Seminar:
DRL-Assisted UAV Placement over IRS-based HAP networks

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Outline:

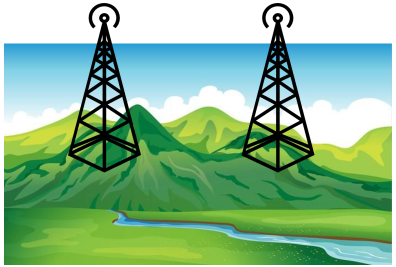
1. Introduction
2. System model
3. Multi-agent DRL for UAV placement
4. Simulation results
5. Future plan

Non-terrestrial networks (NTNs)

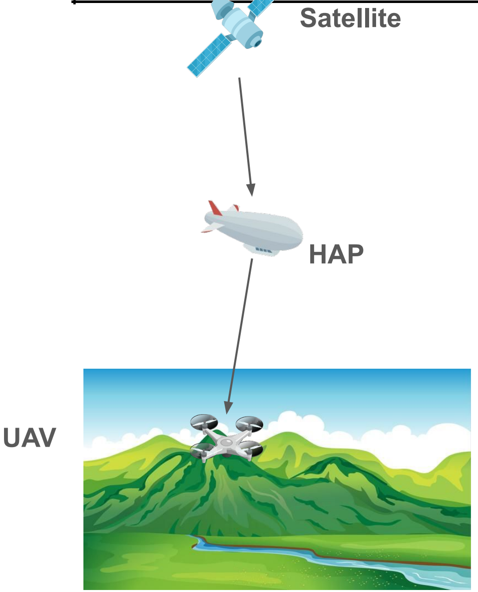
- **NTN: definition**
- Why NTN is a trend?
    - reason 1
    - reason 2
    - reason 3

=> **Non-Terrestrial Networks (NTNs)** (including satellites, HAPs, and UAVs) have emerged as potential solutions to extend network coverage in rural or remote areas.

It doesn't make economic sense



Terrestrial Networks



Non-Terrestrial Networks

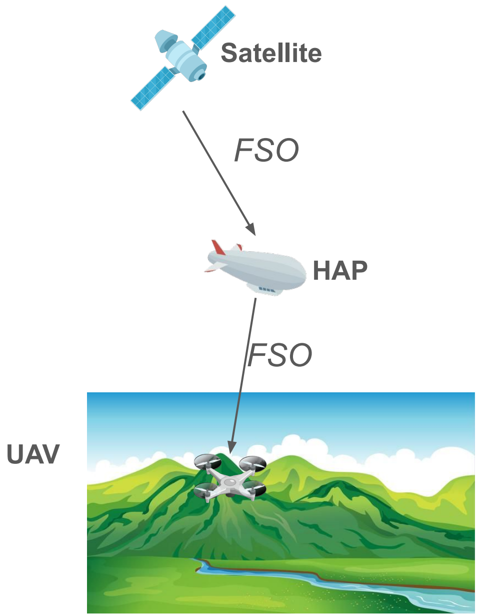
1.Introduction:

Free Space Optical (FSO)-based NTNs:

FSO is a line-of-sight technology using infrared frequency bands (200 - 400 THz) for data transmission in free-space:

- Large bandwidth, high frequencies => High-speed data rate
- Free-license bandwidth

=> The integration of FSO for backhaul is the promising NTN architecture to achieve high data-speed transmission.



An typical Application: FSO Backhaul assisted mutilpe UAV

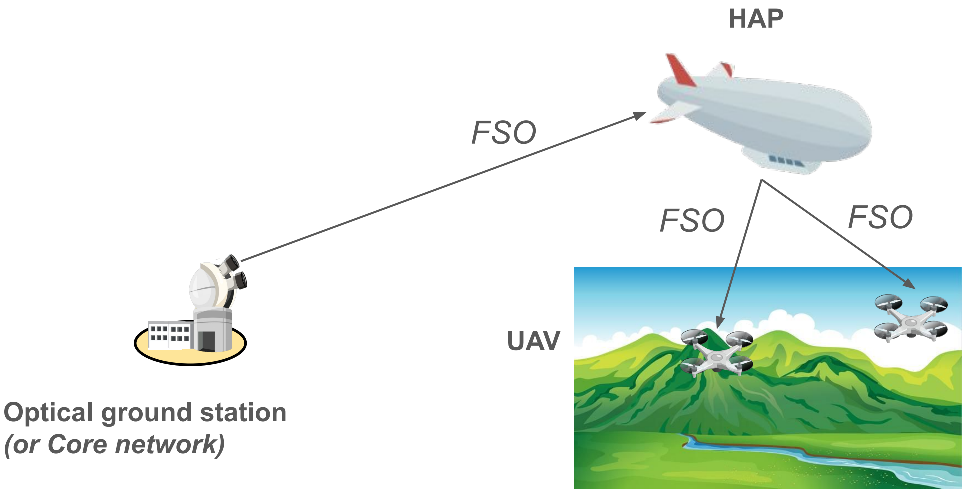
(1)FSO is a line-of-sight technology using infrared frequency bands (187 - 400 THz) for data transmission in free-space:

- Large bandwidth, high frequencies => High-speed data rate
- Free-license bandwidth

(2)Employing Unmanned Aerial Vehicle (UAV), and High-Altitude Platform (HAP) as relay base station

=> Wide coverage, flexible deployment, and strong light-of-sight connectivity, low cost

(1) + (2) => The integration of HAP for FSO backhaul and UAV for last-mile access will be a potential NTN architecture in NTNs.



