Spatial Resource Allocation for Optical IRS-Aided HAP-Assisted Multi-UAV Networks

Khanh D. Dang[1], Hoang D. Le[1], Chuyen T. Nguyen[2], Vuong Mai[3] and Anh T. Pham[1]

[1] Computer Communications Laboratory, The University of Aizu, Japan
[2] School of Electrical and Electronic Engineering, Hanoi University of Science and Technology, Vietnam
[3] Bradford-Renduchintala Centre for Space AI, University of Bradford, UK

Oslo – Norway , June 19, 2025

Outline of Presentation

I. Introduction

II. Total Rate-optimized Spatial Resource Allocation

III. Numerical Results

IV. Conclusions

Outline of Presentation

I. Introduction

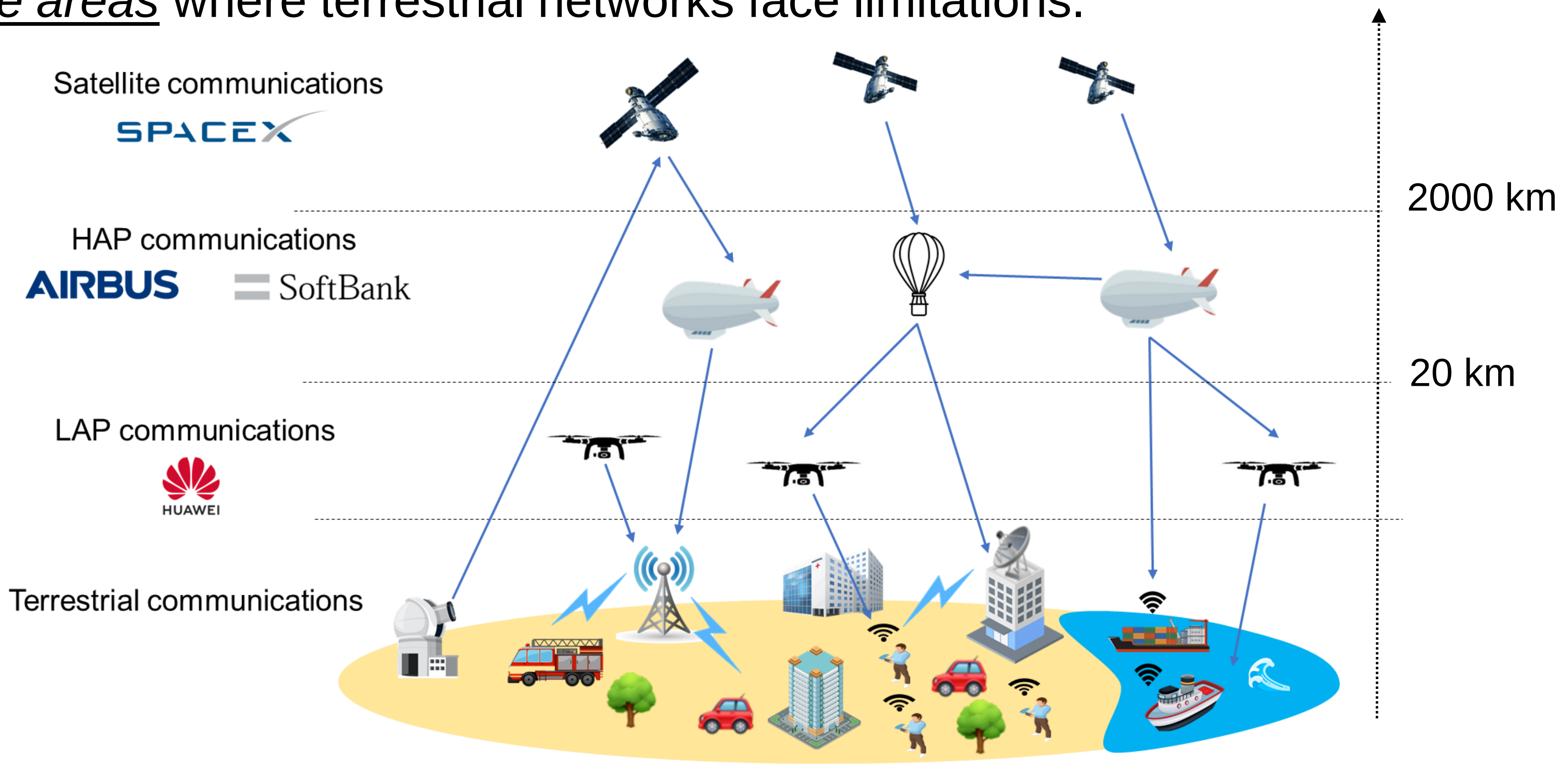
II. Total Rate-optimized Spatial Resource Allocation

III. Numerical Results

IV. Conclusions

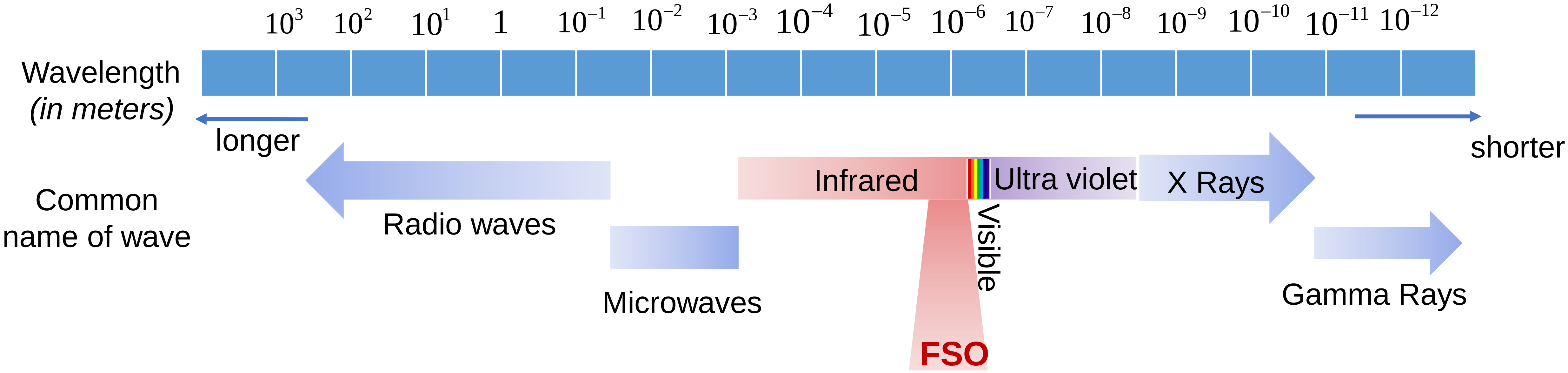
Non-Terrestrial Networks

- Non-terrestrial networks (NTNs) *provide global connectivity* by using satellites, high-altitude platforms (HAP), and UAVs.
- NTNs *enhance traditional ground-based infrastructures*, especially useful for connecting *rural and remote areas* where terrestrial networks face limitations.



