$$

Subject to:

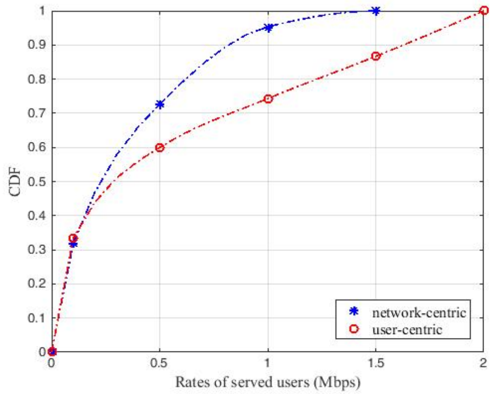
$$
\begin{aligned}
\sum_{i=1}^{N_U} r_i \cdot I_i &\leq R \\
\sum_{i=1}^{N_U} b_i \cdot I_i &\leq B \\
\mathrm{PL}_i \cdot I_i &\leq \mathrm{PL}_{\max}, \quad \forall i \\
x_{min} &\leq x \leq x_{max} \\
y_{min} &\leq y \leq y_{max} \\
h_{min} &\leq h \leq h_{max} \\
I_i &\in \{0,1\}, \quad \forall i
\end{aligned}
$$

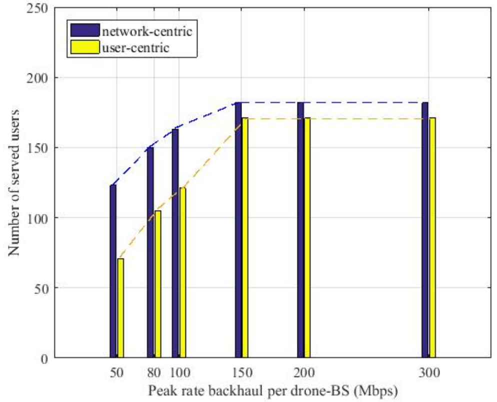


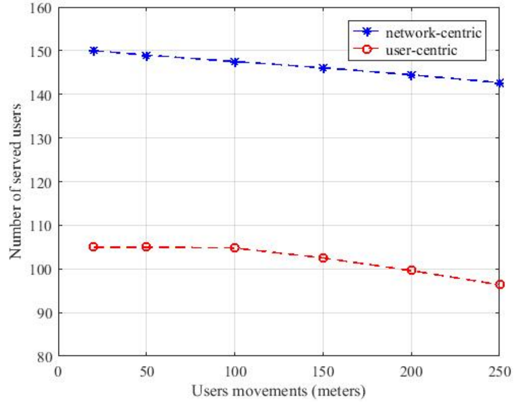
network-centric



user-centric







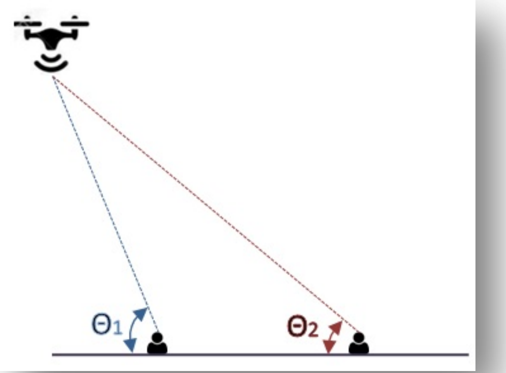
Air-to-Ground Channel Model

$$\text{PL (dB)} = \text{FSPL} + \boxed{\psi_i}$$

Excessive pathloss due to LoS or NLoS channel between TX and RX

$$\psi_i = \mathcal{N}(\eta_i, \sigma_i^2), i = \{\text{LoS}, \text{NLoS}\}$$

η_i and σ_i are Frequency- and environment dependant parameters.

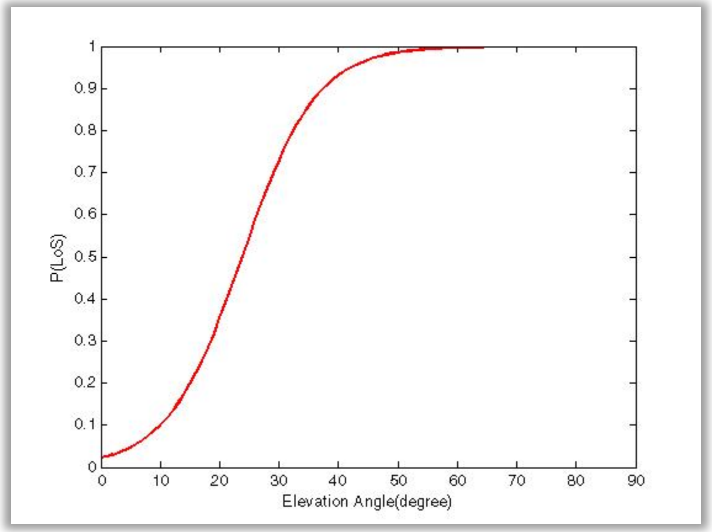


$$\theta_1 \geq \theta_2 \Rightarrow P(\text{LoS})_{\theta_1} \geq P(\text{LoS})_{\theta_2}$$

Probability of LoS:

$$P(\text{LoS}) = \frac{1}{1 + a\exp(-b(\theta - a))}$$

- P(LoS) increases as the elevation angle is increased.