1.Introduction:

Introduction to Intelligent Reflecting Surfaces (IRSs):

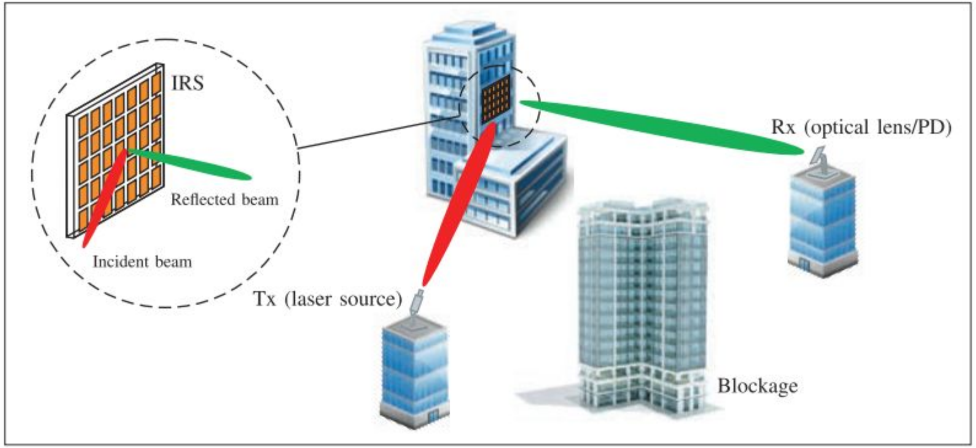
Motivation of IRS:

- In FSO, the LoS transmission can be limited by blockage
- Optical Relay nodes are currently used to solve this problem
- But Optical Relay nodes are expensive and inconvenient as they require considerable hardware deployment
- Recently, Intelligent Reflecting Surface (IRSs) are investigated in FSO communications, which addresses these above challenges

=> IRS is defined as a “mirror” reflecting the waves with the aim of overcoming “blockage” in LoS wireless communications

Advantages (compared to optical relays):

- Low cost and energy consumption
- Not require hardware complexity

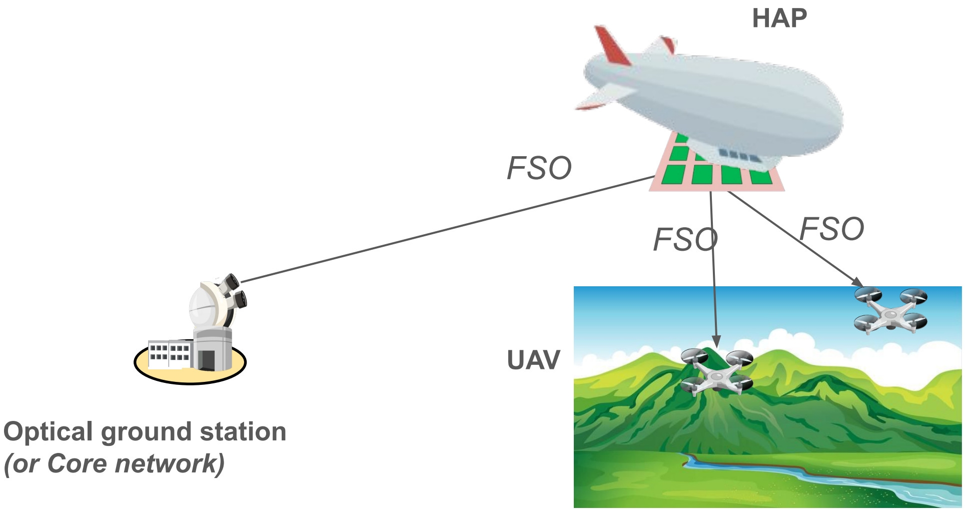


1.Introduction:

