Research Progress: An FSO-based Drone Assisted Access Network

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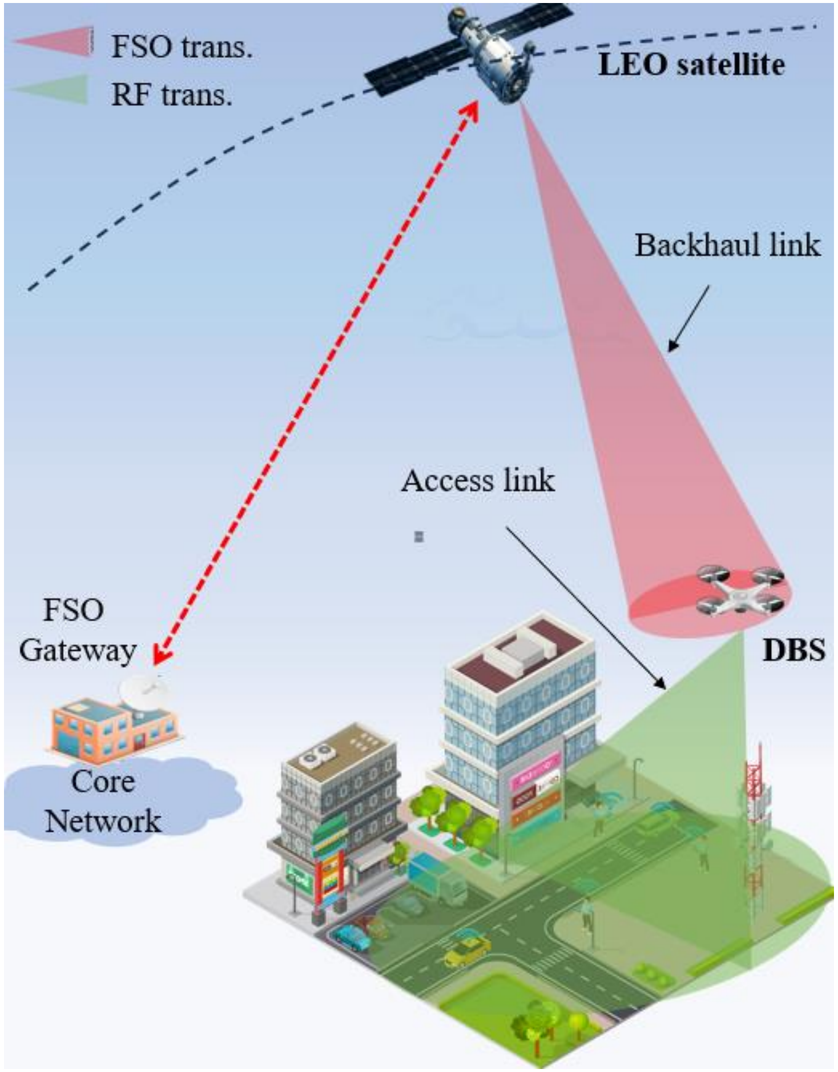
Introduction

Considered End-to-End Network Scenario

- Recently, ***free-space optics (FSO)*** is envisioned as a promising candidate for backhaul networks thanks to its ***extremely high-speed connection***

- In addition, using ***drone base station (DBS)*** can significantly improve the performance of current cellular networks thanks to its ability to ***establish Line of Sight (LoS) communication links*** with ground users

→ End-to-end networks, including FSO-based backhaul links and DBS-based access links, are expected to be a key network architecture for beyond 5G/6G wireless networks



Literature Review (1)

- Some major papers that consider both access and FSO-based backhaul links

Ref.	Year	Journal	Title
1	2020	Trans. Netw. Sci. Eng.	An FSO-Based Drone Assisted Mobile Access Network for Emergency Communications
2	2021	Trans. Veh. Technol.	Latency Aware 3D Placement and User Association in Drone-Assisted Heterogeneous Networks With FSO-Based Backhaul
3	2023	Trans. Netw. Sci. Eng.	Backhaul-Aware Drone Base Station Placement and Resource Management for FSO-Based Drone-Assisted Mobile Networks
4	2023	Trans. Veh. Technol.	Trajectory Design and Bandwidth Allocation Considering Power-Consumption Outage for UAV Communication: A Machine Learning Approach
5	2023	Internet Things J.	Cooperative UAV Trajectory Design for Disaster Area Emergency Communications: A Multi-Agent PPO Method
6	2023	Photon. J.	Outage Probability Analysis and Joint Optimization for UAV-aided FSO/RF Systems with Nonlinear Power Amplifiers

