Computer Communication Laboratory

Research Seminar

Resource Allocation for Optical IRS-Assisted Multi-UAVs Networks

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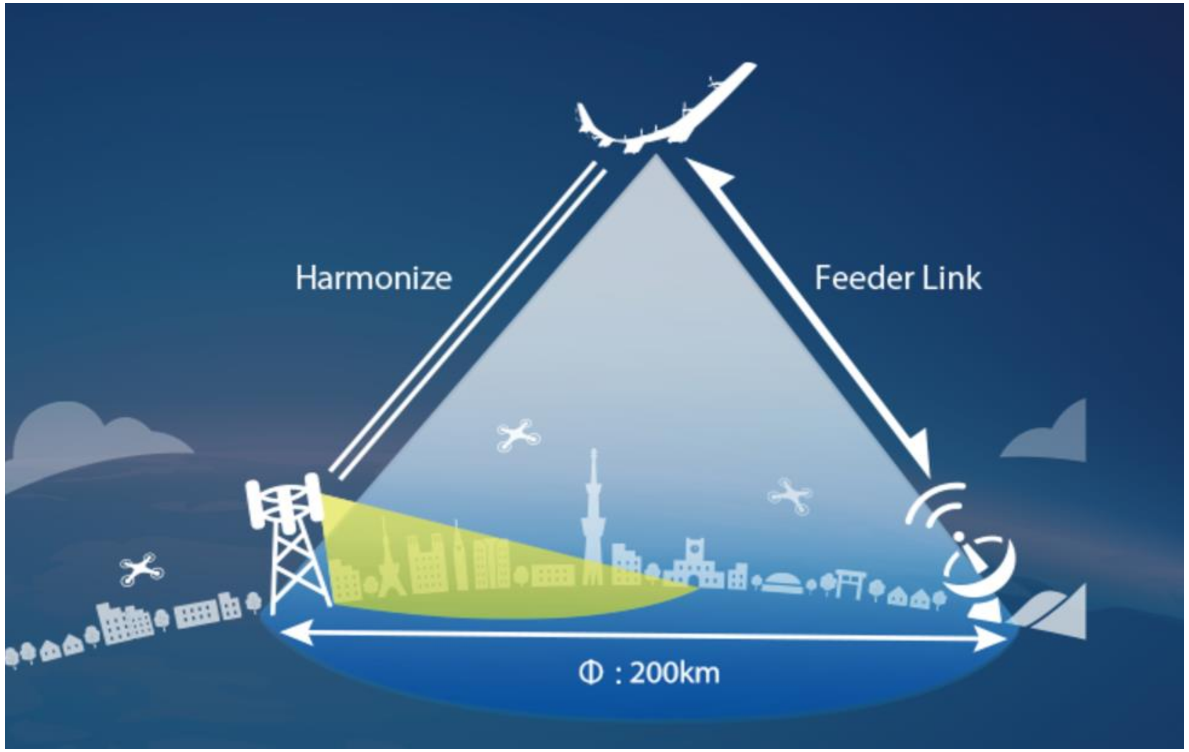
Aizuwakamatsu, Dec. 5 2024

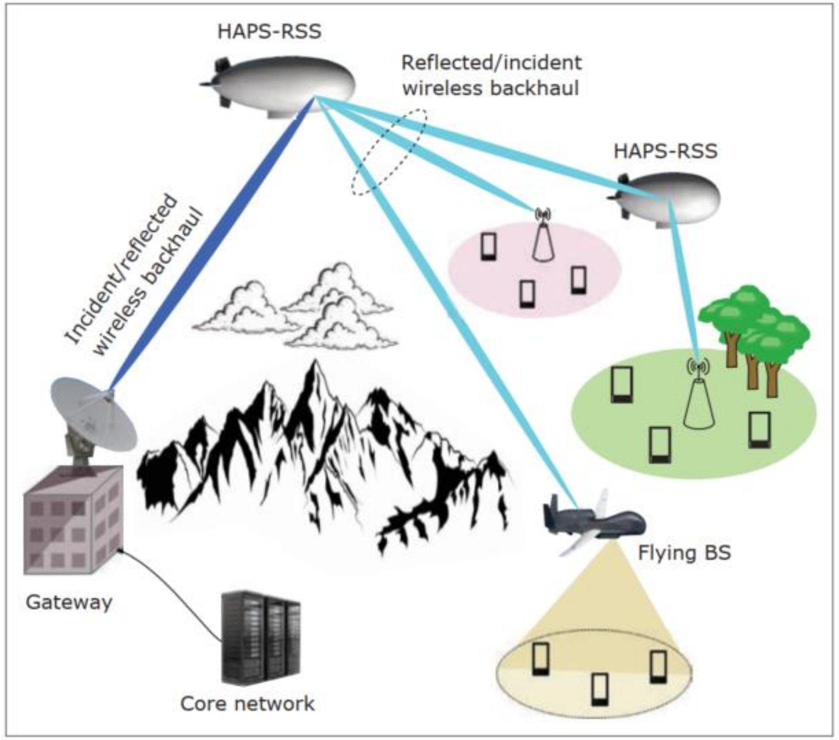
Outline of Presentation

1. Research Background: the FSO-based HAP networks

In recent years, the success of various projects involving HAPs (e.g., SoftBank's Sunglider in Japan) has emerged potential of using HAP to support a wide coverage and provide internet from space.



Internet from space by **high altitude platform (HAP) by SoftBank [1]**

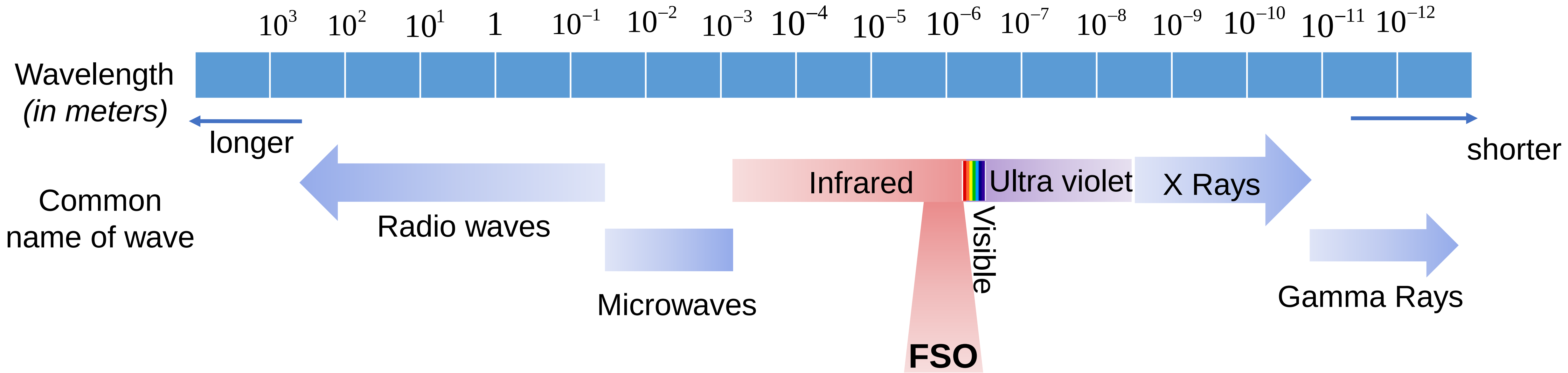


Backhauling support isolated users in remote rural areas using HAP

- Moreover, HAPs can serves ***as a relay node*** between core network other base stations to provide connectivity for end-users in rural/remote areas.

