Tapping into the Full Potential of the Stratosphere

Mohamed-Slim Alouini
CTL

6G is Coming

Vehicle-to-everything

E-Health

Extended Reality

Super eMBB

Artificial Intelligence

Industrial IoT

[1] *S. Dang, O. Amin, B. Shihada, & M. –S. Alouini*, **"What Should 6G Be?"**, Nature Electronics, 2020.

UNESCO
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Connect the Unconnected

The Global Connectivity Divide

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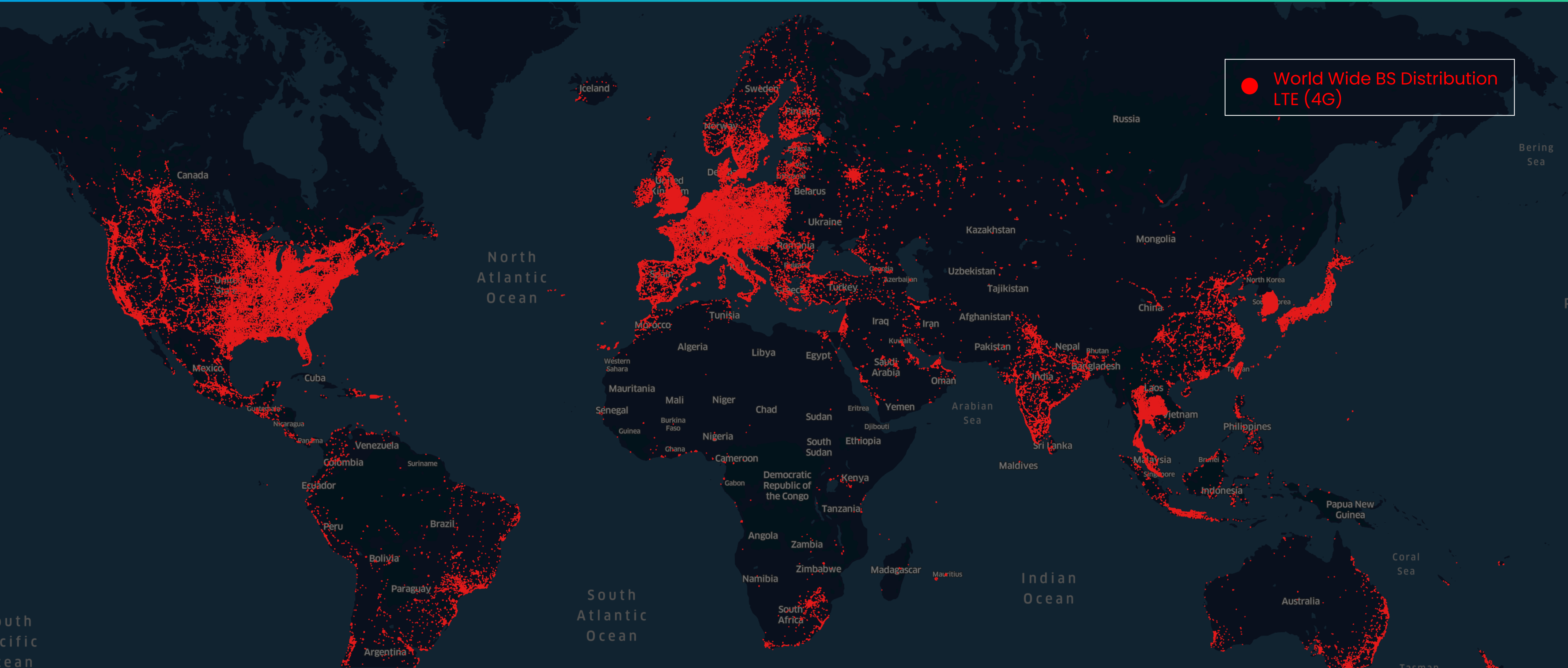
King Abdullah University of Science and Technology



We are suffering from *serious gaps* in global *internet connectivity*

E. Yaacoub and M.-S. Alouini, "**A Key 6G Challenge and Opportunity - Connecting the Base of the Pyramid: A Survey on Rural Connectivity**", Proceedings of IEEE, 2020.

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Resilience with On-Demand Pop-up Networking

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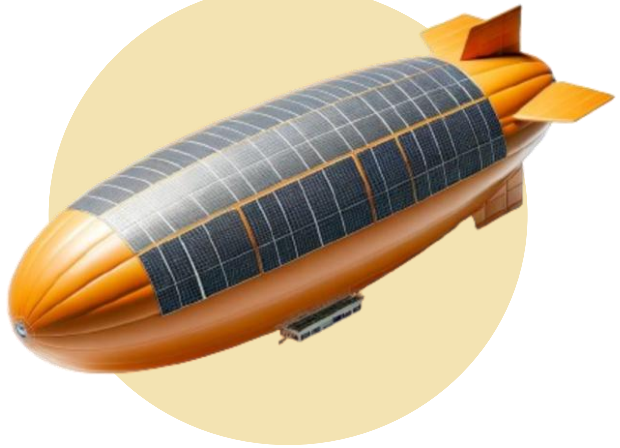
King Abdullah University of
Science and Technology

[1] *M. Matracia, M. Kishk, and M.-S. Alouini*, "**Post-disaster communications: Enabling technologies, architectures, & open challenges**", IEEE Open Journal of Communication Society, 2022.
[2] *F. Alqurashi, A. Trichili, N. Saeed, B. Ooi, and M. -S. Alouini*, "**Maritime communications: A survey on enabling technologies, opportunities, and challenges**", IEEE Internet of Things Journ
2023. a

Aerial/Space-Based Stations

High Altitude Platform Stations (HAPS)

Fixed-Wing

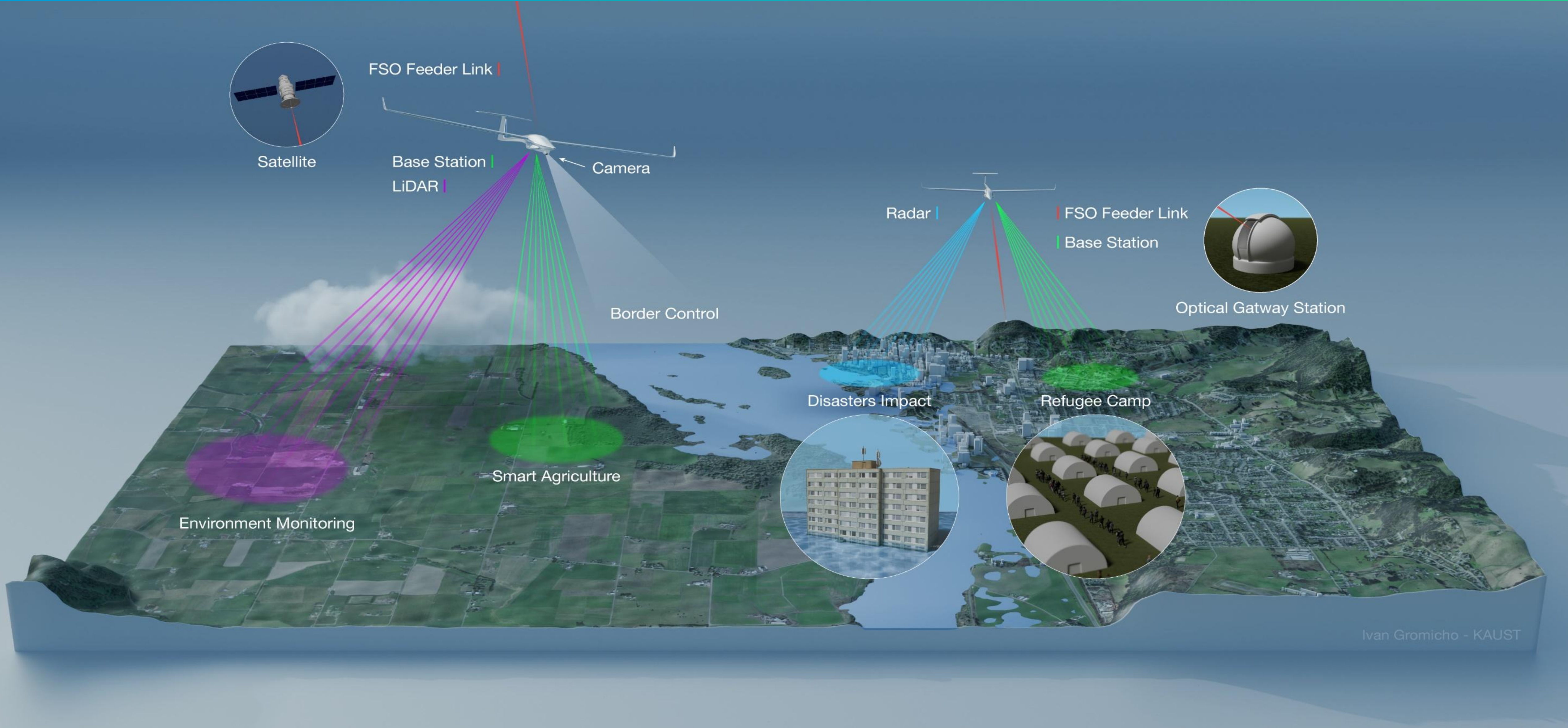


Airship

Balloon

[1] *Z. Lou, B. E. Y. Belmekki, and M. -S. Alouini*, "**HAPS in the Non-Terrestrial Network Nexus: Prospective Architectures and Performance Insights**", IEEE Wireless Communications, 2023.
[2] *B.E.Y. Belmekki, A. J. Aljohani, S. A. Althubaity, A. Al Harthi, K. Bean, A. Aijaz, and M.-S Alouini*, "**Cellular Network From the Sky: Toward People-Centered Smart Communities**8JCS, 2024.

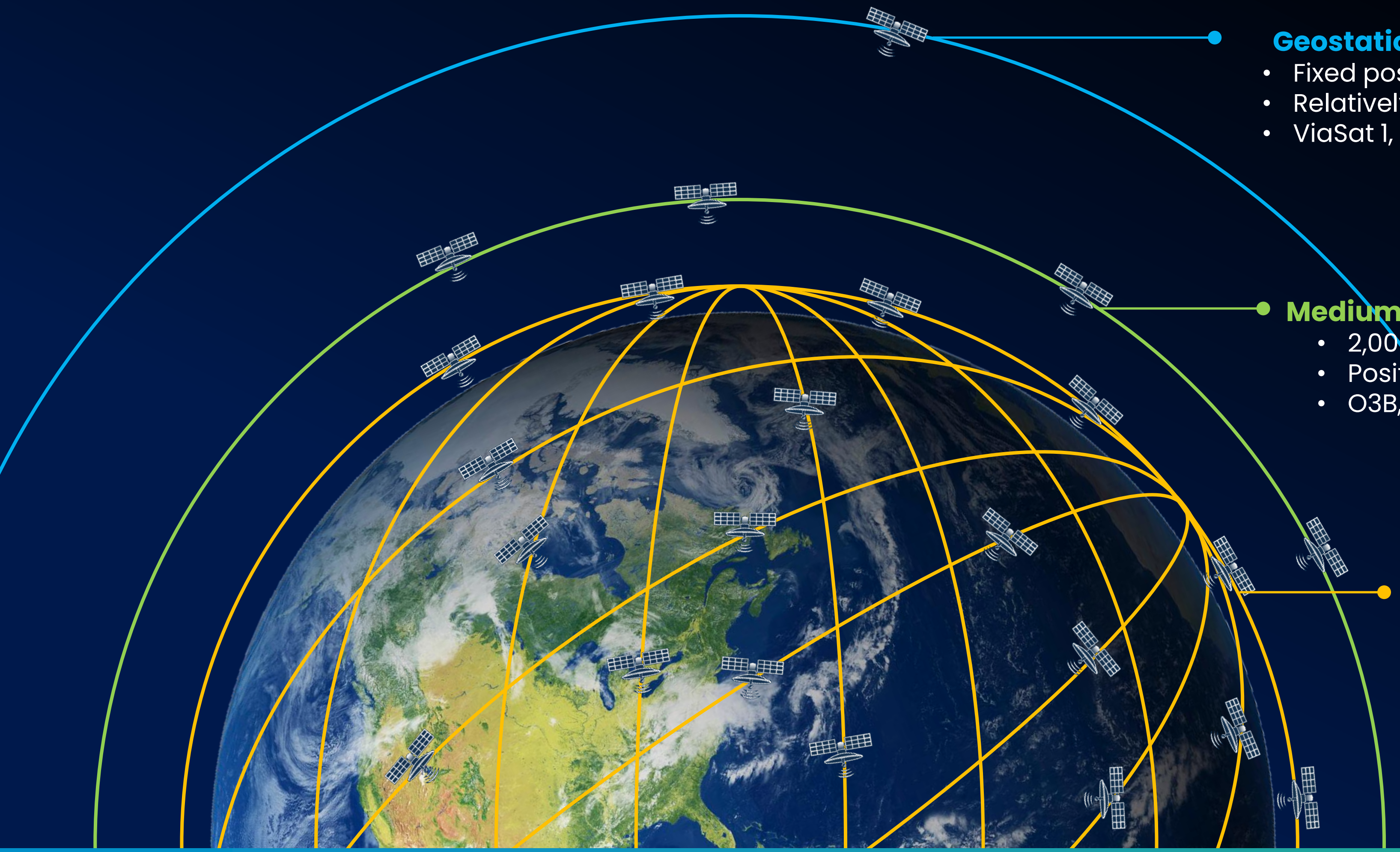
HAPS with Multiple Missions



[1] *Z. Lou, B. E. Y. Belmekki, and M. -S. Alouini*, "**HAPS in the Non-Terrestrial Network Nexus: Prospective Architectures and Performance Insights**", IEEE Wireless Communications, 2023.
[2] *B.E.Y. Belmekki, A. J. Aljohani, S. A. Althubaity, A. Al Harthi, K. Bean, A. Aijaz, and M.-S Alouini*, "**Cellular Network From the Sky: Toward People-Centered Smart Communities**8JSS, 2024.