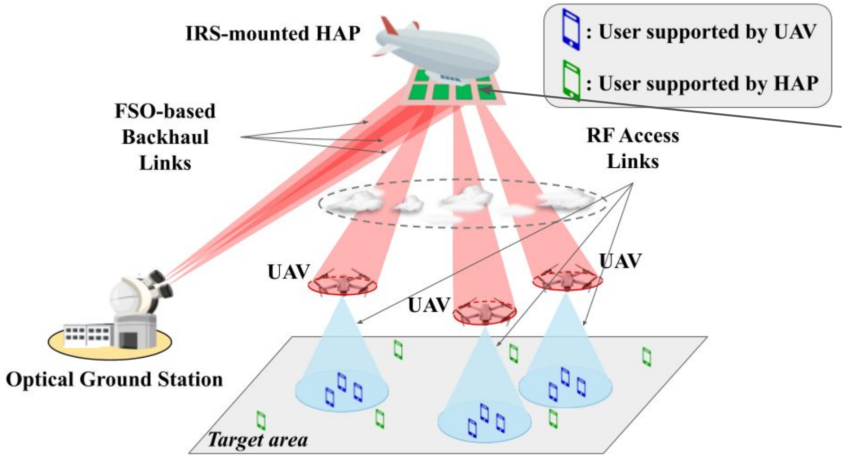
Motivated by 2 advantages of IRS:

- Low cost and energy consumption
- Not require hardware complexity

=> We apply IRS to the HAP-assisted NTNs.



2. System model



Motivated by IRS's advantages:
We deploy a IRS mounted on HAP instead of optical relay
=> Be <u>cheaper</u> than optical relay and <u>save energy consumption</u>

<u>Our scenario:</u> End-to-End network

One HAP and multiple UAVs are deployed to provide internet connection to rural/remote areas or temporary events

- **FSO-based Backhaul Links:** Optical Lasers transmitted by Optical Ground Station are <u>reflected by IRS</u> mounted on HAP.
- **RF Access Links:** Multiple UAVs are deployed to maximize the number of high-speed users.

<u>Our Problem:</u>

Given: Consider End-to-End network

- Backhaul Links: affected by Cloud Attenuation and Geometric Loss [1]
- Access Links: affected by the distance (Path Loss)

Objective: Maximize the number of <u>high-speed users supported by UAVs</u>

Reference:

[1] H. Ajam, M. Najafi, V. Jamali, and R. Schober, "Power scaling law for optical irss and comparison with optical relays," in GLOBECOM 2022- 2022 IEEE Global Communications Conference. IEEE, 2022, pp. 1527– 1533

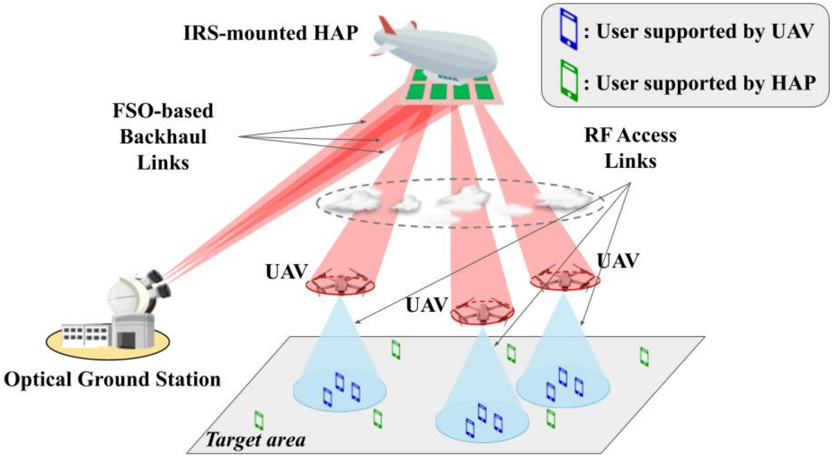
2. System model

Critical Issues of End-to-End Network:

- Backhaul Links: Unstable and time-varying channel, backhaul capacity fluctuates over time
- Access Links: The dynamic of users' distribution and movement (Users moving follows Gaussian Markov mobility model)

=> Dynamic network => Require a robust algorithm to solve this optimization problem

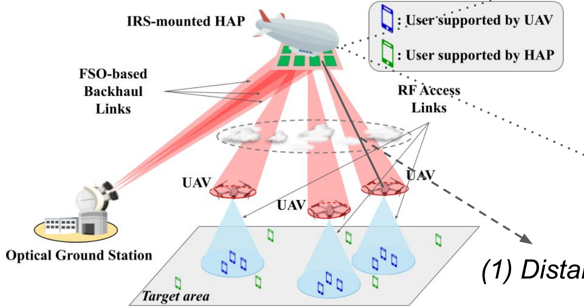
=> Our approach: We deploy an optimization framework leveraging deep reinforcement learning to address the UAV placement problem in the end-to-end network

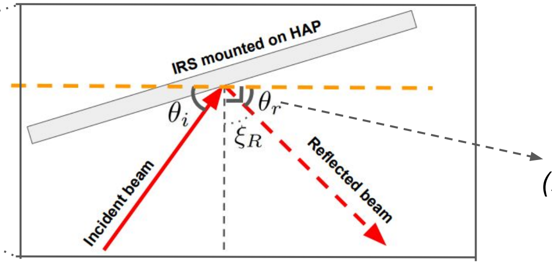


2. System model

2 factors affect **Geometric Loss**: (1) Distance HAP-UAV, (2) reflected angle

Backhaul links in our scenario:





