Computer Communication Laboratory

Research Seminar: Idea proposal

Intelligence Reflecting Surface for Free Space Optical Communication Systems

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Outline of Presentation

I. Research Background

- The FSO communication system
- The optical IRS

II. The optical IRS-assisted terrestrial network

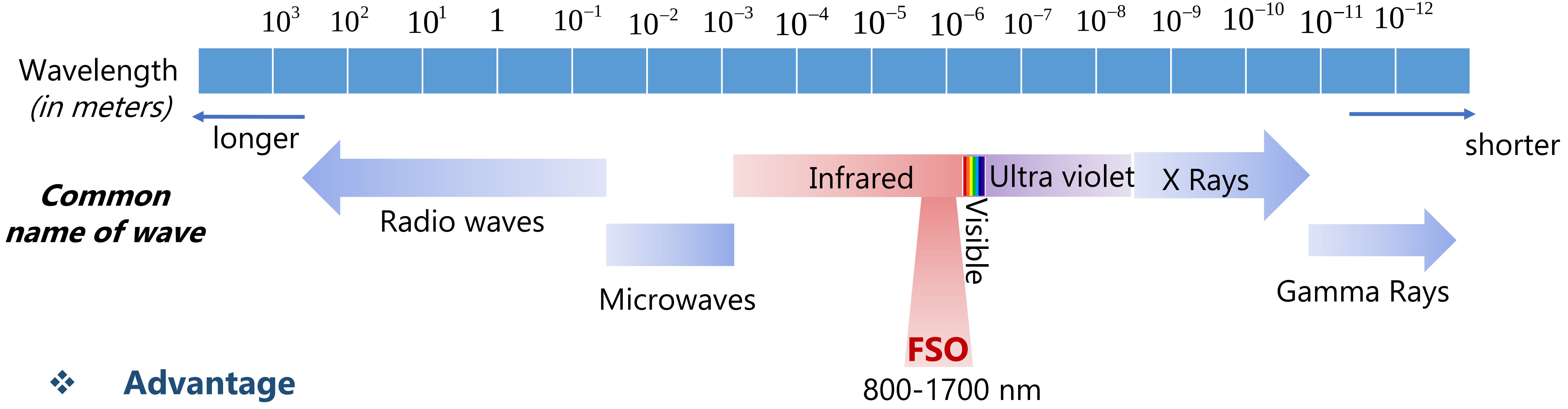
III. The optical IRS-assisted HAP networks

IV. Idea proposal 1: Problem statement and goal

V. Idea proposal 2: Problem statement and goal

❖ Free Space Optical (FSO) communications

- Using near infrared light *(200-400 THz)* to transmit data through free space (air or vacuum)



❖ Advantage

- High-speed connection (Gbps and even Tbps)
- Free-license bandwidth

1. Research Background: FSO communication

❖ Applications

- Terrestrial networks (e.g., building to building link)
- Non-terrestrial networks (e.g., ground to UAV, HAP, Satellite or aerial platforms link)
- Underwater communication (e.g., submarine to submarine)

❖ Challenges

- Weather conditions: rain, fog, cloud,…
- Atmospheric turbulence
- *Line-of-sight (LoS) requirement due to obstruction blocks the link*

❖ Solutions

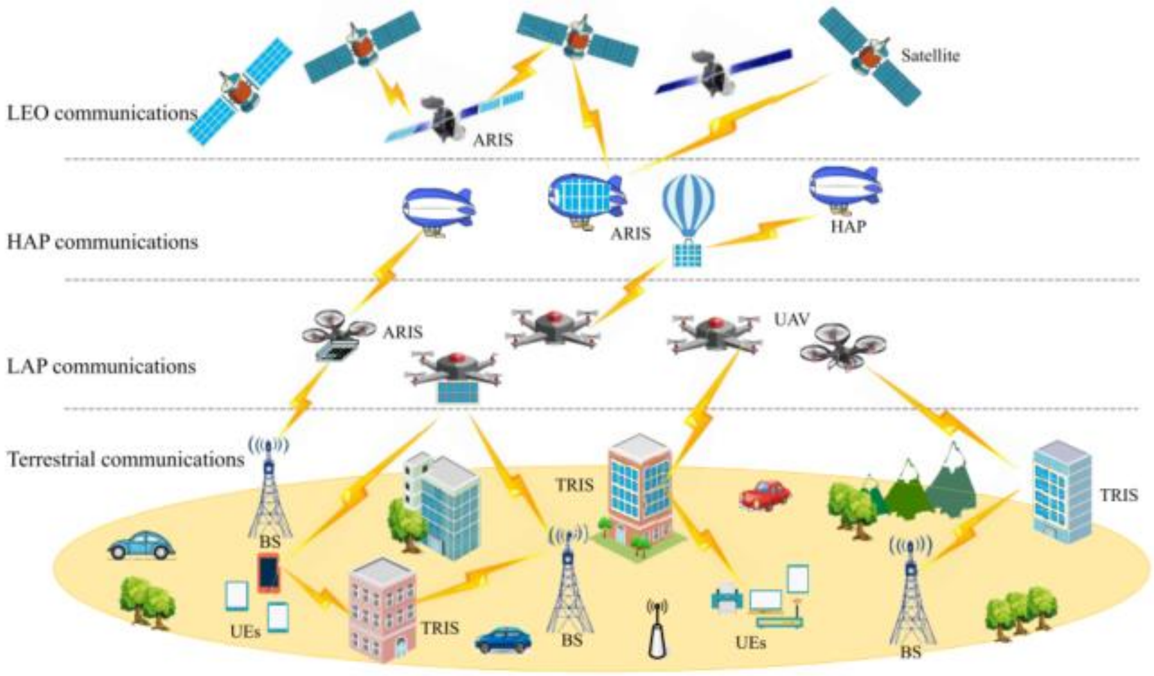
- Aperture averaging
- Diversity techniques
- Adaptive optics
- Hybrid FSO/RF
- Relay

➡ Limits the operational transmission distance and reduce the system's reliability

Recently, many studies have developed ***Intelligent reflecting surface (IRS)*** as *a green and effective solution* to relax the LoS requirement.

❖ 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.*



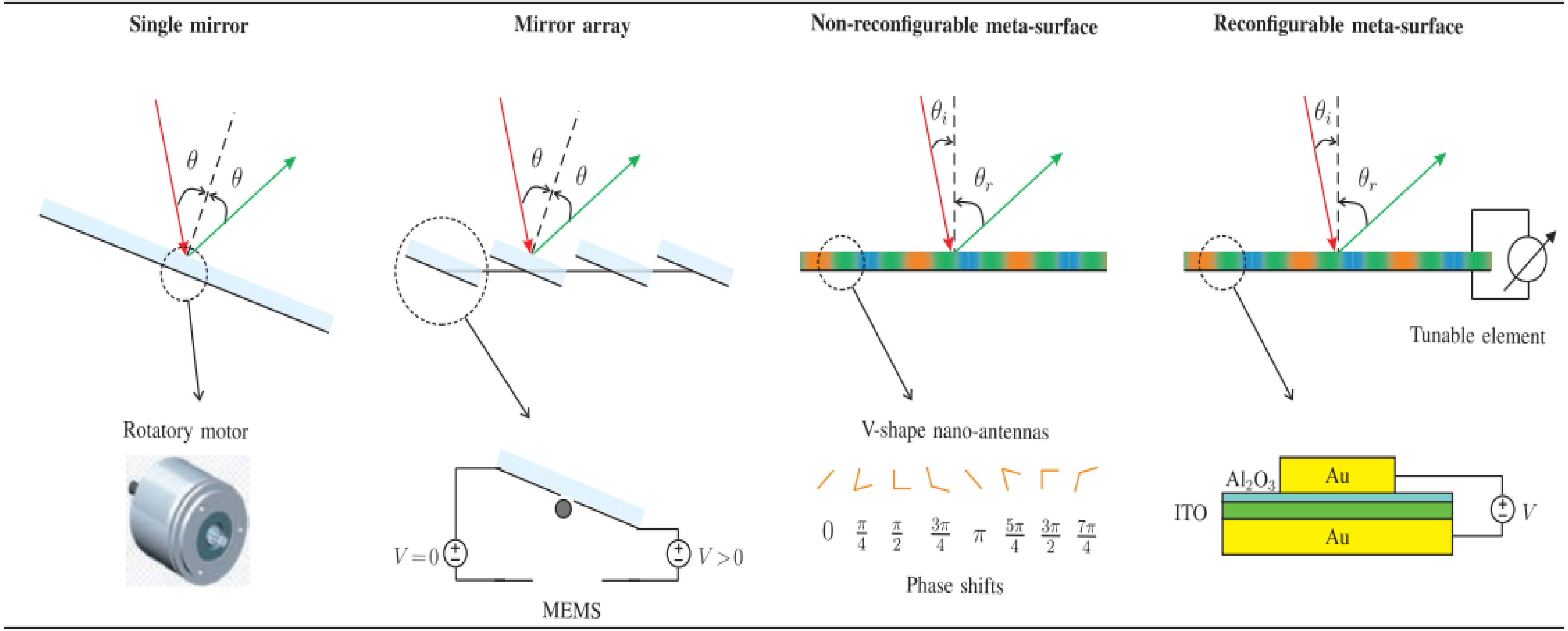
The operation concept of IRS [1]