Satellite Constellations Backhaul

Manufacturing Cost Down => Mass Production



Geostationary Earth Orbit (GEO) Satellite

- Fixed position in the sky at ~35,000 km
- Relatively large delay
- ViaSat 1, 2, 3

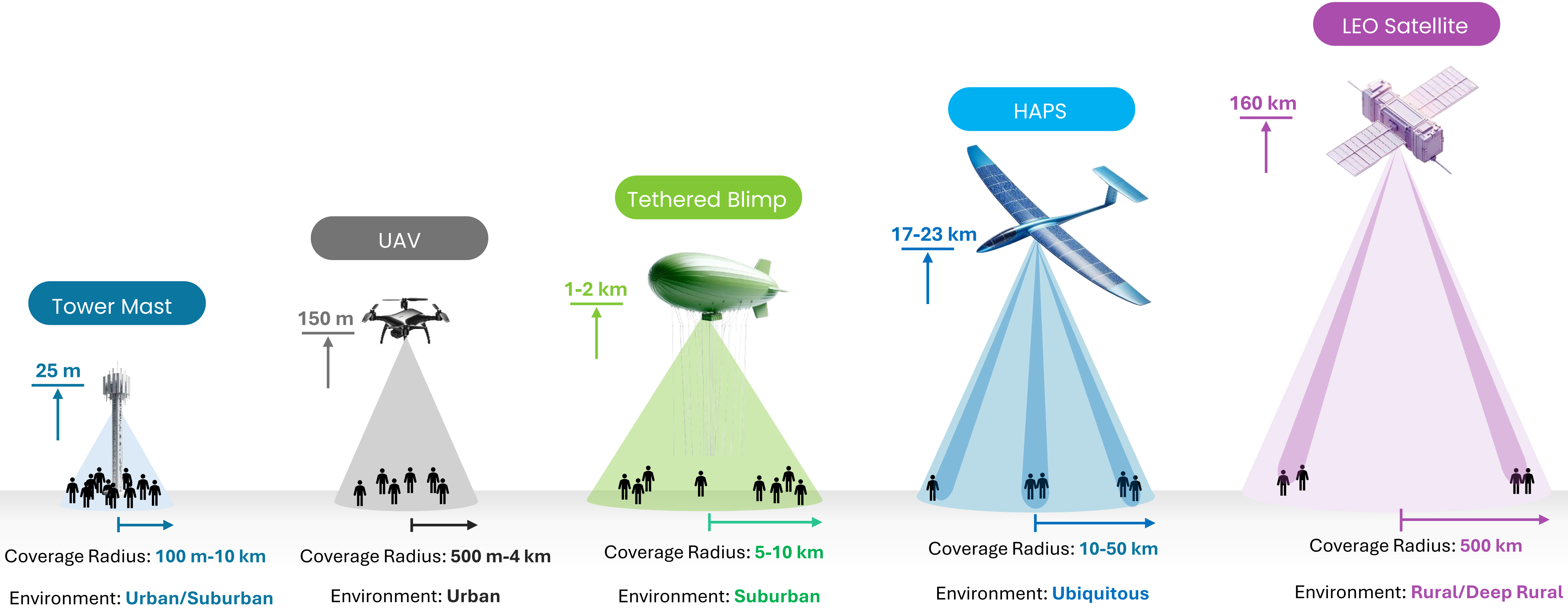
Medium Earth Orbit (MEO) Satellite

- 2,000~35,000 km
- Position and tracking
- O3B, SES Networks

Low Earth Orbit (LEO) Satellite

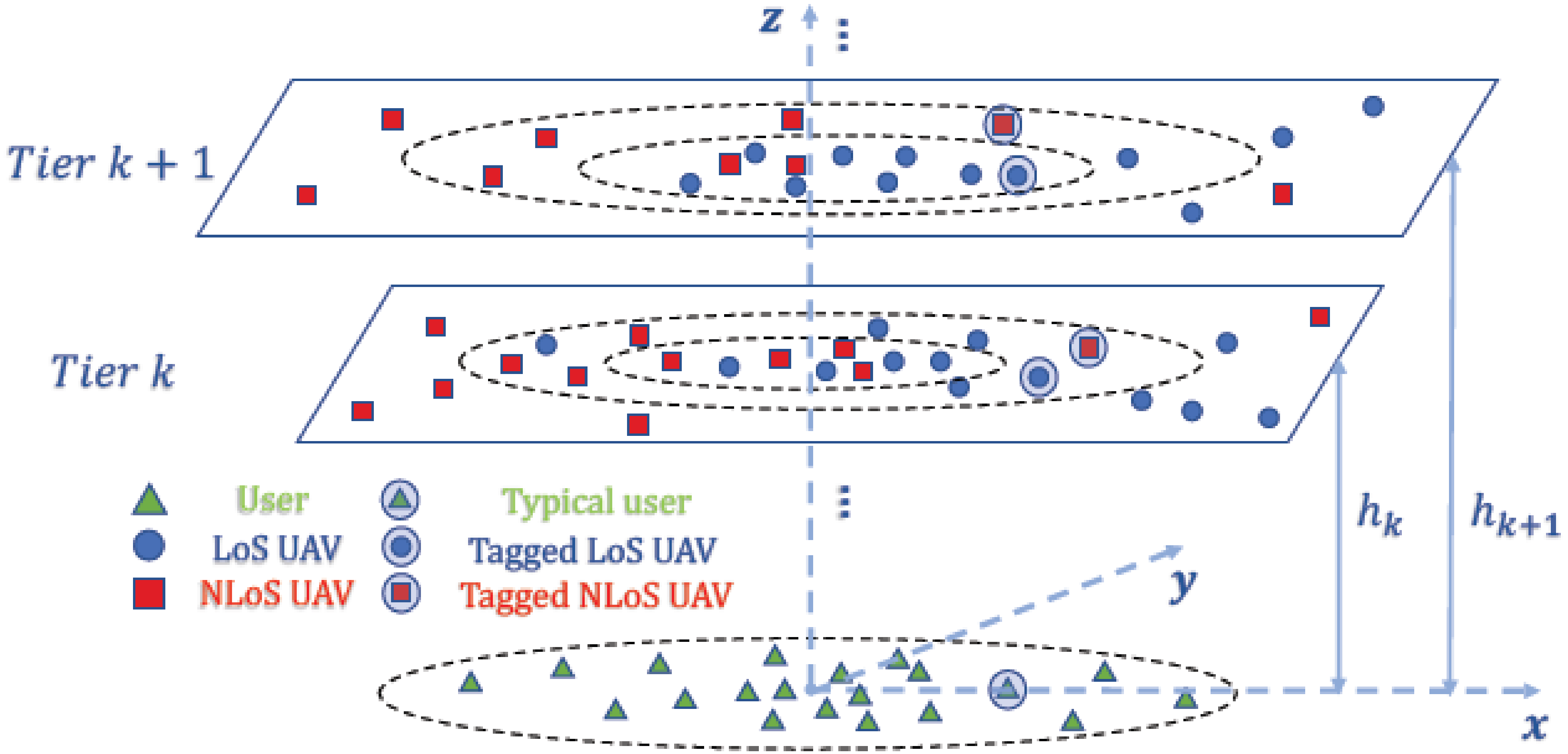
- 160~2,000 km
- Hand-Over
- OneWeb, Starlink, Lightspeed, Kuiper

Different Towers in the Sky/Space



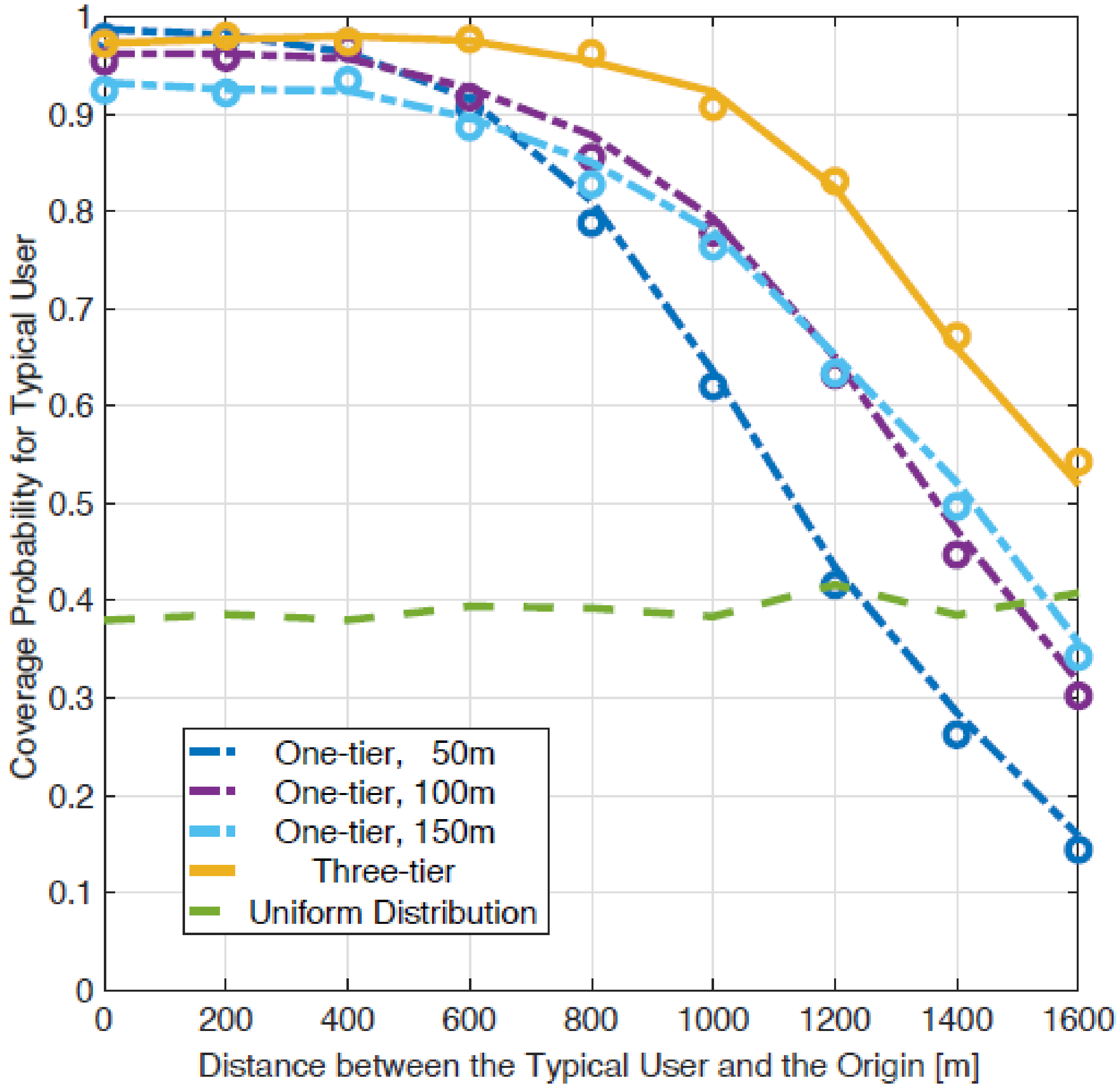
[1] *R. Wang, M. Kishk, and M. -S. Alouini*, "**Resident Population Density-Inspired Deployment of K-Tier Aerial Cellular Network**", IEEE Transaction on Wireless Communications, 2023.

Coverage Enhancement in Rural Areas



[1] R. Wang, M. A. Kishk and M. -S. Alouini, "Resident Population Density-inspired Deployment of K-tier Aerial Cellular Network," IEEE Transactions on Wireless Communications, 2023.