Literature Review (2)

- Purpose: optimize the access network performance under the constraint of the backhaul link
- Objective function:
  (1) Max num. users [1],[3]
  (2) Min outage prob. [6]
  (3) Max users' data rate [4-5]
  (4) Min latency [2]
- Approach:
  - Conventional optimization techniques [1-3],[6]
  - Deep reinforcement learning (DRL) approach [4-5]

Motivations

- The current works mainly focus on the access network
  - The impacts of atmospheric turbulence and clouds are usually ignored
- Motivations
  - ***My goal:***
    1. Focus on the backhaul links
    2. Investigate the impact of the channel conditions of the backhaul links on the access links and end-to-end performance
  - I need more time to get familiar with optimization techniques/DRL approach

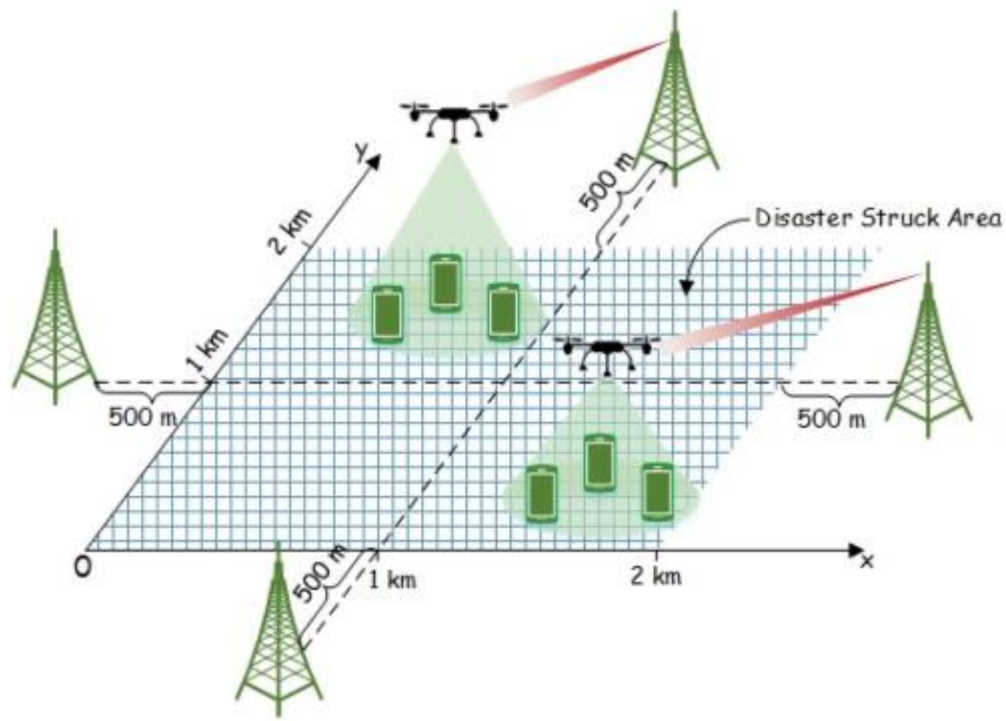
➔ *As the first step, I would like to adopt a simple access network model to investigate the impact of the backhaul link.*

➔ *The ref. [1] that utilizes a simple heuristic algorithm is a potential approach to start with*

An FSO-Based Drone Assisted Mobile Access Network [1]

System Model

- A disaster area is divided into 4 locations of the same size, with a total of J mobile users (MUs)
- A set of 4 Drone Base Stations (DBS) are deployed to deliver traffic. Each DBS supports 1 location and is connected to a nearby macro base station (GBS)
- The UAVs are independent and do not have interconnection with each other
- Each MU is only associated with 1 UAV
- FSO transmission is used for the backhaul links, while RF is used for the access links