- A. Al-Hourani, S. Kandeepan, and A. Jamalipour, “Modeling air-to-ground path loss for low altitude platforms in urban environments,” in IEEE Global Communications Conference (GLOBECOM), Dec 2014, pp. 2898–2904.
- 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.

Air-to-Ground Channel Model

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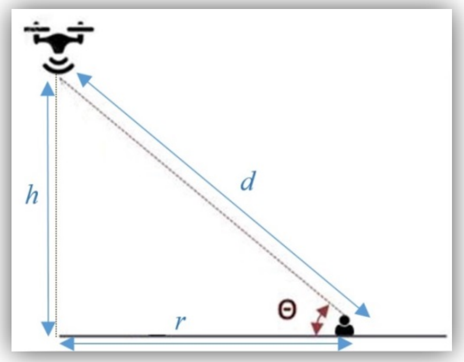
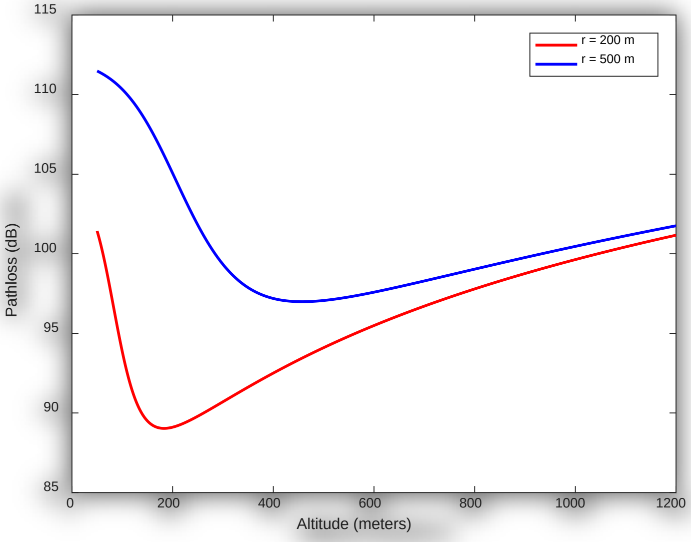
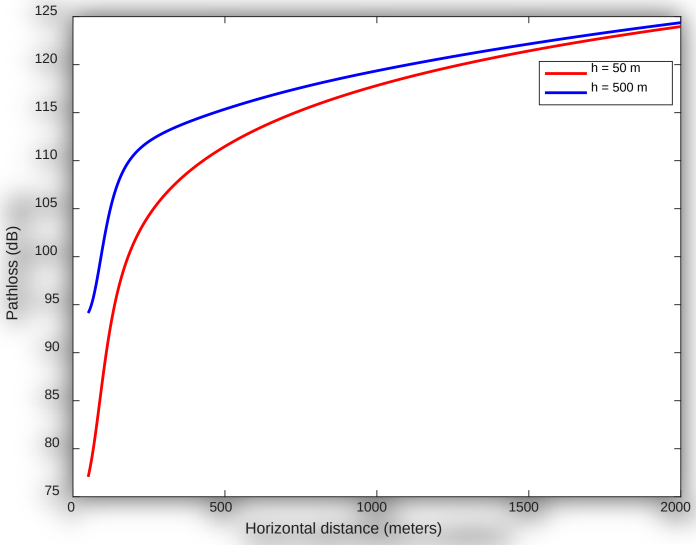
$$\mathrm{PL(dB)} = 20\log\left(\frac{4\pi f_c d}{c}\right) + \psi_i$$







Problem Definition

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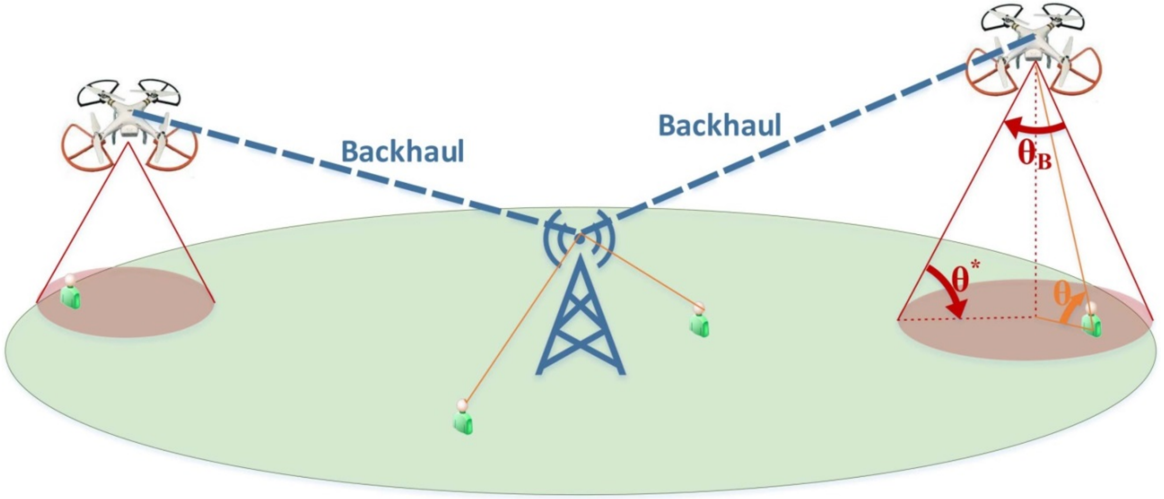
- We assume downlink wireless HetNet including two tiers of BSs, an MBS and a number of DBSs.
- Wireless Backhaul is not fixed unlike the previous work. In-band wireless backhaul is employed for DBSs and the MBS is utilized as a hub to connect DBSs to the network.