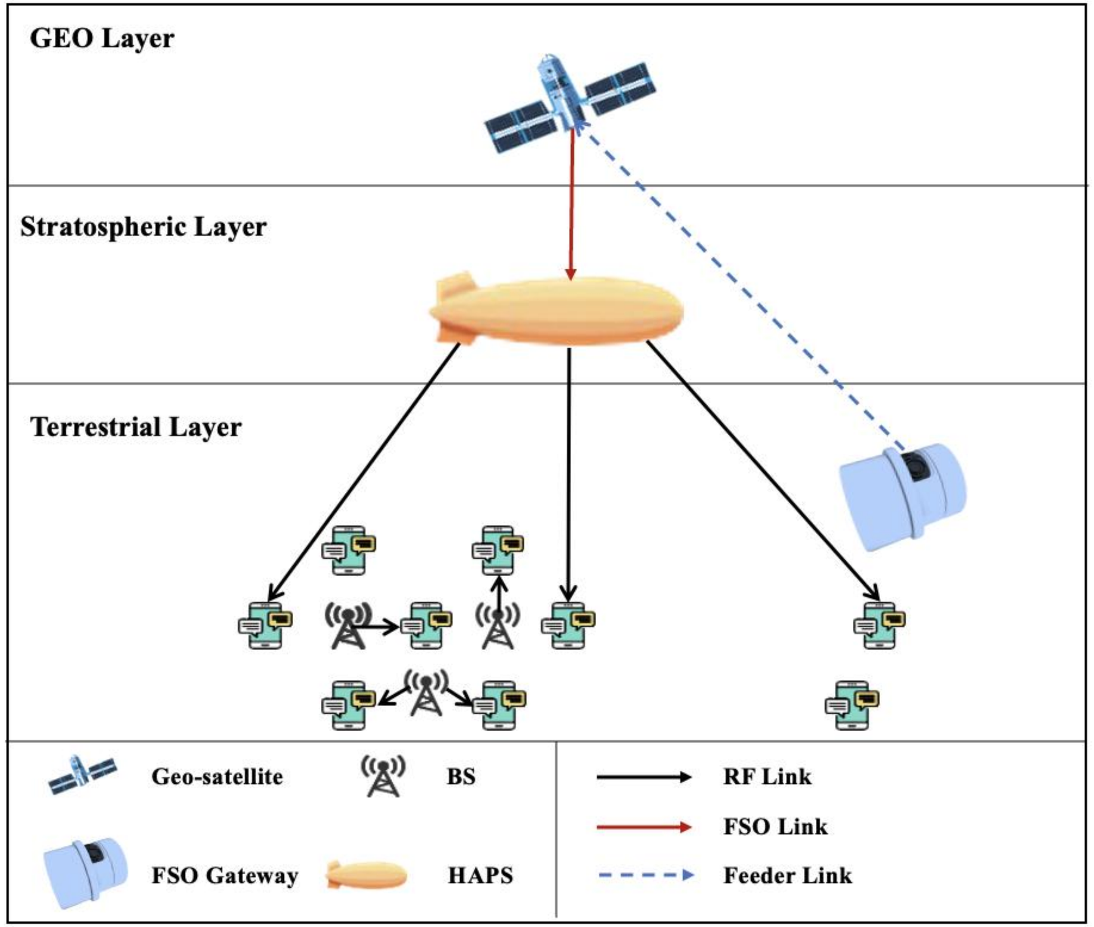
Coverage Enhancement in Rural Areas



[1] R. Wang, M. A. Kishk and M. -S. Alouini, "Resident Population Density-inspired Deployment of K-tier Aerial Cellular Network," IEEE Transactions on Wireless Communications, 2023.

Resource Allocation in Satellite-HAPS-Ground Integrated Networks

Resource Allocation in SAGIN



- Integrated satellite-HAPS-ground network

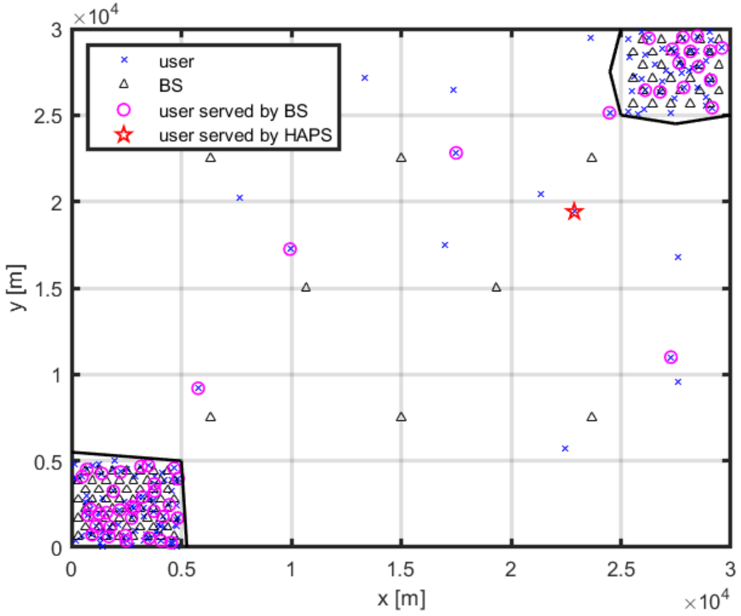
Network Configuration:

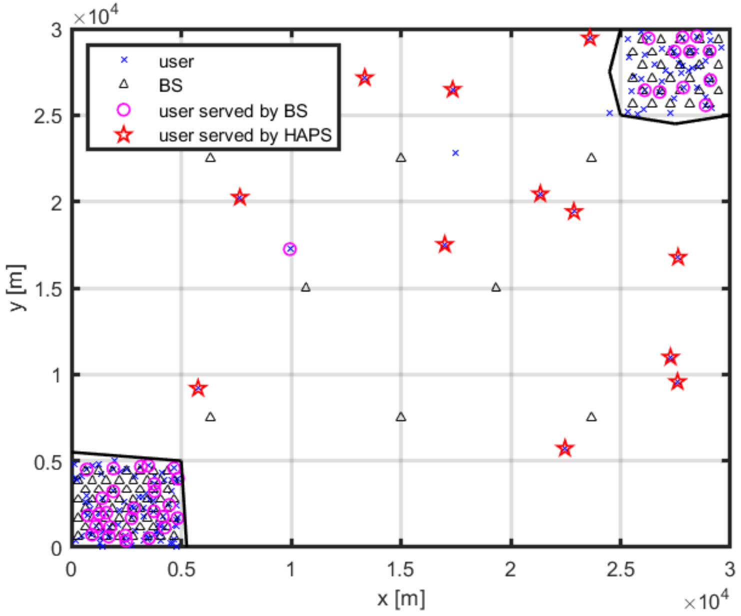
- The satellite-HAPS-ground integrated network consists of one satellite, one HAPS, multiple ground BSs and users.

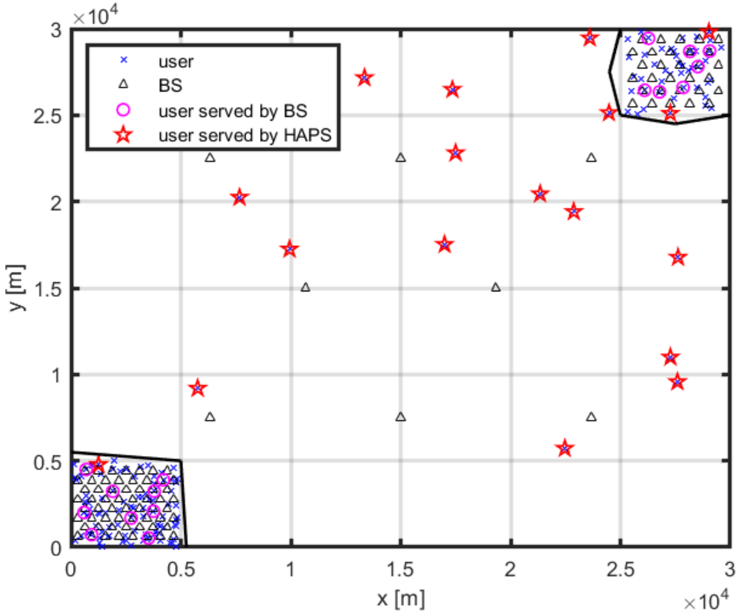
- The satellite and HAPS are connected via FSO, and each user is served by either one of the BSs or by the HAPS via RF links.

[1] *S. Liu, H. Dahrouj and M. -S. Alouini*, "**Joint user association and beamforming in integrated satellite-HAPS-ground networks**", in IEEE Transactions on Vehicular Technology. Nov. 2023.

Resource Allocation in SAGIN





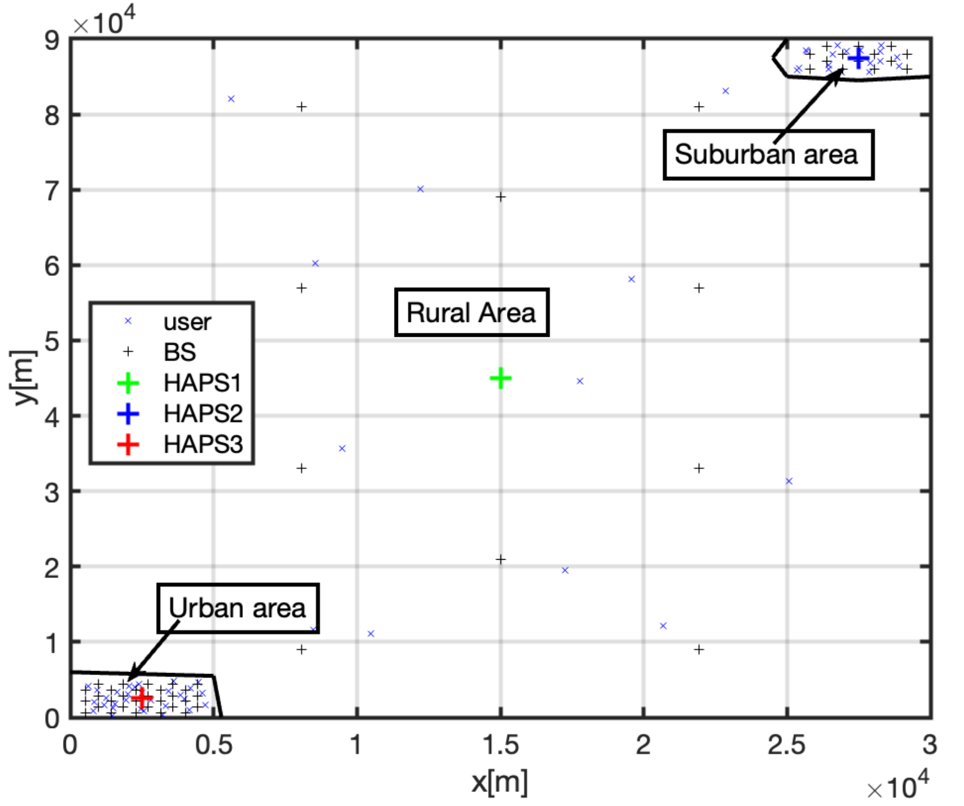


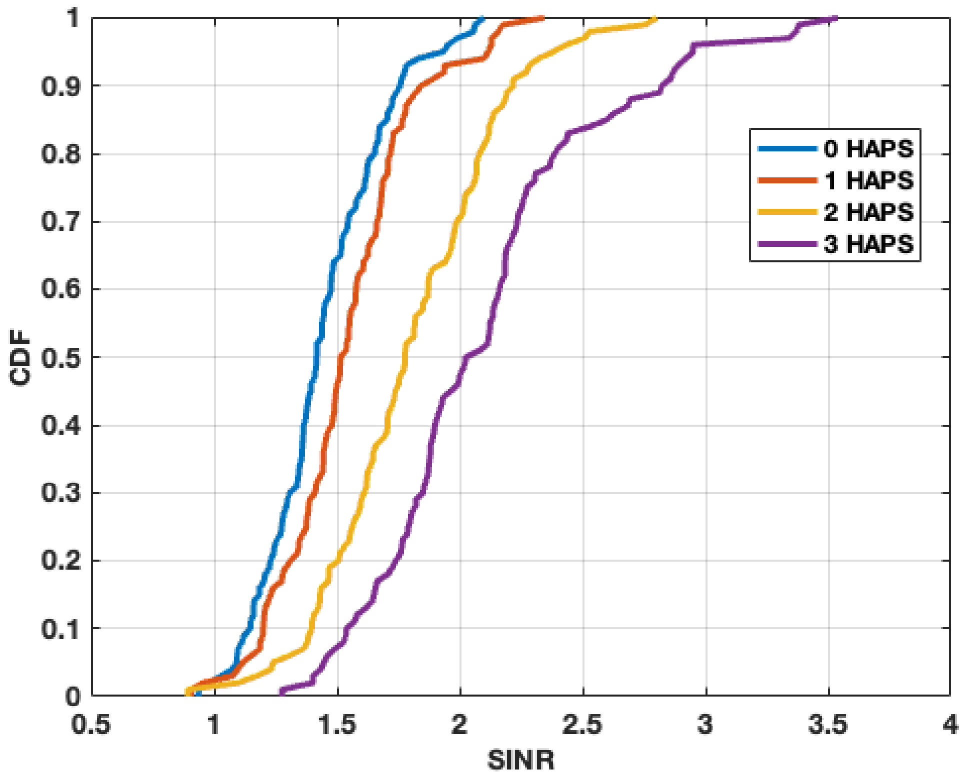
- Maximum power of HAPS is -40dBw.
- Maximum power of HAPS is 10dBw.
- Maximum power of HAPS is 30 dBw.