(2) Reflected angle

(1) Distance HAP-UAV

*1 factor affect **Cloud Attenuation**: Cloud Liquid Water Content (CLWC) at where the UAV locates*

2. System model

We consider : M UAVs, N Users, T time-slots

Problem formulation:

Step 1: Calculate the set of users within UAV's coverage

$$\downarrow$$

$$\mathcal{N}_m$$

$$\downarrow$$

Step 2: Calculate the set of users supported by UAV

- To save UAV's power, a power allocation scheme is adopted
- The constraint of Backhaul capacity

$$\downarrow$$

$$\mathcal{H}_m$$

$$\downarrow$$

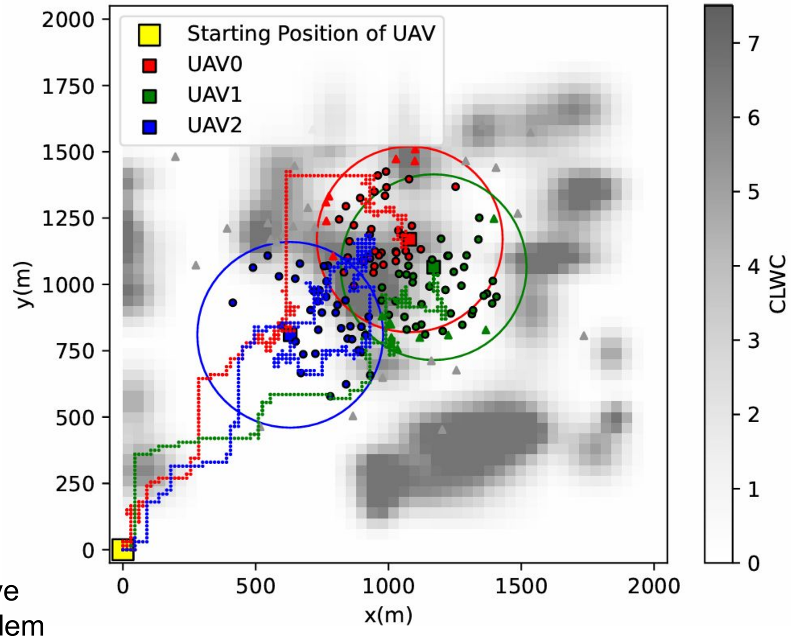
Step 3: Objective: maximize the number of users supported by UAVs

$$\max_{\mathcal{U}} \quad Q = \sum_{m=1}^{M} |\mathcal{H}_m|$$

Subject to: Backhaul capacity, UAV's power, placement constraints of UAVs,....

DRL is applied to solve this optimization problem

Circle: *represents high-speed users supported by UAV*
Triangle: *represents low-speed users supported by HAP*



2. System model

We consider : M UAVs, N Users, T time-slots

Problem formulation:

Step 1: Calculate the set of users within UAV's coverage

$\mathcal{N}_m$

If backhaul capacity is perfect which is able to provide enough data-rate for all users within UAV's coverage, UAV's power is always enough to allocate

~~**Step 2:** Calculate the set of users supported by UAV~~

~~- To save UAV's power, a power allocation scheme is adopted~~
~~- The constraint of Backhaul capacity~~

$\mathcal{H}_m$

Step 3: Objective: maximize the number of users supported by UAVs

$$\max_{\mathcal{U}} \quad Q = \sum_{m=1}^{M} |\mathcal{H}_m|$$

Subject to: Backhaul capacity, UAV's power, placement constraints of UAVs,....

DRL is applied to solve this optimization problem

2. System model

We consider : M UAVs, N Users, T time-slots

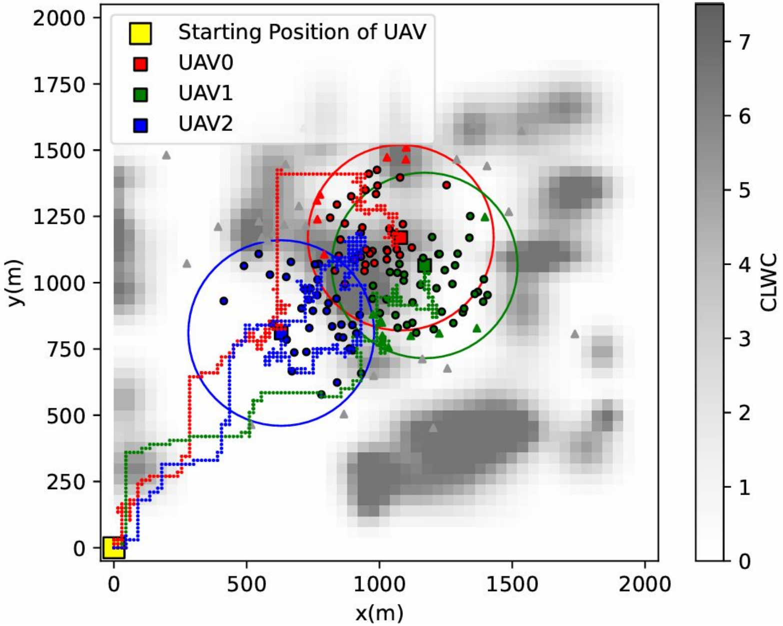
(Step 1) Algorithm: Calculate the set of users within UAV's coverage

