THE UNIVERSITY OF NEW MEXICO

Smart Edge Computing & Networking Lab

Free Space Optical Communications for Aerial Networks

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Outline

- Introduction
  - FSO communications concept
  - Attenuation/Loss of an FSO link
  - Capacity of an FSO link
  - FSO vs RF
- Applications of FSO Communications in aerial networks
  - FSO for Counter UAV Communications
  - Ground-to-Air Communications
- Acquisition, Pointing, and Tracking (ATP) systems for FSO
- Full-duplex FSO communications in Airel Networks

What is Free Space Optical Communications

- The fundamental idea goes back to ancient times, when light/smoke were used to transmit information.

- As technology develops, Free Space Optical (FSO) communications was designed to wireless transmission of data via a modulated optical beam directed through free space, without fiber optics or other optical systems guiding the light.

Source: Agrawal, J., Farook, O., & Sekhar, C. (2005, June). Designing A Free Space Optical/Wireless Link. In 2005 Annual Conference (pp. 10-416).

Attenuation/Loss of an FSO Link

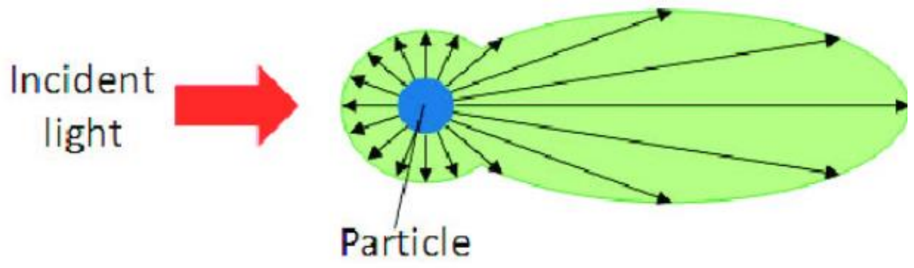
- The optical signal is vulnerable to atmospheric attenuation (scattering and turbulence) and other losses such as geometrical and pointing losses.

- Scattering occurs when the FSO beam collides with the particles in the atmosphere

  - Scatting loss can be estimated by

$$L^{sca} = e^{-\sigma_a l}$$

✓ l : distance between a transmitter and a receiver
✓ σ_a: atmospheric attenuation coefficient in dB/km



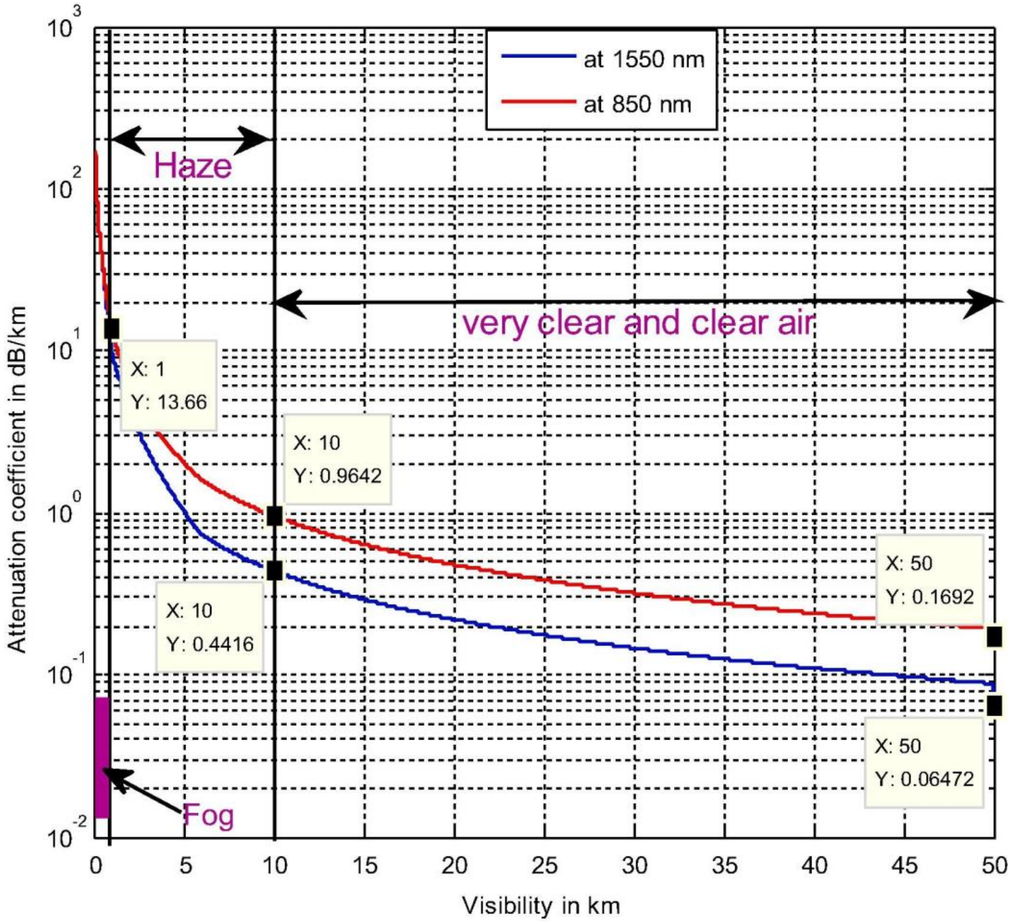
Attenuation/Loss of an FSO Link

$$L^{sca} = e^{-\sigma_a l}$$

- Atmospheric attenuation coefficient $\boldsymbol{\sigma_a}$ is determined by the visibility range V.

$$\sigma_a = \frac{3.91}{V}\left(\frac{\lambda}{550}\right)^{-q} \qquad q = \begin{cases} 1.6, & V > 50 \text{ km}, \\ 1.3, & 6 \text{ km} \leq V \leq 50 \text{ km}, \\ 0.585V^{\frac{1}{3}}, & V < 6 \text{ km}. \end{cases}$$

- The FSO beam has stronger attenuation in foggy condition than haze and sunny condition.



Source: El-Nayal, Muhammad K., et al. "Adaptive free space optic system based on visibility detector to overcome atmospheric attenuation." *Results in Physics* 14 (2019): 102392.

Attenuation/Loss of an FSO Link

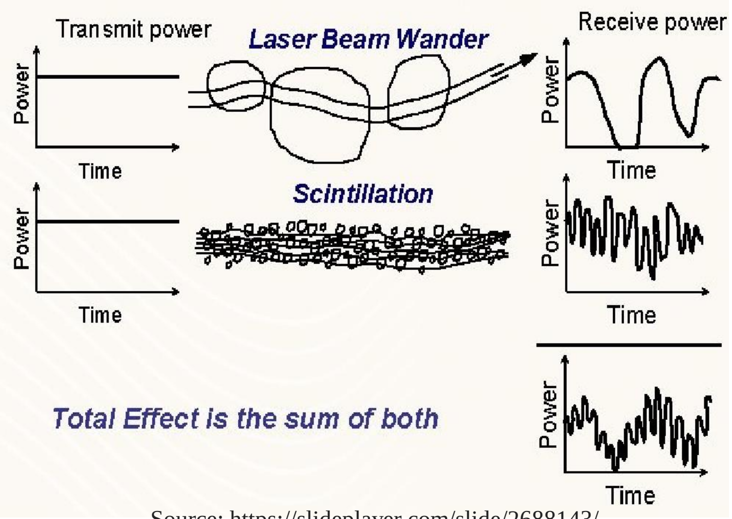
- The optical signal is vulnerable to atmospheric attenuation (scattering and turbulence) and other losses such as geometrical and pointing losses.