- The behavior of user to HAPS and ground BSs association for different HAPS power levels.

[1] *S. Liu, H. Dahrouj and M. -S. Alouini*, "**Joint user association and beamforming in integrated satellite-HAPS-ground networks**", in IEEE Transactions on Vehicular Technology. Nov. 2023.

Extension to Multi-HAPS Constellation

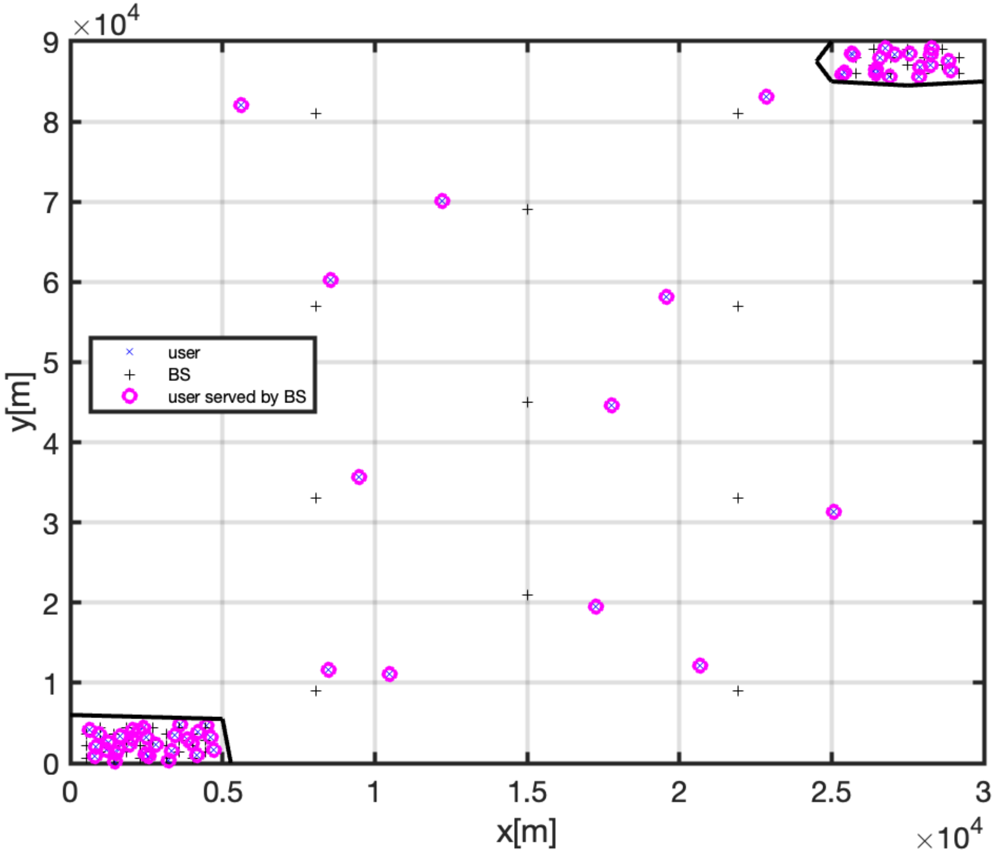




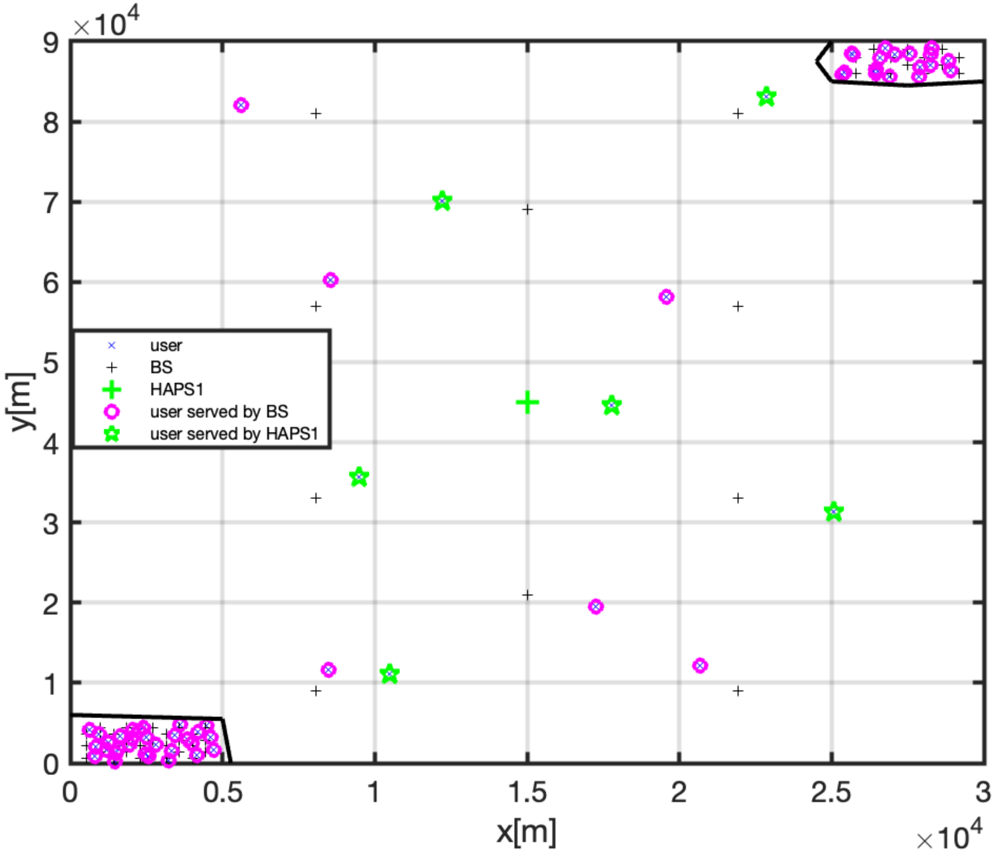
- Layout of the network
- CDF of minimum SINR

[1] *S. Liu, H. Dahrouj and M. -S. Alouini,* "Toward the Democratization of Future Energy-Efficient Networks: A Multi-HAPS Approach", Under Review.

Users Association (1)



- The number of HAPS is 0.

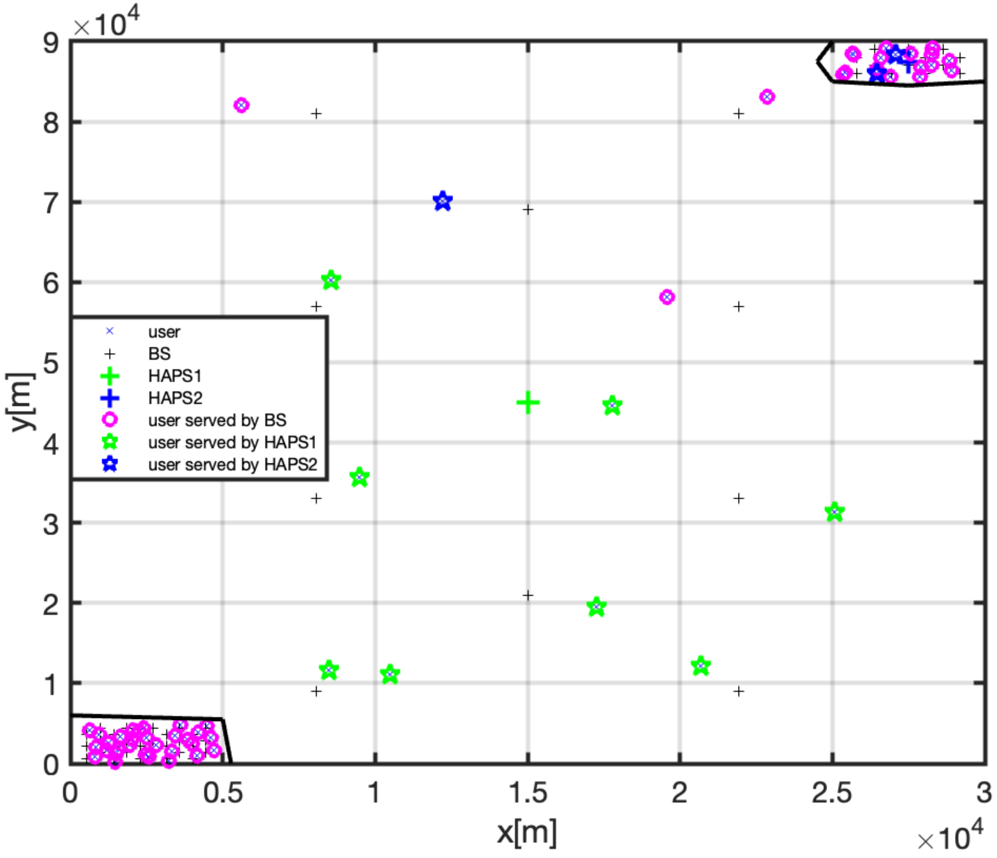


- The number of HAPS is 1.

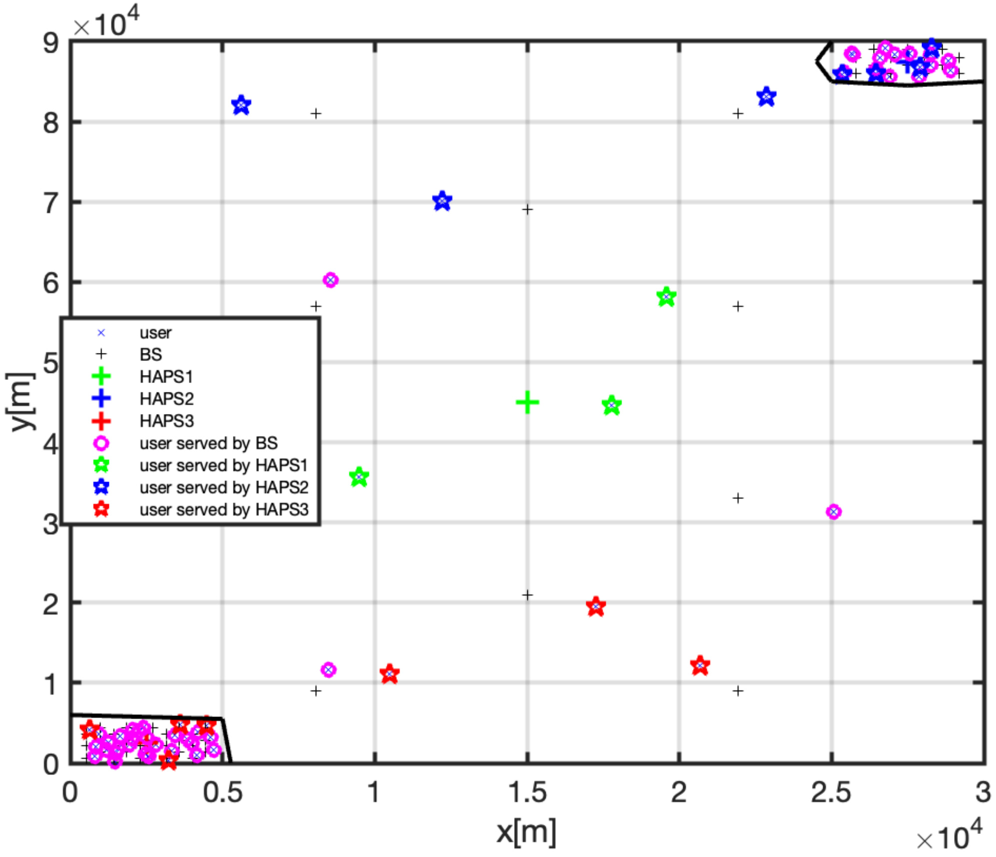
- The behavior of user to HAPS and ground BSs association for different number of HAPS.

[1] *S. Liu, H. Dahrouj and M. -S. Alouini,* "Toward the Democratization of Future Energy-Efficient Networks: A Multi-HAPS Approach", Under Review.

Users Association (2)



- The number of HAPS is 2.