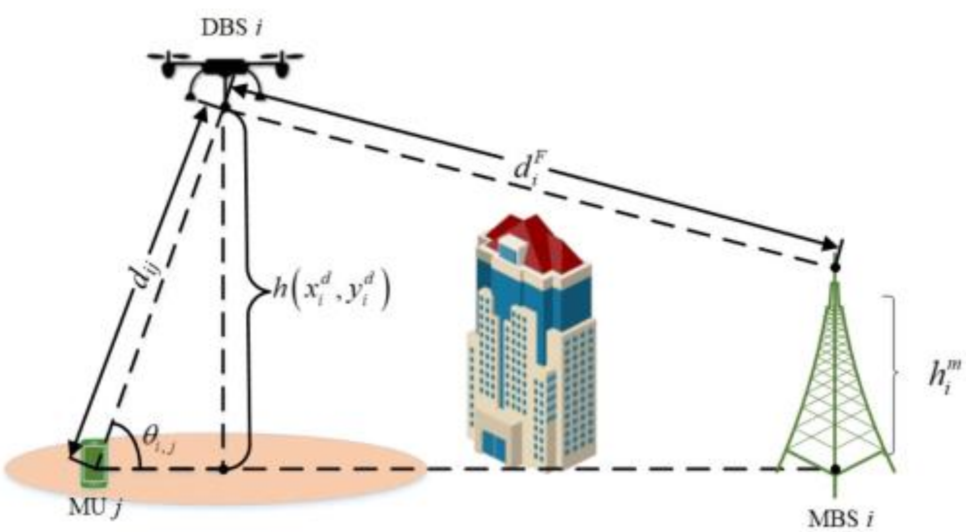


Backhaul Link: FSO Data Rate

- The data rate of the FSO link between DBS i and its GBS is modelled as

$$R_i = \frac{P_t}{E_p N_b}\left(\frac{r_s}{\left(\theta_g d_i^F 2\right)^2}\right)\eta_t \eta_r 10^{-\exp \sigma d_i^F}$$

  - Where N_b is the sensitivity of the receiver, E_b is the Plank’s constant, c is the speed of light, r_s and θ_g are the radius and divergence angle of the FSO beam, respectively. In addition, η_t and η_r are the coefficient to convert electrical to optical energy and vise versa; d_i^F is the distance between DBS i and its GBS and σ is atmospheric attenuation coefficient.

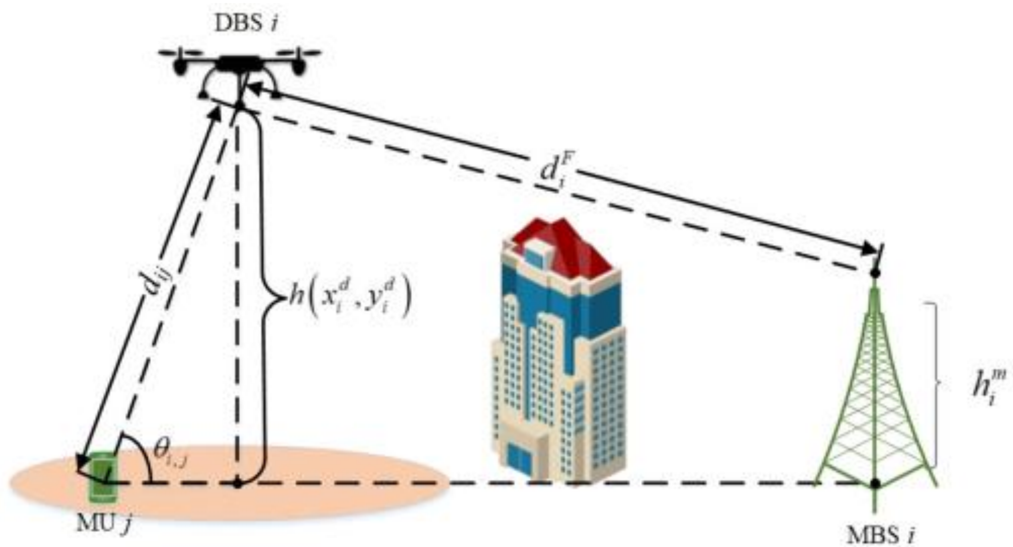


Access Network: Pathloss Model

- The channel between an MU and their associated DBS is modeled as a probabilistic Line-of-Sight (LoS) channel. The average pathloss between the DBS i and MU j is expressed as