- Turbulence appears due to the variations in the refractive index along the propagation path, which can cause fluctuations in both the intensity and phase of the received optical signal
  - PDF of the turbulence loss L^{tur} is

$$p\left(L^{tur}\right) = \frac{1}{2\sqrt{2\pi}\xi_x}\frac{1}{L^{tur}}\exp\left(-\frac{\left(\ln\left(L^{tur}\right)+2\xi_x^2\right)^2}{8\xi_x^2}\right)$$

  - The expectation of the turbulence loss L^{tur}

$$E\left(L^{tur}\right) = \int_0^1 L^{tur} p\left(L^{tur}\right) dL^{tur} = \frac{1}{2} - \frac{erf\left(\frac{\xi_x}{\sqrt{\pi}}\right)}{2}.$$

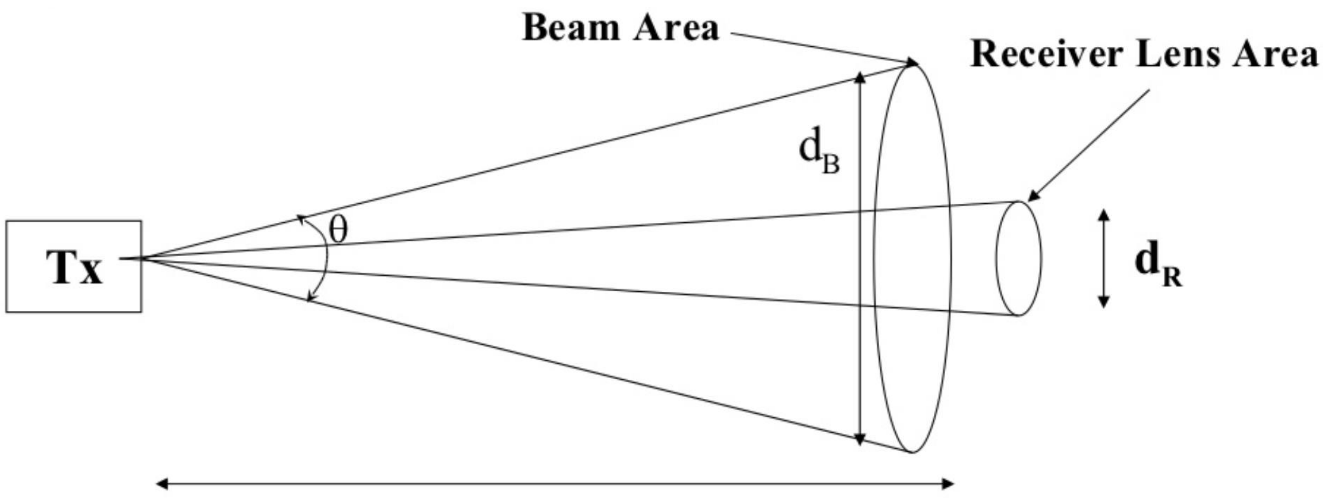


Source: https://slideplayer.com/slide/2688143/

Attenuation/Loss of an FSO Link

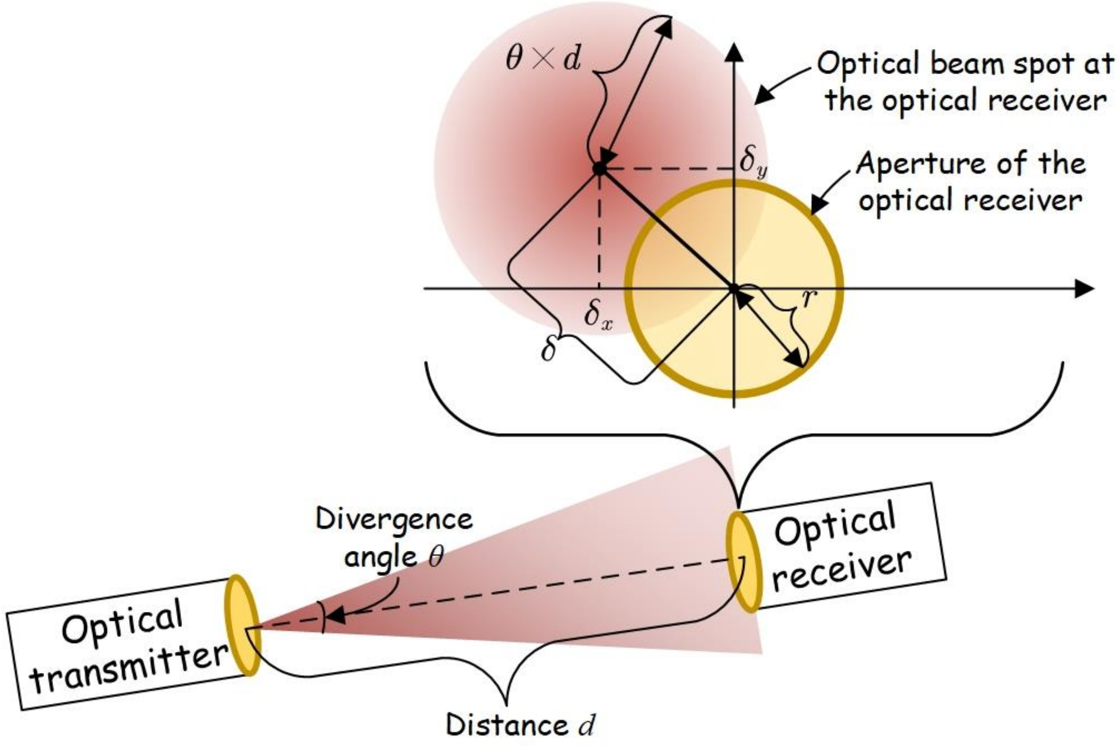
- The optical signal is vulnerable to atmospheric attenuation (scattering and turbulence) and other losses such as geometrical and pointing losses.

- Geometrical loss occurs when the beam width at the receiver is larger than the aperture size of the receiver.



Attenuation/Loss of an FSO Link

- The optical signal is vulnerable to atmospheric attenuation (scattering and turbulence) and other losses such as geometrical and pointing losses.
- Pointing loss occurs when the misalignment between a transmitter and a receiver exists.
- Pointing loss can be alleviate by developing the acquisition, pointing, and tracking (ATP) system.



Capacity an FSO Link

- The optical signal is vulnerable to atmospheric attenuation (scattering and turbulence) and other losses such as geometrical and pointing losses.