❖ Advantages

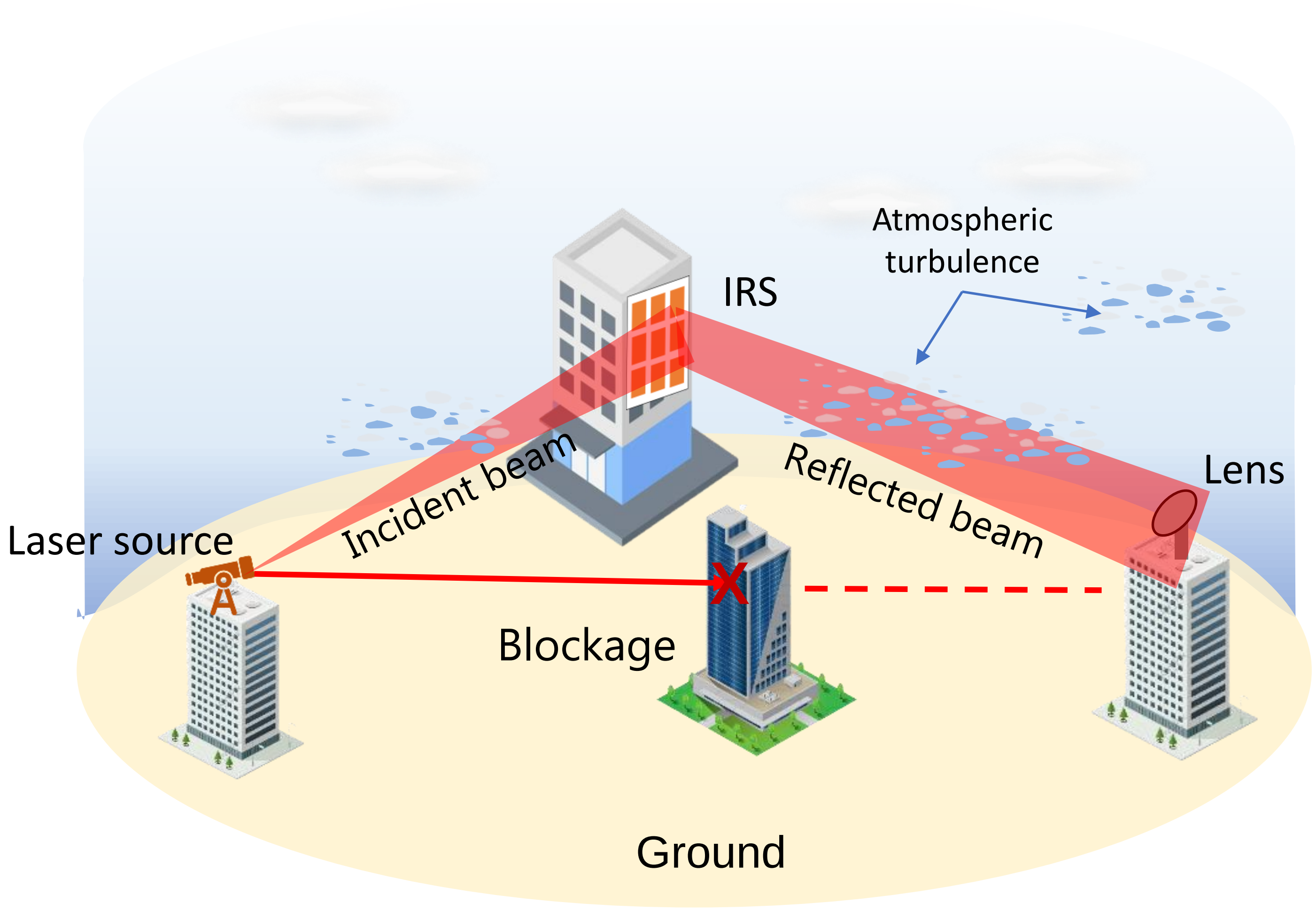
- *Low energy consumption.*
- *Light payload, reduce hardware complexity compared to relay*
- *Extend coverage and avoid blockage.*

➡ ***OIRS can be equipped in terrestrial or aerial platforms to reflect the FSO signal.***

Optical IRS (OIRS) is created to reflect the light waves



A mechanical rotary structure controlled by electrical motors	Use micro-electro-mechanical systems (MEMSs)	Using V-shaped optical nano-antennas	Use oxide material and control electricity to turn the phase of incident waves



❖ **System description:**

- **1. Source:** a laser source on top of the building.
- **2.** One OIRS mounted on building.
- **3. Destinations:** a lens on top of the building.

What is the impact of IRS to end-to-end channel?

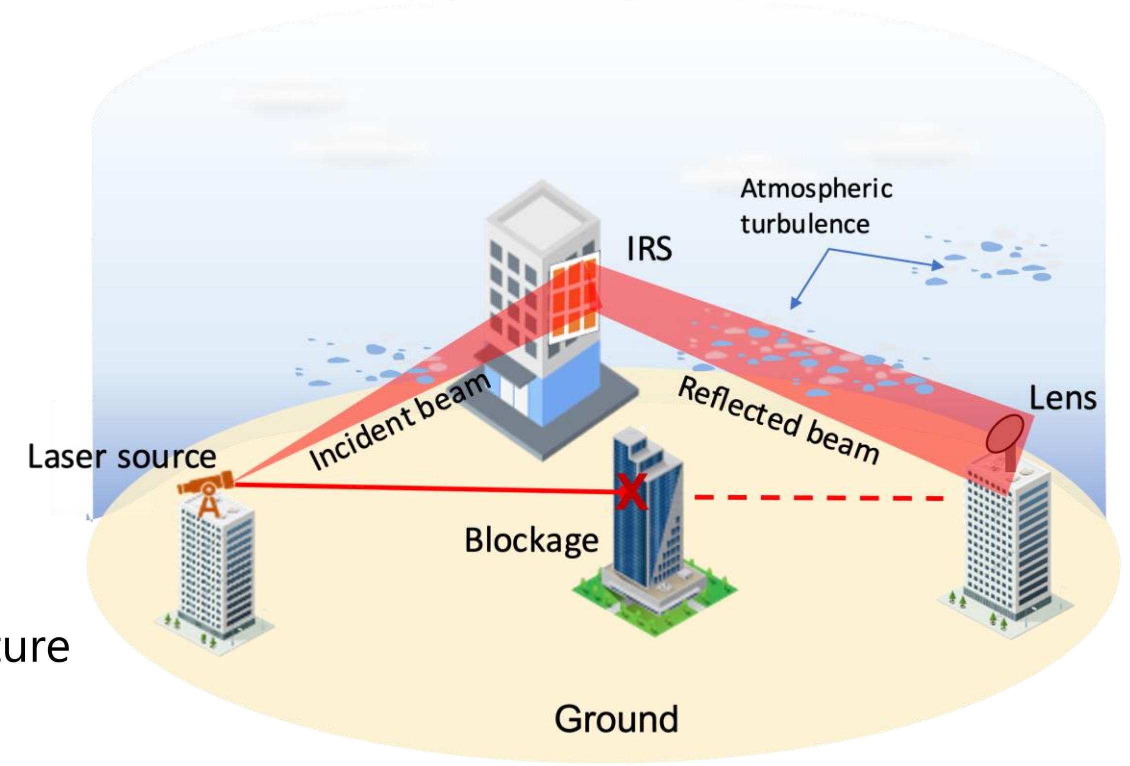
Composite channel model: $h = \eta \times h_p \times h_t \times h_{gml}$

- **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.