ITU classifications of 5G services:

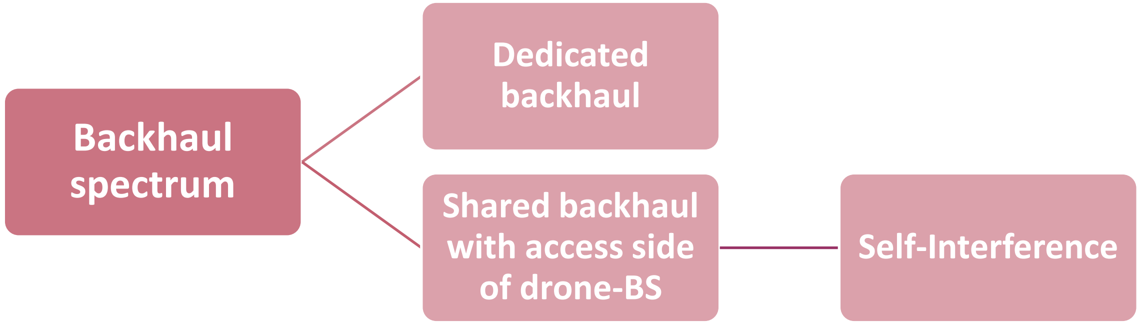
- Enhanced mobile broadband (eMBB),
- Massive machine-type communications (mMTC),
- Ultra reliable and low latency communications (uRLLC).

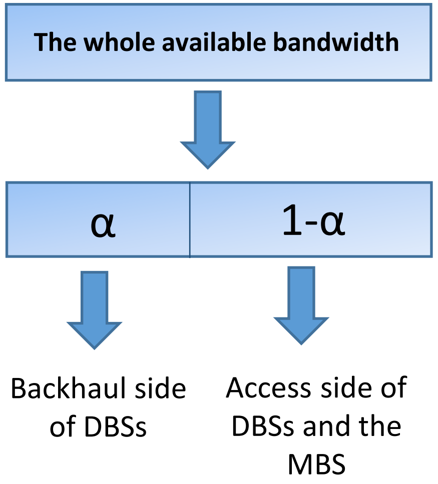
- URLLC users with delay-sensitive applications co-exist with regular eMBB users.

The mobility of the DBSs and different types of users require that the following key issues are considered to provide wireless services efficiently:

- Finding the locations of DBSs,
- Determining the user-BS associations with consideration to user type,
- Bandwidth allocation for access and backhaul links.

Bandwidth allocation





- To avoid self-interference, orthogonal frequency channels in the backhaul and access side of the DBSs is employed.
- Bandwidth is shared between the access side of the MBS and DBSs.

Problem Constraints

$$\sum_{j\in\mathcal{J}} x_{ij} = 1, \forall i \in \mathcal{I}$$

Association with only one BS

$$\sum_{i\in\mathcal{I}} x_{ij} \cdot y_{ij} \leq 1-\alpha, \forall j \in \mathcal{J}$$

Total available bandwidth

$$\sum_{i\in\mathcal{I}} R_{ij} \leq C_j, \forall j \in \mathcal{J}\backslash 0$$

Backhaul constraint for DBSs

$$\sum_{j\in\mathcal{J}\backslash 0} x_{ij} \leq 1-\tau_i, \forall i \in \mathcal{I}$$

$$\tau_i \in \{0,1\}$$

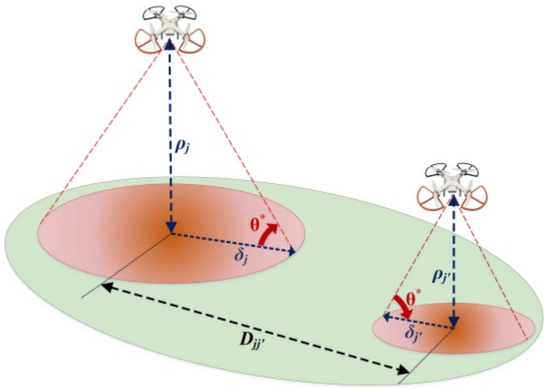
Delay-sensitive and delay-tolerant users

$$x_{ij} \cdot (\theta_{ij} - \theta^*) \geq 0, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}\backslash 0$$

The DBS user should be in coverage footprint of the DBS

$$D_{jj'} > \frac{\rho_j + \rho_{j'}}{\tan(\theta^*)}, \forall j, j' \in \mathcal{J}\backslash 0$$

Minimum distance to avoid interference



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Problem Formulation

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$$\max_{\{l_{j\in\mathcal{J}\setminus 0}\},\{x_{ij}\},\{y_{ij}\},\{\alpha\}} \sum_{i\in\mathcal{I}} U(R_i)$$