- The received power of an FSO link can be estimated by

$$p^{rx} = p^{tx} L^{\mathrm{sca}} L^{\mathrm{tur}} L^{\mathrm{geo+pointing}}$$

- The capacity (i.e., achievable data rate) of an FSO link

$$r = \frac{p^{rx}}{E_p N_b}$$

FSO VS Radio Frequency Communications

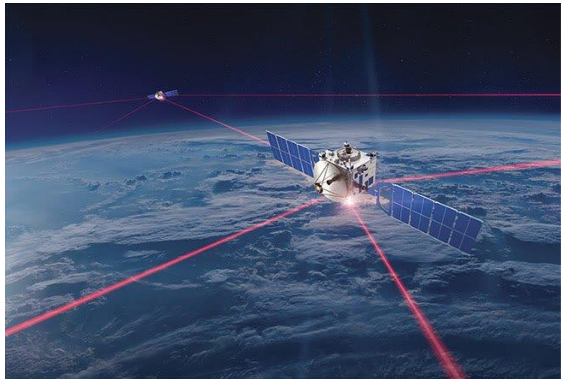
- Pros
  - ❖ A higher data rate over a longer distance.
  - ❖ No licensing cost.
  - ❖ Low interference.
  - ❖ Reliable communications.
- Cons
  - ❖ Line-of-sight communications.
  - ❖ Sensitive to weather conditions.

Difference between FSO communication and microwave link

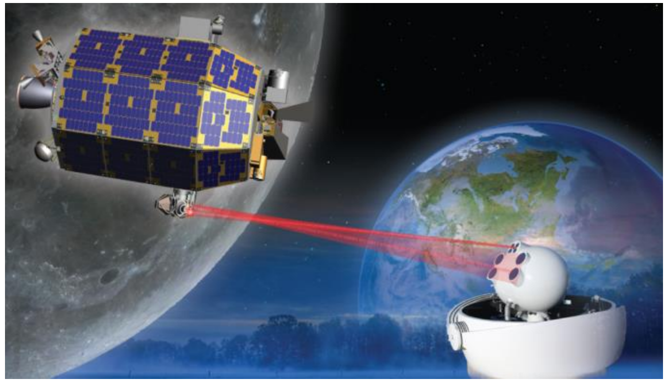
Issue	FSO Communication	Microwave Link
Transmission medium	NIR, VL, or UV	Millimeter waves
Maximum communication distance	More than 10,000 km	More than 100 km
Data rate	40 Gbps [38] at a communication distance of 20 m, 5.6 Gbps with LEO-LEO [124]	12.5 Gbps at communication distance of 5.8 m [133]
Interference	Low	High
Environmental impact	High	Low
Infrastructure cost	Less	High

Source: M. Z. Chowdhury, M. T. Hossan, A. Islam and Y. M. Jang, "A Comparative Survey of Optical Wireless Technologies: Architectures and Applications," in *IEEE Access*, vol. 6, pp. 9819-9840, 2018, doi: 10.1109/ACCESS.2018.2792419.

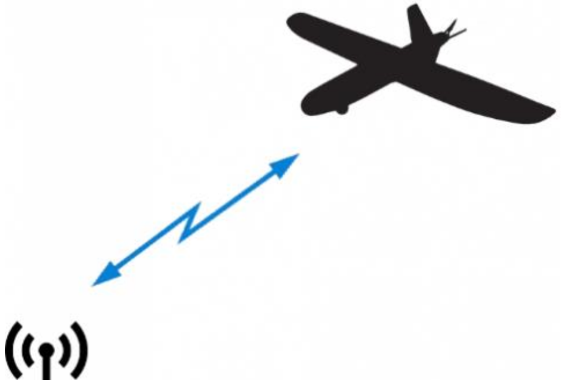
Applications of FSO Communications



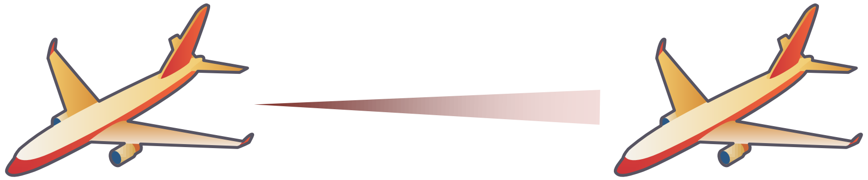
Satellite-to-Satellite Communications



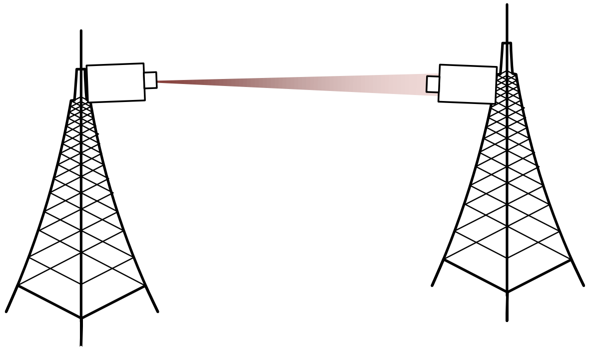
Satellite-to-Ground Communications



Ground-to-Air Communications



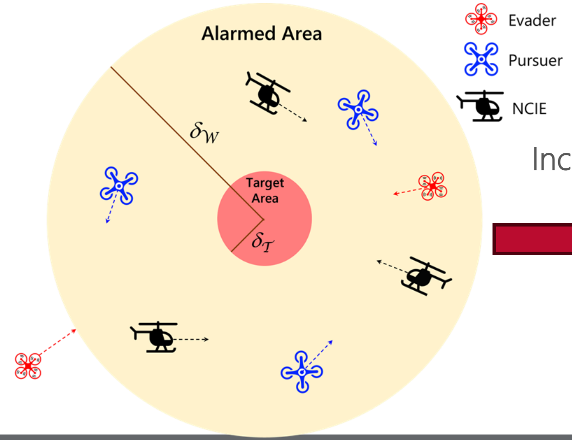
Air-to-Air Communications



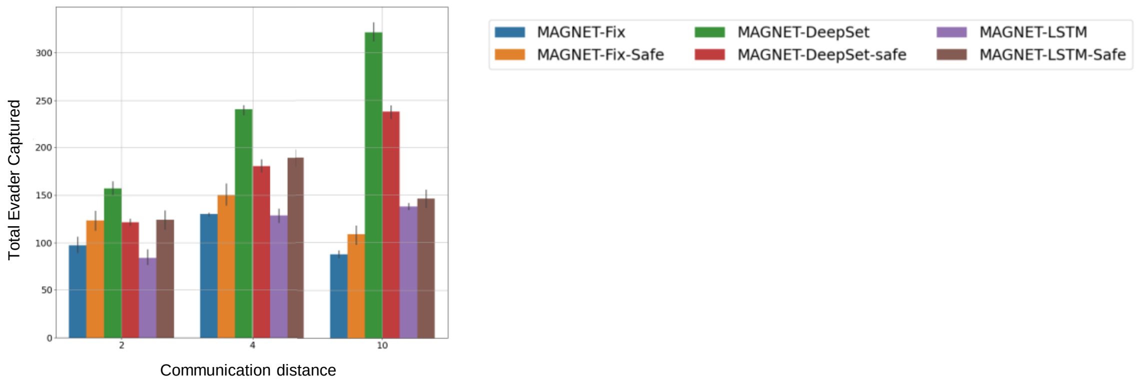
Terrestrial communication

FSO for Counter UAV Applications

- Counter-UAV (C-UAV) scenario
  - ❖ An evader to enter the target area, while escaping from pursuers' captures.
  - ❖ Multiple pursuers aim to
    - ✓ capture the evader in the alarmed area.
    - ✓ avoid the collisions with other pursuers and non-cooperative interactive entities (NCIEs).
  - ❖ Many NCIEs that are moving randomly in the area.
  - ❖ The max speed of an evader is larger than the max speed of a pursuer.