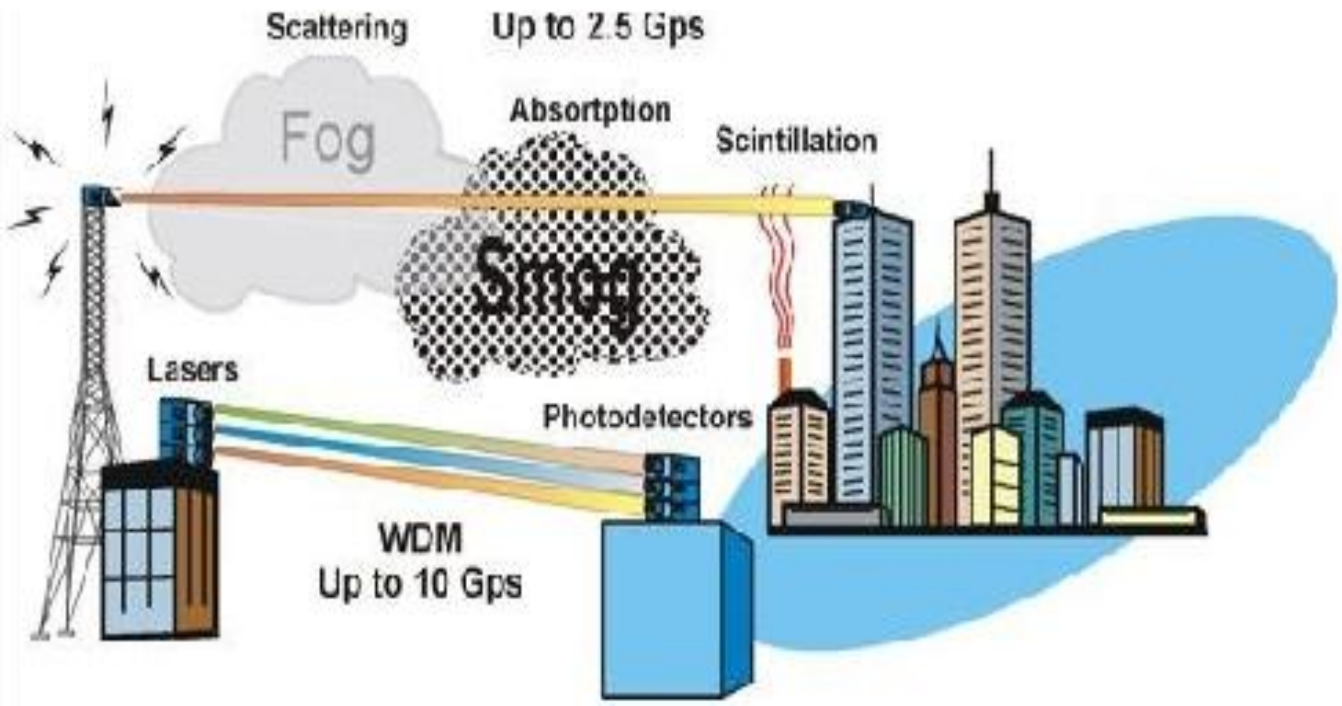
- The number of HAPS is 3.

- The behavior of user to HAPS and ground BSs association for different number of HAPS.

[1] *S. Liu, H. Dahrouj and M. -S. Alouini,* "Toward the Democratization of Future Energy-Efficient Networks: A Multi-HAPS Approach", Under Review.

A Light in Digital Darkness

Free Space Optics (FSO) Communication



Narrow beam connects two optical wireless transceivers in LOS.

Benefits

- Unlicensed and unbounded spectrum
- Cost-effective
- Narrow beam-widths (Energy efficient, immune to interference and secure)
- Behind windows
- Fast turn-around time
- Suitable for brown-field

Applications

- Initially used for secure military and in space
- Last mile solution
- Optical fiber back-up
- High data rate temporary links
- Wireless Fronthaul/Backhaul in cellular network

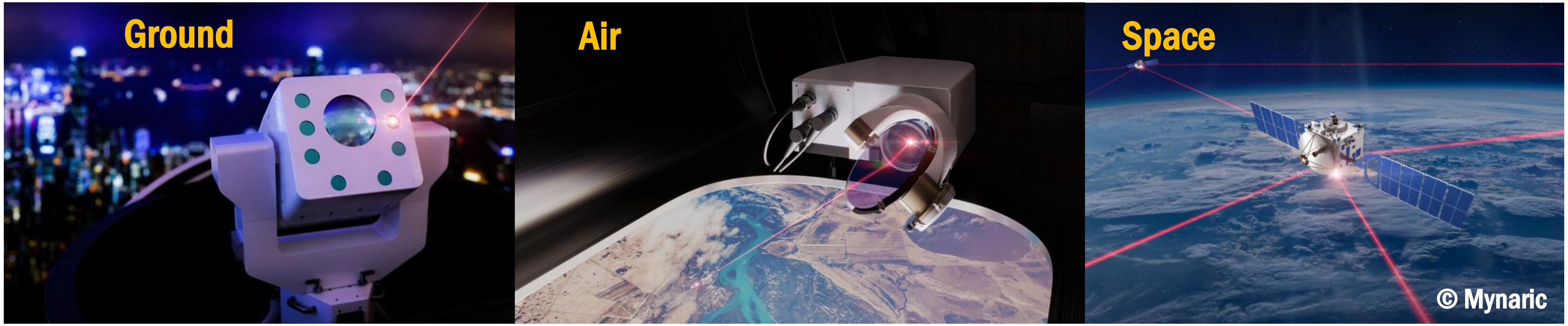
Challenges

- Additive noise and background radiation
- Atmospheric path loss and attenuation
- Atmospheric Turbulences
- Alignment and tracking

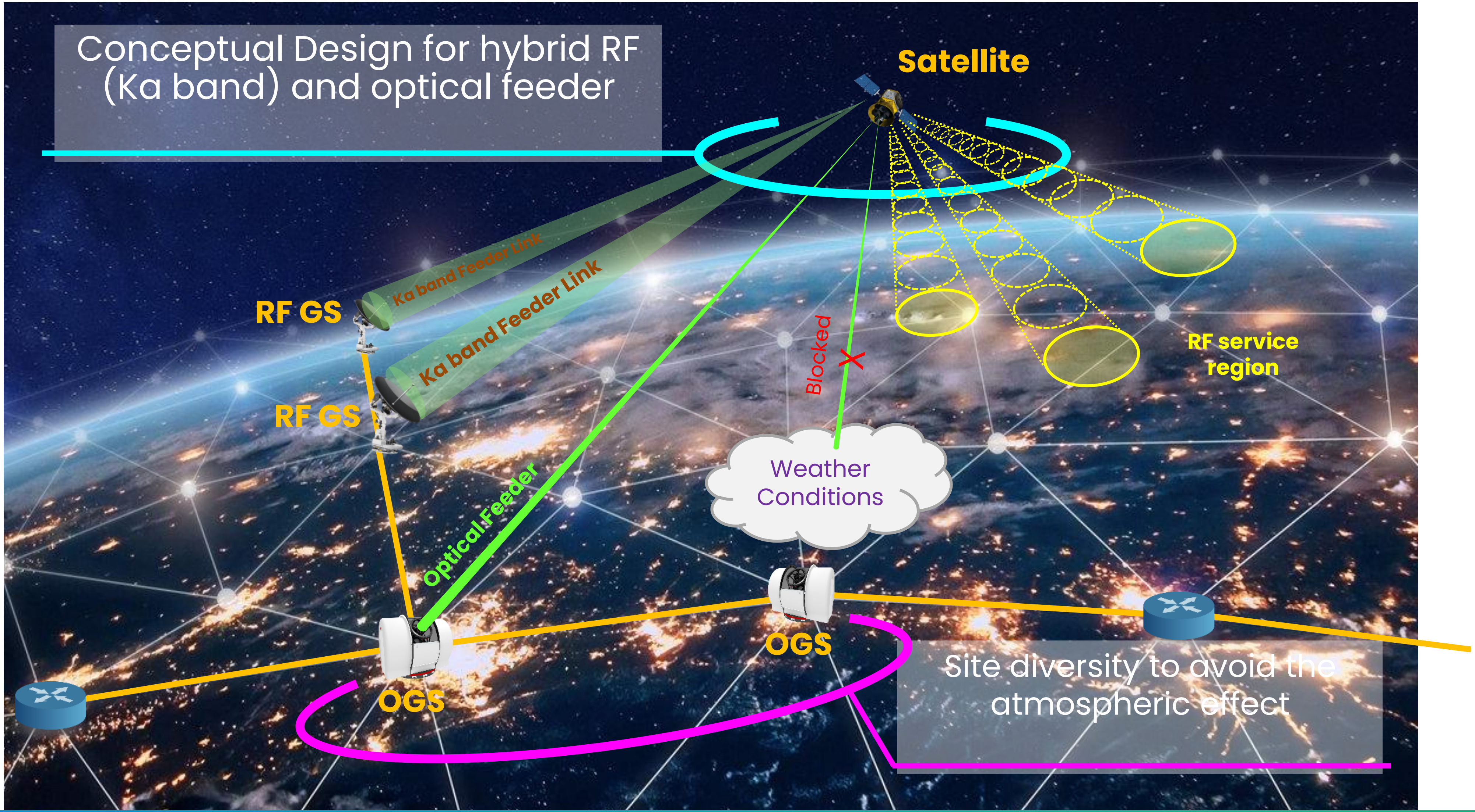
[1] *M. Esmail, A. Raghed, H. Fathallah, and M. -S. Alouini,*"**Investigation and demonstration of high speed full-optical hybrid FSO/fiber communication system under light and storm condition**", IEEE Photonics Journal, 2017.
[2] *A. Trichili, M. Cox, B. S. Ooi, and M.-S. Alouini,* "**'Roadmap to free space optics**", Journal of Optical Society of America B, 2020.

FSO for Aerial and Space Links

- **Key issues in RF HAPS/satellite backhaul systems**
  - Interference with terrestrial RF networks
  - Bandwidth limitation of conventional RF solutions
  - SWaP constraints of airborne and spatial platforms
- **FSO feeder is an attractive alternative for future very high throughput (VHT) HAPS/satellite systems without spectrum regulation.**



Hybrid VHT Satellite with Site Diversity

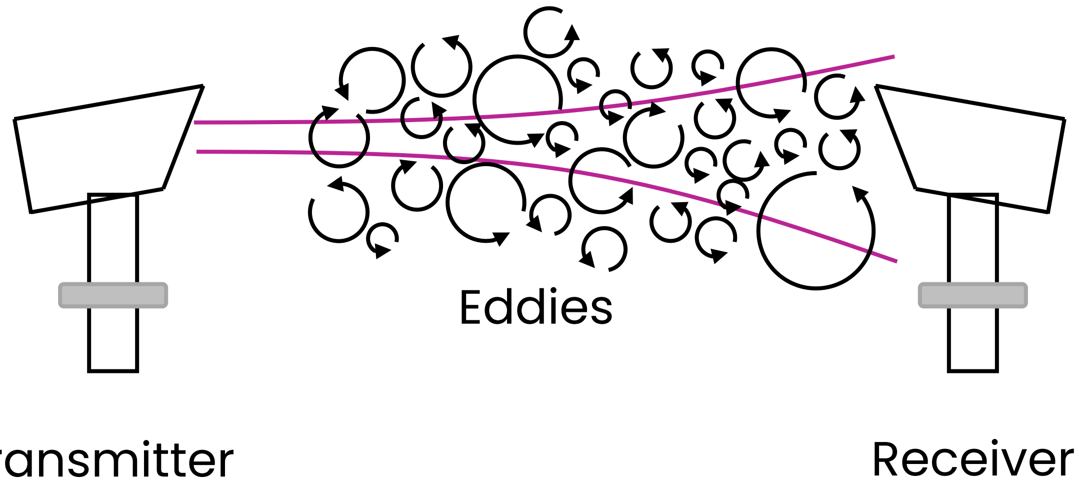


[1] *E. Zedini, A. Kammoun, and M. –S. Alouini,* "**Performance of multibeam very high throughput satellite systems based on FSO feeder links with HPA nonlinearity** ", IEEE Trans. On Wireless Comm., 2020