❖ Free Space Optical (FSO) communications

- Using near infrared frequency bands *(200-400 THz)* to transmit data.
- High-speed connection (Gbps and even Tbps)
- Free-license bandwidth



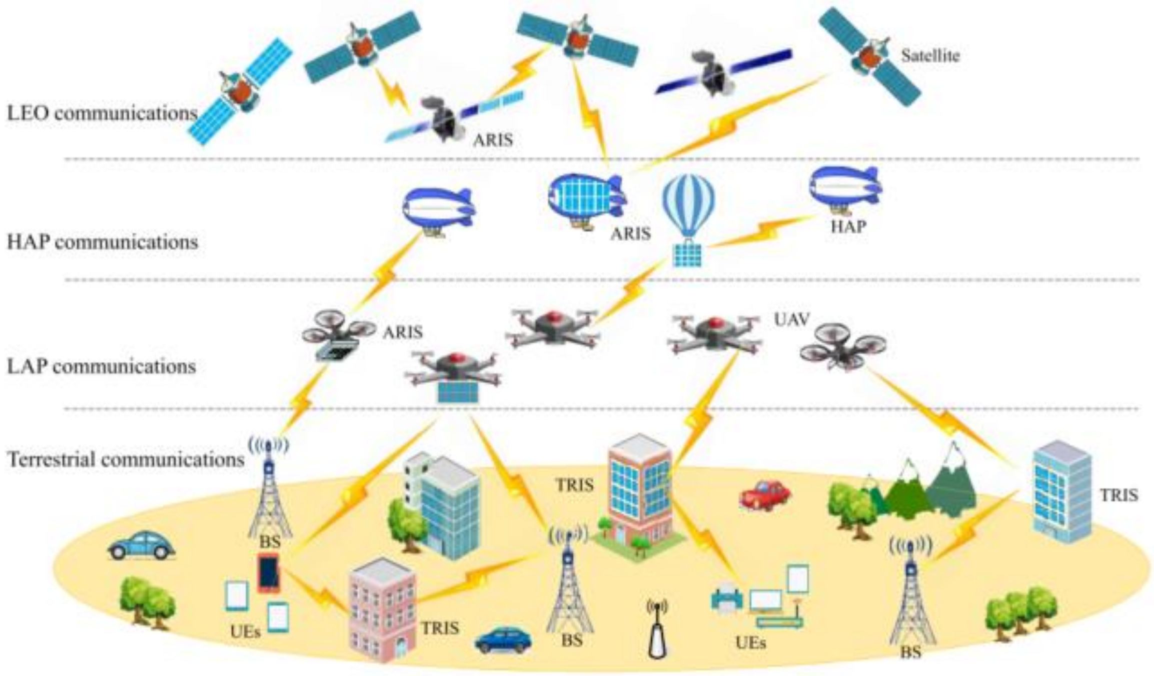
➡ **The FSO-based HAP system can provide *high data-rate and wide coverage.***

➡ However, using HAP as a relay can lead to *power consumption* and *hardware complexity*.

Recently, many studies have developed ***Intelligent reflecting surface (IRS)*** as *a green* and *alternative solution* of conventional relay networks.

❖ Optical Intelligent Reflecting Surface (OIRS):

- A surface is used to ***reflect signal*** in a ***controlled way.***
- Comprises: an ***array of mirrors*** or ***metamaterial elements.***
- ***Nearly-passive:*** only low power is used for the microcontroller to *control every OIRS element* to "reflect" incident laser beam *into the expected direction.*

