Traffic-aware Dynamic Deployment for UAV-Aided Communications

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Outline

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Background

- **UAV-aided wireless communication network** can establish rapid wireless connectivity for the mobile devices that are beyond the coverage of the terrestrial communication infrastructure.
Advantages of UAV-aided communication network

- Mobility → fly and serve the local users closely;
- High altitude → more reliable air-to-ground channel (LoS Link)
**Static Network**

- **Trajectory design [1,2]**
  - Delay-tolerant systems;
  - User locations are fixed and do not change over time.

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**Random Network**

- **Stochastic geometric analysis [3-5]**
  - Model the random user locations as PPP;
  - Coverage analysis [3], optimal density[4], optimal altitude [5].

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Limitation and Motivation

- **Non-adaptive UAV deployment**
  - Current works deploy the UAVs in a probabilistic or average sense;
  - UAV’s deployment is not adaptive to the dynamic demand of the users;
  - What if we know some **side information** of users (e.g., hot spot)?
  - This requires the **traffic-award adaptive deployment**.

(a) non-adaptive UAV deployment

(b) adaptive UAV deployment
Traffic-aware Adaptive UAV deployment

- **Limited information**
  - Difficult to precisely know the exact user locations (e.g., the nearby terrestrial base stations experience congestion or failure; users are moving and their locations change over time);
  - UAV may only have some **limited side information** of user locations in a period of time (e.g., user numbers in the sub-areas).

- **How to adapt the UAV to the dynamic users?**
  - The UAV has to make two decisions:
    - Which direction to fly?
    - How far to fly?
System Model

- Two dimensional user network

- Homogeneous Poisson point process (PPP) with density $\lambda$;
- The user number $k$ in the cell follow a Poisson distribution;
- Target cell is partitioned into four equal sectors $S_1, S_2, S_3$ and $S_4$. 
Traffic-aware Adaptive UAV Deployment Scheme

- Step 1: Observation
  - For each realization, the UAV observes which sector has the largest number of users.

  ➢ Side information at the UAV:
    - Statistical information: user density $\lambda$.
    - Temporal side information: which sector has the largest number of users, e.g., $k_1 > \max(k_2, k_3, k_4)$.
Traffic-aware Adaptive UAV Deployment Scheme

- Step 2: Adaptation
  - The UAV quickly flies to one of the five candidate stop points $U = U_j$ according to “majority-vote” criteria.

\[
U = \begin{cases} 
U_j, & \text{if } k_j > \max_{i \neq j}(k_i) \\
U_0, & \text{otherwise.}
\end{cases}
\]

- Which direction to fly?
  - Move to the sector with the largest number of users
  - Due to the symmetry brought by limited information, the optimal directional is along diagonal line.

- How far to fly?
  - Displacement distance $\sqrt{2} \beta R$
  - $\beta \in [0,1]$ is the displacement factor
Traffic-aware Adaptive UAV Deployment Scheme

- Step 3: Transmission
  - The UAV transmits information to the MUs in the downlink (or collects information from the MUs in the uplink).
  - Assume no interference (broadcasting or orthogonal transmission).
Tradeoff for $\beta$ Design

- Tradeoff for the design of displacement distance

If the UAV moves into one sector, it shortens the distance from some users, which however comes at the cost of farther distance from other users.
  - Small $\beta$: cannot serve the users in sector $S_1$ efficiently;
  - Large $\beta$: the users in other sectors may suffer from more performance loss.

- How to find the optimal $\beta$ that maximizes the average throughput of all users?

- How does the user density $\lambda$ affect the optimal $\beta$?
Average Throughput

- **Typical User**
  - Since users are i.i.d., we randomly pick one user $MU_0$ (located at $(W_0, 0)$) from the $k$ users in each realization.

- **Air-to-ground channel**
  - In the sub-urban and rural areas, line-of-sight (LoS) link is usually significantly dominating over other links. We adopt the free-space path loss model, i.e.,

$$g_0 = \theta \left[ \frac{\sqrt{||W_0 - U||^2 + h^2}}{d} \right]^2$$

where $\theta$ is the channel power coefficient, $d$ is the reference distance, $h$ is the operating altitude of the UAV.

- **Two random variables:**
  - $W_0$: the location of the typical MU ($W_0 \in S_i$ has four options) — don’t know the exact user location
  - $U$: the displaced location of the UAV ($U \in U_j$ has five options)

- **Average throughput of $MU_0$**

$$E[C | k \geq 1] = E_{[W_{0,U}]}\left[\log_2 \left(1 + \frac{P_t g_0}{\sigma^2}\right) | k \geq 1 \right]$$
Average Throughput

According to probability chain rule, the average throughput is given by

$$E[C | k \geq 1] = \sum_{j=0}^{4} \sum_{i=0}^{4} \Pr[U = U_j, W_0 \in S_i | k \geq 1] E[C | U = U_j, W_0 \in S_i, k \geq 1]$$

joint probability that MU_0 is in sector S_i and UAV is displaced to U_j

expected throughput of MU_0 given it is inside S_i and UAV is at U_j

The derivation of the joint probability is non-trivial.