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

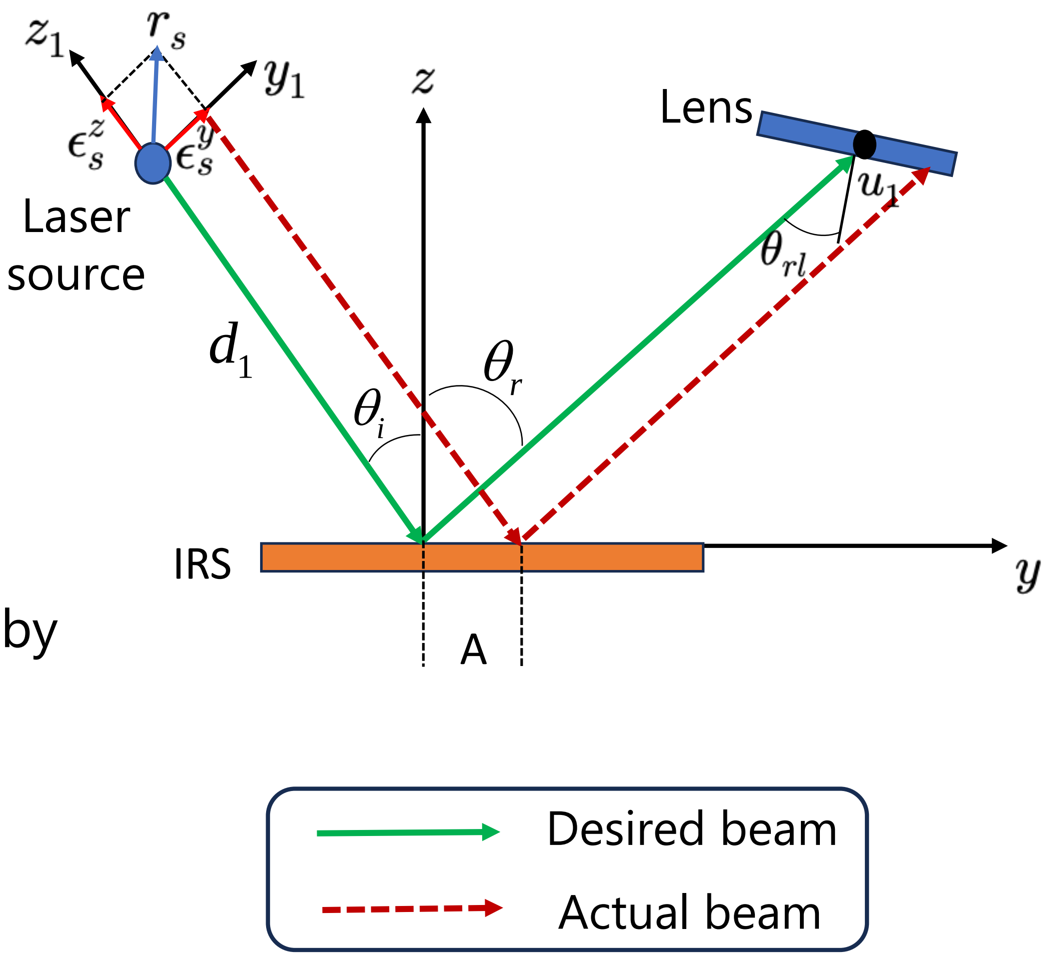
- **Geometric and misalignment loss:** deterministic geometric loss due to the divergence of laser beam along the transmission path and random misalignment of beam due to building sway.

- Laser source, IRS, lens fluctuate because of building sway in both y and z direction
- Each fluctuation can be projected in two directions, one parallel to beam line and one orthogonal to it
- Laser source fluctuation

$$r_s = (\epsilon_s^z, \epsilon_s^y)$$

$$\epsilon_s^y \sim N(0, \sigma_s^2)$$

$d_1 \gg \epsilon_s^z \longrightarrow$ The impact of $\epsilon_s^z \approx 0$



- The misalignment at lens can be calculated by

$$u_1 = \frac{1}{\cos\theta_{rl}} \cos\theta_r \frac{\epsilon_s^y}{\cos\theta_i}$$

*Proof

- Lens fluctuation

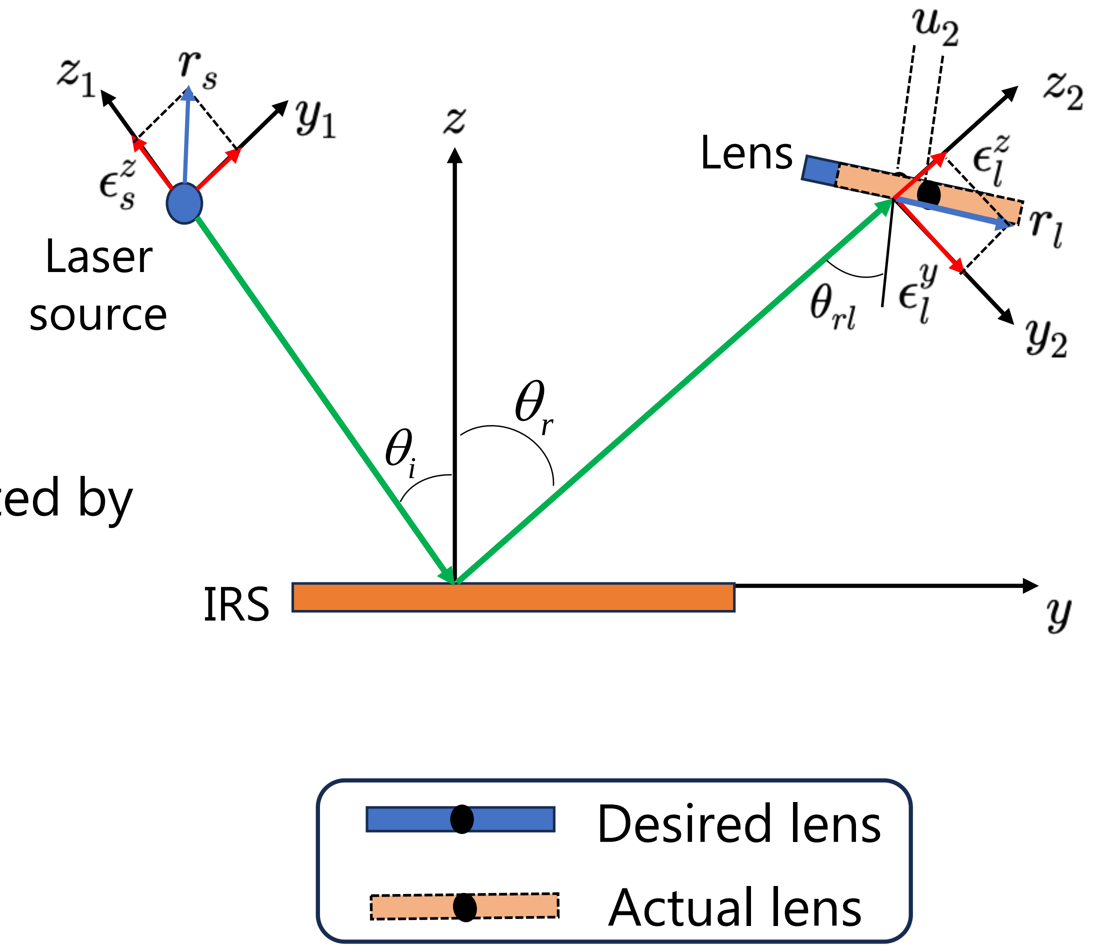
$$r_l = (\epsilon_l^y, \epsilon_l^z)$$

$$\epsilon_l^y \sim N(0, \sigma_l^2)$$

$d_2 \gg \epsilon_l^z \longrightarrow$ The impact of $\epsilon_l^z \approx 0$

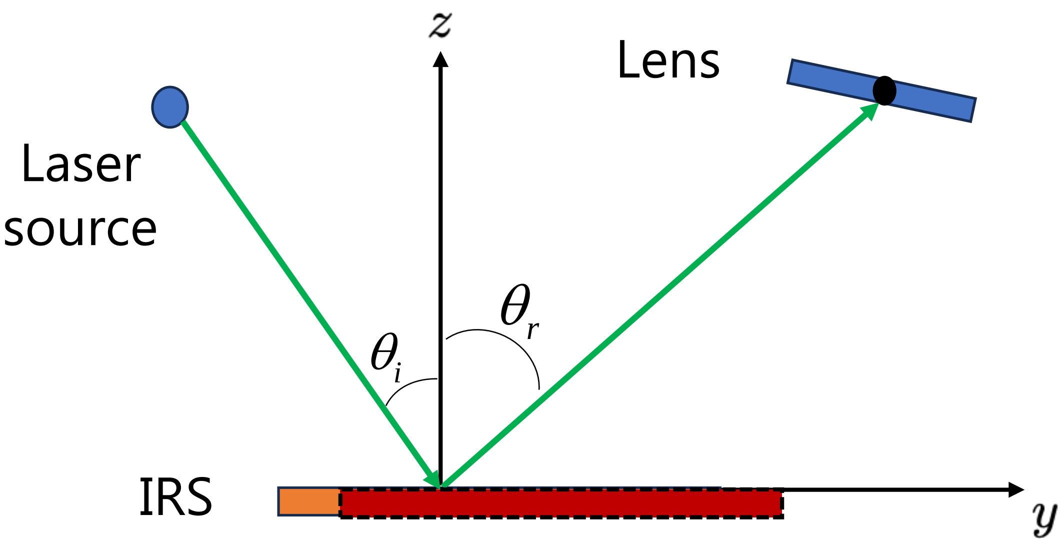
- The misalignment at lens can be calculated by