Atmospheric Turbulence

Atmospheric Turbulence

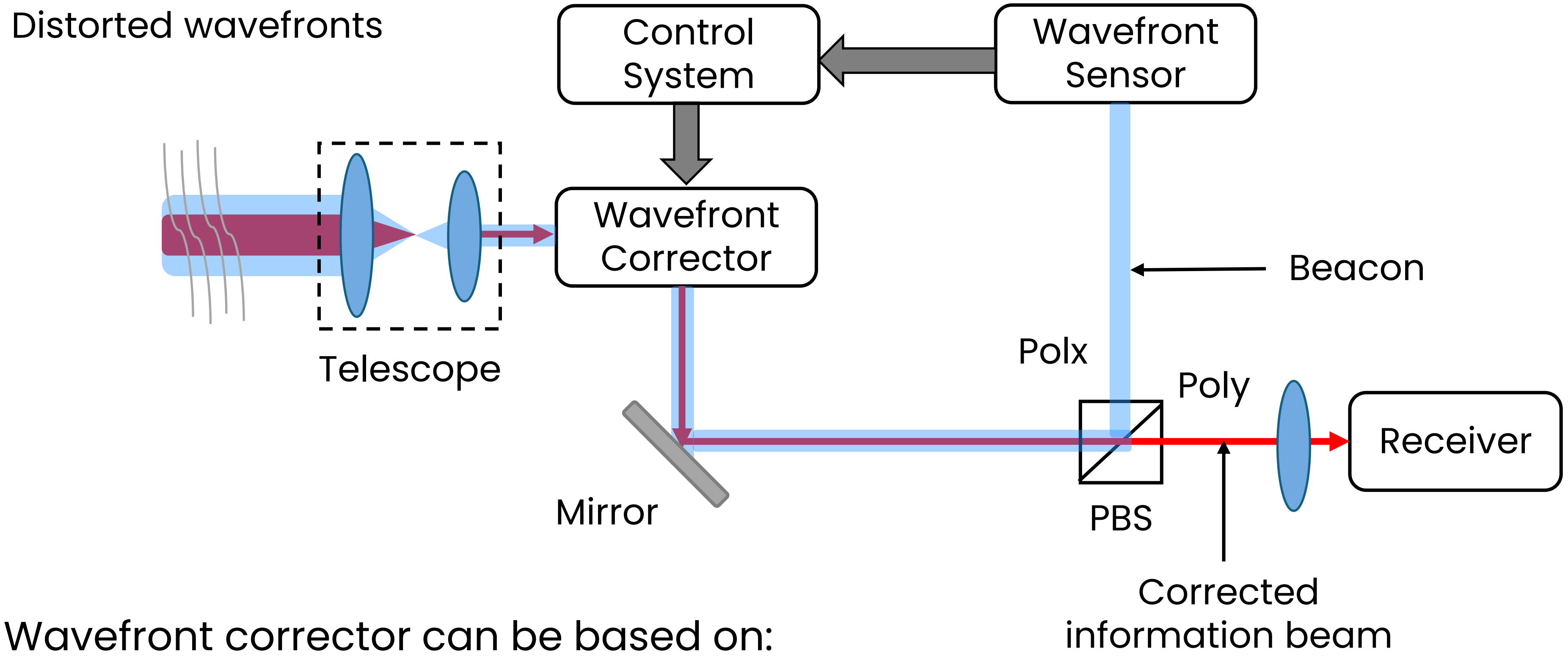
Propagation through turbulent atmosphere:



Scintillation index: $$\sigma_I^{\,2} = \frac{\mathrm{E}\{I^2\}}{\mathrm{E}\{I\}^2} - 1$$

Main reasons: Random variations in temperature and pressure leading to random variation in the refractive index structure.

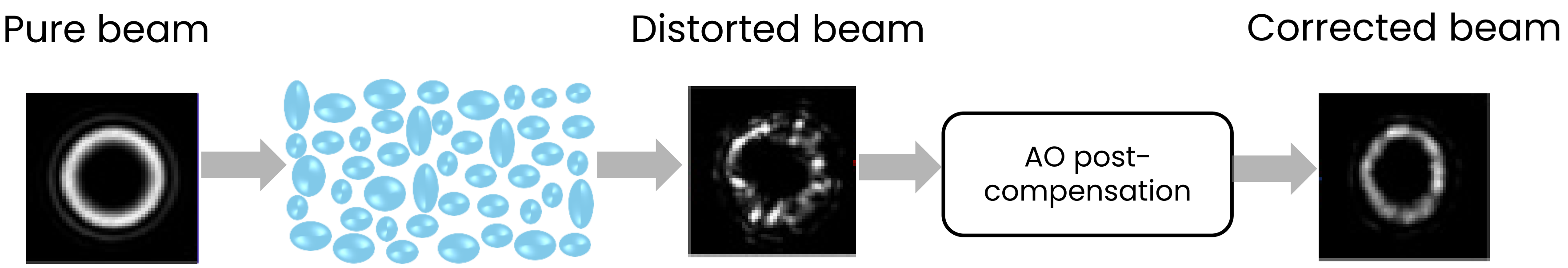
Principle of Adaptive Optics



Wavefront corrector can be based on:
- A liquid crystal display (slow)
- An array of deformable mirrors (fast)

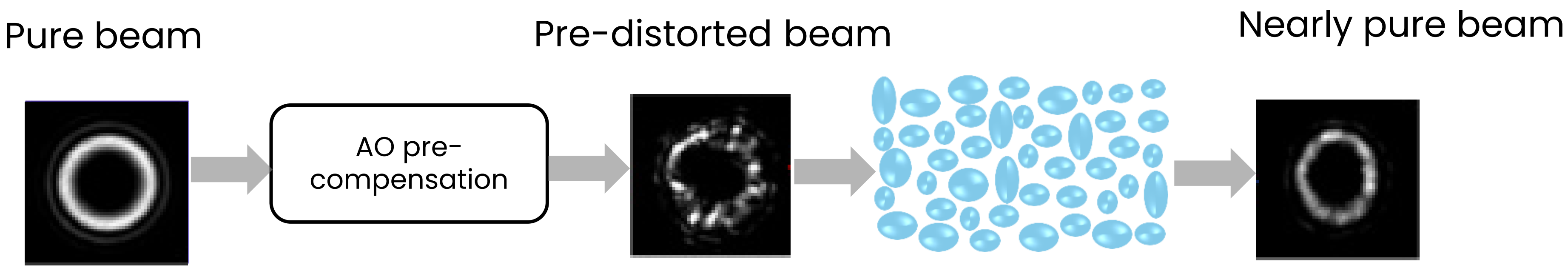
Adaptive Optics Schemes

Post-compensation



Requires a beacon Gaussian beam from the transmitter.

Pre-compensation



Requires a beacon Gaussian beam from the receiver.

Outage Probability Gamma-Gamma Turbulence Model

- Imbalanced vibrations

$$P_{out} = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}} \eta_s^2 h_{af} e^{-\frac{\sigma_0^2}{2}} {}_1F_1\left(-\frac{1}{2}, \frac{1}{2}; \frac{\sigma_0^2}{2}\right)}{2\pi q_H A_0^{(\alpha+\beta)/2} \Gamma(\alpha)\Gamma(\beta) h_{al}^{(\alpha+\beta)/2}} \int_{-\pi}^{\pi} h_{th}^{\frac{\alpha+\beta}{2}}$$

$$\times G_{2,4}^{3,1}\left(\frac{\alpha\beta h_{th}}{A_0 h_{al}} \middle| \begin{matrix} \frac{2-\alpha-\beta}{2}, \frac{2-\alpha-\beta+2\eta_s^2\xi(\varphi)}{2} \\ \frac{-\alpha-\beta+2\eta_s^2\xi(\varphi)}{2}, \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, \frac{-\alpha-\beta}{2} \end{matrix}\right) d\varphi.$$

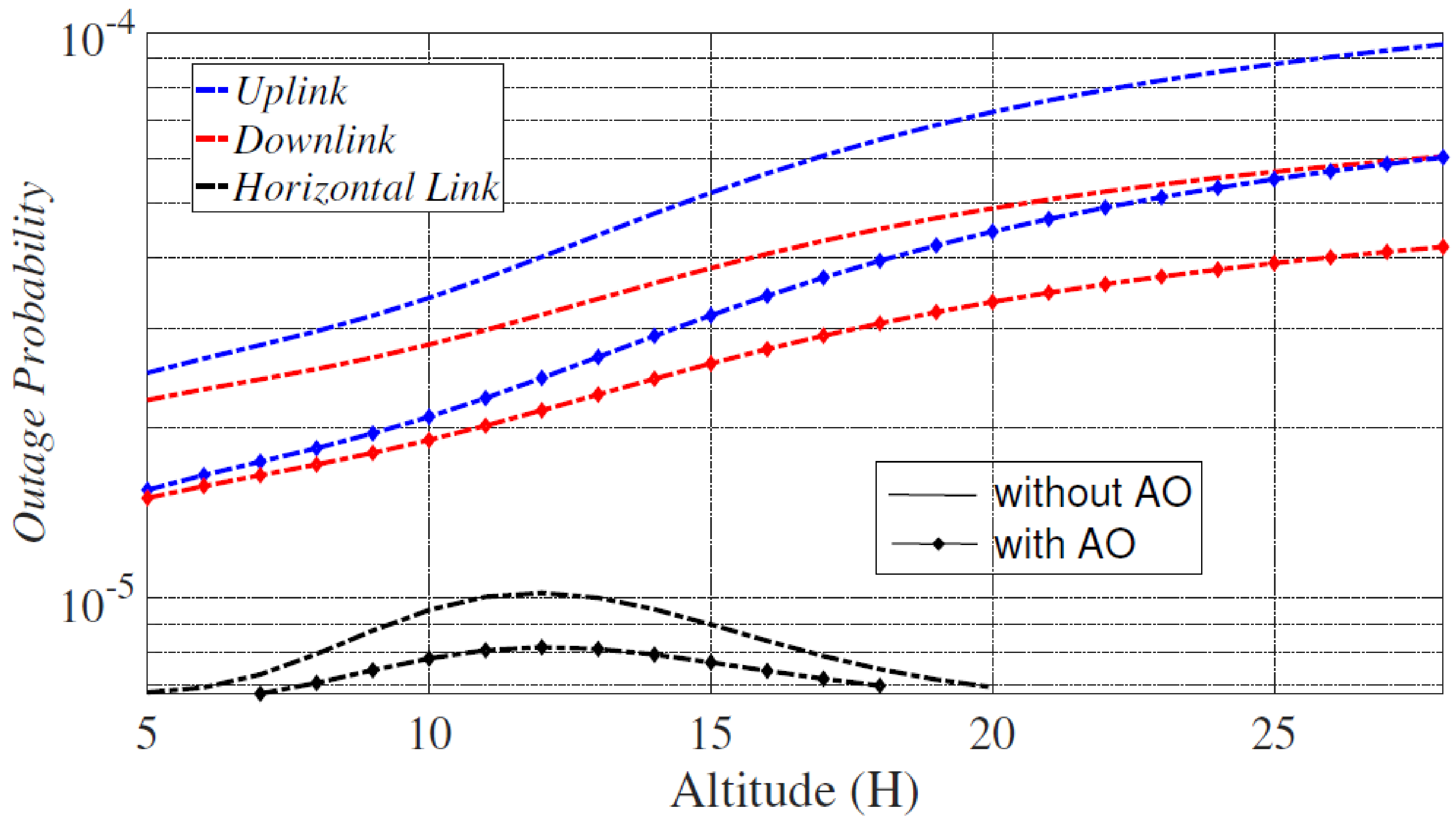
- Balanced vibrations

$$P_{out} = \frac{(\alpha\beta)^{\frac{\alpha+\beta}{2}} \eta_s^2 h_{af} e^{-\frac{\sigma_0^2}{2}} {}_1F_1\left(-\frac{1}{2}, \frac{1}{2}; \frac{\sigma_0^2}{2}\right)}{A_0^{(\alpha+\beta)/2} \Gamma(\alpha)\Gamma(\beta) h_{al}^{(\alpha+\beta)/2}} h_{th}^{\frac{\alpha+\beta}{2}}$$

$$\times G_{2,4}^{3,1}\left(\frac{\alpha\beta}{A_0 h_{al}} h_{th} \middle| \begin{matrix} \frac{2-\alpha-\beta}{2}, \frac{2-\alpha-\beta+2\eta_s^2}{2} \\ \frac{-\alpha-\beta+2\eta_s^2}{2}, \frac{\alpha-\beta}{2}, \frac{\beta-\alpha}{2}, \frac{-\alpha-\beta}{2} \end{matrix}\right).$$