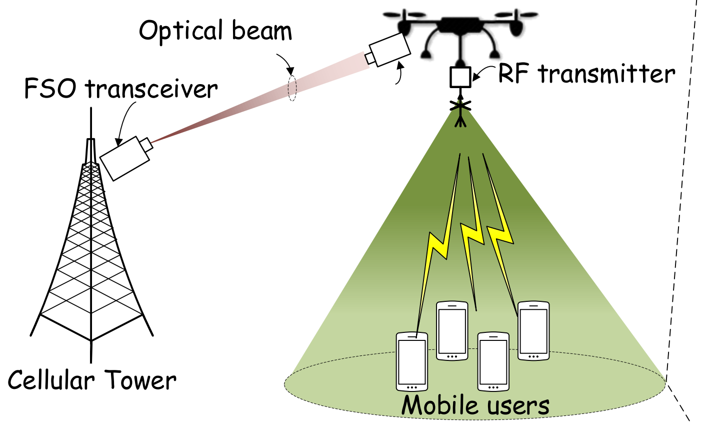


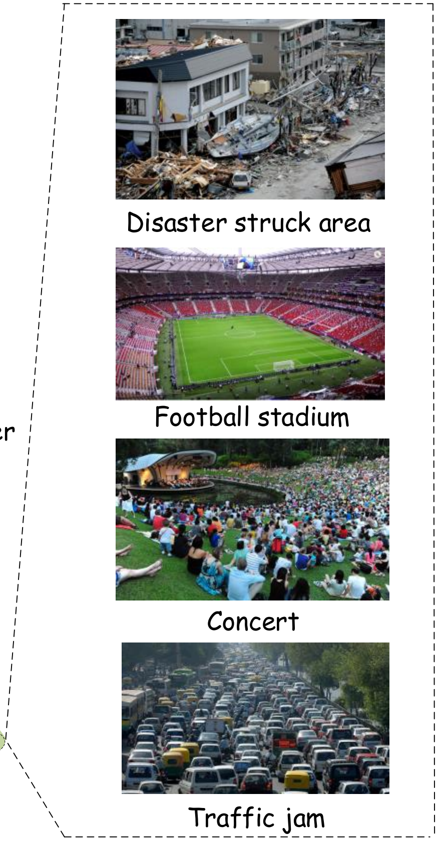
Increase Communications distance



FSO based Drone Assisted Mobile Access Networks

- Applying FSO in Drone Assisted Mobile Access Networks
  - ❖ The fronthaul link between a cellular tower and a drone is using FSO.
  - ❖ In the downlink communications, data streams are transmitted from the cellular tower to the drone via an FSO link. The drone converts the received optical signals into the RF signals, and then transmits the RF signals to mobile users.

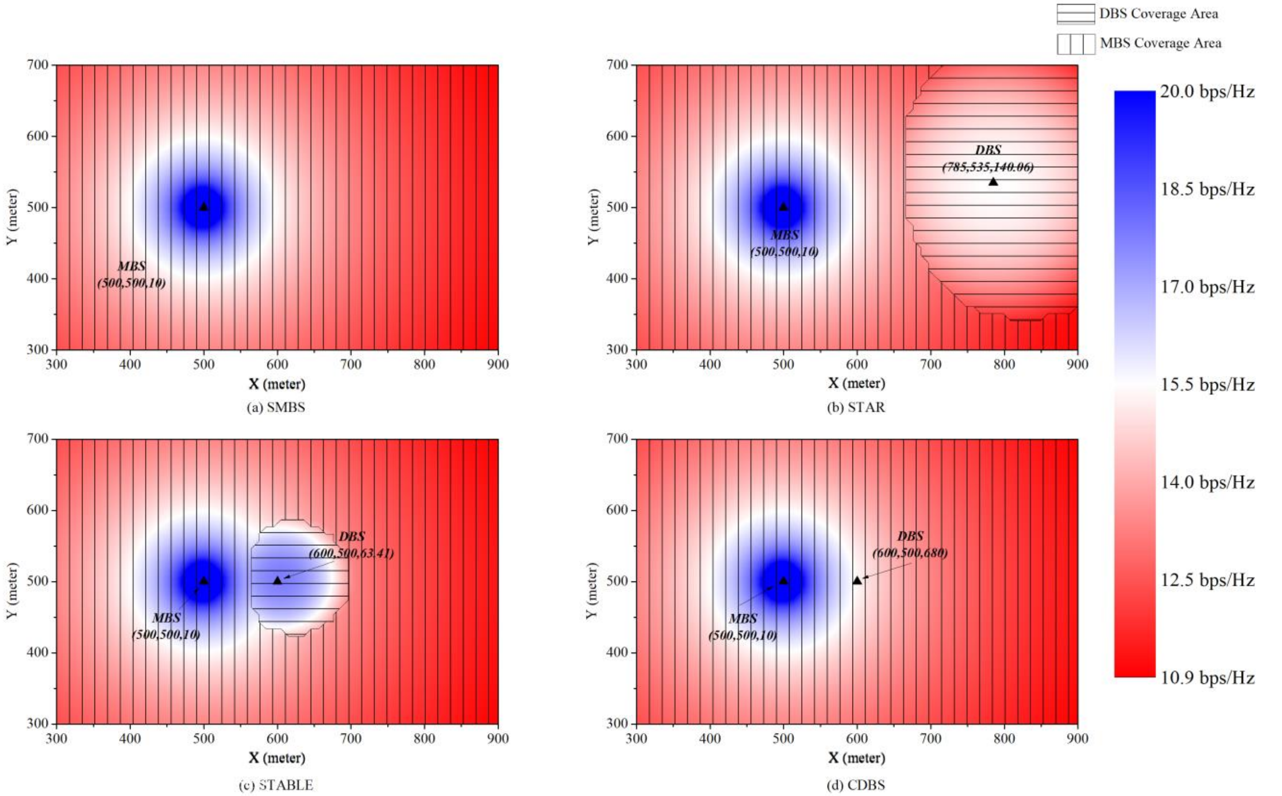




FSO based Drone Assisted Mobile Access Networks

- The capacity of an FSO link is sufficient for the access network 1) under haze and sunny condition, and 2) pointing loss is negligible.