Subject to:

$$\sum_{j\in\mathcal{J}} x_{ij} = 1, \forall i \in \mathcal{I},$$

$$\sum_{i\in\mathcal{I}} x_{ij}\cdot y_{ij} \leq 1-\alpha, \forall j \in \mathcal{J},$$

$$\sum_{i\in\mathcal{I}} x_{ij}\cdot y_{ij}\cdot r_{ij} \leq \alpha\cdot r_{j0}, \forall j \in \mathcal{J}\setminus 0,$$

$$\sum_{j\in\mathcal{J}\setminus 0} x_{ij} \leq 1-\tau_i, \forall i \in \mathcal{I},$$

$$x_{ij}\cdot(\theta_{ij}-\theta^*) \geq 0, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}\setminus 0,$$

$$D_{jj'} \geq \frac{\rho_j+\rho_{j'}}{\tan(\theta^*)}, \forall j, j' \in \mathcal{J}\setminus 0, j\neq j',$$

$$x_{ij} \in \{0,1\},$$

$$\alpha \in [0,1],$$

$$y_{ij} \in [0, 1-\alpha].$$

- Logarithmic utility function is assumed to consider fairness; therefore,

$$U(R_i) = \log R_i$$

- Equal resource allocation is the optimal allocation for the logarithmic utility; therefore,

$$y_{ij} = \frac{1-\alpha}{\sum_{k\in\mathcal{I}} x_{kj}}$$

Proposed algorithm

The procedure includes three main processes:

1- The user-BS association problem can be written as a convex sub problem for a fixed α and locations of DBSs.

$$\max_{\{x_{ij}\}} \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} x_{ij} \log \frac{r_{ij}\cdot(1-\alpha)}{\sum_{k\in\mathcal{I}} x_{kj}}$$

subject to:

$$\sum_{j\in\mathcal{J}} x_{ij} = 1, \forall i \in \mathcal{I},$$

$$\sum_{i\in\mathcal{I}} x_{ij} \cdot \frac{1-\alpha}{\sum_{k\in\mathcal{I}} x_{kj}} \cdot r_{ij} \le \alpha \cdot r_{j0}, \forall j \in \mathcal{J}\backslash 0,$$

$$\sum_{j\in\mathcal{J}\backslash 0} x_{ij} \le 1-\tau_i, \forall i \in \mathcal{I},$$

$$x_{ij}\cdot(\theta_{ij}-\theta^*) \ge 0, \forall i \in \mathcal{I}, \forall j \in \mathcal{J}\backslash 0,$$

$$x_{ij} \in [0,1].$$

(a)

2- For fixed x_{ij}s (after rounding them), the convex master problem that finds α can be solved.

$$\max_{\alpha} \log(1-\alpha)$$

Subject to:

$$\sum_{i\in\mathcal{I}} x_{ij} \cdot \frac{1-\alpha}{\sum_{k\in\mathcal{I}} x_{kj}} \cdot r_{ij} \le \alpha \cdot r_{j0}, \forall j \in \mathcal{J}\backslash 0,$$

$$\alpha \in [0,1].$$

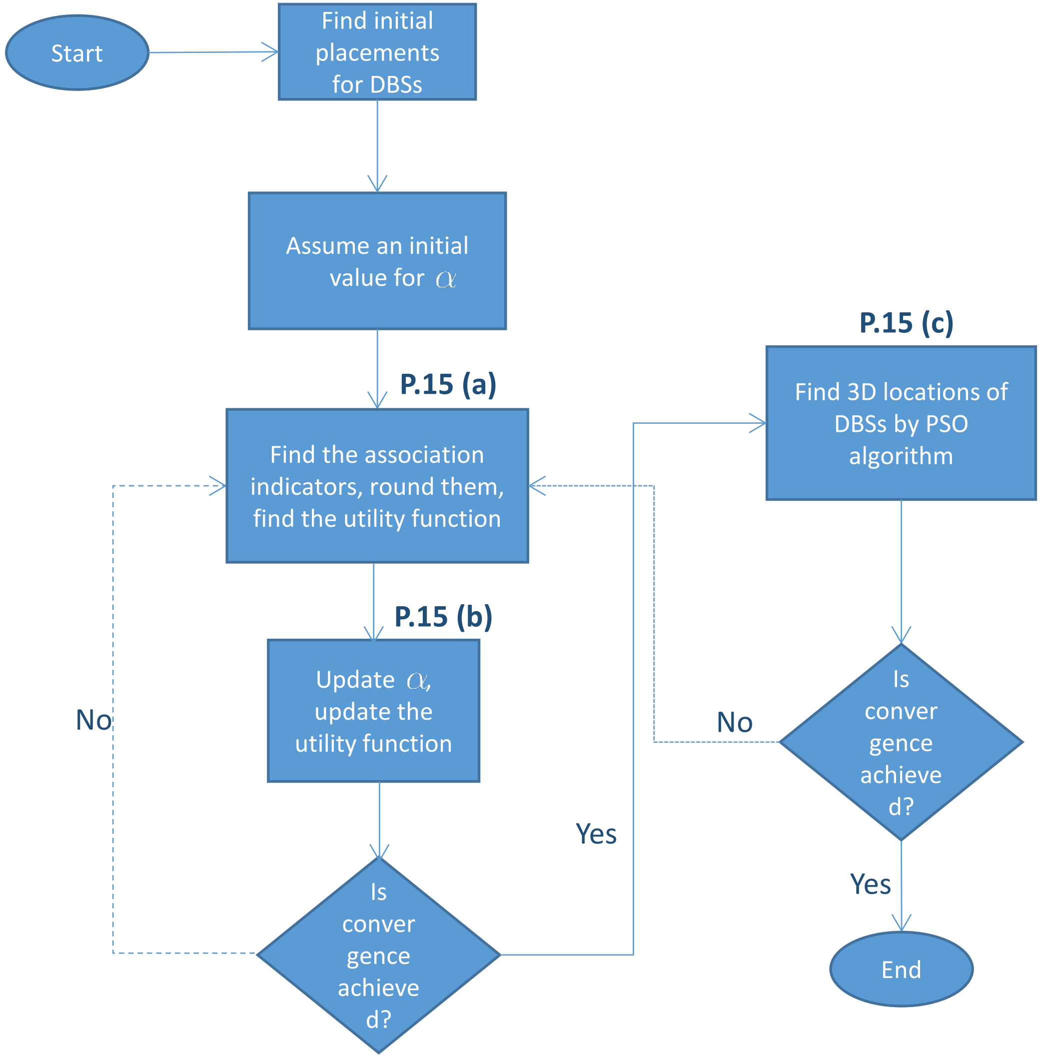
(b)

