Efficient 3-D Placement of an Aerial Base Station in Next Generation Cellular Networks

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Outline

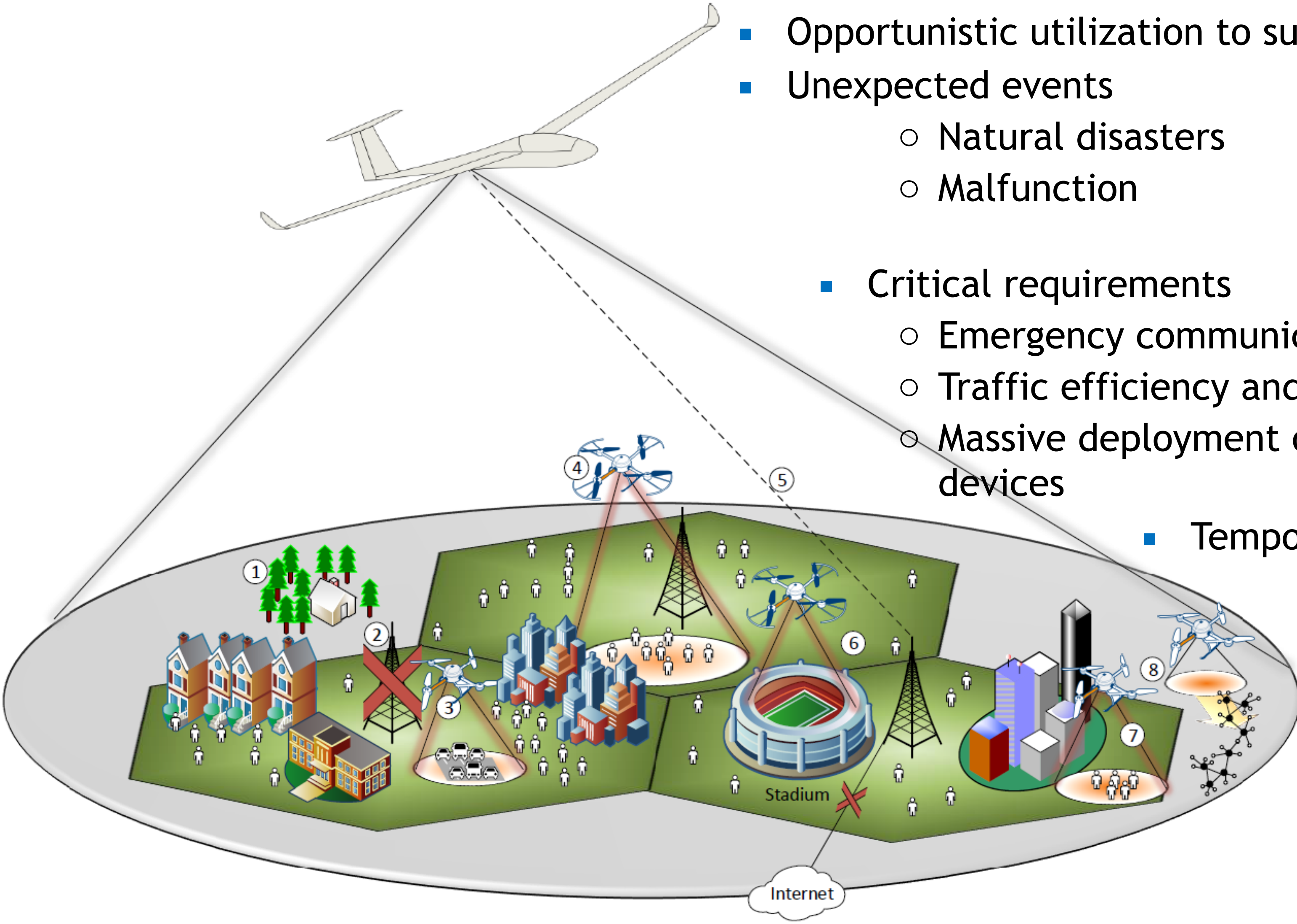
- Description
- Channel Model
  - Air-to-ground channel
  - Path loss model
- 3-D Placement
  - A use case: Congested cell offloading
  - Problem formulation
- Solution Method
- Results
- Conclusions and future work