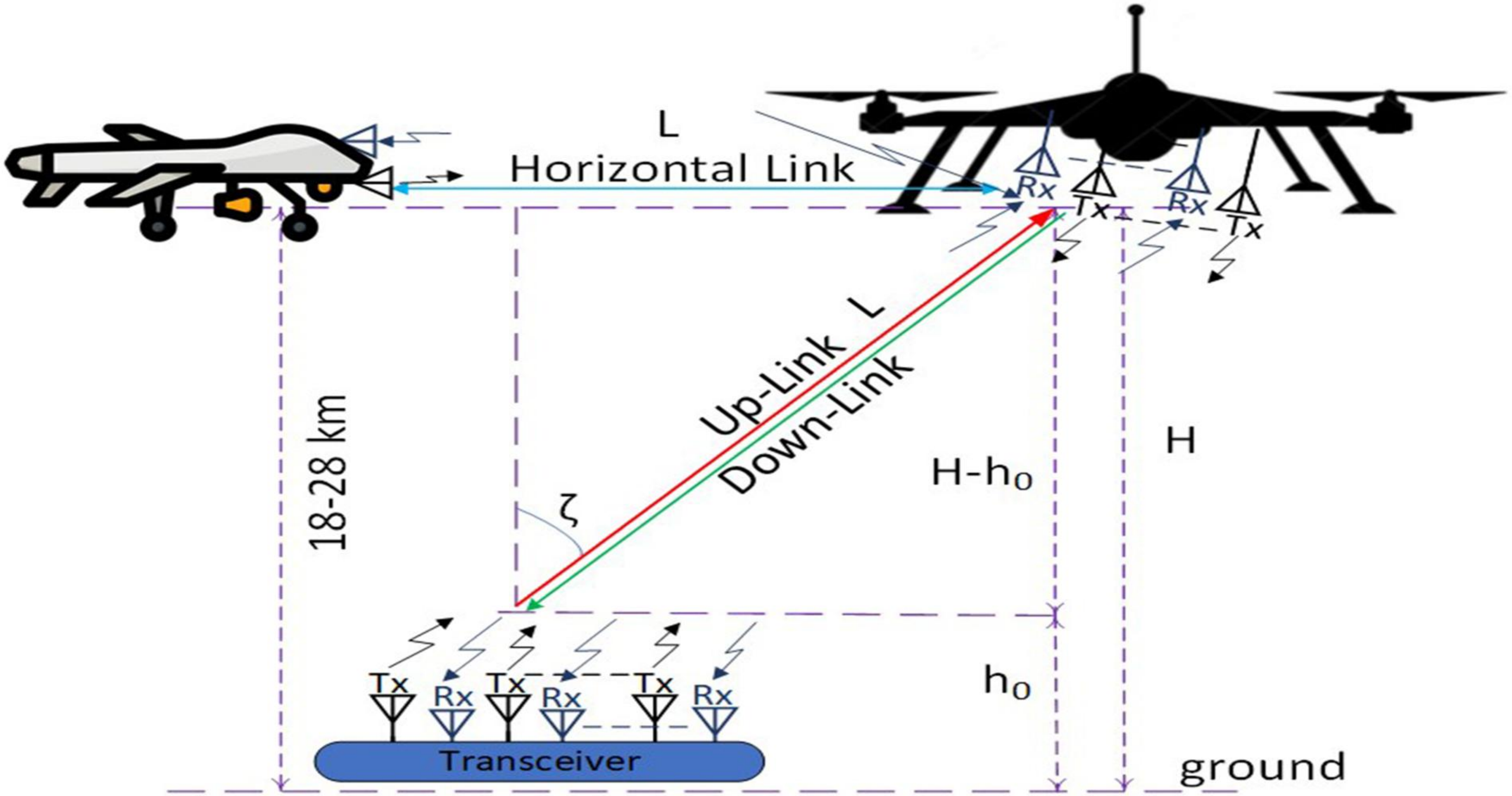
[1] *H. –J. Moon, C. –B. Chae, K. –K. Wong, and M. –S. Alouini*, "**A generalized pointing error model for FSO links with fixed wings UAV for 6G**", IEEE Trans On Wireless Com, 2025
[2] *Y. Ata and M.-S. Alouini, "**HAPS based FSO links performance analysis and improvement with adaptive optics correction** ", IEEE Trans. On Wireless Com., 2023.*
[3] M. Borwein and R. E. Crandall, "**Closed forms: What they are and why we care ?'',** Notices of the AMCS, vol. 60, no. 1, pp. 50-65, January 2013.

Uplink, Downlink, Horizontal Link Comparison



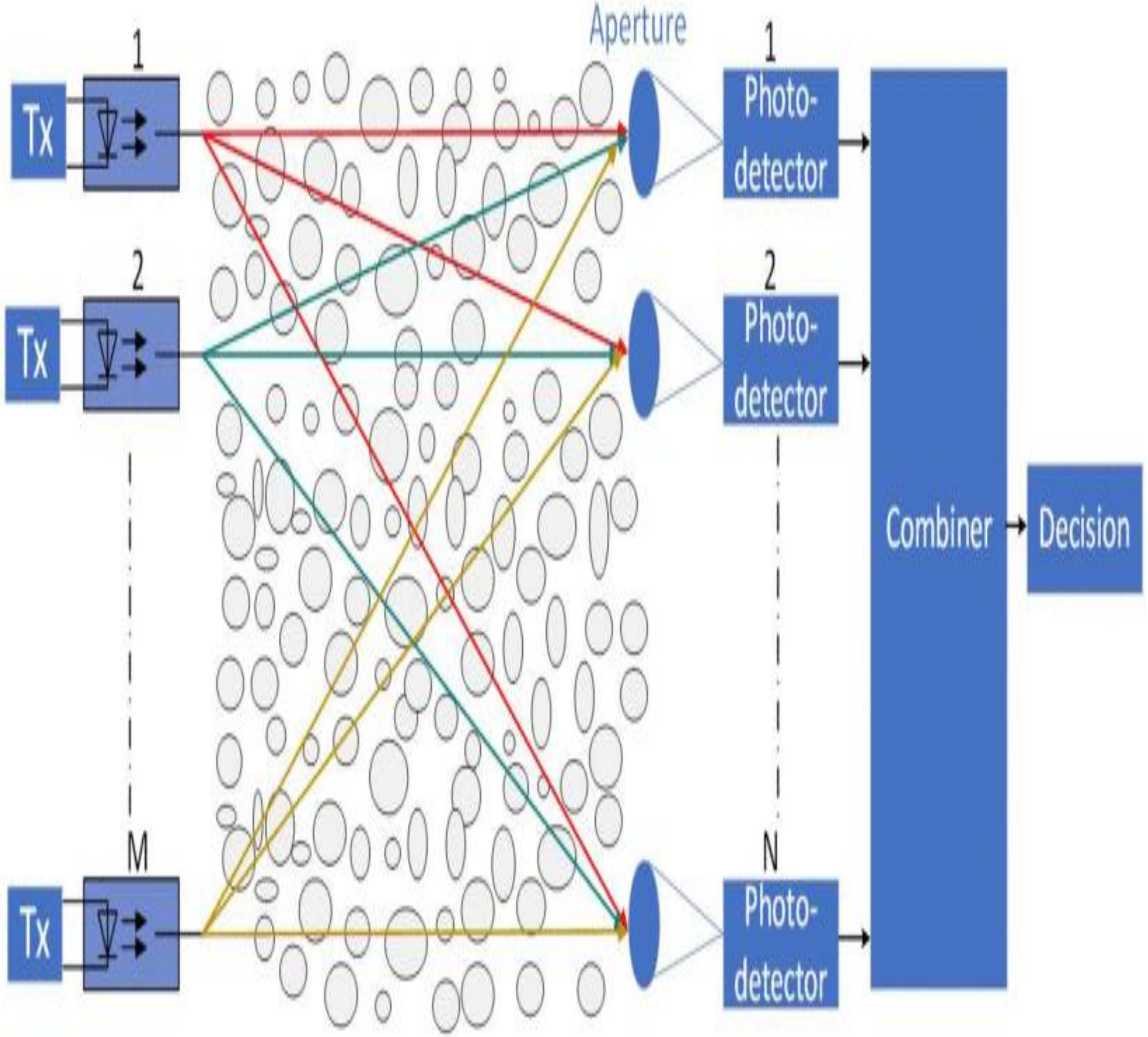
[1] *Y. Ata and M.-S. Alouini,* "**HAPS based FSO links performance analysis and improvement with adaptive optics correction** ", IEEE Trans. On Wireless Com., 2023.

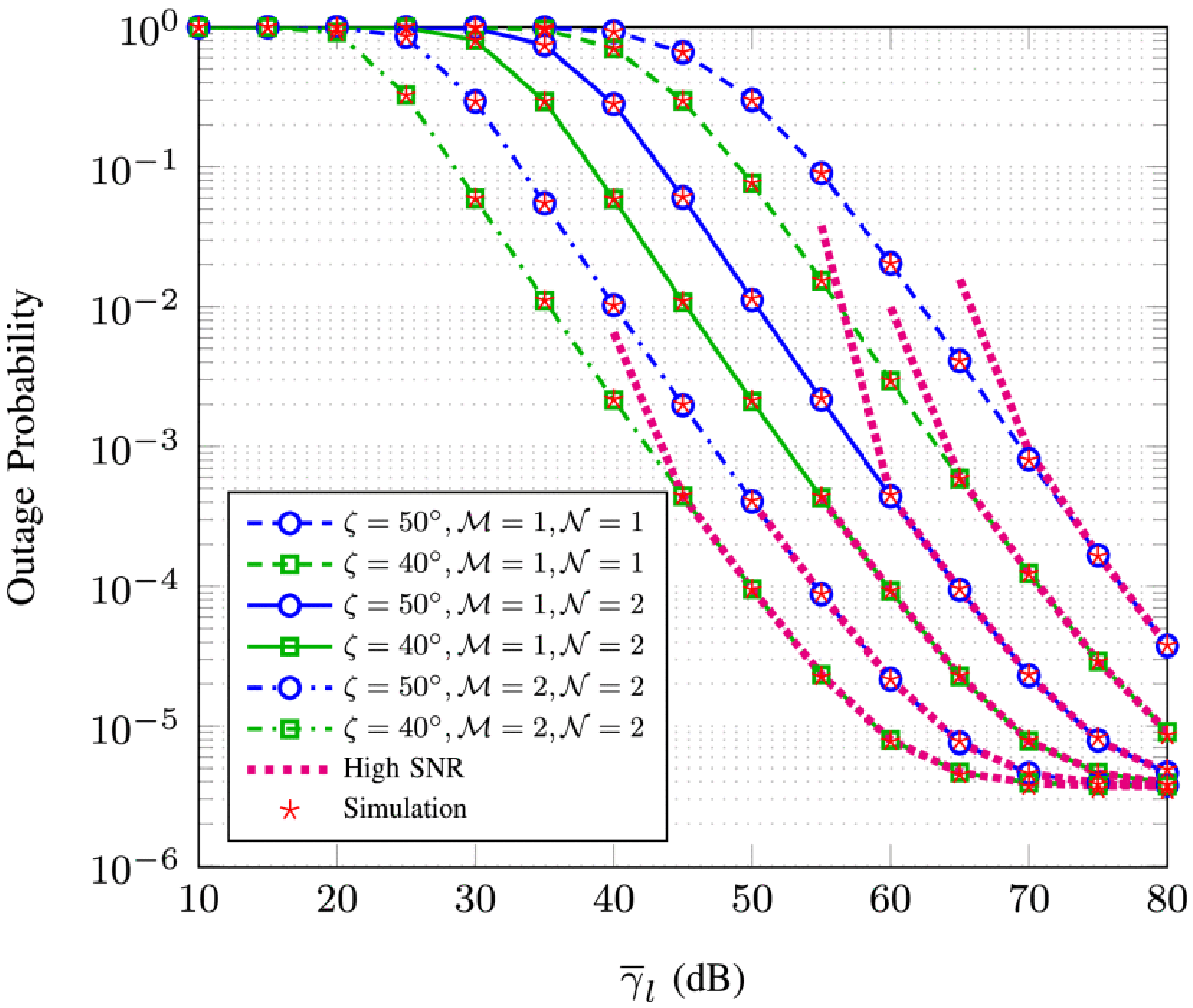
Multiple Input Multiple Output (MIMO) FSO



[1] *E. Zedini, Y. Ata, and M.-S. Alouini*, "**Improving Performance of Integrated Ground-HAPS FSO Communication Links With MIMO Application** ", IEEE Photonics Journal, April 2024.