- The placement of a UAV matters.
  - ❖ Goal: determine the 3D position of a UAV that maximizes the bandwidth utilization of a hotspot area identified as a rectangle area at the 2D coordinates of <300-900 m; 300-700 m>

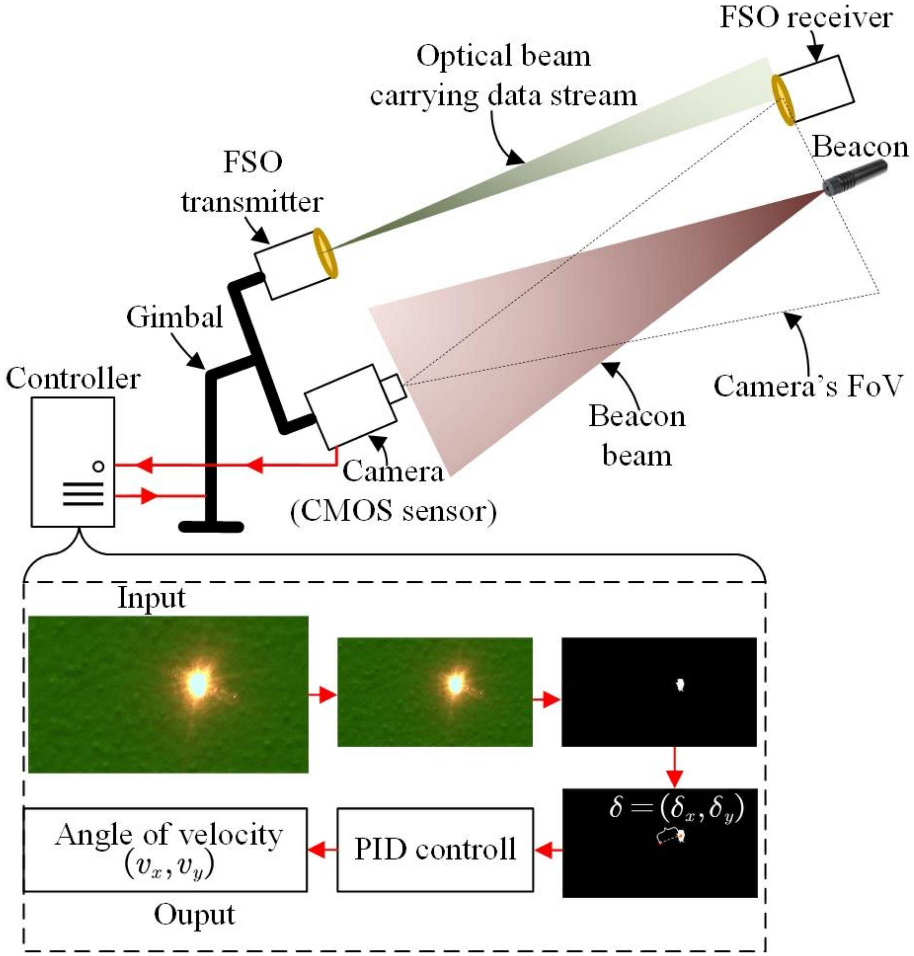


X. Sun, N. Ansari and R. Fierro, "Jointly Optimized 3D Drone Mounted Base Station Deployment and User Association in Drone Assisted Mobile Access Networks," in *IEEE Transactions on Vehicular Technology*, vol. 69, no. 2, pp. 2195-2203, Feb. 2020, doi: 10.1109/TVT.2019.2961086.

Acquisition, pointing, and tracking (ATP) system for FSO

- Design a cost effective and lightweight ATP system, which comprises
  - ❖ A beacon at the drone;
  - ❖ A camera mounted on a gimbal at the wireless access point (WAP);
  - ❖ A controller at the WAP.

- The functions achieved by the controller at the WAP
  - ❖ Down Sampling
  - ❖ Image Filtering
  - ❖ Displacement Identification
  - ❖ PID Control



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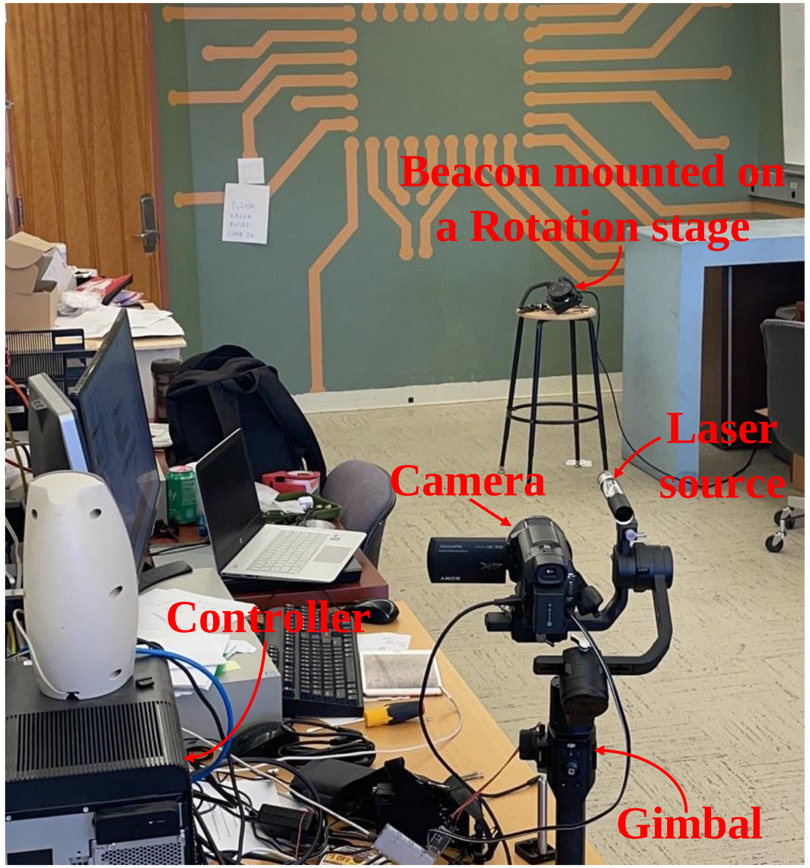