Concept of Drone-cells as Aerial Base Stations

- Drone-BS
  - Low-altitude unmanned aerial vehicle equipped with a base station (BS)
- Drone-cell
  - Coverage area of a drone-BS
- Type
  - Unmanned aerial vehicles come in various size, payload, operating altitudes…
- Altitude
  - Lower than stratosphere, not high altitude platform (HAP)
- Differences
  - Placement: Cannot depend on long-term observations as in the case of terrestrial BSs
  - Air-to-ground channel model: Requires consideration of both horizontal and vertical locations (3-D placement)

New Frontier in RAN Heterogeneity: Multi-tier Drone-cells

- Paper under review in IEEE Communications Magazine



- Opportunistic utilization to support
- Unexpected events
  - Natural disasters
  - Malfunction
- Critical requirements
  - Emergency communications
  - Traffic efficiency and safety
  - Massive deployment of sensor type devices
- Temporary events
  - Stadium
  - Traffic jam
  - Public safety

Channel Model I – Air-to-ground Channel

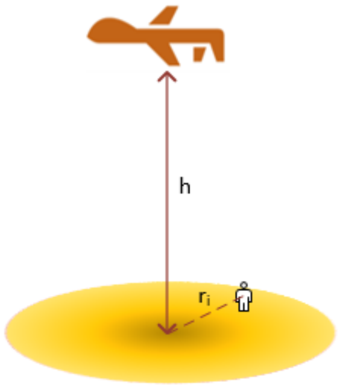
- Lack of studies compared to terrestrial channel modelling

- Probability of having line of sight

- $$P(h, r_i) = \frac{1}{1 + a \exp\left(-b\left(\arctan\left(\frac{h}{r_i}\right) - a\right)\right)}$$

Constant values depending on environment

$$r_i = \left(\sqrt{(x_i - x_D)^2 + (y_i - y_D)^2}\right)$$



[1]: Al-Hourani, A., S. Kandeepan, and S. Lardner. “Optimal LAP Altitude for Maximum Coverage.” IEEE Wireless Communications Letters 3, no. 6 (Dec. 2014).
[2]:“Propagation data and prediction methods required for the design of terrestrial broadband radio access systems operating in a frequency range from 3 to 60 GHz,” ITU-R, Tech. Rep., 2012.

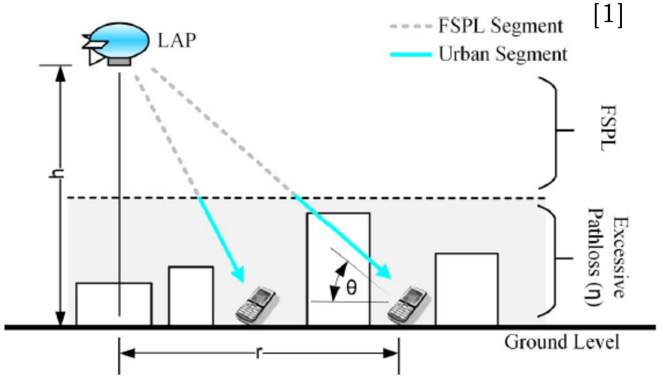
Channel Model II – Path Loss Model

- A combination of free-space path loss model (Friis Equation) with the excessive loss due to environment

$$L(h, r_i) = \underbrace{20\log\left(\frac{4\pi f_c}{c}\right) + 20\log\left(\sqrt{h^2 + r_i^2}\right)}_{\text{Free space path loss}}$$

$$+$$

$$\underbrace{P(h, r_i)\underbrace{\eta_{\mathrm{LoS}}}_{\text{LoS loss (dB)}} + (1 - P(h, r_i))\underbrace{\eta_{\mathrm{NLoS}}}_{\text{Non-LoS loss (dB)}}}_{\text{Excessive loss due to environment}}$$



[1]

[1]: Al-Hourani, A., S. Kandeepan, and S. Lardner. "Optimal LAP Altitude for Maximum Coverage." IEEE Wireless Communications Letters 3, no. 6 (December 2014).