$$c_{n,m,t} = \begin{cases} 1, & \text{if } d^{\text{UAV}}_{n,m,t} = \min\{d^{\text{UAV}}_{n,1,t}, \ldots, d^{\text{UAV}}_{n,M,t}\} \leq D^{\text{UAV}} \\ 0, & \text{otherwise} \end{cases} .$$

This user is closest to the UAV

The distance UAV-user must be below the radius coverage of UAV

Output: The set of users within UAV's coverage: $\mathcal{N}_m = \{n | c_{n,m,t} = 1\}_{n \in \mathcal{N}}$



2. System model

We consider : M UAVs, N Users, T time-slots

(Step 2) Algorithm: Calculate the set of users supported by UAV

Power allocation scheme (UAV-user) : We calculate the needed power to achieve the fixed data rate (threshold) to be transmitted to user
=> To save UAV's power

1

Based on Shannon's formula:

Input: fixed data rate

$$C^{\mathrm{RF}} = B^{\mathrm{RF}} \log_2 \left(1 + \frac{P^{\mathrm{UAV}}_{n,m,t} \times g^{\mathrm{UAV}}_{m,n,t}}{\sigma^2} \right)$$

Output: needed power

2

Algorithm 1 User Association Algorithm `UA_Algo()`

Input: $\mathcal{N}_m = \{n | c_{n,m,t} = 1\}_{n \in \mathcal{N}}$ denotes the set of users within the coverage area of m-th UAV at time-slot t
Compute the set of needed power $\{P^{\mathrm{UAV}}_{n,m,t}\}_{n \in \mathcal{N}_m}$ by equation (10)
Initialize the list of high-speed users $\mathcal{H}_m = \{\}$
while `true` **do**
  if $C^{FSO}_{m,t} < 0 \vee P^{\mathrm{UAV}} < 0 \vee |\mathcal{H}_m| = \{|P^{\mathrm{UAV}}_{n,m,t}\}_{n \in \mathcal{N}_m}|$ **then**
    `break`
  end if
  $P^{\mathrm{UAV}} -= \min\{P^{\mathrm{UAV}}_{n,m,t}\}_{n \in \mathcal{N}_m}$
  $C^{\mathrm{FSO}}_{m,t} -= C^{\mathrm{RF}}$
  Append $\arg\min_n \{P^{\mathrm{UAV}}_{n,m,t}\}_{n \in \mathcal{N}_m}$ to $\mathcal{H}_m$
end while
Return $\mathcal{H}_m$

Power allocation scheme: prioritize users need less power

The constraints of Backhaul capacity and UAV's power

The UAV can not support all users within its coverage

Output: The set of users supported by UAVs

3

SUMMARY:

Consider 1 UAV:
(1) Set of users within 1 UAV's coverage
(2) Calculate the set of needed-power of users
(3) Transmit fixed data rate with allocating needed power to each user
(4) Do it until we run out of backhaul capacity or the UAV's power
(5) Finally, we get the set of users supported by UAVs

2. System model

We consider : M UAVs, N Users, T time-slots

(Step 3) Our optimization problem:

$$\mathcal{P}: \max_{\mathcal{U}} \quad Q = \sum_{m=1}^{M} |\mathcal{H}_m| \tag{11a}$$

Objective: maximize the number of users supported by UAVs

$$\text{s.t.} \quad (9) \tag{11b}$$

$$\mathcal{H}_m = \texttt{UA\_Algo}(\mathcal{N}_m) \tag{11c}$$

The set of users supported by UAVs

$$|\mathcal{H}_m| C^{\mathrm{RF}} \leq C^{\mathrm{FSO}}_{m,t}, \forall m \tag{11d}$$

The constraint of backhaul capacity

$$\sum_{n \in \mathcal{H}_m} P^{\mathrm{UAV}}_{m,n,t} \leq P^{\mathrm{UAV}} \forall m, t \tag{11e}$$