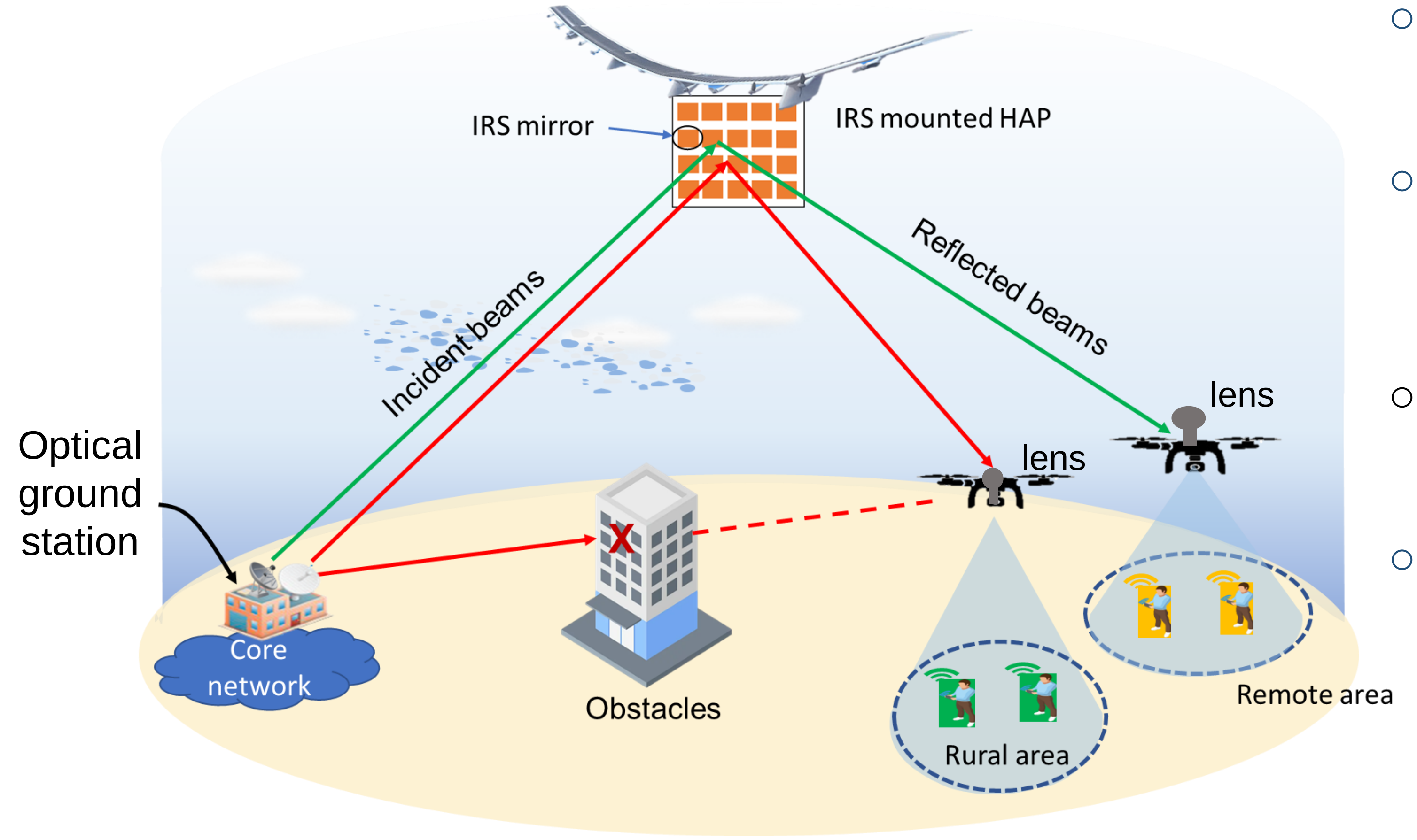


The operation concept of IRS [1]

❖ Advantages

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

➡ ***OIRS can be equipped in HAP to reflect the FSO signal.***



FSO-based HAP-Assisted Multi-UAVs with IRS

❖ System description:

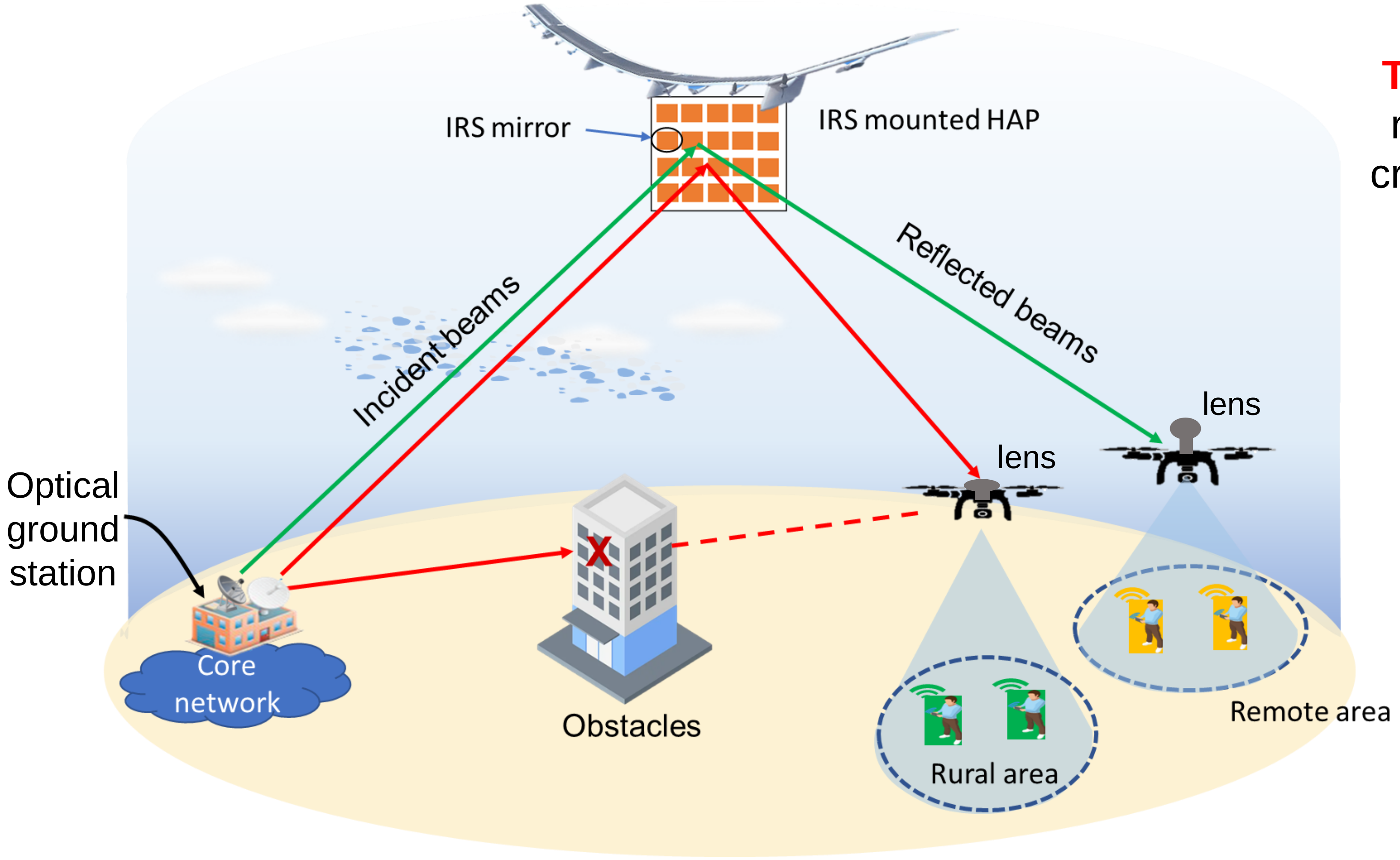
- **1. Source:** multiple laser sources in the optical ground station.
- **2.** One OIRS (an array of mirrors) mounted HAP.

$$\sum irs = L_x \times L_y$$

- Each mirror can rotate independently with angle θ to reflect the beam to expected users.
- **3. Destinations:** multiple UAVs mounted base stations in rural/remote areas.

❖ **Application:** provide the internet connection to rural/remote areas where ground base stations are unavailable or assumed to be blockage connection.

3. Problem Statement and Goal



Limited OIRS Resources

The limited OIRS size mounted in HAP restricts the number of OIRS elements, creating ***critical issues*** in **sharing these elements** among multiple UAVs.

Resource Allocation for OIRS to support multiple UAVs

Given:

- Different channel conditions
- Maintain targeted Quality of Service (QoS) among all UAVs

❑ Goal:

Resource Allocation for OIRS to support multiple UAVs based on channel conditions to ***maximize the total achievable rate*** while ***maintaining targeted QoS*** (minimum achievable rate) among all UAVs.