- Several successful projects have demonstrated the *feasibility and potential* of NTNs.

- **The Free Space Optical (FSO)-based NTNs can provide high data-rate and wide coverage.**
  - **FSO communications**
    - Using near-infrared frequency bands *(200-400 THz)* to transmit data.
    - High-speed connection (Gbps and even Tbps)
    - Free-license bandwidth



- However, FSO-based NTNs face *constraints on weight, size, power consumption, and hardware complexity*, since aerial platforms must *carry optical components* to receive, process, or transmit data.

The optical IRS-assisted FSO-based NTNs

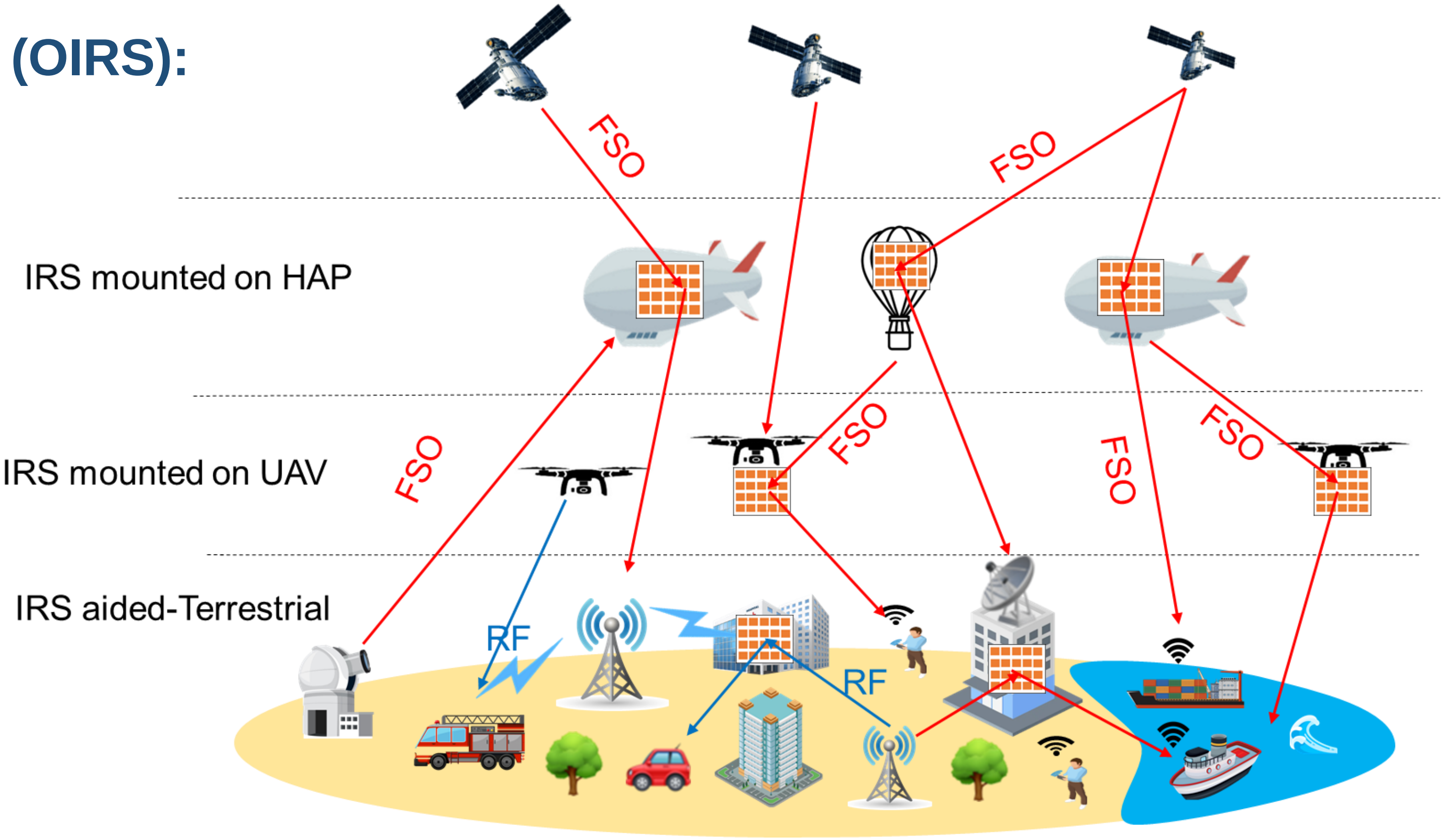
- Many studies have developed ***optical intelligent reflecting surfaces (OIRS)*** as a potential technology to *enhance coverage* while maintaining *low cost, minimal energy consumption, and reduced complexity.*

❖ Optical Intelligent Reflecting Surface (OIRS):

- A surface ***reflects FSO signal*** in a ***controlled way.***
- Comprises: an ***array of mirrors*** or ***metamaterial elements.***
- Nearly-passive: consume low power.