The constraint of UAV power

$$x_{\min} \leq x^{\mathrm{UAV}}_{m,t} \leq x_{\max} \forall m, t \tag{11f}$$

$$y_{\min} \leq y^{\mathrm{UAV}}_{m,t} \leq y_{\max} \forall m, t \tag{11g}$$

Placement constraints of UAVs in the target area,

$$(x^{\mathrm{UAV}}_{m,0}, y^{\mathrm{UAV}}_{m,0}) = (0,0) \forall m \tag{11h}$$

Starting position of UAVs

$$(x^{\mathrm{UAV}}_{m,t}, y^{\mathrm{UAV}}_{m,t}) = (x^{\mathrm{UAV}}_{m,t-1}, y^{\mathrm{UAV}}_{m,t-1}) + \mathbf{v}^{m}_{t} \forall m, t \tag{11i}$$

The movement of UAVs

=> Find optimal UAV's placement to maximize the number of users supported by UAVs (given by above constraints)

2. System model

We consider : M UAVs, N Users, T time-slots

Problem formulation:

Step 1: Calculate the set of users within UAV's coverage

$$\mathcal{N}_m$$

Step 2: Calculate the set of users supported by UAV

- Due to the constraint of UAV's power, a power allocation scheme is adopted
- The constraint of Backhaul capacity

$$\mathcal{H}_m$$

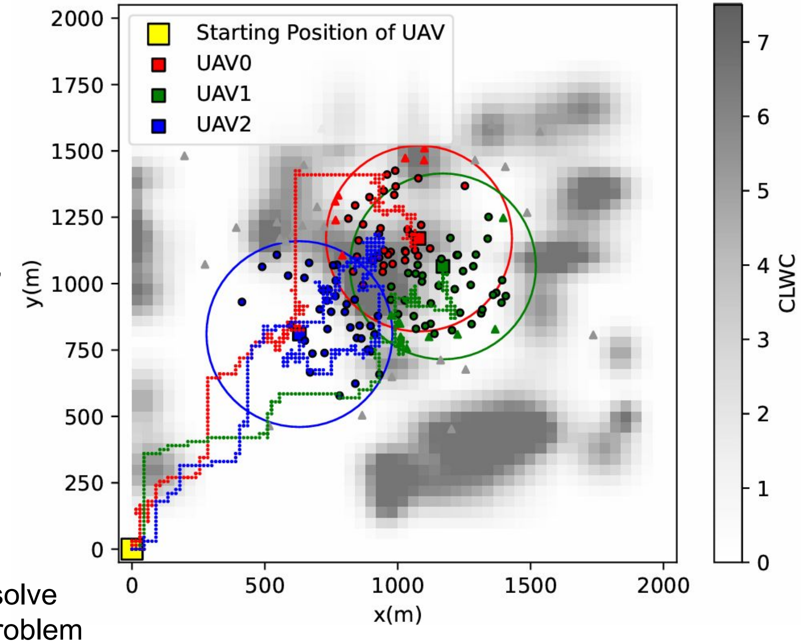
Step 3: Objective: maximize the number of users supported by UAVs

$$\max_{\mathcal{U}} \quad Q = \sum_{m=1}^{M} |\mathcal{H}_m|$$

Subject to: Backhaul capacity, UAV's power, placement constraints of UAVs,....

DRL is applied to solve this optimization problem

Circle: *represents high-speed users supported by UAV*
Triangle: *represents low-speed users supported by HAP*



3. Multi-agent DRL for UAV placement

Deep Reinforcement Learning:

(1) Define observation, action, reward:

- Observation: includes 2 components

- ${\mathbf{s_1}}_t^m$: Current the UAV's coordination, other UAVs' coordination, heatmap of all users, heatmap of users within UAV's coverage, its current backhaul capacity, current total users supported by UAVs, current time-slot -> Vector
- ${\mathbf{s_2}}_t^m$: Cloud map -> Matrix

=> Shared observations among agents => **Multi-agent**

- Action: Remain Stationary, Up, Down, Left, Right

- Reward: $R_t^m = l_t^m \zeta + g_t(1 - \zeta)$

- l_t^m : Individual reward, based on the change of the number of users within UAV's coverage
- g_t : Global reward, based on the change of the total number of users supported by all UAVs