3- Locations of DBSs are updated using PSO algorithm.

$$\max \sum_{i\in\mathcal{I}} \sum_{j\in\mathcal{J}} x_{ij} \log \frac{r_{ij}\cdot(1-\alpha)}{\sum_{k\in\mathcal{I}} x_{kj}} - \sum_{j,j'\in\mathcal{J}\backslash 0, j\neq j'} \Big(\tan(\theta^*)\cdot D_{jj'} - \rho_j - \rho_{j'}\Big) - \sum_{j\in\mathcal{J}\backslash 0} \Big(\alpha\cdot r_{j0} - \sum_{i\in\mathcal{I}} x_{ij}\cdot\frac{(1-\alpha)\cdot r_{ij}}{\sum_{k\in\mathcal{I}} x_{kj}} - \sum_{i\in\mathcal{I}} x_{ij}\cdot(\theta_{ij}-\theta^*)\Big)$$

(c)

Flowchart for the proposed algorithm



Algorithm 1 Finds 3D locations of DBSs, user-BS association and bandwidth allocation for access and backhaul of DBSs.

Inputs: Users' locations, number of DBSs.
Initialization: Cluster the users based on the number of DBSs using k-means clustering. Assume the initial location of DBSs is the center of the clusters. Set $t = 1$, $m(t) = U(t) - U(t-1)$, $t' = 1$, $n(t') = U(t') - U(t'-1)$; define $\alpha(1) = a$, $m(1) = n(1) = M$, where M is a big number. ν and ϵ are small positive numbers.
while $n(t') \geq \nu$ **do**
  while $m(t) \geq \epsilon$ **do**
    Find $x_{ij}(t), U(t)$. Round $x_{ij}(t)$.
    $t = t + 1$.
    Find $\alpha(t), U(t)$.
  end while
  Find $U(t')$.
  $t' = t' + 1$.
  Update the 3D locations of DBSs using PSO algorithm. Find $U(t')$.
end while

Simulation Assumptions

Parameter	Value	Parameter	Value
f_c	2 GHz	Noise power spectral density	-174 dBm/Hz
P_0	46 dBm	$P_j, \forall j \in \mathcal{J}\backslash 0$	36 dBm
$h_{\max}$	500 m	System Bandwidth	10 MHz
P{delay-sensitive, delay-tolerant}	$\{0.2, 0.8\}$	2D area	250000 m^2
number of DBSs	3	User distribution	*Matérn*

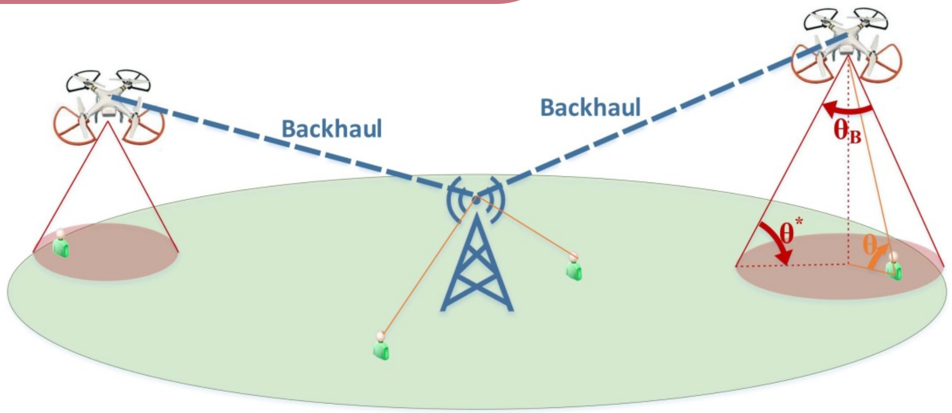
Antenna gain for drone-BSs:

$$G = \begin{cases} G_0, -\frac{\theta_B}{2} \leq \phi \leq \frac{\theta_B}{2}, \\ g(\phi), \text{otherwise.} \end{cases}$$