❖ Advantages

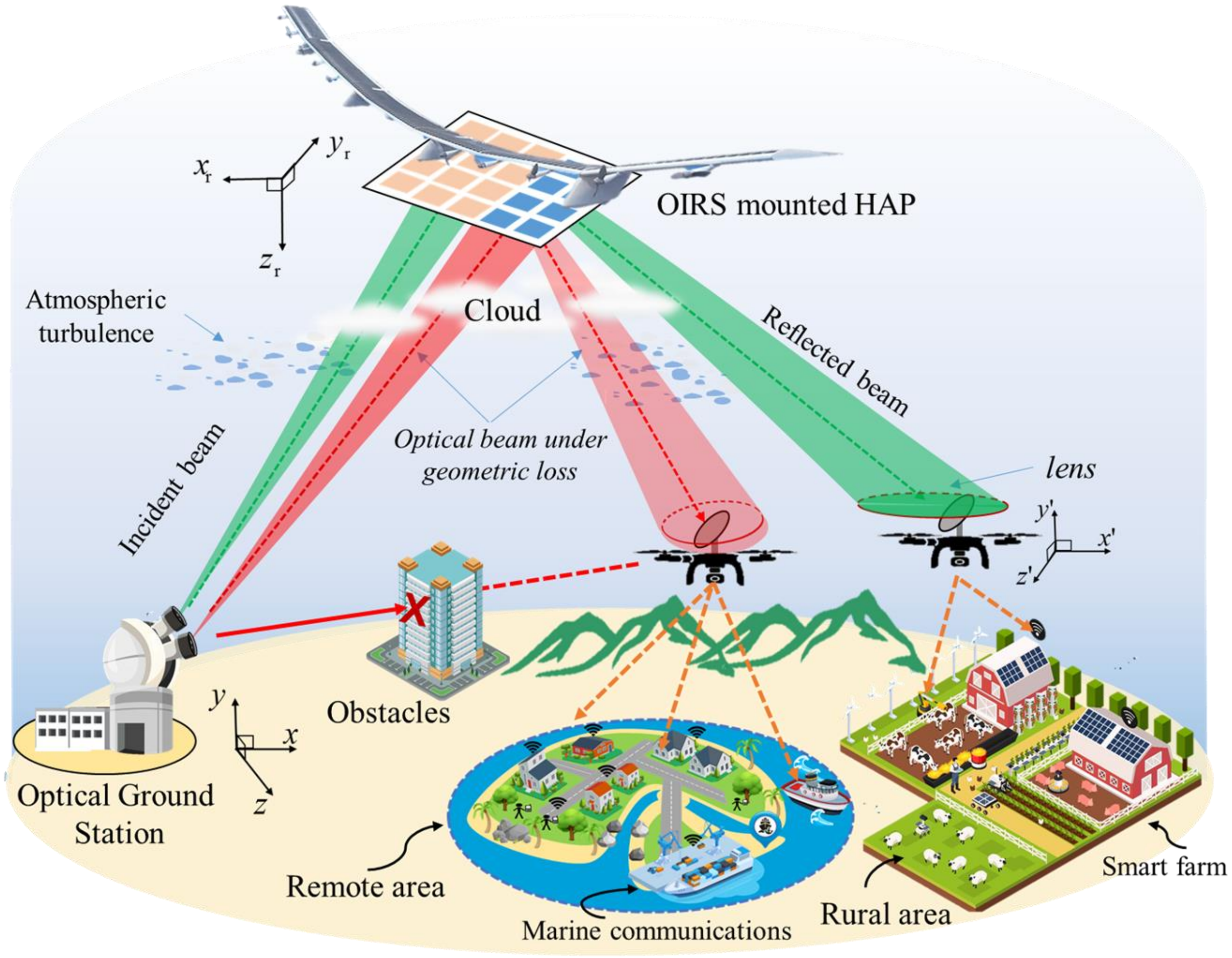
- *Extend coverage and avoid blockage.*
- *Low cost and low energy consumption.*
- *Light payload, reduce hardware complexity compared to relay*



The operation concept of optical IRS

➡ ***The optical IRS-assisted FSO-based NTNs are promising architectures for 6G.***

System Model and Challenging Issue



The optical IRS-aided HAP-assisted Multi-UAV network

❑ System Model:

- **1. Source:** ***N*** **laser sources** in the optical GS.
- **2. One OIRS** (an **array of mirrors**) mounted on HAP.
  - Each mirror can *rotate independently* to reflect the beam to expected users.
- **3. Destinations:** ***N*** **UAVs-**mounted base stations in rural/remote areas.

❑ Challenging issue:

The limited OIRS size mounted on HAP creating **critical issues** in **sharing IRS** among multiple UAVs.

Resource Allocation for ***OIRS mounted on HAP*** to support ***multiple UAVs***

Conventional Approaches and Motivations

- To the best of our knowledge, most of the existing studies ***in optical IRS-assisted NTNs*** focus on *single user:* channel modeling and analyze the system's performance [1][2][3]

  => *Resource allocation for multiple users have not been investigated yet.*

Possible Resource Allocation Schemes:

1. ***Equal Spatial Resource Allocation:*** *every users get the same IRS resource [4] [5].*

   => This method *might be inefficient and not maximize the total performance in the optical IRS-assisted NTNs.*

2. ***Fixed Spatial Resource Allocation:*** *each user received a different IRS resource but fixed over time.*

   => This scheme may be *not work well* in the *mobility scenario*, where UAVs are moving.

Our Goal/Contribution:

*We propose a **novel spatial resource allocation scheme** for optical IRS mounted on HAP-assisted multi-UAV networks. This scheme **effectively allocates** IRS resource and **optimize total performance, including mobility scenario.***

Outline of Presentation

I. Introduction

II. Total Rate-optimized Spatial Resource Allocation

III. Numerical Results

IV. Conclusions

Proposed Total Rate-optimized Spatial Resource Allocation (R-SRA)

- We propose a **Total Rate-optimized Spatial Resource Allocation Scheme (R-SRA)** for OIRS mounted on HAP:
  1. Maximize the number of *supported UAVs* **(Phase I)** *Supported UAV: $R_{\text{UAV}} \geq R_{\text{target}}$
  2. Maximize total achievable data rate **(Phase II)**
- **Our Approach:**
  - **Step 1: Analyze the impact of IRS on end-to-end FSO channel.**
    - ✓ *How much IRS resource does each UAV need?*
    - ✓ *What is the required IRS resource for each UAV to meet its QoS?*

Proposed R-SRA

- **Step 2: Maximize the number of supported UAVs in set of *N* UAVs *(PHASE I)***
  - ✓ Allocate the IRS resource to UAV in order of lowest to highest requirement
- **Step 3: Maximize the total achievable data rate *(PHASE II)***
  - ✓ Use exhaustive search to allocate each remaining IRS resource