Channel Model III – Path Loss Model

- Equivalently,
  - $$L(h, r_i) = 20\log\left(\sqrt{h^2 + r_i^2}\right) + AP(h, r_i) + B$$
    - where $\boxed{A = \eta_{\text{LoS}} - \eta_{\text{NLoS}}}$ and $\boxed{B = 20\log(\frac{4\pi f_c}{c}) + \eta_{\text{NLoS}}}$
- Note that path loss depends on both the horizontal and vertical dimensions $\rightarrow$ 3-D placement

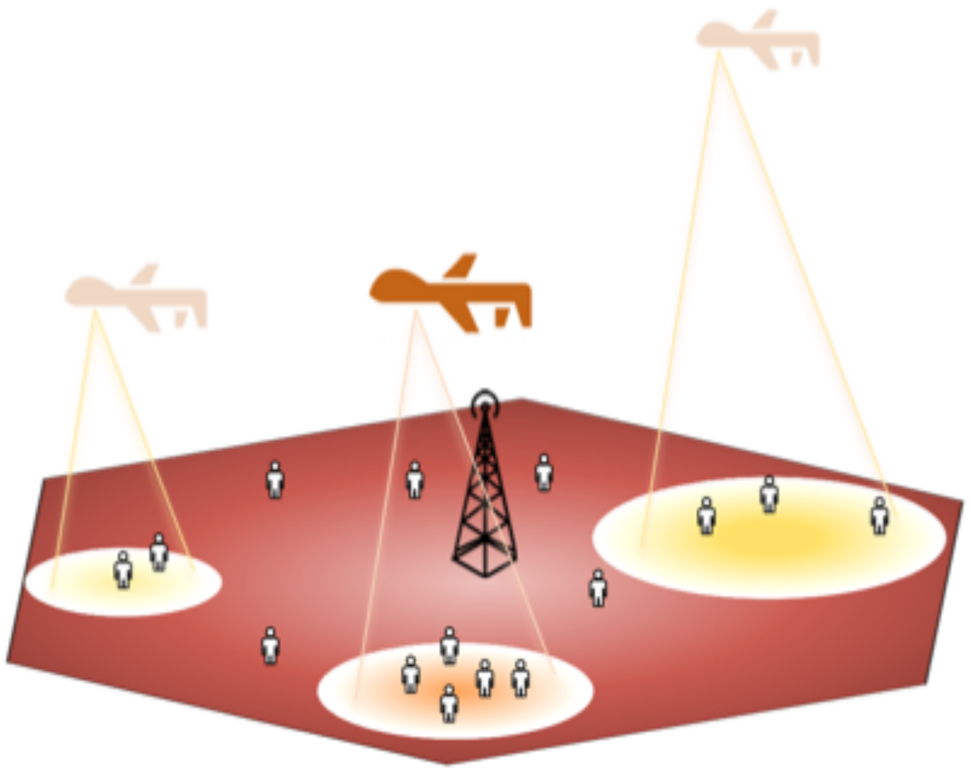
Placement Problem

- Previous studies:
  - 1-D Placement
    - Location in the horizontal plane (x and y axis) is fixed, altitude for optimum coverage is found [1]
  - 2-D Placement
    - Altitude is fixed, location in the horizontal plane is found [3]
- This work:
  - 3-D Placement
    - Introduced for the first time
    - Determining altitude in the vertical dimension, and location in the horizontal dimension jointly (based on the benefit of the network)
    - A recent study from our group [4]

[1]: Al-Hourani, A., S. Kandeepan, and S. Lardner. “Optimal LAP Altitude for Maximum Coverage.” IEEE Wireless Communications Letters 3, no. 6 (Dec. 2014).
[3]: Merwaday, A., and I. Guvenc. “UAV Assisted Heterogeneous Networks for Public Safety Communications.” In *2015 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*.
[4]: E. Kalantari, H. Yanikomeroglu, and A. Yongacoglu, “On the number and 3D placement of drone base stations in wireless cellular networks”, *IEEE Vehicular Technology Conference*, 18-21 September 2016, Montreal, QC, Canada.

Case Study: Congested Cell Offloading

- Maximum revenue varies
  - Investigated in more detail in "*New Frontier in RAN Heterogeneity: Multi-tier Drone-cells*"
  - Covering as many users as possible with drone-cell
- Only the users that cannot be served by the eNB are shown
- 3 possible placements: The coverage area, altitude and horizontal location changes



1. Drone's location in the horizontal space (x_D, y_D), and its altitude, h
   - Must be determined jointly
2. The coverage area of drone-cell is unknown
   - Depends on h
3. Drone-cell moves to wherever the demand is
   - The coverage region providing the maximum revenue to the network should be found

Efficient 3-D Placement – Analytical Steps

- The user is served if $L(h, r_i) \leq \gamma$

QoS requirement in dB

- Equivalently
  - $u_i(h^2 + r_i^2) \leq 10^{\frac{\gamma - (AP(h,r_i)+B)}{10}}$