❑ Steps:

- **Step 1:** Analyze ***the impact of IRS element to channel condition.***

$$h = f\left(h_a, h_t, h_{gml}\right) = f\left(\sum irs\right)$$

How much the received power grows by increasing the number of IRS elements (mirrors)?

- **Step 2:** Calculate the ***minimum number of IRS elements*** to satisfy the targeted QoS.

$$\text{Achievable rate} = f\,(SNR) = f\left(P_{received}\right) = f\left(h\right) = f\left(\sum irs\right)$$

How many required IRS elements to achieve a targeted QoS?

- **Step 3:** Apply algorithm, i.e., exhausted search to ***allocate the remaining IRS elements*** to maximize the total achievable rate.

How to allocate the remaining IRS elements to maximize total rate?

Composite Channel model: $h = \eta \times h_p \times h_t \times h_{gml}$

- **IRS reflection coefficient:** imperfect reflection of IRS, η
- **Atmospheric loss:** laser beam energy loss due to absorption and scattering.

$$h_p = \exp\left(-\zeta(L_1 + L_2)\right)$$

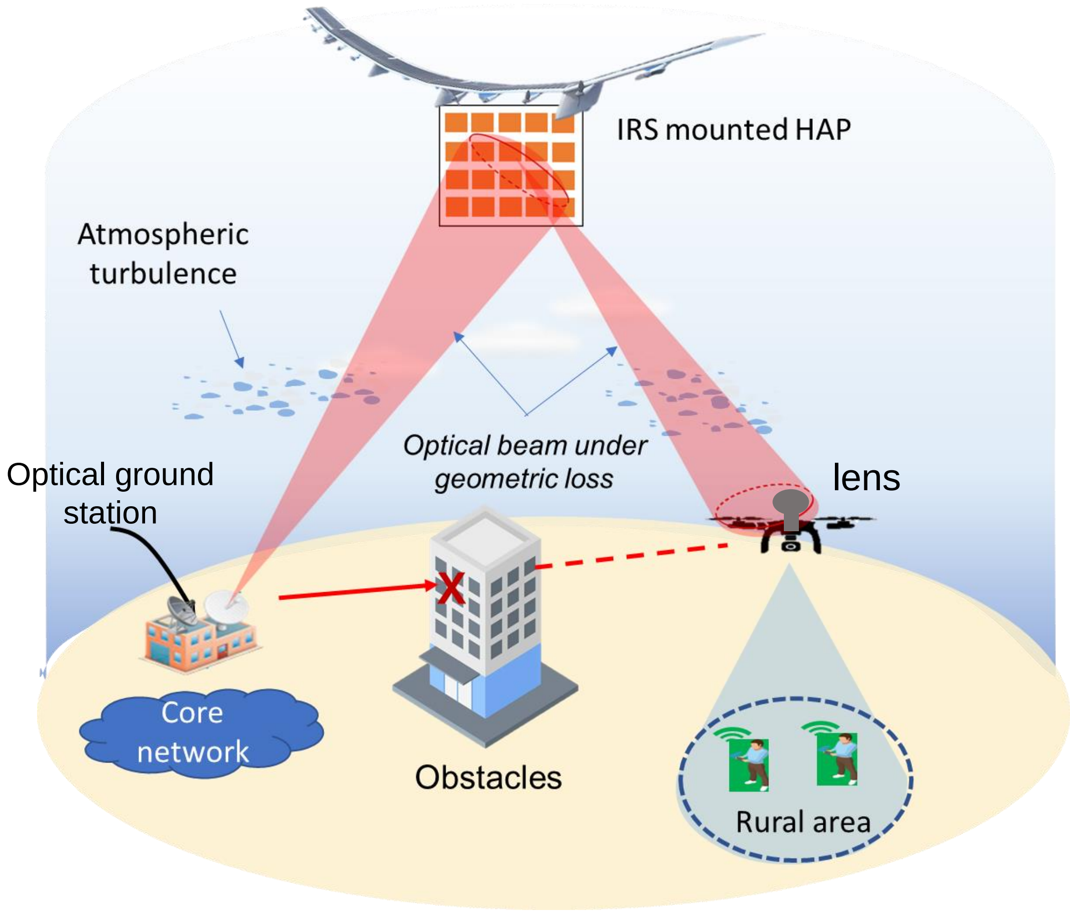
ζ : attenuation coefficient

L_1, L_2 : distance between GS-IRS, IRS-UAV

- **Atmospheric turbulence:** random variation of temperature and pressure of atmospheric cause the scintillation effect.

$$\left.\begin{array}{l} h_{t,1} \sim GG(\alpha_1, \beta_1) \\ h_{t,2} \sim GG(\alpha_2, \beta_2) \end{array}\right\} \quad h_t = h_{t,1} \times h_{t,2} \approx GG$$

- **Geometric loss:** deterministic geometric loss due to the divergence of laser beam along the transmission path.



- **Geometric loss:** $h_{gml} = \dfrac{\text{Received power at lens}}{\text{Total power}}$