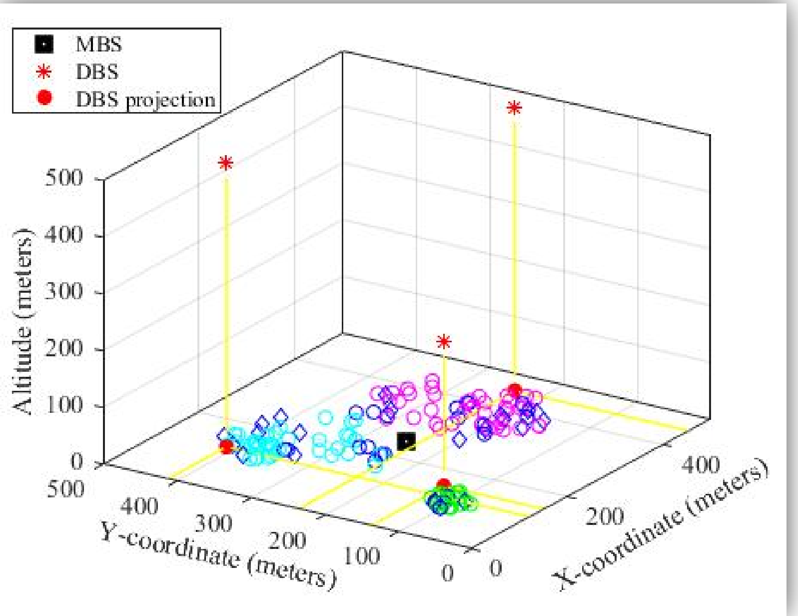
$$|\phi| = 90 - \theta$$

θ_B : the DBS directional antenna's half-power beamwidth

$G_0 \approx \frac{30{,}000}{\theta_B^2}$: the maximum gain of the directional antenna



Simulation Results

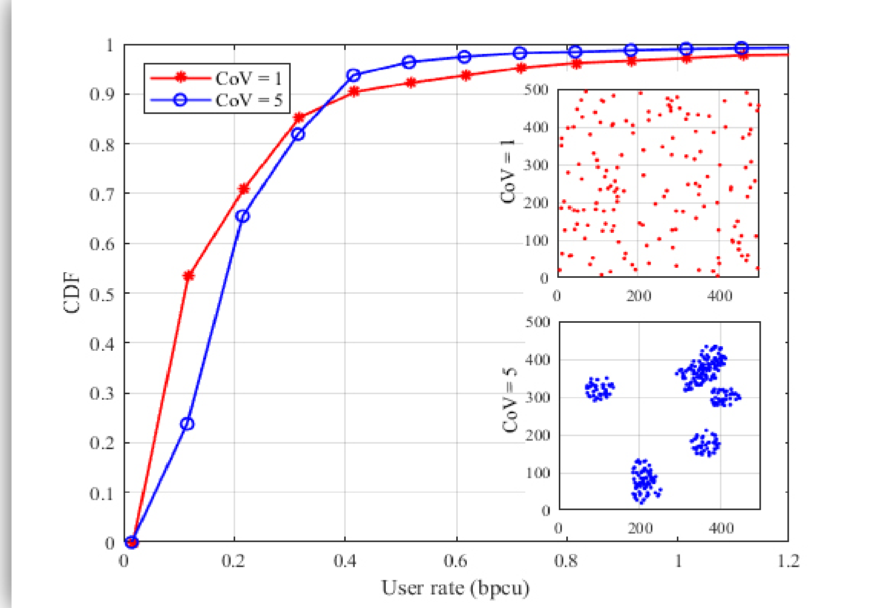


The heterogeneity of the users distribution is measured by the coefficient of variation (CoV) of the Voronoi area of the users.

$$\mathrm{CoV} = \frac{1}{0.529}\frac{\sigma_V}{\mu_V}$$

σ_V and μ_V are the standard deviation and the mean of the Voronoi tessellation areas of the users, respectively.

CoV=1 corresponds to the Poisson point process.
CoV>1 represents clustered distribution of the users.



In a more clustered distribution, the probability that each user receives a higher rate increases. This confirms that the proposed algorithm can increase the performance of the cellular network in terms of users' satisfactions in more clustered distributions.