1 if served, 0 otherwise

$$L(h, r_i) = 20 \log \left(\sqrt{h^2 + r_i^2} \right) + AP(h, r_i) + B$$

- Further manipulations
  - $h^2 + r_i^2 \leq 10^{\frac{\gamma - (AP(h,r_i)+B)}{10}} + M_1(1 - u_i)$

Larger than maximum possible value of left-hand-side

Efficient 3-D Placement Problem - I

- Accordingly the problem formulation

$$\underset{x_D, y_D, h, \{u_i\}}{\text{maximize}} \quad \sum_{i \in \mathbb{U}} u_i$$

subject to

$$h^2 + r_i^2 \leq 10^{\frac{\gamma - (AP(h, r_i) + B)}{10}} + M_1(1 - u_i), \quad \forall i \in \mathbb{U},$$

$$x_l \leq x_D \leq x_u,$$

$$y_l \leq y_D \leq y_u,$$

$$h_l \leq h \leq h_u,$$

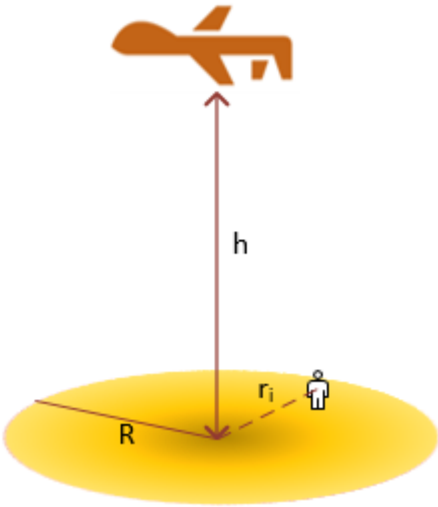
$$u_i \in \{0, 1\}, \quad \forall i \in \mathbb{U},$$

$$\boxed{P(h, r_i) = \frac{1}{1 + a \exp\left(-b\left(\arctan\left(\frac{h}{r_i}\right) - a\right)\right)}}$$

Efficient 3-D Placement Problem - II

- Let R be the radius of the coverage region of the drone-BS and introduce
  - $\alpha = \frac{h}{R}$

If user i is covered, $R \geq r_i$.



$$
\begin{aligned}
\underset{x_D, y_D, \{u_i\}, R, \alpha}{\text{maximize}} \quad & \sum_{i \in \mathbb{U}} u_i \\
\text{subject to} \quad & R^2 \leq \Gamma(\alpha) + M_1(1 - u_i), && \forall i \in \mathbb{U}, \\
& R \geq r_i - M_2(1 - u_i), && \forall i \in \mathbb{U}, \\
& x_l \leq x_D \leq x_u, \\
& y_l \leq y_D \leq y_u, \\
& R \geq 0, \\
& u_i \in \{0, 1\}, && \forall i \in \mathbb{U}.
\end{aligned}
$$

$$\Gamma(\alpha) = \frac{10^{\frac{\gamma - (AP(\alpha) + B)}{10}}}{(1 + \alpha^2)}$$

Determines the size of the feasible set

Efficient 3-D Placement Problem - III

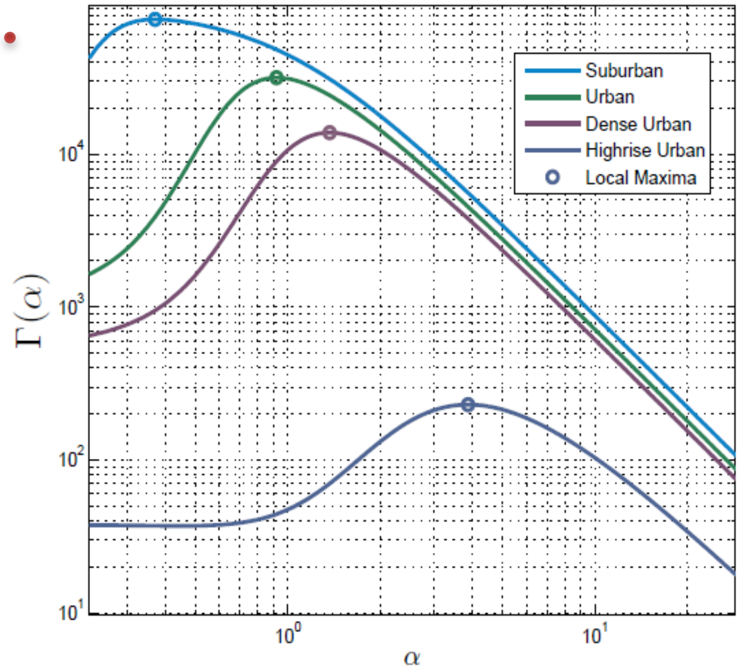


Fig. 2: $\Gamma(\alpha)$ versus α for various environments.