To encourage a UAV to maximize the number of users within its coverage

To encourage a UAV to maximize the total number of users supported by all UAVs

=> Global reward => **Multi-agent**

=> We are going to Multi-agent DRL

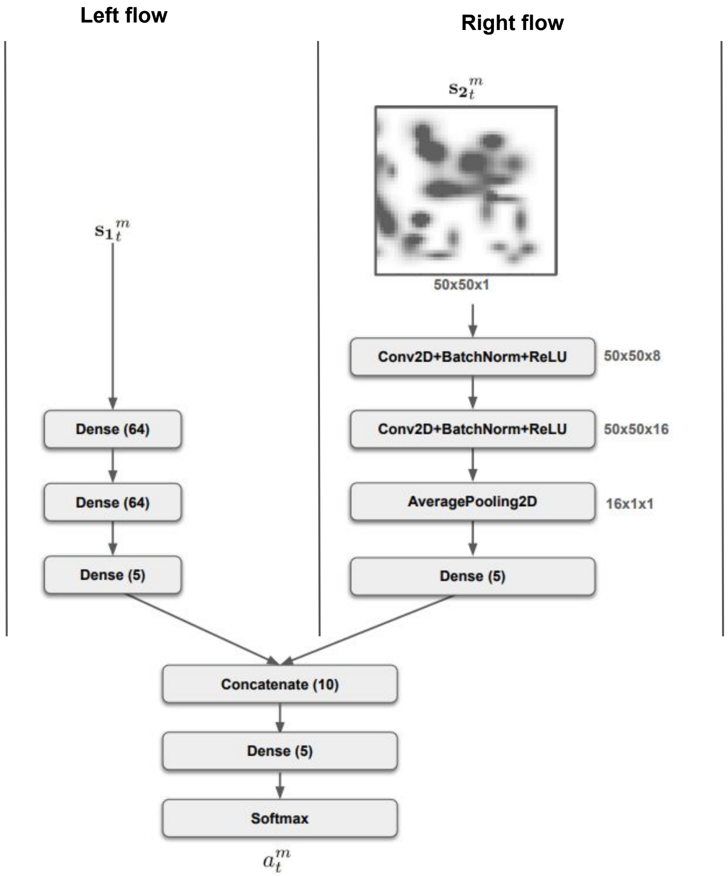
3. Multi-agent DRL for UAV placement

Deep Reinforcement Learning:

(2) CNN-based policy: *Cloud map is included -> CNN-based policy need to be adopted*

- **Left flow:** extract feature from first component ${\mathbf{s_1}}_t^m$
- **Right flow:** extract feature from second component ${\mathbf{s_2}}_t^m$

(3) Deep reinforcement learning mode: PPO model (with multi-agent)



CNN-based policy

4. Simulation results

Simulation Settings:

Parameter	Value
The number of M UAVs, N Users (Gaussian distribution), T Time-slot, Target area	M = 3 (UAVs), 150 (Users), T=500 (Time-slots), 2(km)x2(km)
Distance (Ground station-> HAP)	40 (km)
HAP’s altitude, zenith angle of HAP-UAV	20 (km), 60°
IRS size (divided equally into 3 regions)	40(m) x 40(m)
Data rate threshold C^{RF}	100 (Mbps)

4. Simulation results

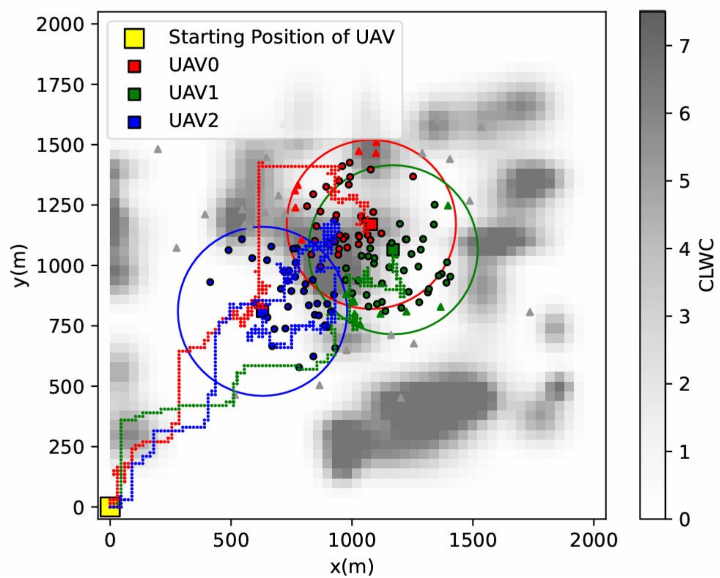
Objective of our optimization problem

An example of 3 UAVs moving:

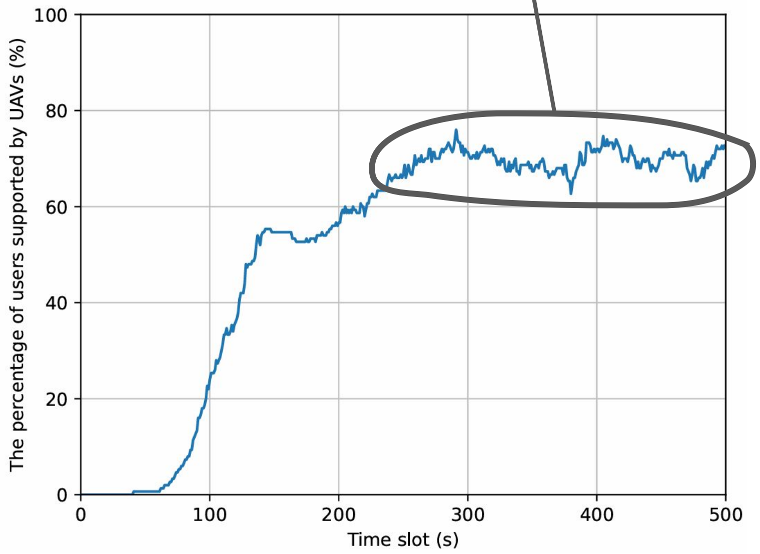
The number users supported by UAVs increases significantly, and then saturates
After UAVs move 500 steps, over 75% of users is supported by UAVs