Step 1. Chanel modeling: analyze the impact of IRS on the e2e FSO channel

- Composite FSO channel coefficient can be calculated by:

$$h = \eta \times h_{gml} \times h_{cloud} \times h_t$$

Imperfect reflection of IRS

Cloud attenuation

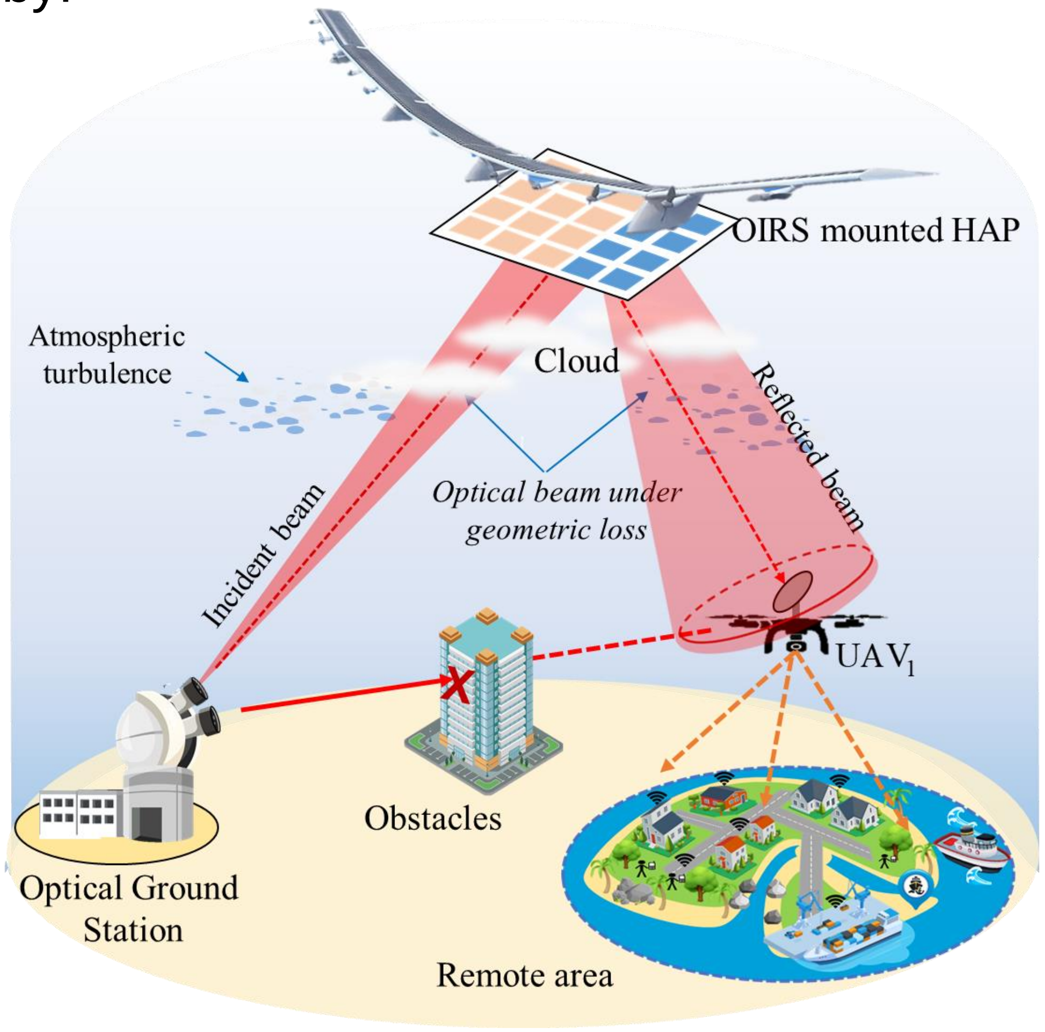
Atmospheric turbulence

Geometric loss

Received beam footprint

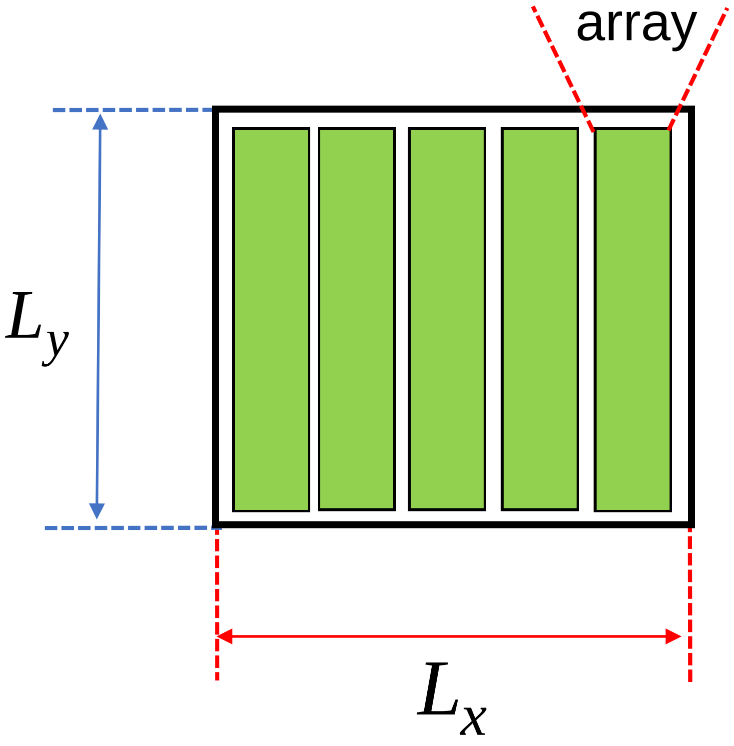
Lens

IRS size



Step 1. Chanel modeling: analyze the impact of IRS on the e2e FSO channel

✓ *What is the **required IRS resource** for each UAV to **meet its QoS**?*



An IRS resource = An array

Required IRS array

$$\text{QoS: } R_{\text{target}} \rightarrow \gamma_{threshold} \rightarrow h^* \rightarrow h^*_{gml} \rightarrow S^*_{irs} \rightarrow L^*_x = \frac{S^*_{irs}}{L_y}$$