$\sum irs = L_x \times L_y$: area of IRS

A_{in} : area of incident beam footprint

A_{rx} : area of reflection beam footprint radius

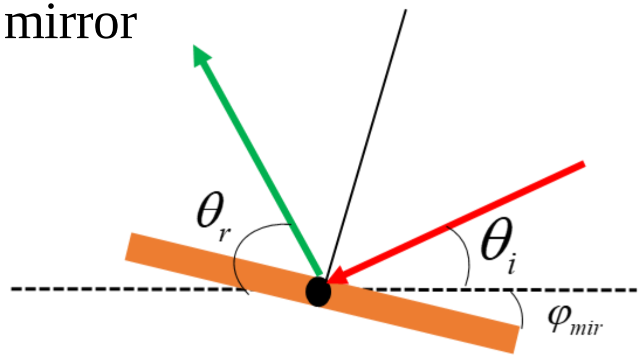
$\sum lens$: area of receiver lens

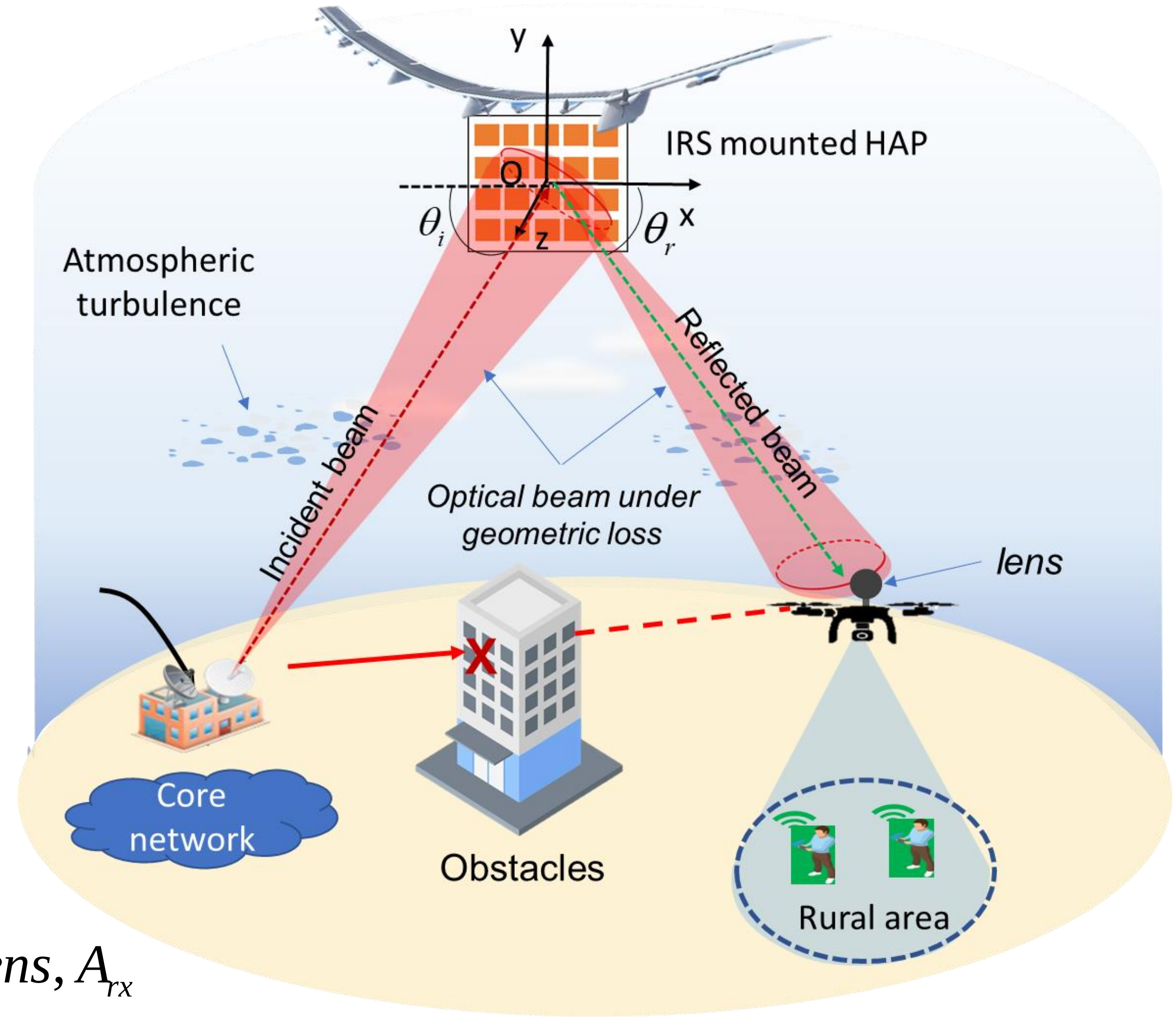
θ_i : angle between xy-plane and incident beam

θ_i : angle between xy-plane and reflected beam

φ_{mir} : elevation angle of mirror

$$\varphi_{mir} = \frac{|\theta_i - \theta_r|}{2}$$





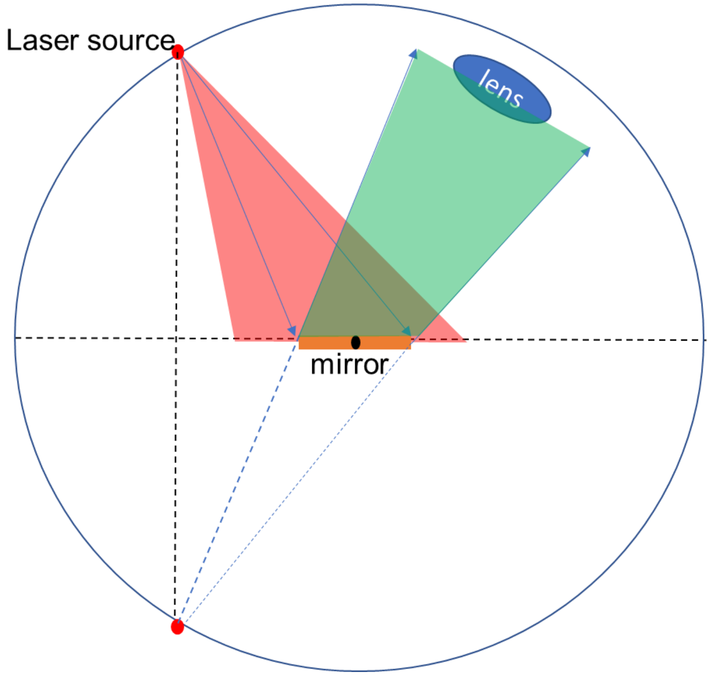
- Based on the relationship between $\sum irs, A_{in}, \sum lens, A_{rx}$