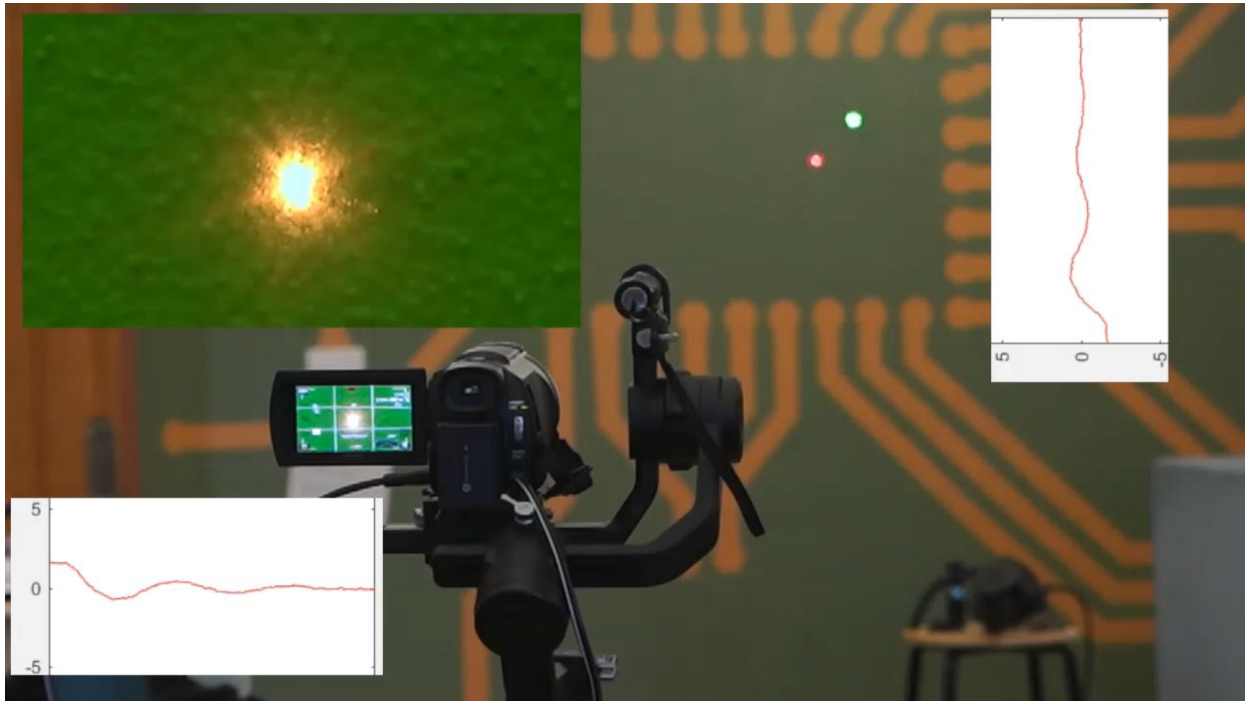

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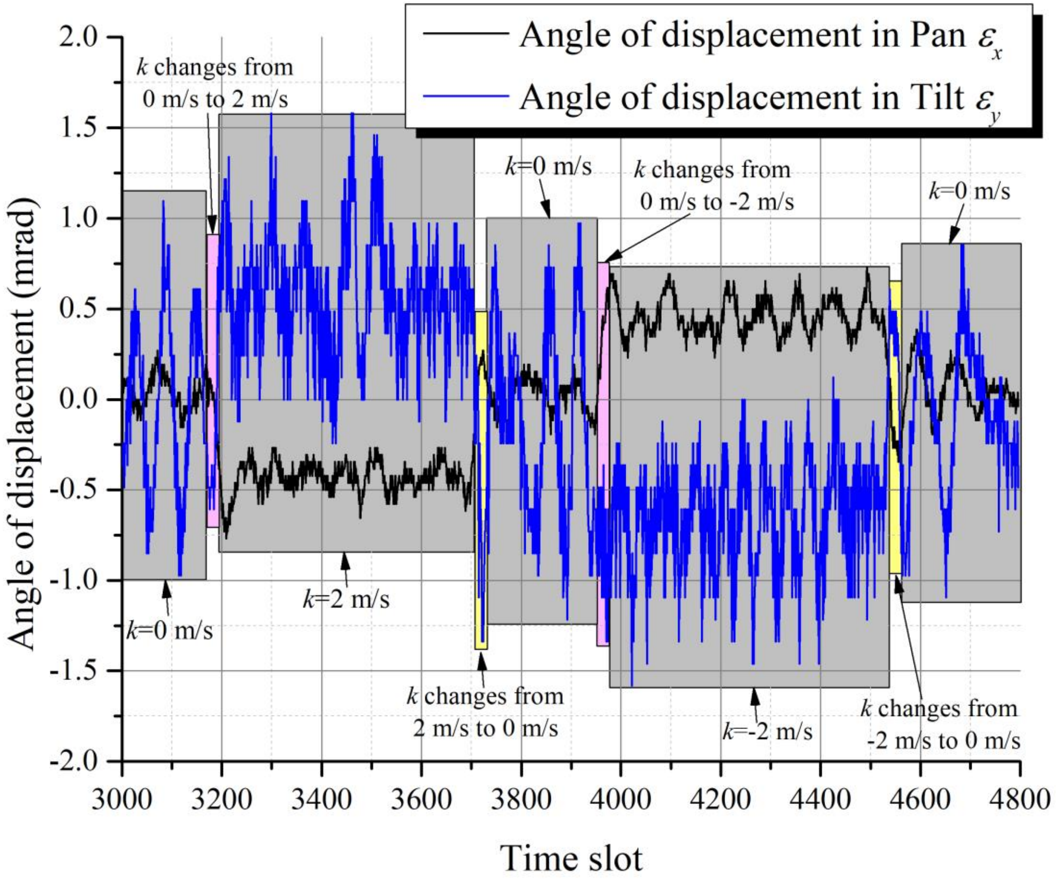

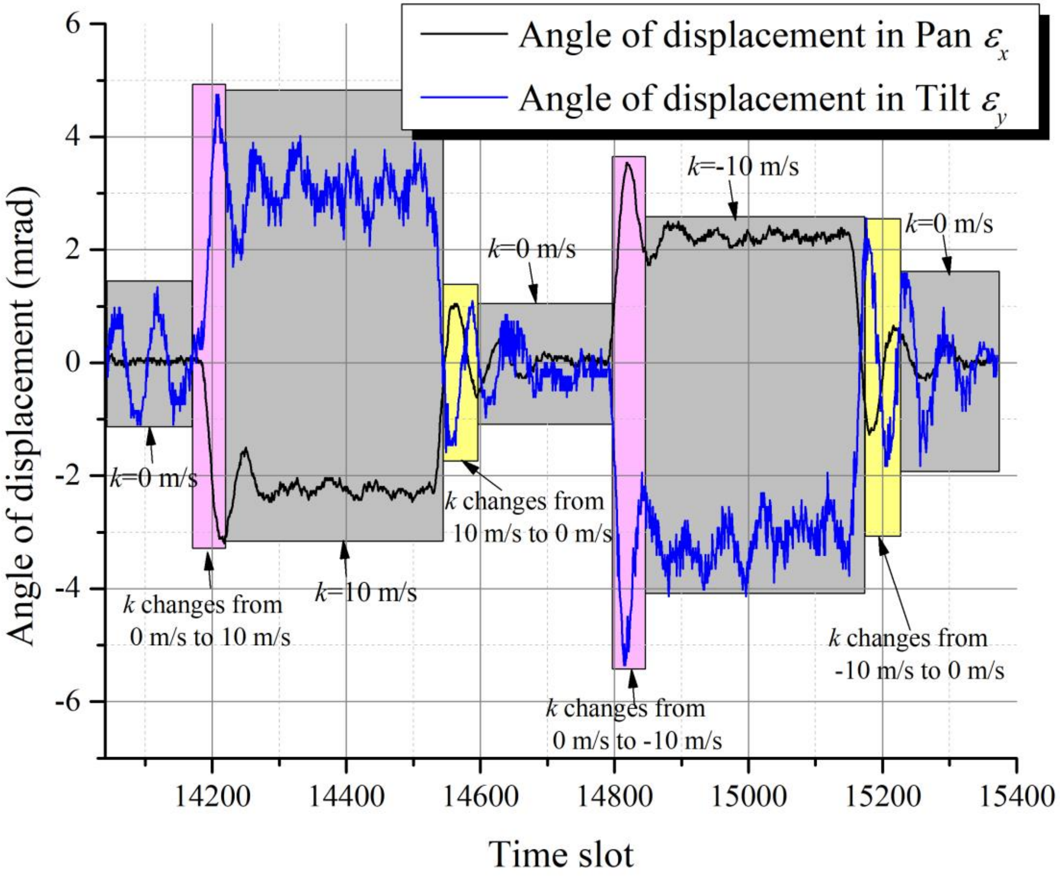

X. Sun, T. Zhang, S. Shao, B. Tice, P. Tice and S. Jayaweera, "Low Cost ATP System Design for Free Space Optics based Drone Assisted Wireless Networks," *2022 IEEE Globecom Workshops (GC Wkshps)*, Rio de Janeiro, Brazil, 2022, pp. 891-896,