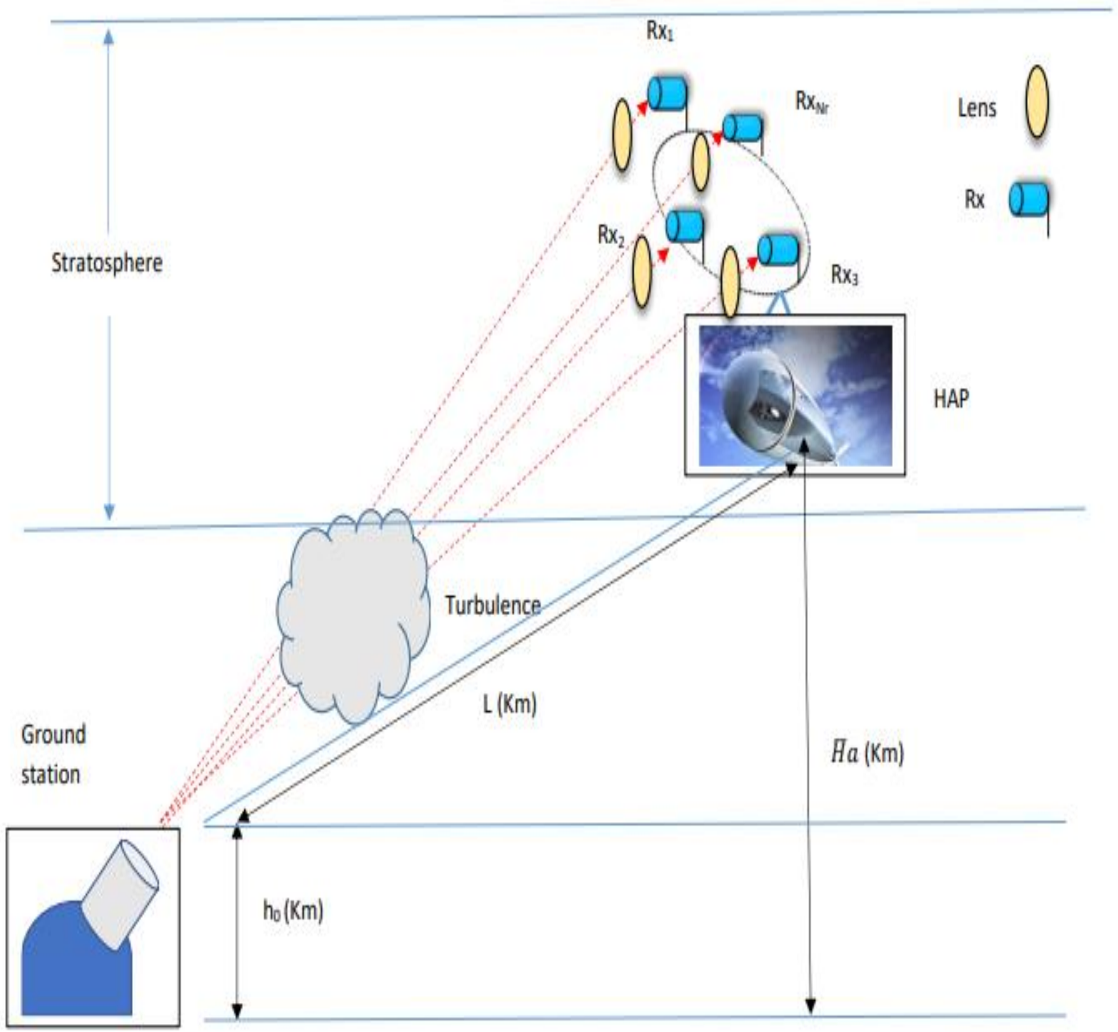
Performance of MIMO FSO Systems

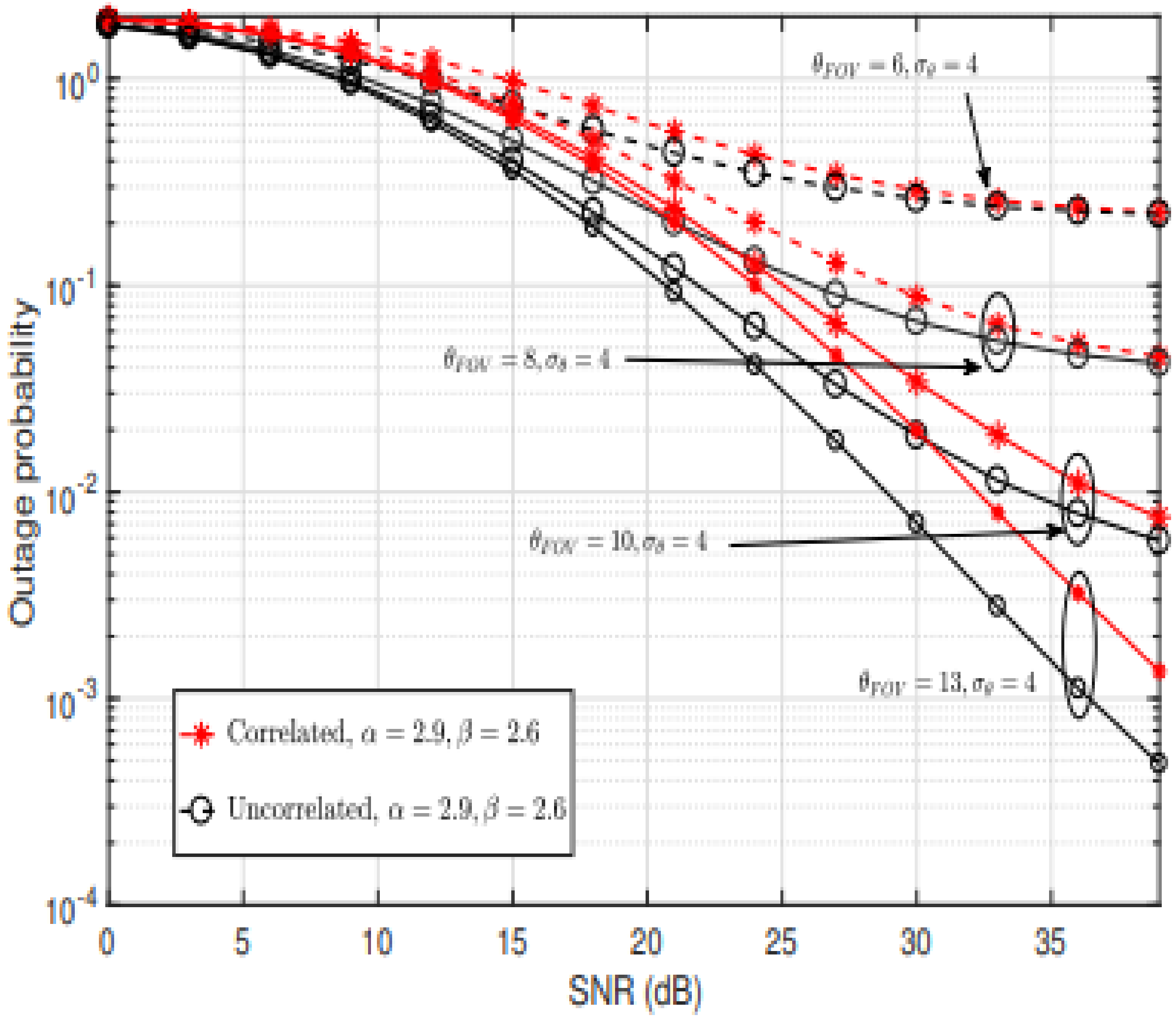




[1] *E. Zedini, Y. Ata, and M.-S. Alouini*, "**Improving Performance of Integrated Ground-HAPS FSO Communication Links With MIMO Application** ", IEEE Photonics Journal, April 2024.

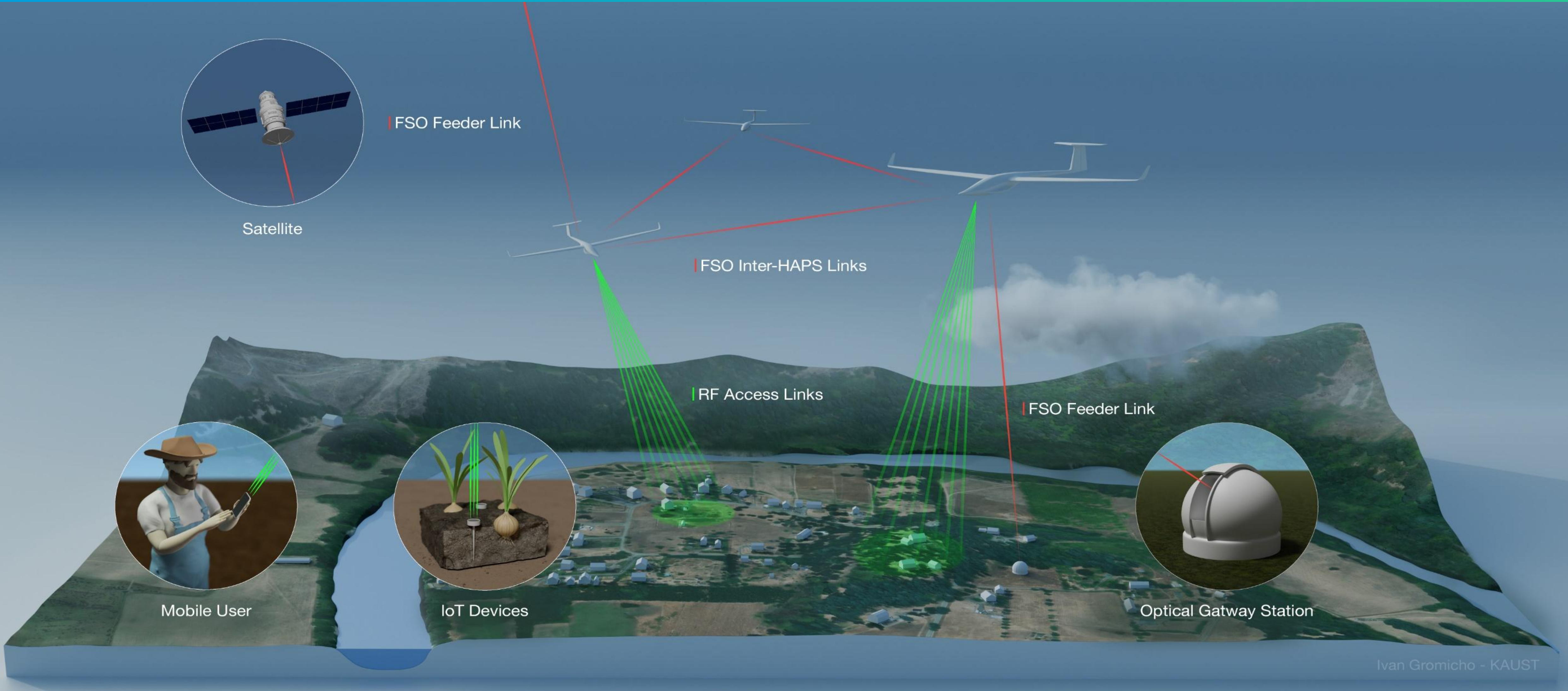
Impact of Turbulence Correlation on MIMO FSO





[1] R. Priyadarshani *and M.-S. Alouini,* "Earth-to-HAP FSO communication with spatial diversity and channel correlation ", IEEE Transactions on Aerospace and Electronic Systems, Feb. 2024.

Hybrid VHT HAPS Stratospheric Cellular IAB Network



Y. Zhang, M. Kishk, and M. -S. Alouini, " Freshness-aware energy efficiency optimization for integrated access and backhaul networks", IEEE Transactions on Wireless Communications, 2024.

Conclusion

- World's dependence on **air and space networks** is growing at a fast paste for land, sea, and air end-user terminals deployed in rural, post-disaster, aeronautical/maritime, or urban offloading broadband communication scenarios
- An opportunity for **massive MIMO** and **FSO communication technology** to capitalize on their unique advantages to enter this expected mass market demands
- Research on (i) energy efficient MIMO, (ii) adaptive optics, (iii) integrated space-air-ground networks, (iv) site and/or RF back-up diversity, (v) practical low-cost PAT systems …. to enable our **global, reliable, and affordable** broadband connectivity holy grail objective.

[2] Z. Lou, *B.E.Y. Belmekki, and M.-S Alouini*, "**HAPS in the Non-Terrestrial Network Nexus: Prospective Architectures and Performance Insights**", IEEE Wireless Communications, 2023.

Where to Find Us

UNESCO
Chair on Education
Connect the Unconnected

LinkedIn

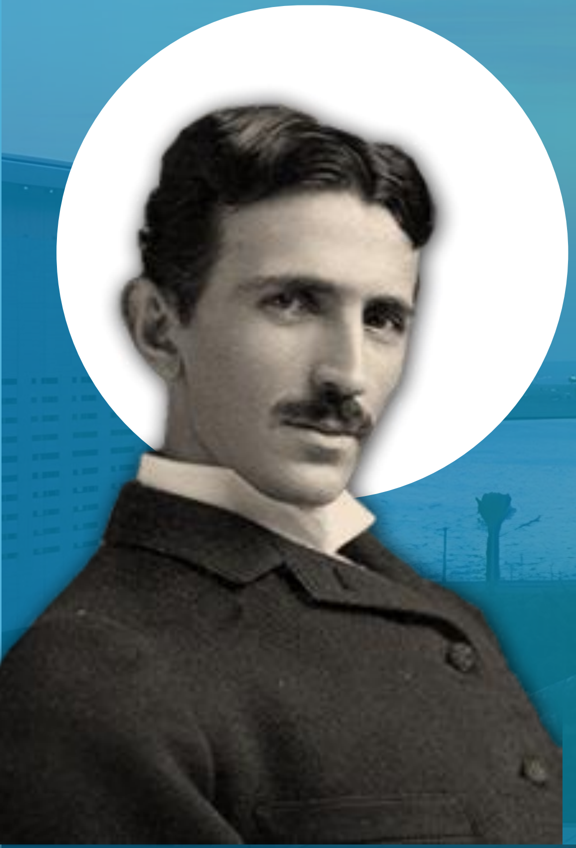
KAUST-CTL Media
YouTube Channel

YouTube

CTL

Website

Thank You



"

*A telephone subscriber here may call up and talk to any other subscriber on the **Globe**. An **inexpensive** receiver, not bigger than a watch, will enable him to listen **anywhere**, on **land** or **sea**, to a speech delivered or music played in some other place, however **distant**.*

— Nikola Tesla 1919