- TABLE I: RF Propagation Parameters of different environments

Environment	Parameters $(a, b, \eta_{\text{LoS}}, \eta_{\text{NLoS}})$
Suburban	(4.88, 0.43, 0.1, 21)
Urban	(9.61, 0.16, 1, 20)
Dense Urban	(12.08, 0.11, 1.6, 23)
High-rise Urban	(27.23, 0.08, 2.3, 34)

Algorithm 1 Bisection Search Algorithm

$N \leftarrow 0,\ \alpha_1 = 0,\ \alpha_2 = \tan(89.9^\circ)$
while $N \leq N_u$ **do**
    $\alpha_3 \leftarrow \frac{\alpha_1+\alpha_2}{2}$
    if $\left(\frac{d\Gamma(\alpha)}{d\alpha}\Big|_{\alpha=\alpha_3}\right) = 0$ **or** $(\alpha_2 - \alpha_1) \leq \epsilon$ **then**
        $\alpha^* = \alpha_3$
        break
    end if
    $N \leftarrow N + 1$
    if $\text{sign}\left(\frac{d\Gamma(\alpha)}{d\alpha}\Big|_{\alpha=\alpha_3}\right) = \text{sign}\left(\frac{d\Gamma(\alpha)}{d\alpha}\Big|_{\alpha=\alpha_1}\right)$ **then**
        $\alpha_1 = \alpha_3$
    else
        $\alpha_2 = \alpha_3$
    end if
end while

- The problem becomes a MINLP
- Efficiently solved via interior-point optimizer of MOSEK solver

Results - I

- 25 users are distributed randomly
- 3-D placement in 4 different environments
- QoS is 100 dB for all users
- Results show that based on the environment
  - Size of the drone-cell (i.e., altitude of drone-BS) changes
  - Horizontal location of the drone-BS changes
  - Users at the edge, optimum coverage for the required area