$$\bar{\eta}_{ij} = \rho_{ij}\eta_{ij}^{LoS} + (1 - \rho_{ij})\eta_{ij}^{NLoS}$$

  - Where ρ_{ij} is the probability of having LoS channel, η_{ij}^{LoS} and η_{ij}^{NLoS} are the pathloss in LoS and NLoS, respectively. These parameters are directly related to the distance between the DBS and MU, i.e., d_{ij}



Problem Formulation

- The optimization problem ($\mathcal{P}$) is formulated as

$$\mathbf{P0}: \quad \arg\max_{x_i^d, y_i^d, h(x_i^d, y_i^d), a_{ij}} \sum_{i \in I} \sum_{j \in J} a_{ij},$$

→ Maximize the total number of users.
Note: $a_{ij} \in \{0,1\}$ to indicate if DBS i is associated with MU j

$$s.t.: C1: \sum_{i \in I} a_{ij} \leq 1, \ \forall j \in J,$$

→ Each MU is only associated with 1 DBS

$$C2: f^{min}(x_i^d, y_i^d) \leq h(x_i^d, y_i^d) \leq f^{max}(x_i^d, y_i^d),$$

→ Altitude constraint of the DBS

$$C3: a_{ij}(\eta_{ij} - \eta_{ij}^{th}) \leq 0, \ \forall j \in J, \ \forall i \in I,$$

→ The pathloss η_{ij}^{th} must be satisfied if the MU j is associated with DBS i (i.e., $a_{ij} = 1$)

$$C4: a_{ij}(r_{ij} - r_j^{th}) \geq 0, \ \forall i \in I, \forall j \in J,$$

→ The rate r_j^{th} must be satisfied if the MU j is associated with DBS i (i.e., $a_{ij} = 1$)

$$C5: \sum_{j \in J} a_{ij} r_{ij} \leq R_i, \ \forall i \in I,$$

→ The total rate of the access link should not be larger than the FSO rate offered by the backhaul link

$$C6: \sum_{j \in J} a_{ij} b_{ij} \leq B_i, \ \forall i \in I,$$

→ The total bandwidth allocated to MUs should be within the available bandwidth

The Proposed Heuristic Algorithm

- To efficiently solve $\mathcal{P}$, the authors propose a heuristic algorithm, i.e., QoS awaRe dronE base Station plaCement and mobile User association strategy (RESCUE)
- **IDEA:** decompose $\mathcal{P}$ into three sub-problems, i.e.,

  $\mathcal{P}_1$: Initial 3D DBS Placement: → *find the optimal initial position of the DBS*

  $\mathcal{P}_2$: Bandwidth Allocation and MU Association → *associate the MUs to the DBS and allocate bandwidth to them*

  $\mathcal{P}_3$: Altitude Adjustment → *find a better altitude of the DBS to support more user*
- We first solve the sub-problem ($\mathcal{P}_1$), then iteratively solve ($\mathcal{P}_2$) and ($\mathcal{P}_3$) to achieve a near-optimal solution of $\mathcal{P}$

$\mathcal{P}_1$ Initial 3D DBS Placement (1)

- Optimal Altitude of the DBS (h_i^*)
  - Let r: the coverage radius of the DBS so that the pathloss of the MU in the covered area is no larger than the pathloss threshold η^{th}.
  - With the provided pathloss model, there exists only one optimal altitude of the DBS that maximize r