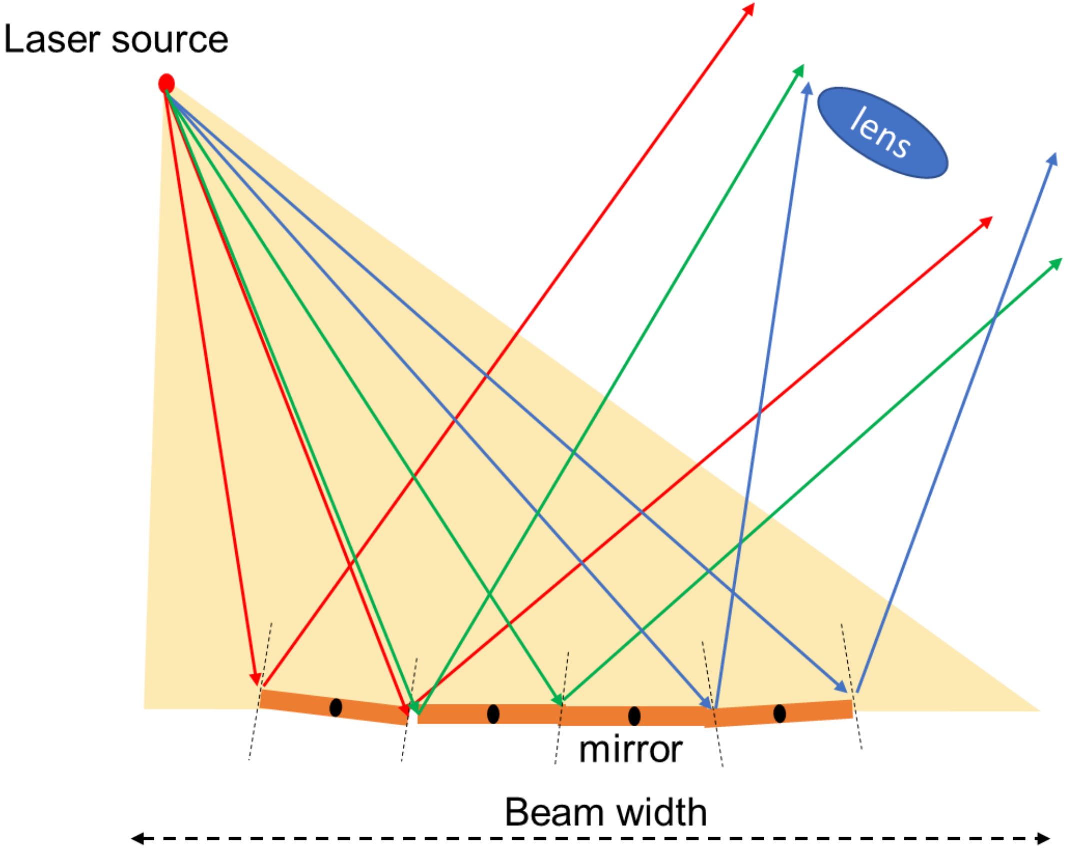
➡ The geometric loss fluctuates by three regimes.

❑ Geometric loss

$$\text{Regime 1}: \sum irs \ll A_{in}, \sum lens \ll A_{rx}$$

$$h_{gml,1} = \frac{16\pi^2 \left(\sum irs\right)^2 \left|\sin\theta_i\right|}{\lambda^4} \times g_{LS} \times g_{PD}$$





- *The IRS, lens* is *much smaller* than beam footprints.
- Beam can be approximated by a *plane wave*.
- Increase the IRS size, the received power increases.

- As increase the size of IRS, beam becomes narrower that introduces the *coherent superposition* of reflected signal (*beamforming gain*).

$$h_{gml} \sim \left(\sum irs\right)^2 : \text{quadratic power scaling regime}$$

Geometric loss

$$\text{Regime 2}: \sum irs \ll A_{in}, \sum lens \gg A_{rx}$$

$$h_{gml,2} = \frac{4\pi \sum irs \left|\sin\theta_i\right|}{\lambda^2} \times g_{LS}$$

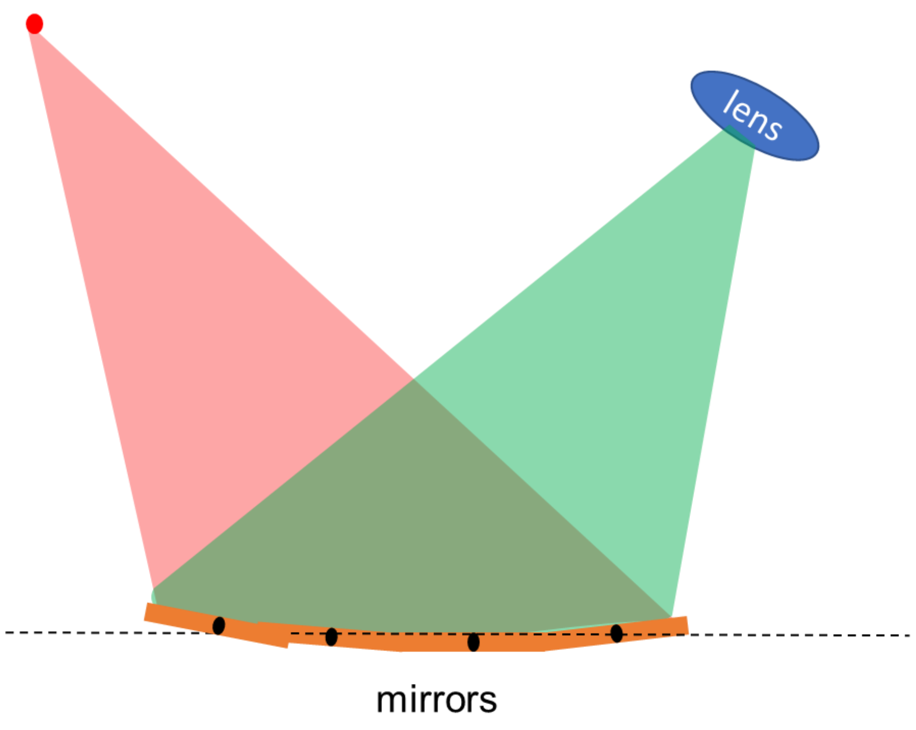
$$\Rightarrow \quad h_{gml} \sim \left(\sum irs\right): \text{linear power scaling regime}$$

$$\text{Regime 3}: \sum irs \gg A_{in}, \sum lens \gg A_{rx}$$

$$h_{gml,3} = \left[erf\left(\sqrt{\frac{\pi}{2}} \frac{a}{\omega_{rx}} \right) \right]^2$$

- Total incident power is reflected by IRS and captured by lens.
- Lens size is a limiting factor for the received power.

$$\Rightarrow \quad h_{gml} \not\subset \left(\sum irs\right): \text{Saturated power scaling regime}$$



- As the size of IRS increases, *beamforming gain of IRS saturates* and *cannot* further increase the received power.
- Increasing the IRS size, the received power increases only linearly.

What are the boundaries among three regimes ?