$$u_2 = \frac{\epsilon_l^y}{\cos\theta_{rl}}$$

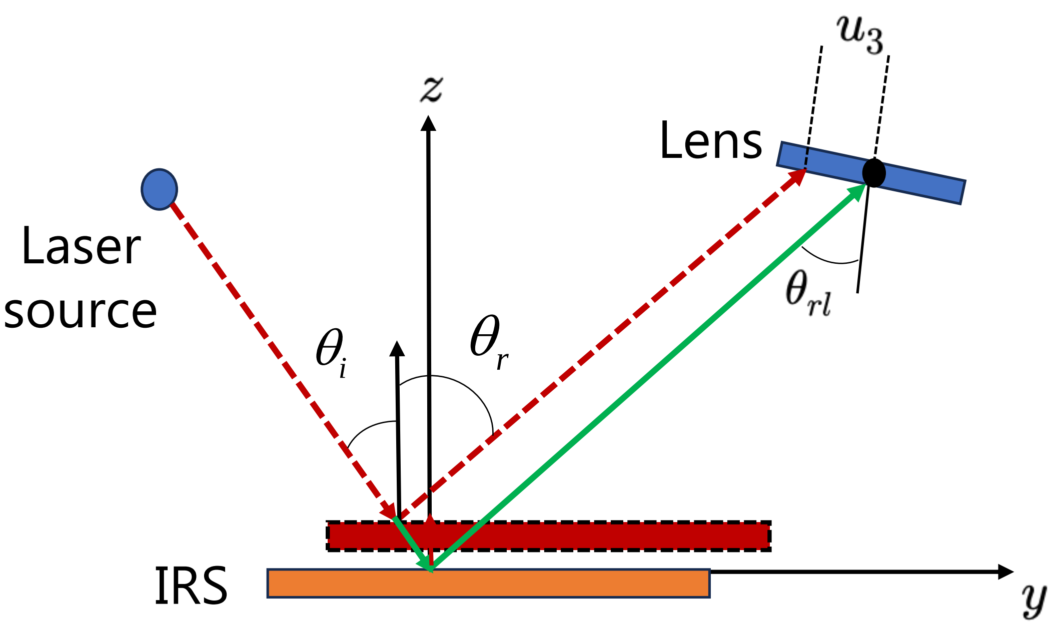


2. Geometric and Misalignment Loss in 2D model

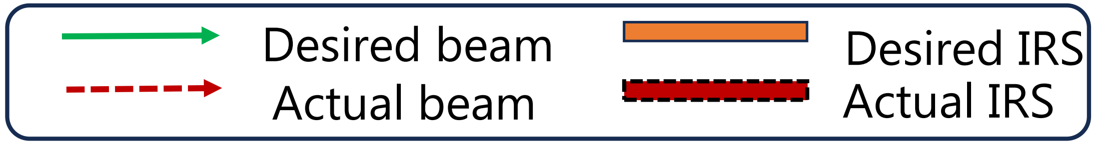
- IRS fluctuation: $r_{irs} = (\epsilon_r^y, \epsilon_r^z)$



The impact of $\epsilon_r^y \approx 0$



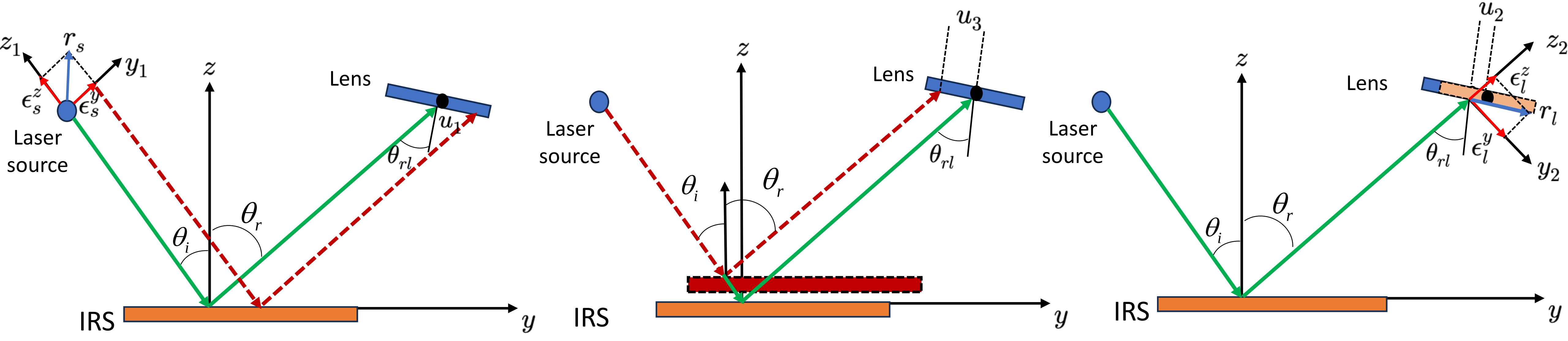
$\epsilon_r^z \sim N(0, \sigma_r^2)$



- The misalignment at lens can be calculated by

$$u_3 = \frac{\epsilon_r^z \sin(\theta_i + \theta_r)}{\cos\theta_{rl} \cos\theta_i}$$

*Proof



- The composite misalignment at lens can be calculated by

$$u = u_1 - u_2 - u_3$$

$$u = \frac{1}{\cos\theta_{rl}}\left(\frac{\cos\theta_r}{\cos\theta_i}\epsilon_s^y - \frac{\sin(\theta_i+\theta_r)}{\cos\theta_i}\epsilon_r^z - \epsilon_l^y\right)$$

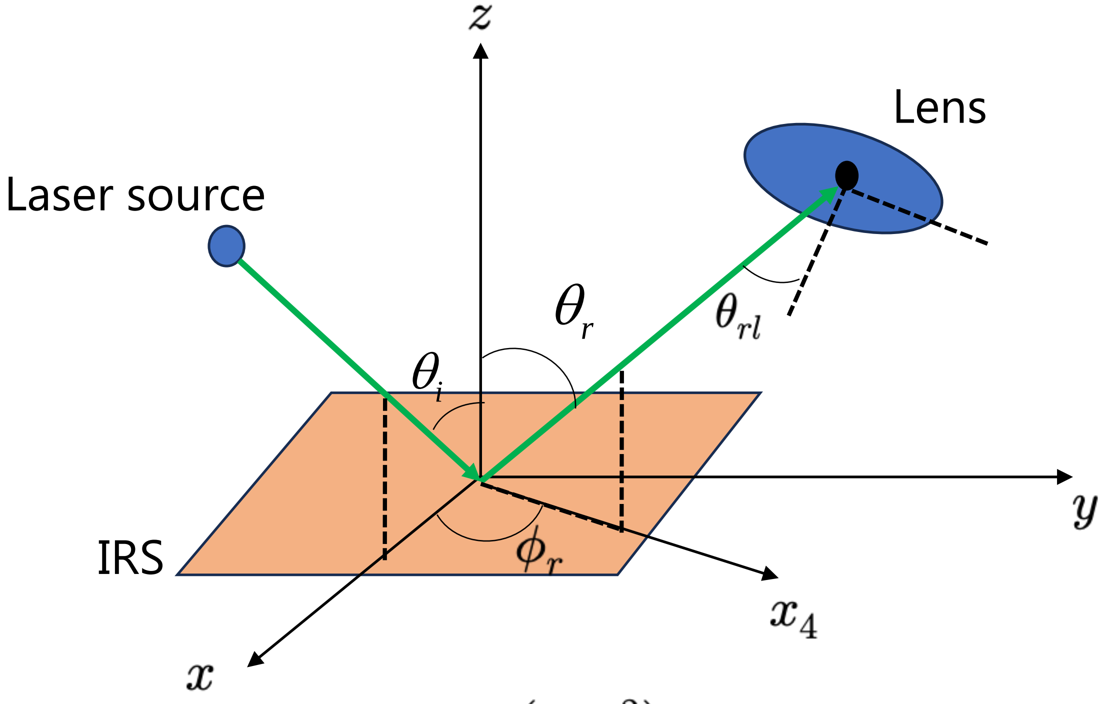
$$\epsilon_s^y \sim N(0,\sigma_s^2)$$
$$\epsilon_r^z \sim N(0,\sigma_r^2)$$
$$\epsilon_l^y \sim N(0,\sigma_l^2)$$