- The two random variables W_0 and U are highly correlated
  1) The UAV is displaced to the sector that has the largest number of users;
  2) The typical user is more likely to be selected from this sector as well.
- This correlation was NOT addressed in the non-adaptive deployment.
- We use multi-layer convolution to characterize this correlation.
Joint Probability $\Pr[U = U_j, W_0 \in S_i | k \geq 1]$

Proposition 1

Conditioned on $k \geq 1$, the joint probability that the UAV chooses the displacement position of $U = U_j$ and the typical MU_0 is inside the sector $S_i$ in the $M$-sector MU network is given by

$$
\Pr(U = U_j, W_0 \in S_i) = \begin{cases} 
\frac{e^{-4R^2\lambda}}{1 - e^{-4R^2\lambda}} \sum_{t_M=1}^{\infty} \ldots \sum_{t_2=1}^{\infty} \sum_{t_1=\max(t_2, \ldots, t_M)}^{\infty} & \frac{t_1 \left( \frac{4R^2\lambda}{M} \right)^{Mt_1-\sum_{i=2}^{M} t_i}}{(Mt_1-\sum_{j=2}^{M} t_i) t_1! \prod_{j=2}^{M} (t_1 - t_i)} & \text{for } j = i \\
\frac{e^{-4R^2\lambda}}{1 - e^{-4R^2\lambda}} \sum_{t_M=1}^{\infty} \ldots \sum_{t_2=1}^{\infty} \sum_{t_1=\max(t_2+1, t_3, \ldots, t_M)}^{\infty} & \frac{(t_1-t_2) \left( \frac{4R^2\lambda}{M} \right)^{Mt_1-\sum_{i=2}^{M} t_i}}{(Mt_1-\sum_{j=2}^{M} t_i) t_1! \prod_{i=2}^{M} (t_1 - t_i)} & \text{for } j \neq 0, i \\
\frac{1}{M} - \sum_{i=1}^{M} & \Pr(U = U_j, W_0 \in S_i), & \text{for } j = 0.
\end{cases}
$$

The joint probability is a function of user density $\lambda$, total sector number $M$, and cell radius $R$.
We derive the optimal displacement factor for average throughput maximization, i.e.,

\[ \text{P1: } \max_{\beta} E[C | k \geq 1] \]
\[ \text{s.t. } \beta \in [0,1] \]

- Given user density \( \lambda \), the average throughput is concave in \( \beta \);
- There exists a unique optimal \( \beta \) that maximizes the average throughput.

Fig. 1, The average throughput versus the displacement factor
Proposition 2

The UAV’s optimal displacement factor $\beta^*$ that maximizes the average throughput of the typical user $MU_0$ under the proposed scheme is the unique solution to

\[
\begin{align*}
\text{Pr}(U = U_j, W_0 \in S_j) - \text{Pr}(U = U_j, W_0 \in S_{i \neq j}) & \cdot [2f(1 - \beta, \beta) - 2f(\beta, \beta) - 2f(\beta, 1 - \beta) + 2g(\beta, \beta) + 2g(\beta, 1 - \beta)] \\
-2g(1 - \beta, \beta) + s(\beta, \beta) + s(1 - \beta, \beta) - s(\beta, 1 - \beta) + 2\text{Pr}(U = U_j, W_0 \in S_j)[f(1 - \beta, 1 - \beta) - g(1 - \beta, 1 - \beta)] \\
-s(1 - \beta, 1 - \beta) & + \text{Pr}(U = U_j, W_0 \in S_{i \neq j})[2f(1 - \beta, 1 + \beta) - 2f(1 + \beta, 1 - \beta) - 2f(1 + \beta, 1 + \beta) + 2g(1 + \beta, 1 - \beta)] \\
+ 2g(1 + \beta, 1 + \beta) - 2g(1 - \beta, 1 + \beta) + s(1 + \beta, 1 + \beta) + s(1 - \beta, 1 + \beta) - s(1 + \beta, 1 - \beta) & = 0
\end{align*}
\]

where

\[
\begin{align*}
f(z, l) & = \sqrt{h^2 + z^2} \frac{R}{\sqrt{h^2 + z^2}^2 \arctan \left( \frac{Rl}{\sqrt{h^2 + z^2}^2} \right)} \\
g(z, l) & = \sqrt{P_t \theta / \sigma^2 + h^2 + z^2} \frac{R}{\sqrt{P_t \theta / \sigma^2 + h^2 + z^2}^2 \arctan \left( \frac{Rl}{\sqrt{P_t \theta / \sigma^2 + h^2 + z^2}^2} \right)} \\
s(z, l) & = zR \log \left( 1 + \frac{P_t \theta / \sigma^2}{h^2 + z^2} \right) + \frac{l^2 + z^2}{h^2 + z^2} \arctan \left( \frac{Rl}{h^2 + z^2} \right)
\end{align*}
\]

Complicated!

We use asymptotic analysis to find more insights.
Asymptotic Analysis

- As $\lambda \to 0$
  - Only one user in the cell (due to $k \geq 1$)
  - UAV is better to fly to the center of the sector
  - The optimal displacement factor is $\beta^* = \frac{1}{2}$

- As $\lambda \to \infty$
  - All sectors have many users
  - UAV is better to be non-adaptive
  - The optimal displacement factor is $\beta^* = 0$

- For other cases
  - The optimal displacement factor $\beta^* \in \left(0, \frac{1}{2}\right)$
Numerical Results

Optimal $\beta^*$ versus $\lambda$

- Optimal $\beta^*$ decreases as the increase of $\lambda$
  - As $\lambda \to 0$, $\beta^* = 0.5$
  - As $\lambda$ increase, $\beta^*$ is approaching 0

Fig. 2, The optimal displacement factor versus the user density
Numerical Results

- Proposed scheme versus non-adaptive scheme
  - Substantial improvement at low density
  - Adaptive deployment at low density is important
  - Better to be non-adaptive for high density

Fig. 3. The ratio between the maximum average throughput for the proposed scheme to that of the non-adaptive scheme.
Conclusions

❑ We are the first work that explores the traffic-aware dynamic UAV deployment in a random network.

❑ We characterized the user randomness using Poisson process and derived the average throughput of the typical user in the two-dimensional user network.

❑ We derived the optimal displacement factor that maximizes the average throughput.

❑ We showed a great benefit by deploying UAV according to the dynamic user movement, especially when the user density is not high.
Thank You!