- The boundary between quadratic regime and linear regime can be determined by

$$h_{gml,1} \leq h_{gml,2}$$
$$\Rightarrow \sum irs \leq \frac{\lambda^2 L_2^2}{\pi a^2 \left|\sin\left(\theta_r\right)\right|} = S_1$$

- The boundary between linear regime and saturated regime can be determined by

$$h_{gml,2} \leq h_{gml,3}$$
$$\Rightarrow \sum irs \leq \frac{h_{gml,3} \lambda^2 L_2^2}{2\pi \left|\sin\left(\theta_i\right)\right|} = S_2$$

- Consequently, the geometric loss scales with IRS size as follow: $h_{gml} = \begin{cases} h_{gml,1} & \text{if } \sum irs < S_1, \\ h_{gml,2} & \text{if } S_1 \leq \sum irs \leq S_2, \\ h_{gml,3} & \text{if } \sum irs > S_2. \end{cases}$

Geometric loss

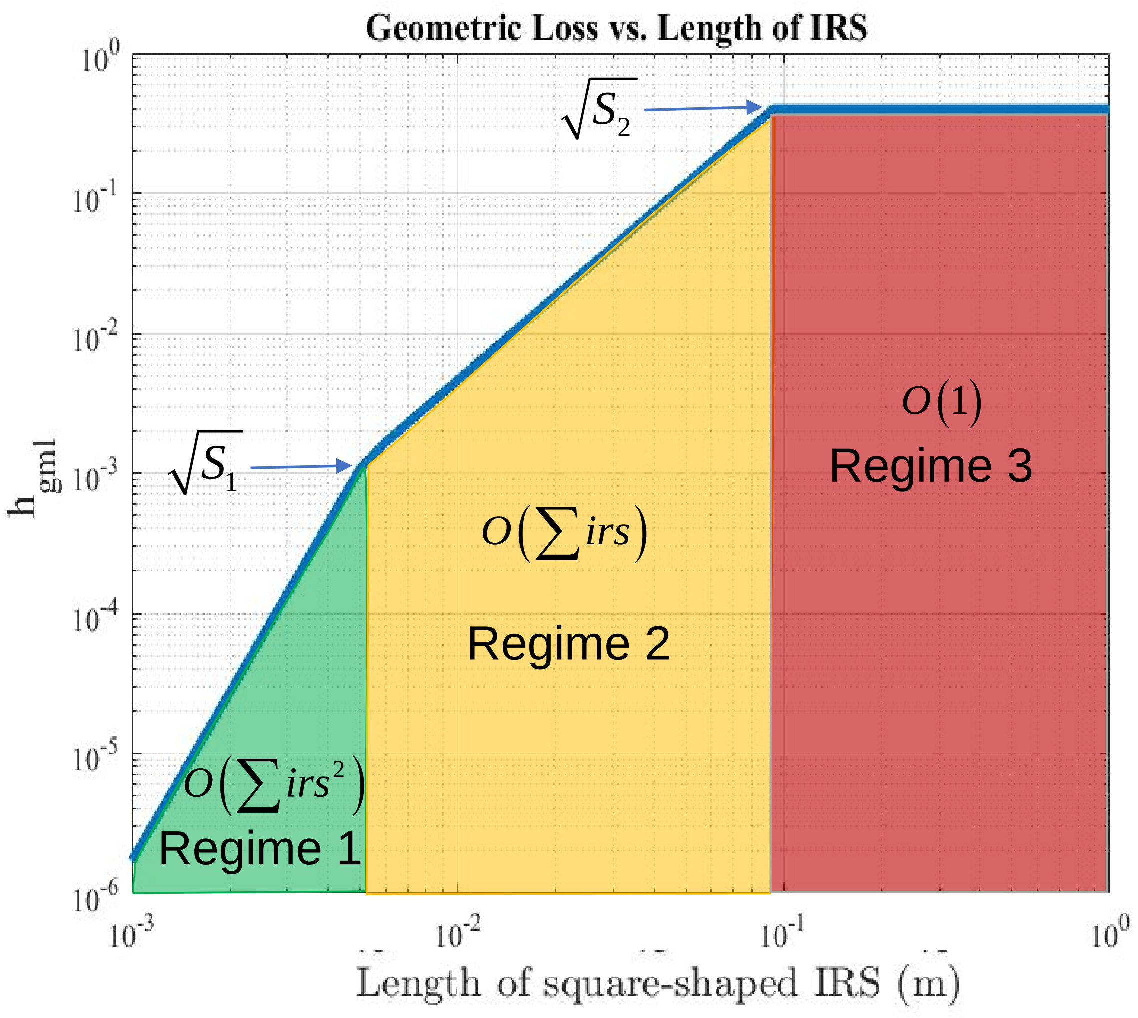


Figure 1

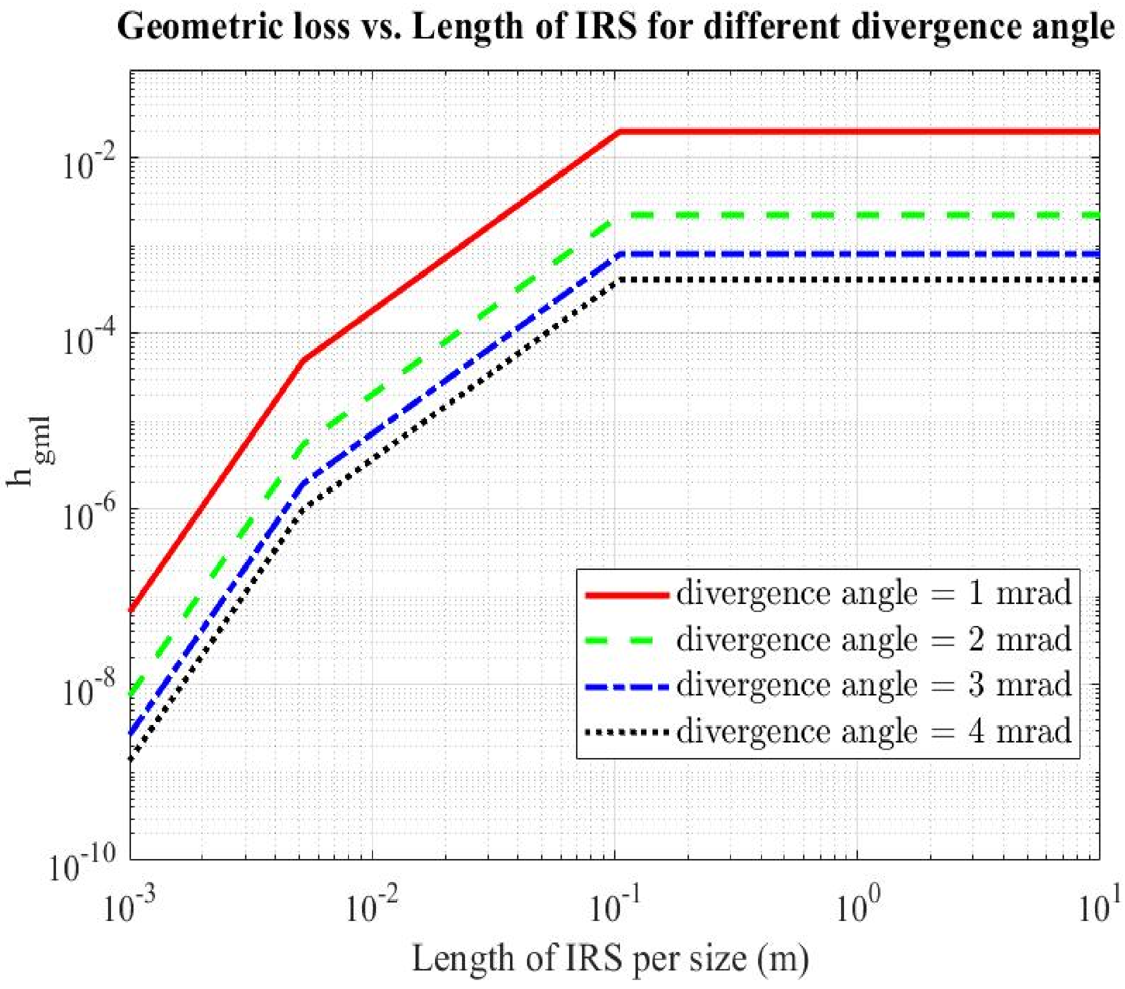
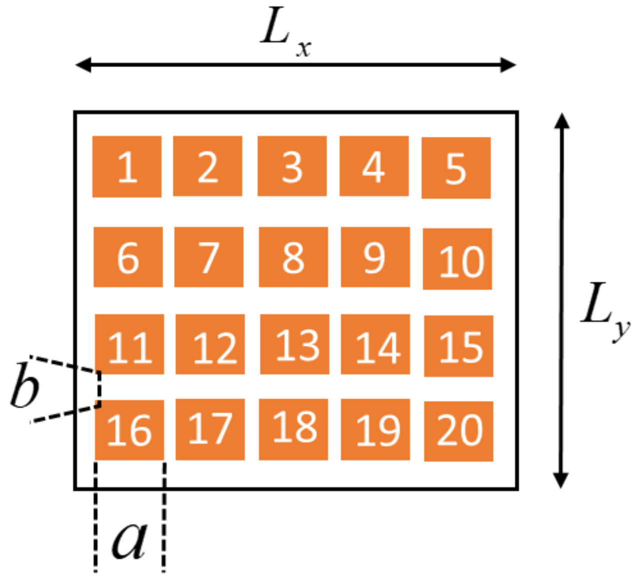