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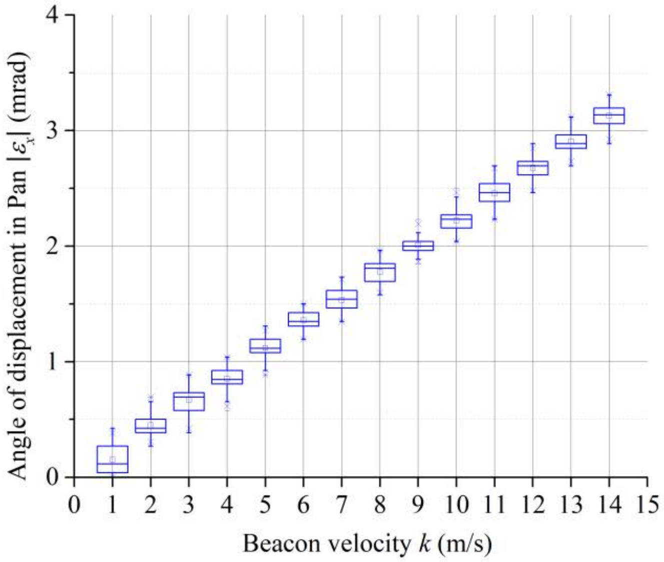

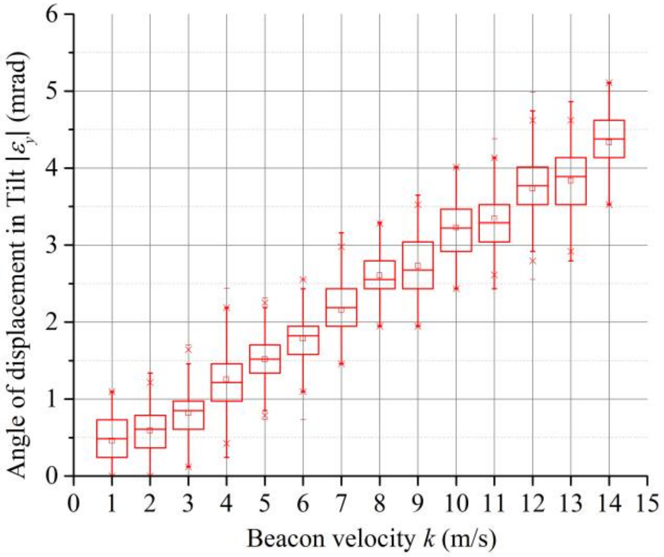

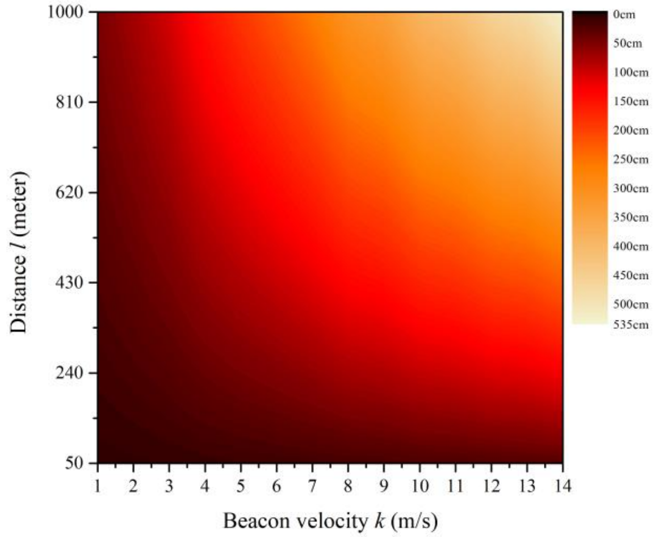

- The displacement is monotonically increasing with respect to the velocity of a UAV and distance between the UAV and the WAP.

X. Sun, T. Zhang, S. Shao, B. Tice, P. Tice and S. Jayaweera, "Low Cost ATP System Design for Free Space Optics based Drone Assisted Wireless Networks," *2022 IEEE Globecom Workshops (GC Wkshps)*, Rio de Janeiro, Brazil, 2022, pp. 891-896,