$$\Rightarrow u \sim N(0,\sigma_u^2)$$

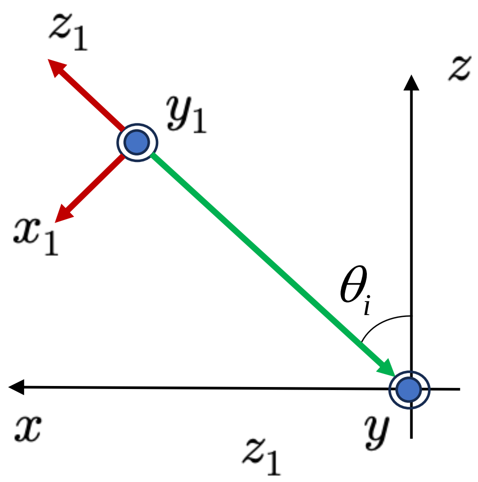
- The GML can be aproximated by

$$h_g \approx A_0 \exp\left(\frac{-2u^2}{tw^2(d_{e2e},\hat{w}_0)}\right) \qquad f_{h_g}(h_g) = \frac{\sqrt{\varpi}}{2A_0\sqrt{\pi}}\left[\ln\left(\frac{A_0}{h_g}\right)\right]^{-\frac{1}{2}}\left(\frac{h_g}{A_0}\right)^{\varpi-1}$$

- Laser source, IRS, lens fluctuate because of building sway in xyz coordinates
- Each fluctuation can be projected in three directions, one parallel to beam line and others orthogonal to it

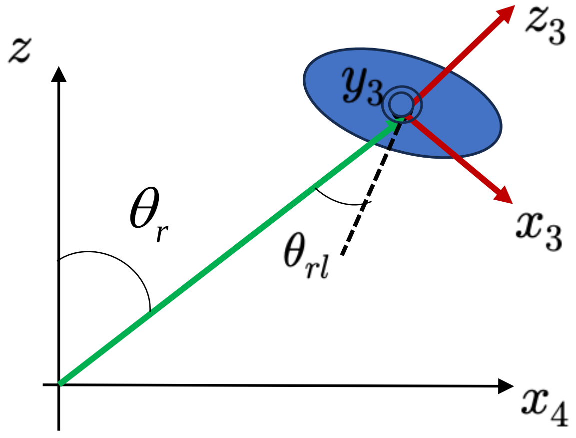


$\epsilon_r^z \sim N(0, \sigma_r^2)$



LS fluctuation

$\epsilon_s^x, \epsilon_s^y \sim N(0, \sigma_s^2)$

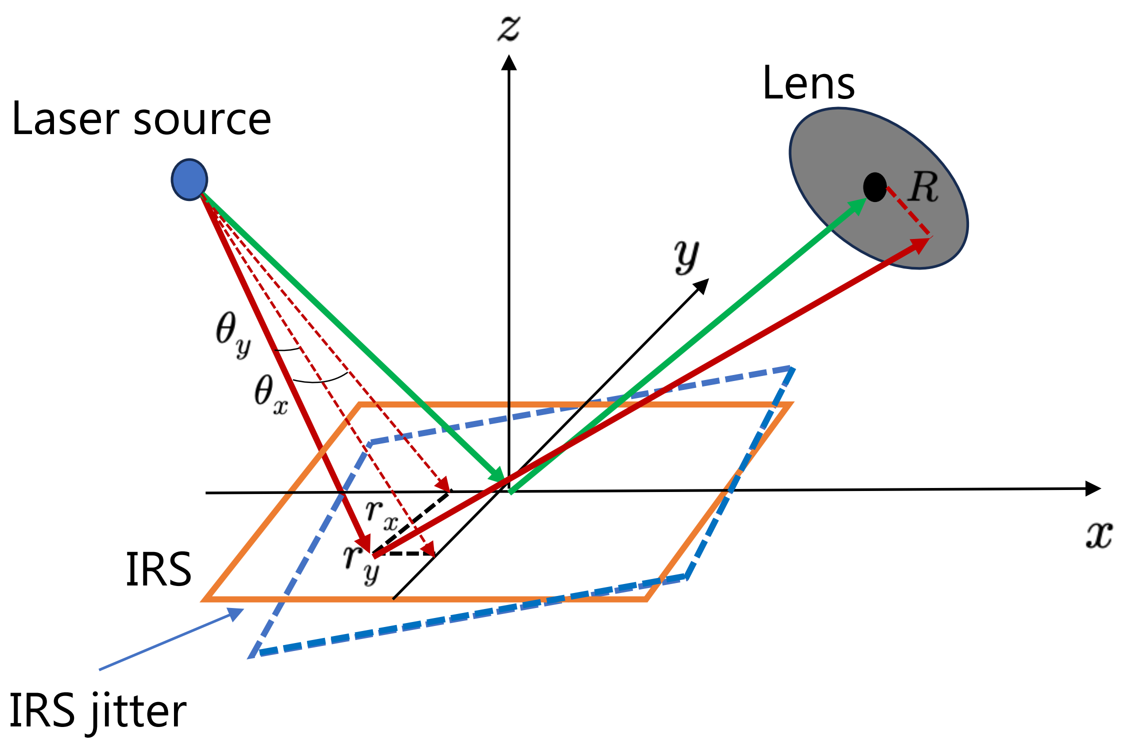


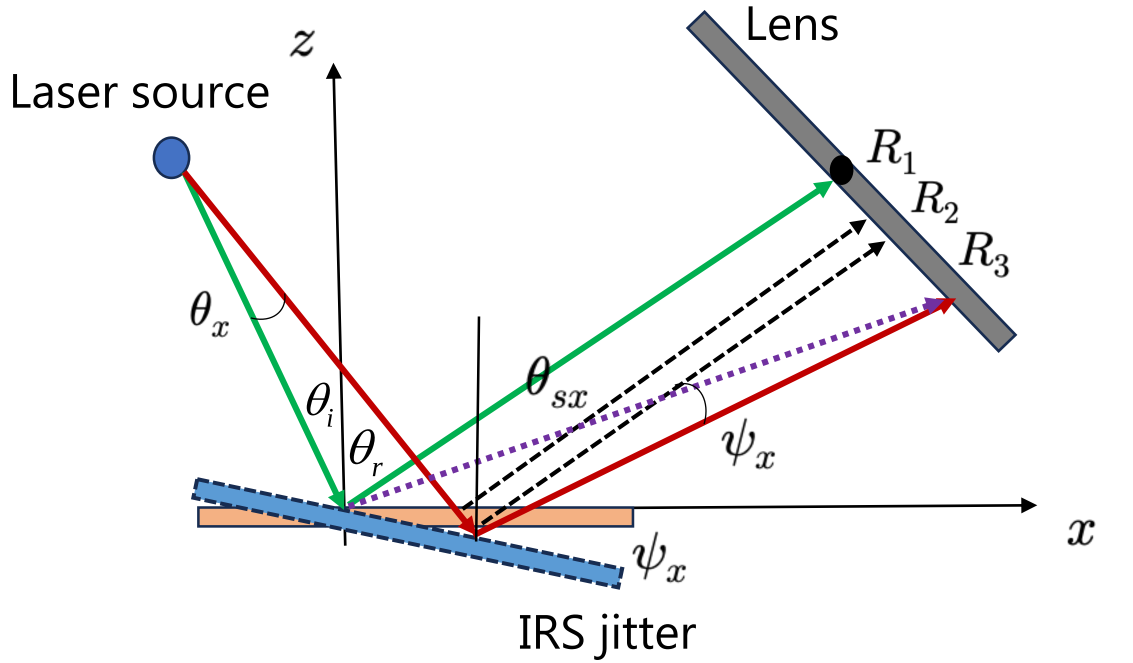
Lens fluctuation

$\epsilon_l^x, \epsilon_l^y \sim N(0, \sigma_l^2)$

The misalignment vector $u = f(\epsilon_s^x, \epsilon_s^y, \epsilon_r^z, \epsilon_l^x, \epsilon_l^y) \sim N(0, \sigma_u^2)$