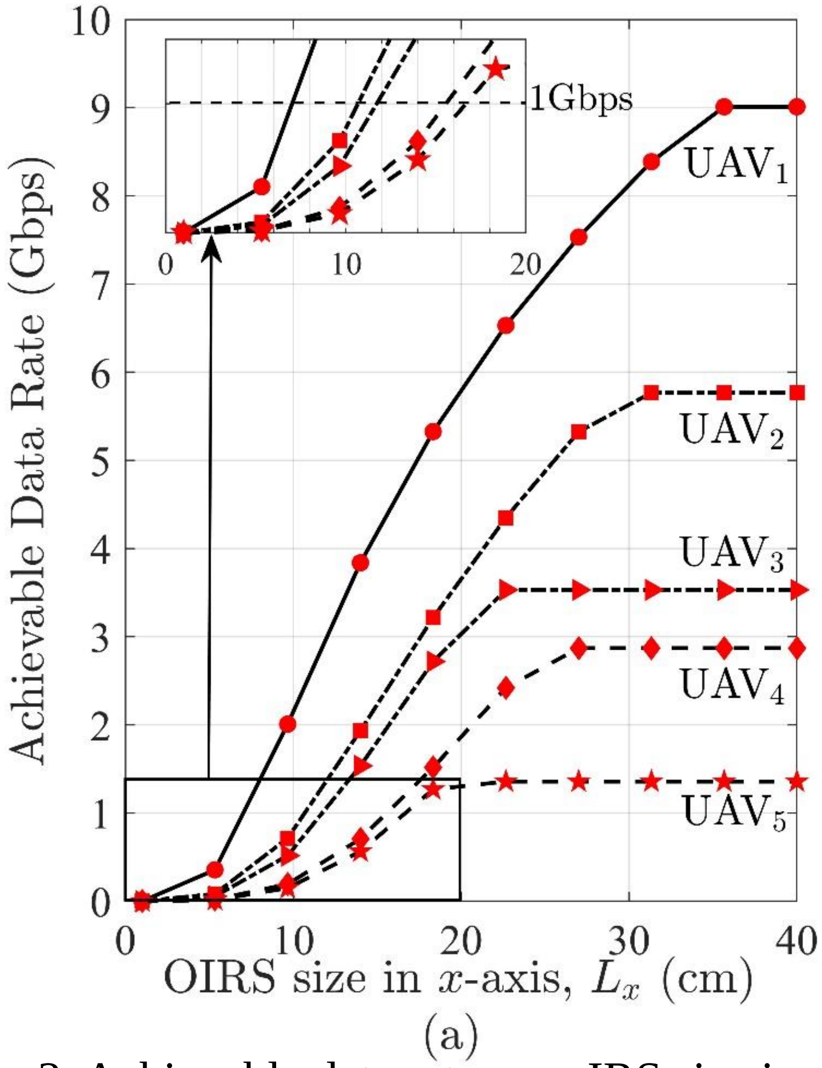
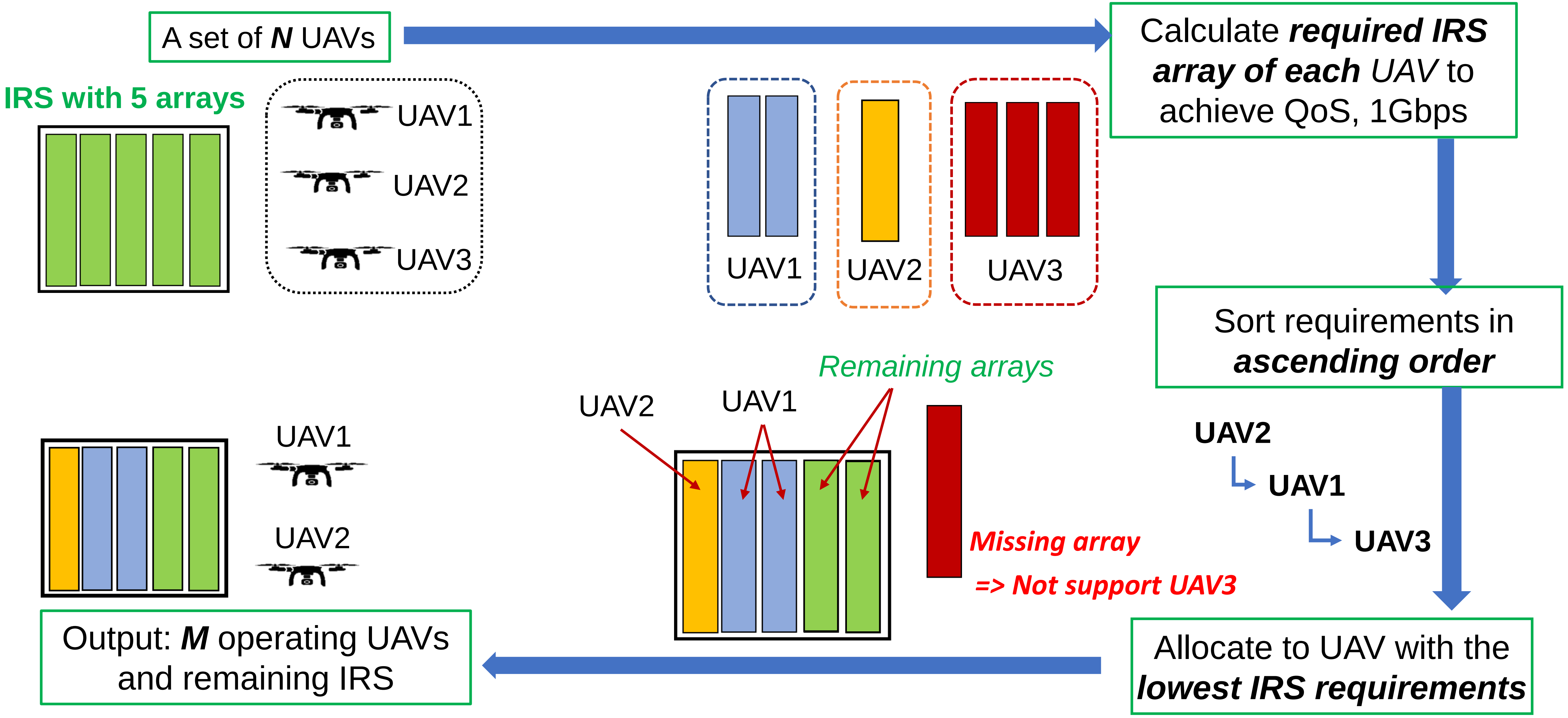