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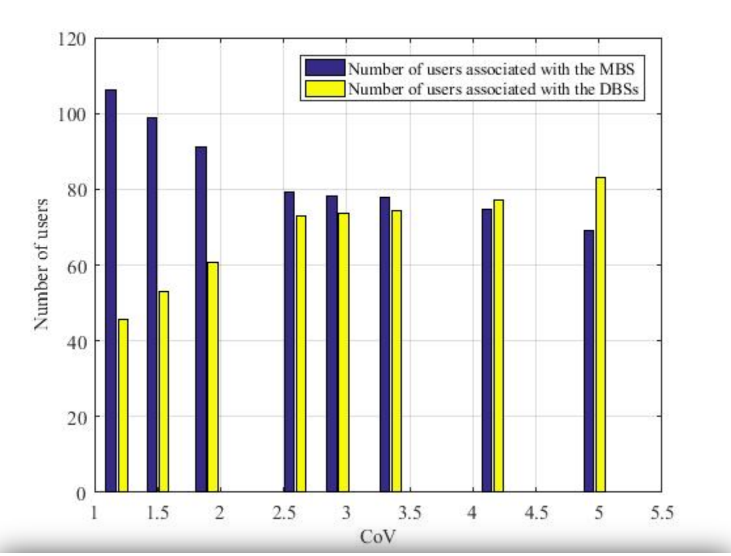
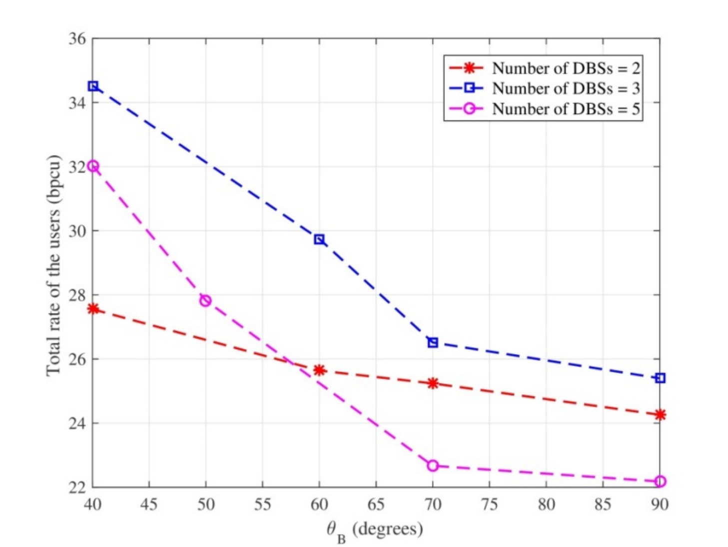


By increasing the CoV, more users could be associated with the DBSs which results in better load balancing in the system.



Increasing θB, increases the maximum possible coverage area. However, it also increases *D,* which means that to prevent overlapping, DBSs have to keep a larger distance between each other. Hence, the total capacity of users decreases, although the coverage radius increases with increasing θB.

The effect of θB becomes more severe as the number of utilized DBSs increases. Therefore, it is necessary to develop efficient interference cancellation methods for dense deployments of DBSs, since preventing overlaps between DBSs causes significant performance loss.

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Conclusion

- ✓ Delay-sensitive users are associated with the MBS, while delay-tolerant users can be associated with either one of the BSs.
- ✓ As all the DBSs share the same bandwidth, using directional antennas is proposed to relieve the effect of the interference.
- ✓ User-BS association and wireless backhaul bandwidth allocation are found through a decomposition method and the locations of DBSs are updated using a PSO algorithm.
- ✓ Further insights is obtained on the effects of CoV and halfpower beamwidth by simulations.
- ✓ The results show that utilizing DBSs in cases where the users are clustered can increase total rate of the users associated with DBSs, despite depleting the resources.
- ✓ In order to prevent interference, overlaps of coverage areas of different DBSs are not allowed. However, the half-power beamwidth should be chosen carefully for these scenarios, as the results show that increasing the beamwidth can decrease total rate by preventing DBSs to be deployed in beneficial locations.

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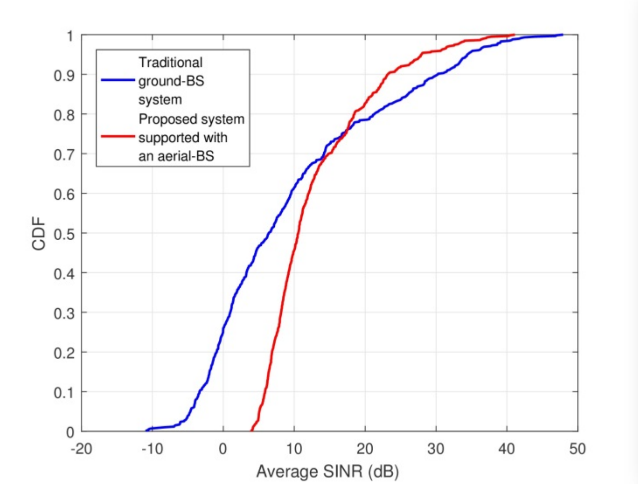
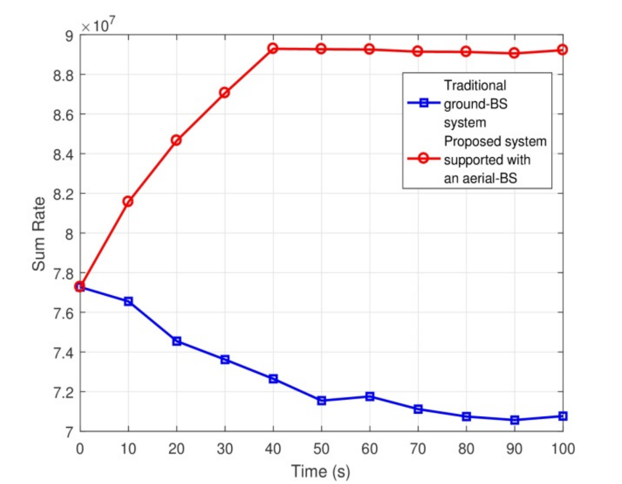
- ✓ Find 3D location of a drone-BS while the users move base on Reinforcement learning method.
- ✓ This method can bring much higher QoS to the network considering users' movements.
- ✓ After giving the agent sufficient time to learn the environment, the processing time to find the optimum position of the drone-BS becomes really low; therefore, it is a promising approach that can keep the agility and flexibility of the future wireless networks.