Figure 2



$$P_{received} = P_{transmit} h_a h_p h_{gml}$$

$$h_{gml} = f\left(\sum irs\right) = f\left(L_x \times L_y\right)$$

$$L_x = L_y = n \times a + (n+1) \times b$$

$$n = \left\lceil \frac{L_x - b}{(a+b)} \right\rceil$$

$\tau_i = f(n) \geq 1$ Gbps (targeted QoS)

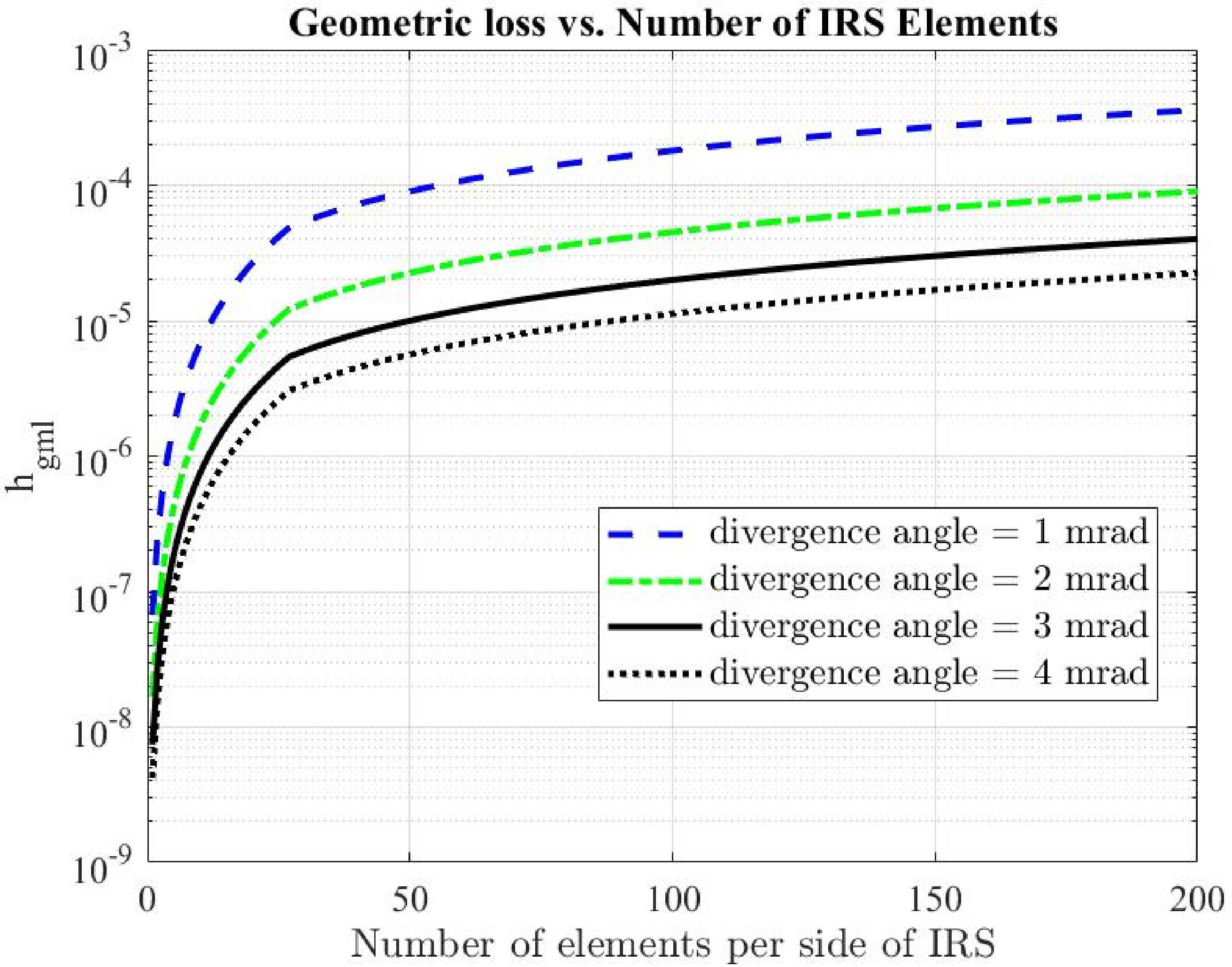


Figure 3

THANK YOU FOR LISTENING!