- Laser source, IRS jitter cause beam displacement in *x* and *y* axis: $\theta_x, \theta_y \sim N(0, \sigma_\theta^2)$





R_1 : Misalignment due to LS jitter

R_2, R_3 : Misalignment due to IRS jitter

$$R_1 = \frac{\cos\theta_r}{\cos\theta_i} L_1 \theta_x$$

$$R_3 \approx (\theta_x + 2\psi_x) L_2$$

$$R_2 \approx 0$$

$$\theta_{sx} = \frac{R_1 + R_3}{L_2} \sim N(0, \sigma_x^2)$$

$$\theta_{sy} \sim N(0, \sigma_y^2)$$

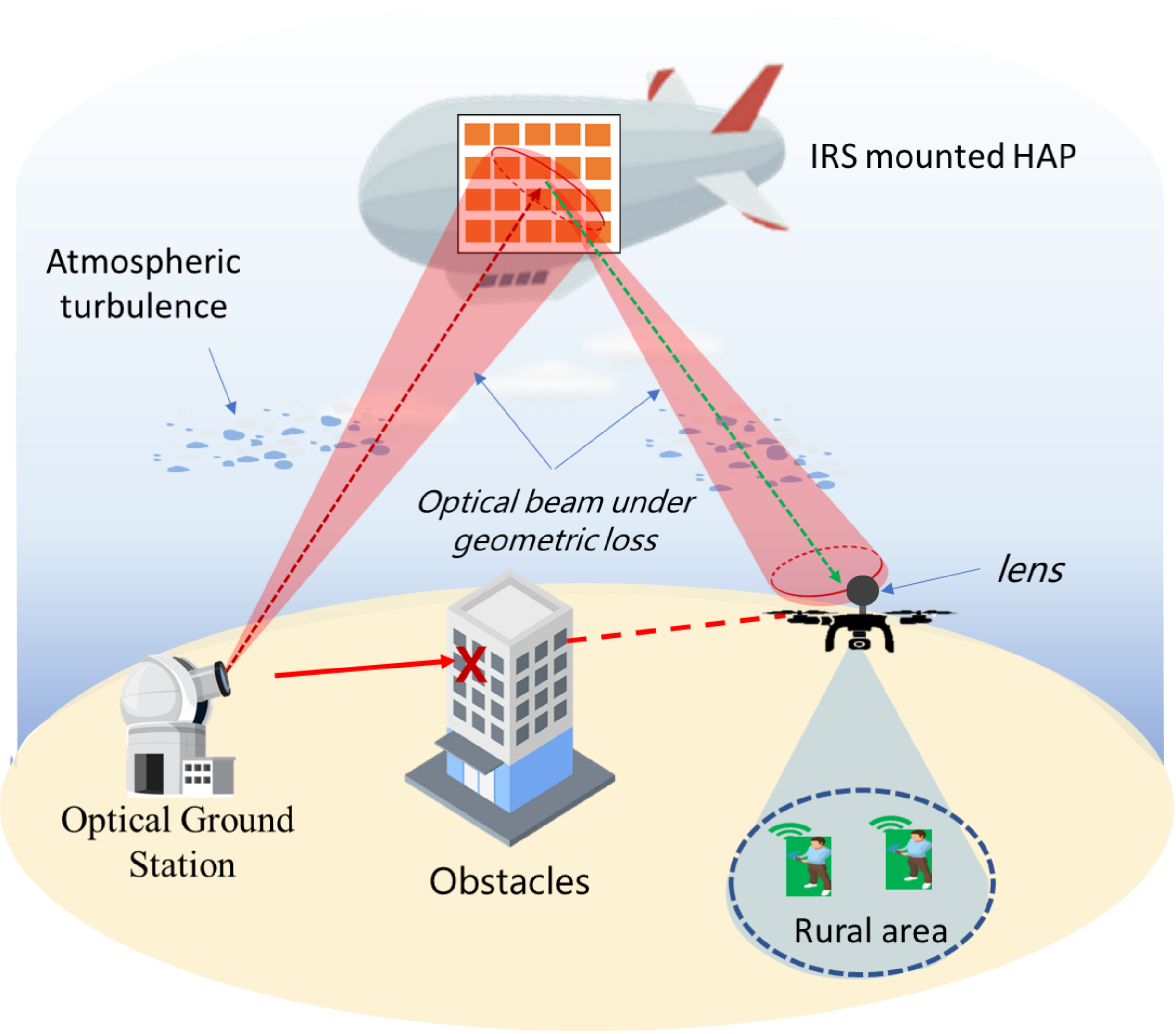
$$\theta_s^2 = \theta_{sx}^2 + \theta_{sy}^2$$

$$R = \theta_s . L_2$$

$$h_p \approx A_0 \exp\left(\frac{-2R^2}{w_{z_{eq}}^2}\right)$$

$$f_{h_p}(h_p) = f_{\theta_s}(\theta_s) \left| \frac{d\theta_s}{dh_p} \right|$$

3. The optical IRS-assisted HAP network



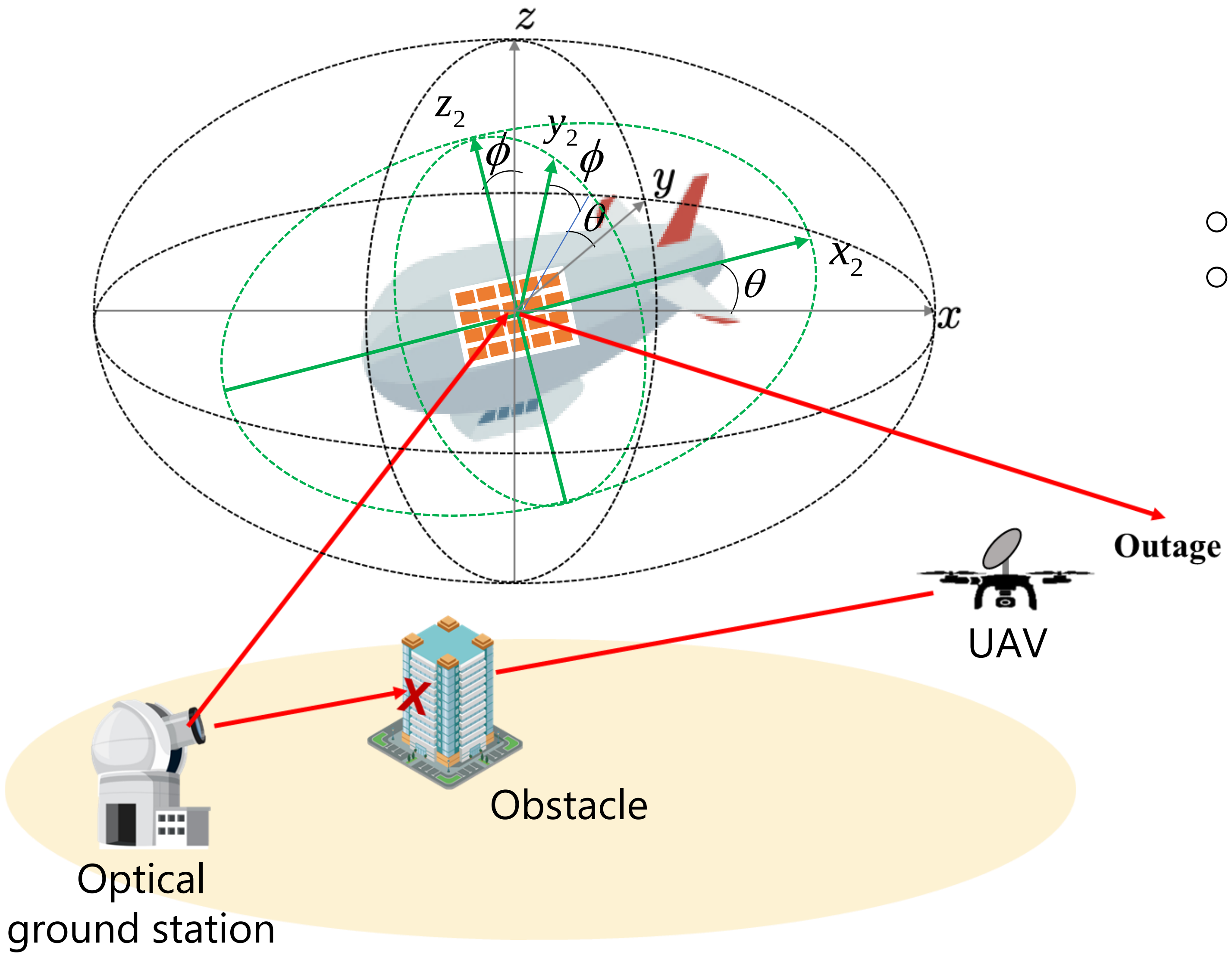
FSO-based HAP-Assisted UAV with IRS

❖ **System description:**

- **1. Source:** a laser source in the optical ground station.
- **2.** One OIRS mounted HAP.