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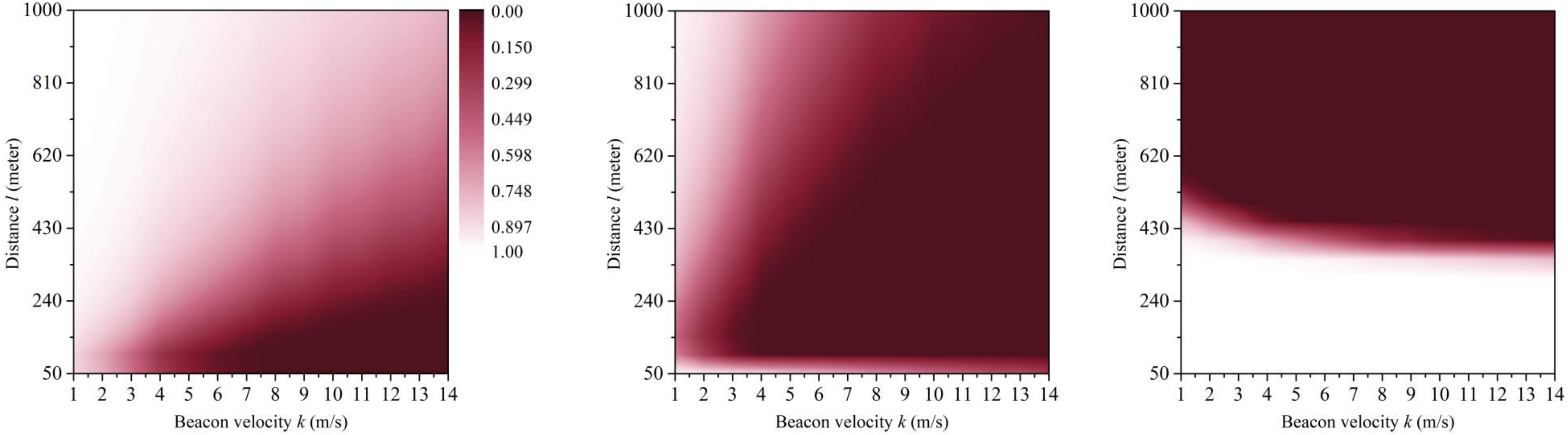
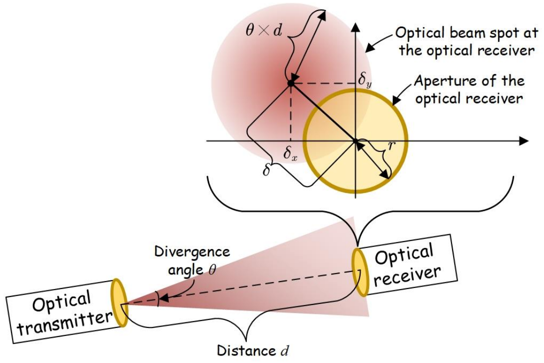
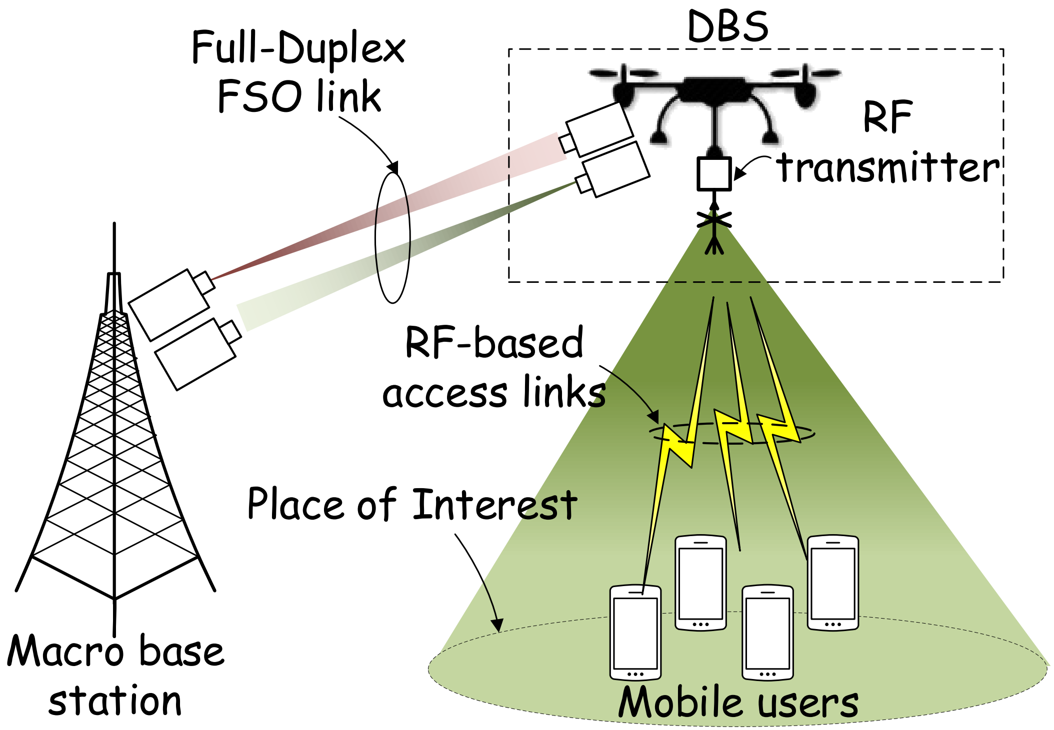




- The designed ATP system is enough to generate low pointing loss when 1) a large divergence angle optical beam is applied to carry data and the velocity of the UAV is not high (e.g., less than 5 m/s) as shown the first figure , or 2) a small divergence angle optical beam is used and the distance between the drone and the WAP is short (e.g., less than 400 m) as shown in the 3rd figure.

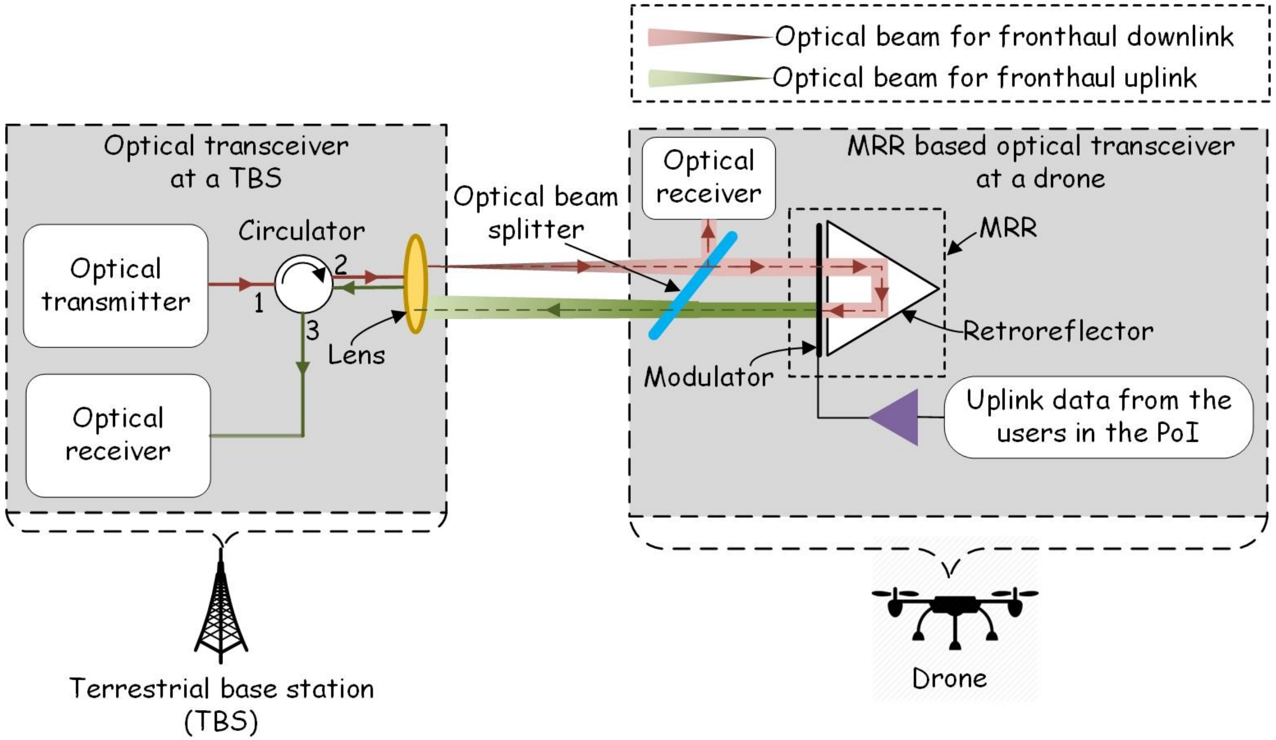
Full-duplex FSO communications in Airel Networks

- If full-duplex FSO communications are required between the drone the wireless access point (WAP), then the drone has to equip additional
  - ❖ An FSO transmitter;
  - ❖ The ATP system, including a **gimbal**, a camera, and a controller.
- The payload and battery capacity of a drone is limited, and so may not be able to carry these.



Full-duplex FSO communications in Airel Networks

- Modulating retro-reflector (MRR) based optical transceiver reflects the part of its received optical beam and uses the reflected optical beam to carry baseband signals.
- The drone does not need to carry the ATP system.



X. Sun, L. Yu and A. Alazzwi, "Free Space Optics as Full Duplex Fronthauling for Drone-Assisted Mobile Networks," 2023 32nd Wireless and Optical Communications Conference (WOCC), Newark, NJ, USA, 2023, pp. 1-5


Q&A