Efficient 3D Aerial Base Station Placement Considering Users Mobility by Reinforcement Learning

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***Abstract*—Aerial base stations (aerial-BSs), such as drones, can make enhancement in coverage and capacity of the wireless networks. Finding the best placement to gain the maximum performance from adding an aerial-BS to the existing network is essential for its usage. Users' movements make the problem more complicated as their movements change network dynamically and affect the provided quality of service (QoS) of wireless network. This effect is not negligible and cannot be ignored. This paper studies the problem of finding the optimum position of an aerial-BS taking into account the mobility of users in the network. We present a novel approach to maintain and increase the QoS of wireless network with adding an aerial-BS to the system, when there is an unexpected change in the network due to the mobility of users. To this end, we need an algorithm which can rely on more general and realistic assumptions and can decide where to go based on the past experiences. The proposed approach for this goal is based on a discounted reward reinforcement learning which is known as Q-learning. Furthermore, we assume that for adding an aerial-BS to the network, we need to turn a ground-BS off to decrease the power consumption. Simulation results show this method provides an effective placement strategy which increases the QoS of wireless networks when it is needed and promises to find the optimum position of the aerial-BS in discrete environments.**

A. Related Work

Use of aerial-BSs in wireless networks has gained attention in recent years. They may offer the most suitable way to enhance the QoS of the system in the next generation of wireless networks. In [1], a novel approach for serving a number of users while using minimum number of aerial-BSs along with finding an efficient 3D placement is proposed. In [2], a backhaul aware 3D placement of an aerial-BS for various network design parameters is discussed. In [3], an aerial-BS is positioned with the use of numerical methods to maximize the number of served user. In [4], a free space optical link is proposed as a method to provide backhaul/fronthaul access for network flying platforms. In [5], the optimal placement of an aerial-BS to maximize the number of users served with minimum transmit power is discussed. In [6], considering delay-tolerant and delay-sensitive users, an algorithm is proposed to find efficient 3D locations of aerial-BSs. The algorithm also investigates the user-BS associations and wireless backhaul bandwidth allocations to maximize the sum logarithmic rate of the users in a heterogeneous network including a macro BS

I. Bor-Yaliniz, HA. El-Keyi, Yanikomeroglu, "Spatial configuration of agile wireless networks with drone-BSs and user-iin-the-loop", under review in *IEEE Transactions on Wireless Communications,* 2017.

F. Lagum, I. Bor-Yaliniz, H. Yanikomeroglu, "Strategic densificationn with UAV-BSs for cellular networks", under review in *IEEE Wireless Communications Letters,* 2017.

S. Andreev, V. Petrov, M. Dohler, H. Yanikomeroglu, "Future of ultra-dense networks beyond 5G: Harnessing heterogeneous moving cells", under review in *IEEE Communications Magazine,* 2017.

I. Bor-Yaliniz, S.S. Szyszkowicz, H. Yanikomeroglu, "Environment aware drone-base-station placements in modern metropolitans", under review in *IEEE Wireless Communications Letters,* 2017.

M. Alzenad, M.Z. Shakir, H. Yanikomeroglu, M.-S. Alouini, "FSO-based vertical backhaul/fronthaul framework for 5G+ wireless networks", under review in *IEEE Communications Magazine,* 2017.

M. Alzenad, A. El-Keyi, H. Yanikomeroglu, "3D placement of an unmanned aerial vehicle BS for maximum coverage of users with different QoS requirements", *IEEE Wireless Commun Letters,* 2017.

M. Alzenad, A. El-Keyi, F. Lagum, H. Yanikomeroglu, "3D placement of unmanned aerial vehicle base station (UAV-BS) for energy-efficient maximal coverage", *IEEE Wireless Communications Letters,* Aug 2017.

I. Bor-Yaliniz, H. Yanikomeroglu, "The new frontier in RAN heterogeneity: Multi-tier drone-cells", *IEEE Communications Magazine,* November 2016.

R. Ghanavi, E. Kalantari, M. Sabbaghian, H. Yanikomeroglu, A. Yongacoglu, "Efficient 3D aerial base station considering users mobility by reinforcement learning ", u/r in *IEEE WCNC 2018*.

M. Gapeyenko, I. Bor-Yaliniz, S. Andreev, H. Yanikomeroglu, Y. Koucheryavy, "Effect of blockage in deploying mmWave drone base stations for beyond-5G networks", u/r in *IEEE WCNC 2018*.

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

E. Kalantari, M.Z. Shakir, H. Yanikomeroglu, A. Yongacoglu, "Backhaul-aware robust 3D drone placement in 5G+ wireless networks", *IEEE ICC Workshops 2017*.

E. Kalantari, H. Yanikomeroglu, A. Yongacoglu, "On the number and 3D placement of drone base stations in wireless cellular networks", *IEEE Vehicular Technology Conference (VTC2016-Fall)*.

I. Bor Yaliniz, A. El-Keyi, H. Yanikomeroglu, "Efficient 3-D placement of an aerial base station in next generation cellular networks", *IEEE ICC 2016*.