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

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



Hovering, vibration and tilt of HAP due to wind, mechanical jitter

- IRS fluctuates in xyz coordinates
- The incident and reflected angle are changed

The misalignment between GS-IRS and IRS-UAV ***is a critical issue***

How to model the end-to-end Geometric and Misalignment Loss?

What is the **maximum allowable IRS tilt angle** to ensure the UAV still receives the signal and maintains **target QoS**?

4. Propose Idea 1: Literature reviews

Ref.	NTN	TN	2D model	3D model	OIRS design		Beam power distribution	Geometric and misalignment loss			
					Mirror	Meta surface		LS	IRS	Receiver	IRS tilt
[1]	v		v		v		Gaussian		v		
[2]	v		v			v	Gaussian		v		
[3]	v			v	v		Gaussian		v		
[4]	v			v	v		Gaussian	v	v	v	
[5]	v			v		v	Gaussian			v	
[6]	v			v			Gaussian		v		v
[7]		v	v	v	v	v	Gaussian	v	v	v	
[8]		v		v		v	Uniform				v
This work	v		v		v		Gaussian	v	v	v	v

To the best of my knowledge, **no existing study** considers the **combined hovering** of **all three nodes** (LS, IRS, UAV) and the impact of **IRS tilt angle** in an **NTN scenario**.

Goal:

- Model the end-to-end FSO channel considering the hovering of LS, HAP, UAV and jilt angle
- Method to calculate the maximum allowable IRS tilt angle to maintain targeted QoS of UAV

Approach:

- **Step 1:** Analyze ***the impact of LS, HAP, UAVs hovering and jilt angle on e2e channel?***

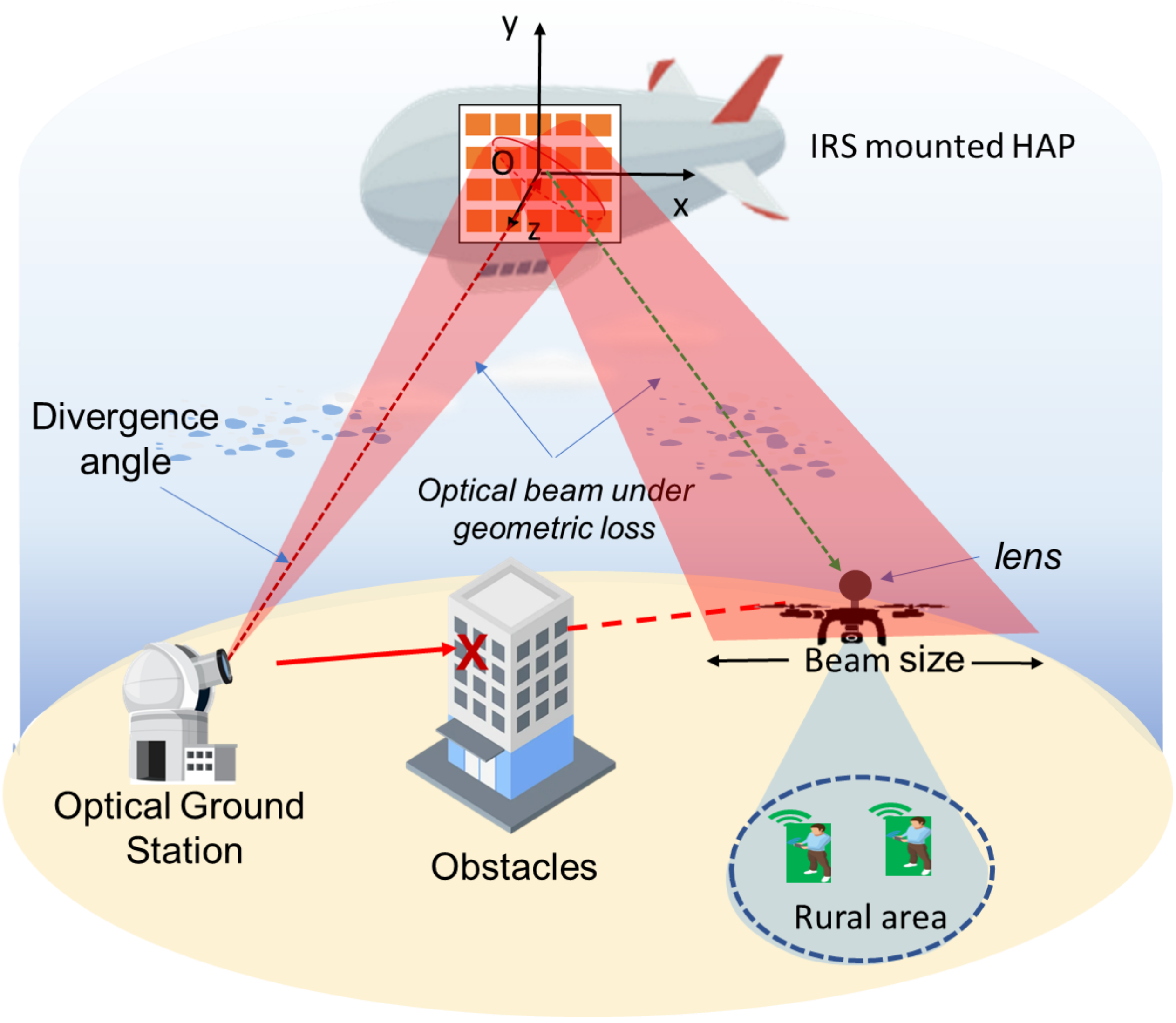
Misalignment vector $u = f\left(\varepsilon_s^x, \varepsilon_s^y, \varepsilon_r^z, \varepsilon_l^x, \varepsilon_l^y, \theta\right)$

Derive the PDF of e2e channel

- **Step 2:** Derive the ***maximum tilt angle*** to maintain the targeted QoS of UAV

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

- **Step 3: Performance Evaluation:** Compare the system's performance, i.e., outage probability of system with and without tilt-aware control



- **Motivation:** The received beam width can be controlled by changing the divergence angle and the size of IRS

  - If the received beam is ***large***, the impact of PE is ***small*** but ***less*** power received at lens

  - If the received beam is ***small***, the impact of PE is ***significant*** but ***more*** power received at lens

How to ***design the divergence angle*** or efficient IRS size to maximize the achievable rate of UAV?