(1)The number of high-speed users supported by UAVs is maximized:

Circle: *represents high-speed users supported by UAV*
Triangle: *represents low-speed users supported by HAP*



(a) The trajectories of 3 UAVs



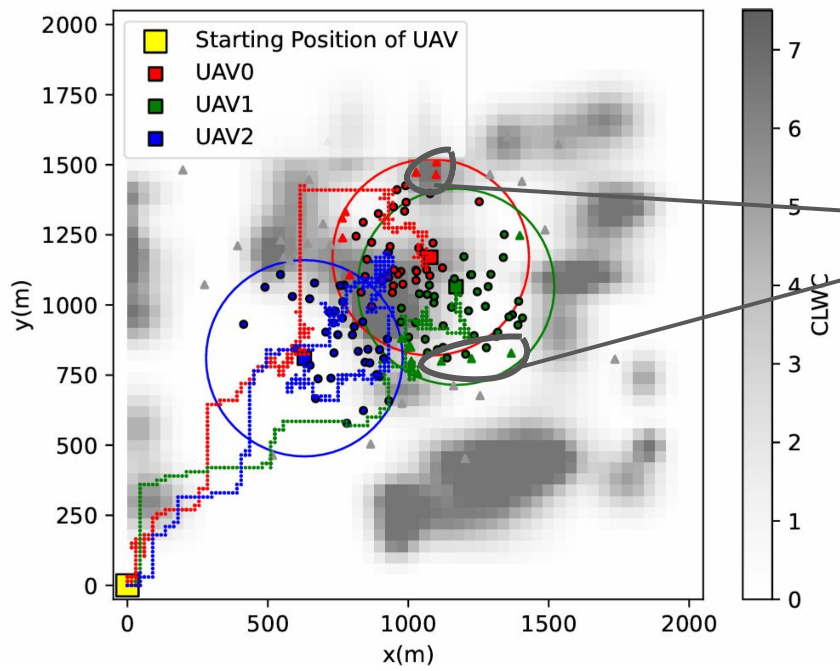
(b) The percentage of users supported by UAVs over time

4. Simulation results

(2)The impact of Backhaul Capacity on the number of high-speed users supported by UAVs:

(a) The trajectories of 3 UAVs

Circle: *represents high-speed users supported by UAV****,*** ***Triangle:*** *represents low-speed users supported by HAP*

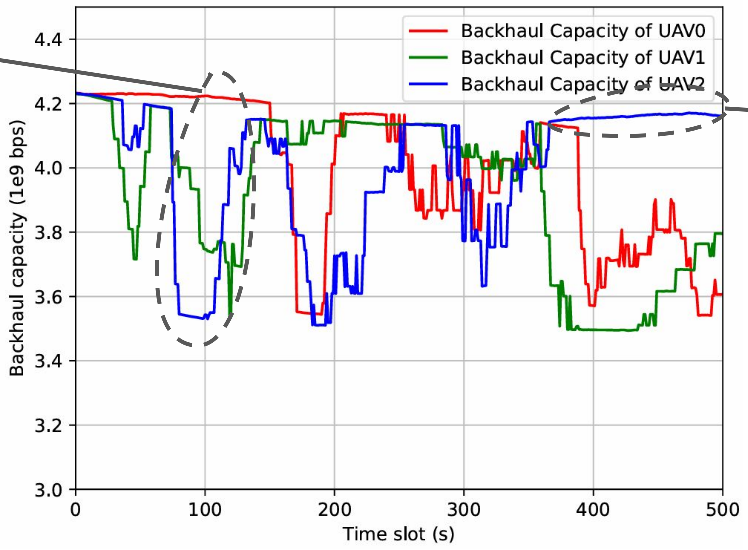


Due to the constraint of Backhaul Capacity

4. Simulation results

(3) The change of backhaul capacity over time:

The backhaul capacity of UAV drops dramatically when moving to cloud region



(c) The backhaul Capacity of 3 UAVs over time

The backhaul capacity of UAV fluctuates slightly due to geometric loss

5. Future plan

Works done: I successfully apply DRL to deploy multiple UAVs to maximize the number of users supported by UAVs in the End-to-End network, where FSO-based Backhaul Links are assisted by IRS

Next steps: Compare performance of DRL with and without considering backhaul capacity