TABLE I: RF Propagation Parameters of different environments

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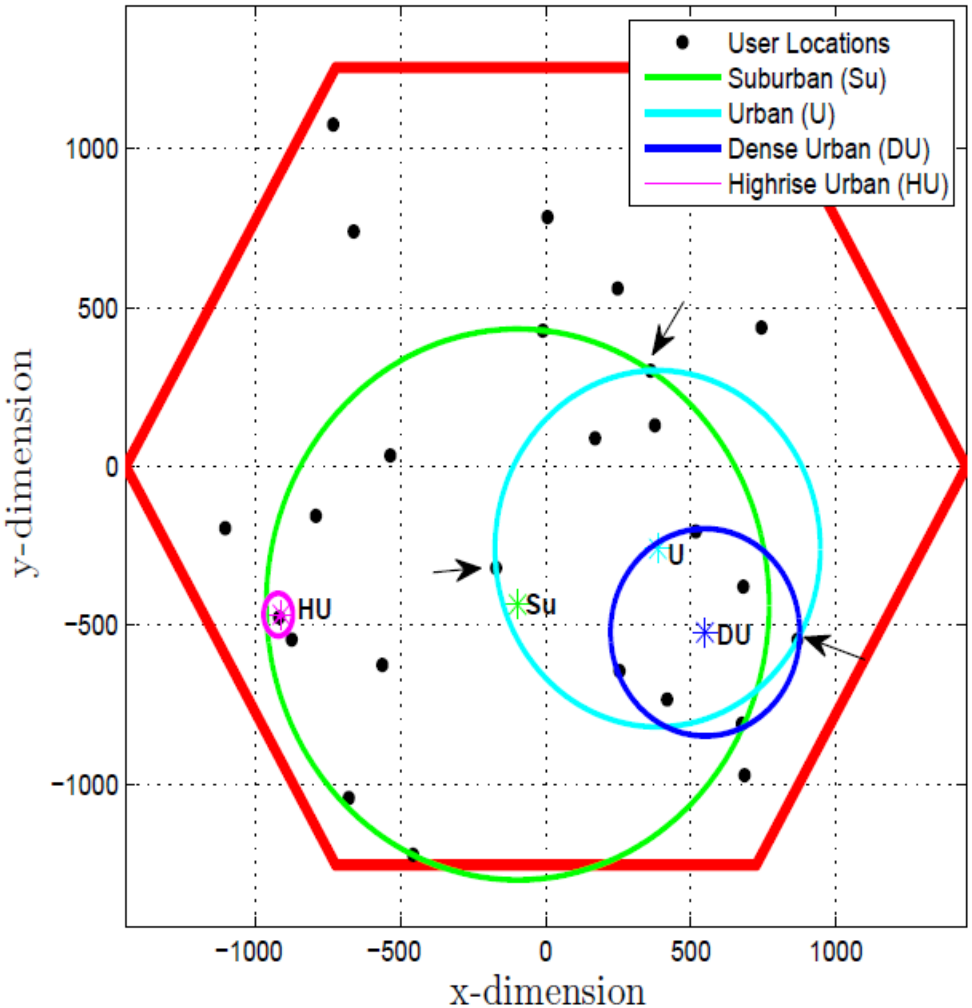
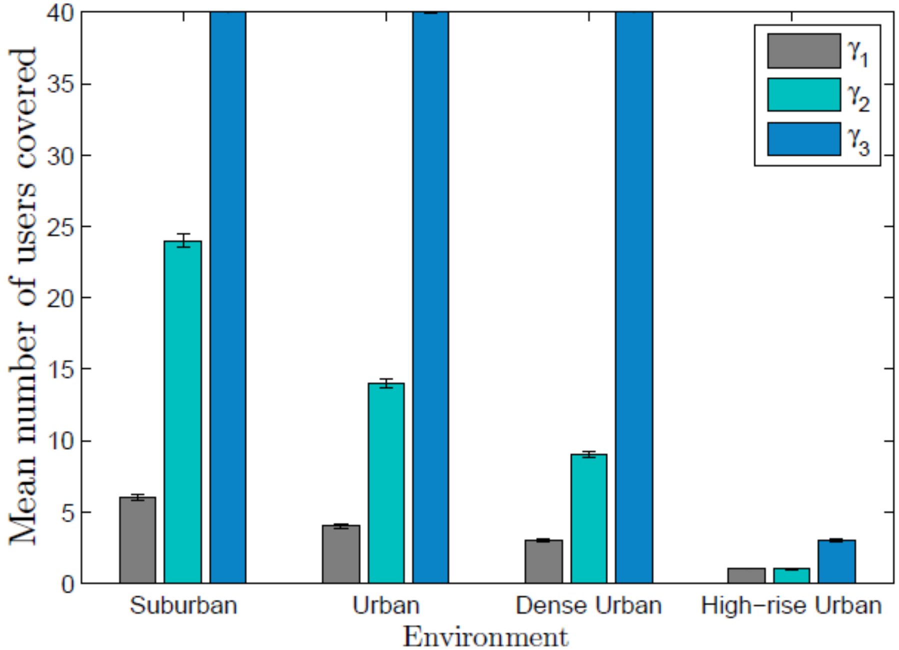


Results - II



- 100 Monte Carlo simulations in each environment, and for each γ
- 40 users are randomly distributed
- 95% confidence interval

- Results show
  - The effect of the environment and γ, e.g., suburban with 90 dB vs. high-rise urban with 125 dB maximum tolerable path loss

TABLE I: RF Propagation Parameters of different environments

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TABLE II: Simulation Parameters

Parameter	Value
(x_l, x_u)	(-1450, 1450) (m)
(y_l, y_u)	(-1258, 1258) (m)
$(\gamma_1, \gamma_2, \gamma_3)$	(90, 100, 125) (dB)
f_c	2.5 GHz
N_u	100
ϵ	10^{-5}
Monte Carlo Runs	100

Conclusions and Future Work

- Conclusions
  - Description of drone-cells and drone-BSs for future cellular networks
  - 3-D placement of a drone-BS by jointly determining horizontal and vertical locations
  - Problem formulation as a MINLP
  - Efficient solution via interior-point optimizer of MOSEK

- Future Work
  - Joint power allocation and 3-D placement of a drone-cell for users with various QoS requirements
  - Performance analysis

References

1. Al-Hourani, A., S. Kandeepan, and S. Lardner. "Optimal LAP Altitude for Maximum Coverage." IEEE Wireless Communications Letters 3, no. 6 (Dec. 2014).
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Thank you!

Questions?