Goal:

- Model the end-to-end FSO channel considering the hovering and vibration of LS, HAP, UAV
- Propose a protocol to adapt divergence angle or determine the effective IRS to maximize the achievable rate

Approach:

- **Step 1:** Analyze ***the impact of LS, HAP, UAVs hovering and vibration on e2e channel?***

  Misalignment vector $u = f\left(\varepsilon_s^x, \varepsilon_s^y, \varepsilon_r^z, \varepsilon_l^x, \varepsilon_l^y, \theta\right)$

  Derive the PDF of e2e channel

- **Step 2:** Determine the divergence angle or on-off IRS element to maximize achievable rate

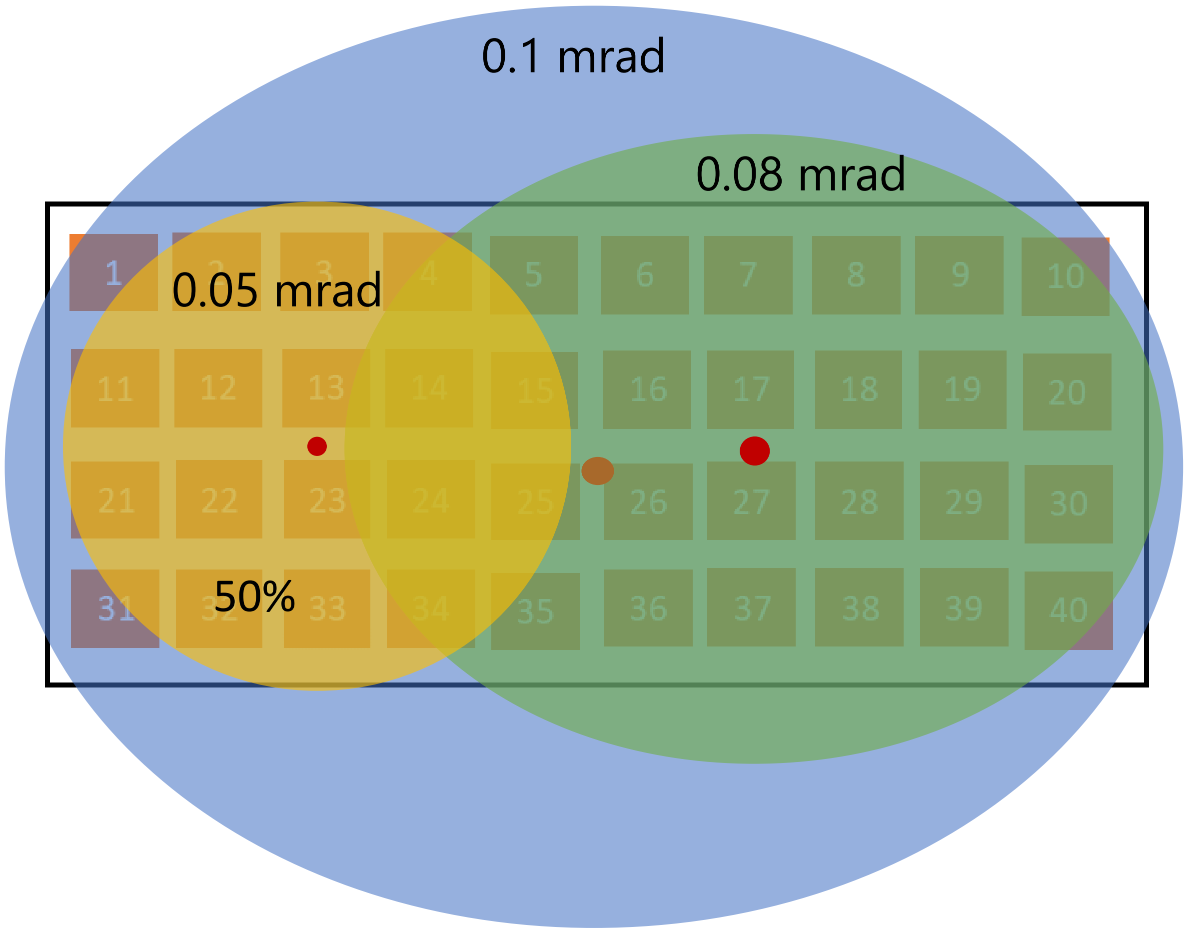
- **Step 3: Performance Evaluation:** Compare the system's performance, i.e., achievable rate of system with and without proposed protocol

4. Propose Idea 2: Approaches

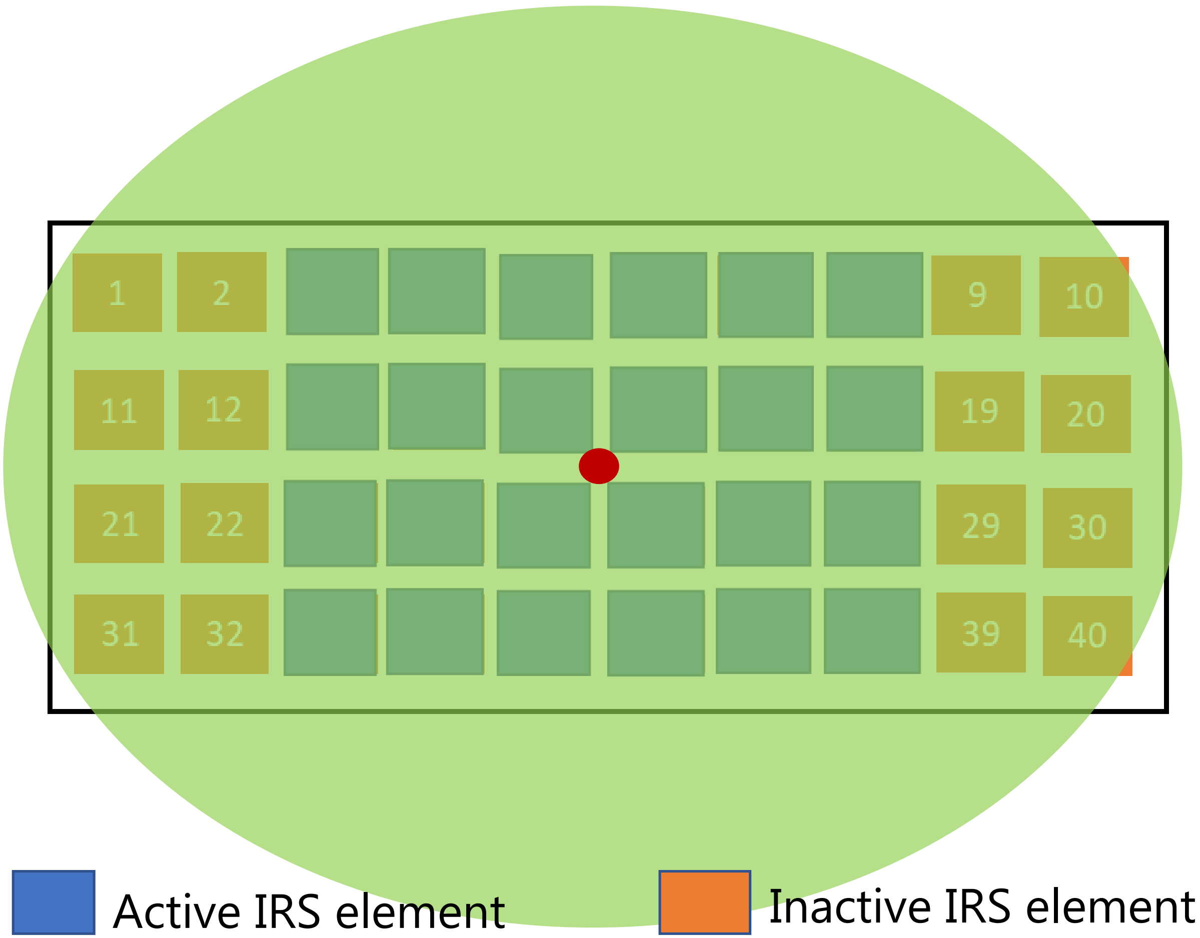
Given the typical size of IRS: 1m x 0.5m; the divergence angle range: 10 µrad to 0.1 mrad

The received beam: few decimeters to few meters

Approach 1: Adaptive divergence angle



Approach 2: On-off IRS element



THANK YOU FOR LISTENING!

[1] 2020. Ergodic Capacity Analysis for FSO Communications with UAV-Equipped IRS in the Presence of Pointing Error

[2] 2022. Performance analysis of a UAV-based IRS-assisted hybrid RF/FSO link with pointing and phase shift errors

[3] 2023. RIS Assisted UAV for Weather-Dependent Satellite Terrestrial Integrated Network With Hybrid FSO/RF Systems

[4] 2024. IRS-Assisted UAV Based FSO System: Modeling Approach for Hovering UAV

[5] 2025. Optical RISs Improve the Secret Key Rate of Free-Space QKD in HAP-to-UAV Scenarios

[6] 2025. A Generalized Pointing Error Model for FSO Links with Fixed-Wing UAVs for 6G: Analysis and Trajectory Optimization

[7] 2021. Intelligence reflecting surface for Free space optical communication

[8] 2024. Performance Analysis of IRS-Assisted Multi-Link FSO System Under Pointing Errors.

[9] 2022. Adaptive Beam Divergence for Expanding Range of Link Distance in FSO With Moving Nodes Toward 6G