Figure 2. Achievable data rate over IRS size in x-axis

Step 2. Maximize the number of supported UAVs *(Phase I)*



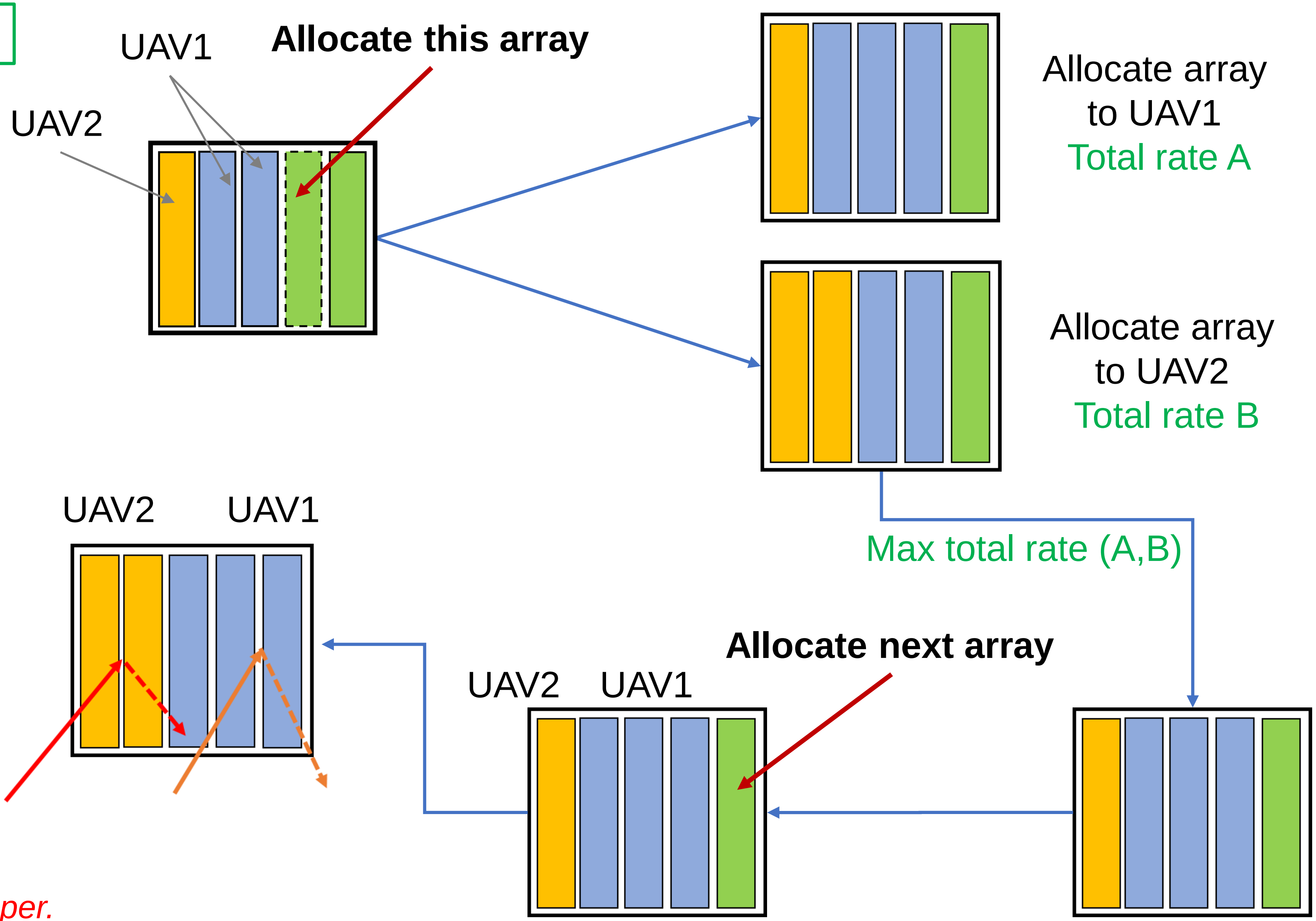
**For the algorithm, please refer to my paper.*

M operating UAVs from **Phase I**

Each remaining array: calculate total rate when allocate that array to each UAVs

Identify UAV providing highest total rate

Output: Total rate and IRS array for each UAVs



**For the algorithm, please refer to my paper.*

Outline of Presentation

I. Introduction

II. Total Rate-optimized Spatial Resource Allocation

III. Numerical Results

IV. Conclusions

Benchmarks and Parameters Setting

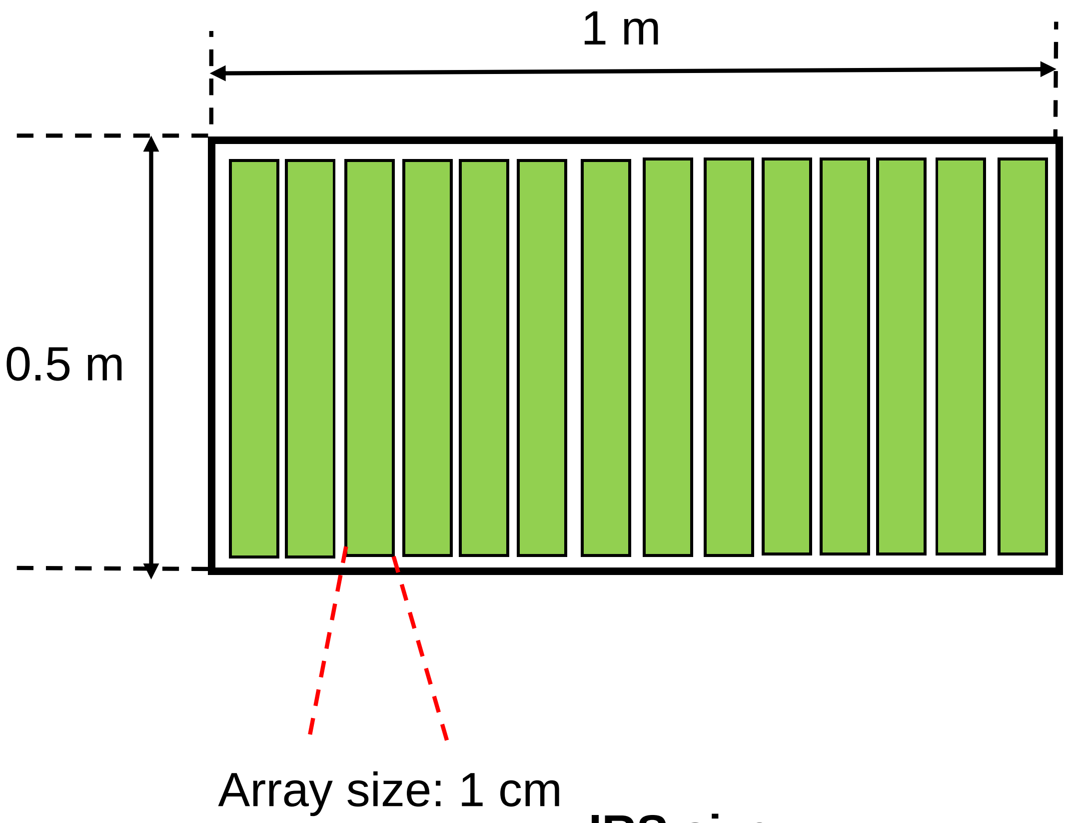
- To evaluate our proposed scheme, we compare it with ***two benchmarks***:

  (1) Conventional SRA: maximize the number of users (Phase I) + Equal allocation remaining arrays.

  (2) Uniform Resource Allocation (URA): the IRS is shared equally among all users from the start.

Name	**Symbol**	**Value**
UAV$_i$ altitude (m)	$H_{\mathrm{U},i}$	100, 120, 150, 200, 250
Reflected angle	θ_r	14°, 16°, 18°, 20°, 22°
Wavelength (nm)	λ_i	1570 , 1565, 1560 , 1555 , 1550
CLWC (mg/m^3)	$L_{c,i}$	0.5 , 1, 1.5 , 1.5 , 2
Targeted Rate (QoS)	$R_{\mathrm{target},i}$	1 Gbps
Bandwidth	B	1 GHz

Table II. A set of 5 UAVs with different locations, channel conditions.



IRS size

The Effectiveness of Proposed R-SRA

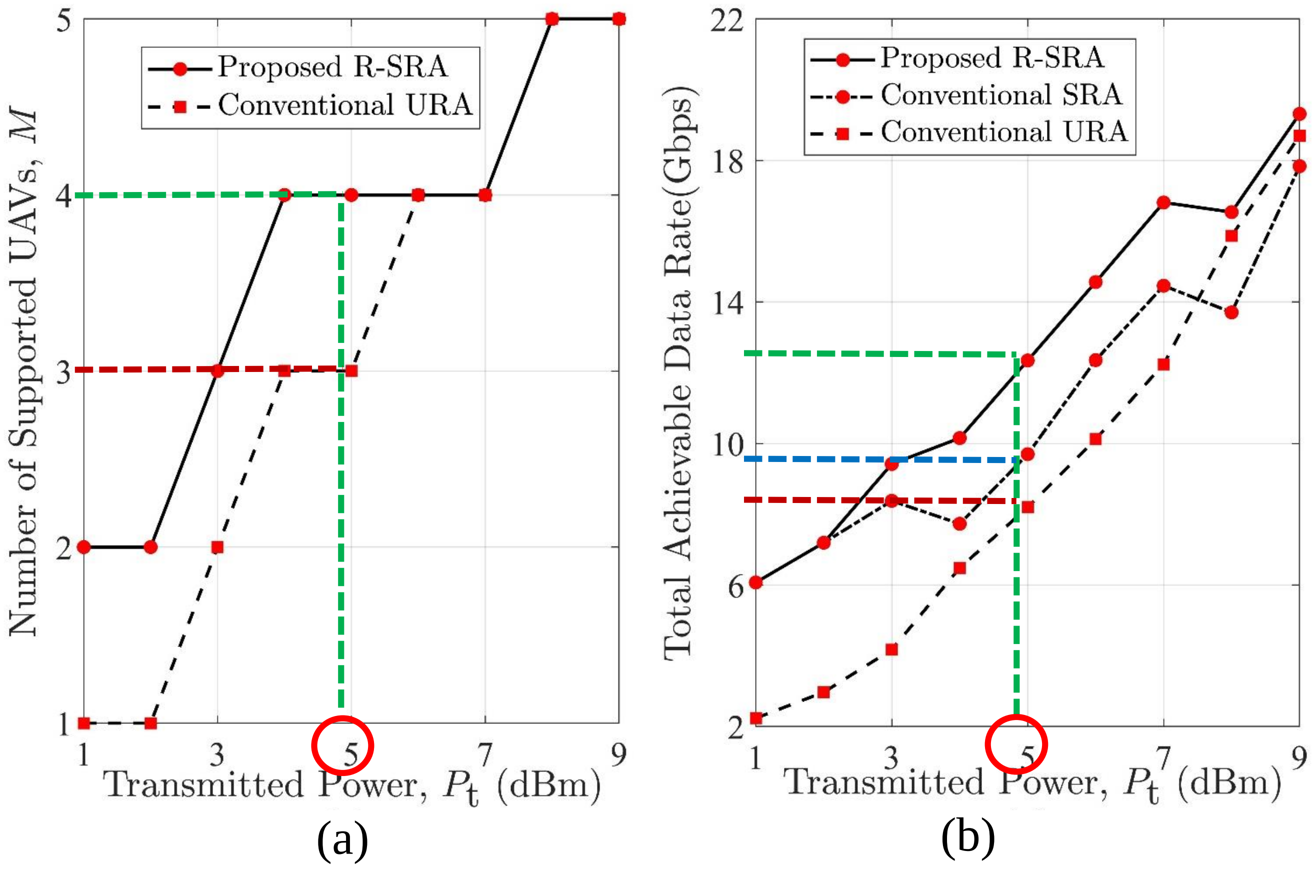


Figure 3. The effectiveness of proposed R-SRA.

- The proposed R-SRA ***outperforms the other allocation schemes*** by ***supporting more UAVs*** and providing a ***higher total achievable rate*.**
- The proposed R-SRA ***ensures the minimum required IRS arrays to as many UAVs as possible***, and then ***allocates the remaining arrays in an efficient way.***

Investigation of Proposed R-SRA in Mobility Scenario

- ❑ UAV1 and UAV2 move far away from IRS for 2400 seconds at velocity of 30 km/h.
  - UAV3,UAV4 and UAV5 are stable

- ❑ R-SRA ***consistently outperforms*** the two conventional schemes, demonstrating its effectiveness in adapting to dynamic UAV movements.

- ❑ R-SRA ***dynamically allocates*** the IRS array for each UAV over time.