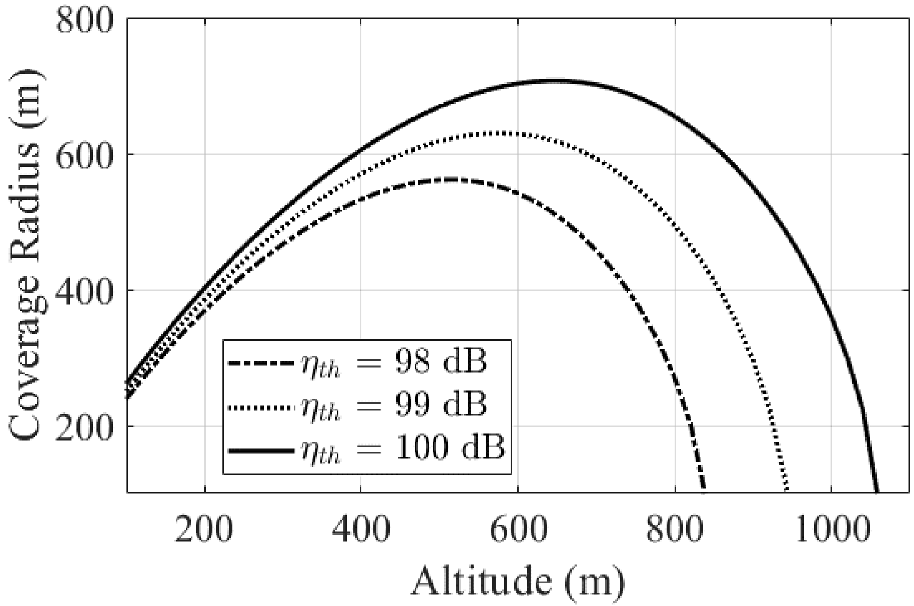


Fig. Altitude versus coverage radius of the DBS

$\mathcal{P}_1$ Initial 3D DBS Placement (2)

- Optimal 2D coordinate of the DBS ($< x_i^d, y_i^d >$)
  - ***Step 1:*** Select DBS i
  - ***Step 2:*** Select location n which has no DBS
  - ***Step 3:*** Place DBS i at the ***center*** of the location n and at the optimal altitude h_i^* that maximizes the coverage area. Then calculate the number of covered MUs, denoted as K_n
  - ***Step 4:*** Iteratively select other locations and calculate K_n based on ***step 2***. The optimal location of the DBS i is the location n^* that incurs *the largest value* of K_n → DBS i will be placed over the ***center*** of location n^*
  - ***Step 5:*** Select another DBS and go to ***step 1***

$\mathcal{P}_2$ Bandwidth Allocation and MU Association

- After having determined the 3-D location of DBS i, each MU covered by DBS i should be allocated sufficient bandwidth
  - Each user has a predetermined data rate requirement. The required bandwidth is calculated based on the required data rate and current pathloss
- Since the available bandwidth is limited → to maximize the number of users, the user with the *least bandwidth requirement will be prioritized* (*Greedy algorithm*). Specifically,

  Step 1: Sort all covered MUs in ascending order according to their bandwidth requirement

  Step 2: Allocate the required bandwidth to the MUs in the order until one of the following conditions is met

    - There are no MUs left
    - There is not enough bandwidth to meet the requirement of the next user
    - The total data rate exceeds the capacity of the backhaul link

$\mathcal{P}_3$ Altitude Adjustment

- If the DBS i is unable to support all cover MUs, the altitude will be adjusted to support more users. In particular,
  - ***Step 1:*** Denote h_i^* as the altitude obtained from $\mathcal{P}_1$, and δ as the step size of adjusting the altitude
  - ***Step 2:*** Let $h_i^- = h_i^* - \delta$, and $h_i^+ = h_i^* + \delta$. Calculate the number of users associated to DBS i by re-excecuting $\mathcal{P}_2$ based on h_i^- and h_i^+
  - ***Step 3:*** Choose the altitude among h_i^*, h_i^- and h_i^+ that provides the highest number of supported users and update h_i^* of the DBS
  - ***Step 4:*** Recursively execute step 2 and 3 until no more users can be supported

Problems/Comments

- Each user has a requested data rate, the required bandwidth is calculated from the required rate and current pathloss

  → *Not practical in real systems*

- In $\mathcal{P}_1$, a DBS needs to investigate each remaining location once before it can choose the best location

  → *Not reasonable because, in the end, each DBS must be at the center of each location*

- The DBSs are placed at the center of each location, and only the altitude is adjusted

  → *Not 3D placement as in the problem formulation*

Thank you for your listening!