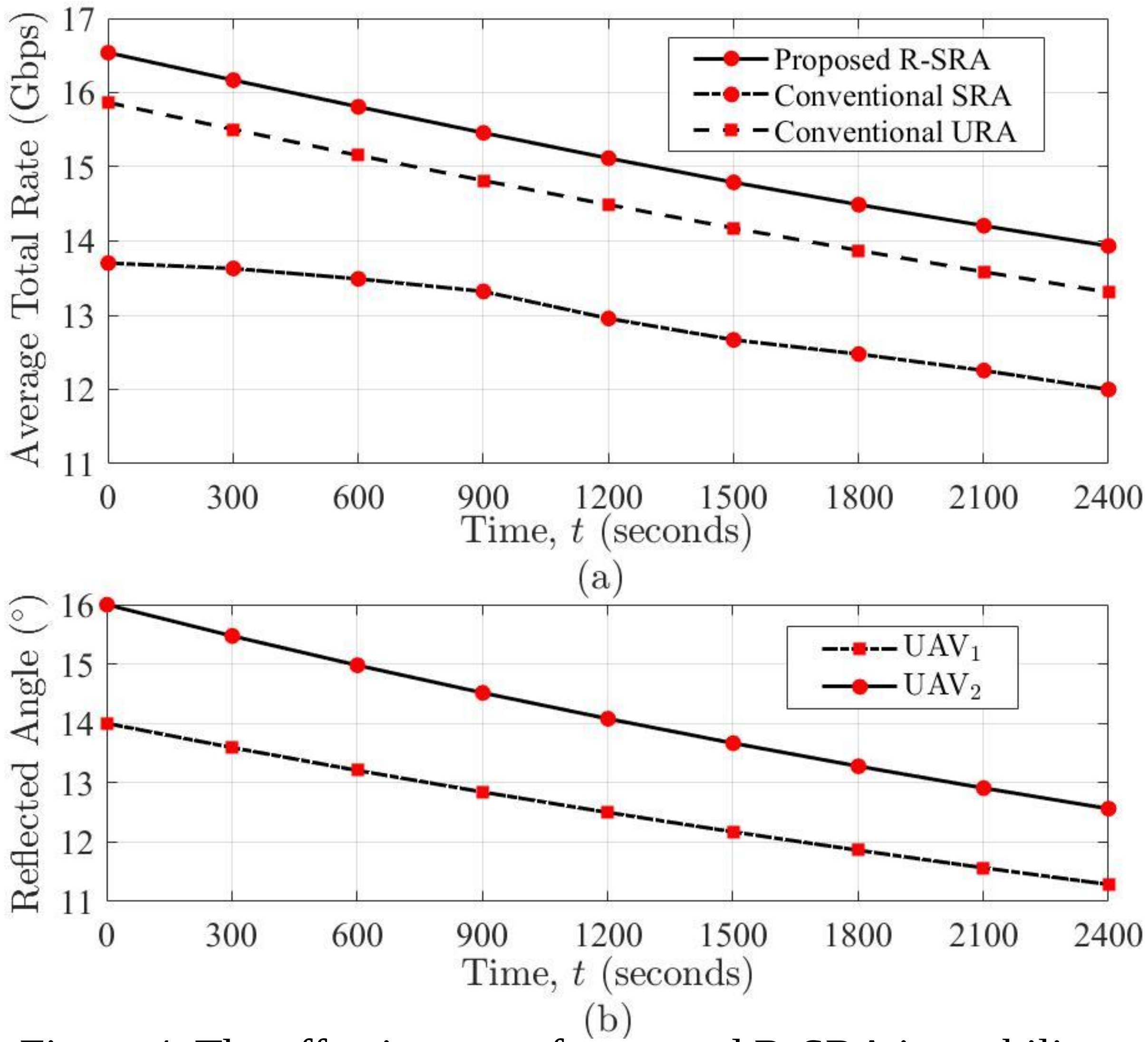


Figure 4. The effectiveness of proposed R-SRA in mobility scenario

**Transmitted power: 8 dBm, 5 operating UAVs.*

Conclusions

- ❖ **In this work, we proposed a *novel total rate-optimized spatial resource allocation* for *optical IRS-aided HAP-assisted multi-UAV networks*.**
  - ❑ The proposed scheme **effectively allocates** IRS resource to **maximizes the number of operating UAVs** at first and **maximizes the total achievable data rate**.
  - ❑ Numerical results confirmed the **effectiveness of proposed scheme** compared to conventional schemes, including the **mobility scenario.**
  - ❑ The results also **provided insights** into the selection of transmitted power to meet specific performance requirements.

THANK YOU FOR LISTENING!

References

[1] A. -A. A. Boulogeorgos, A. Alexiou and M. D. Renzo, "Outage Performance Analysis of RIS-Assisted UAV Wireless Systems Under Disorientation and Misalignment," in IEEE Transactions on Vehicular Technology, vol. 71, no. 10, pp. 10712-10728, Oct. 2022, doi: 10.1109/TVT.2022.3187050.

[2] X. Li, Y. Li, X. Song, L. Shao and H. Li, "RIS Assisted UAV for Weather-Dependent Satellite Terrestrial Integrated Network With Hybrid FSO/RF Systems," in IEEE Photonics Journal, vol. 15, no. 5, pp. 1-17, Oct. 2023, Art no. 7304217, doi: 10.1109/JPHOT.2023.3314664.

[3] Y. Ata, A. M. Vegni and M. -S. Alouini, "RIS-Embedded UAVs Communications for Multi-Hop Fully-FSO Backhaul Links in 6G Networks," in IEEE Transactions on Vehicular Technology, vol. 73, no. 10, pp. 14143-14158, Oct. 2024, doi: 10.1109/TVT.2024.3414850.

[4] H. Ajam, M. Najafi, V. Jamali, B. Schmauss and R. Schober, "Modeling and Design of IRS-Assisted Multilink FSO Systems," in IEEE Transactions on Communications, vol. 70, no. 5, pp. 3333-3349, May 2022, doi: 10.1109/TCOMM.2022.3163767

[5] G. D. Chondrogiannis, A. P. Chrysologou, A.-A. A. Boulogeorgos, N. D. Chatzidiamantis, and H. Haas, “Optical ris-enabled multiple access communications,” 2025. [Online]. Available: https://arxiv.org/abs/2502.06691